COMPARISON OF THE EFFECTIVENESS OF TWO BUDYKO-BASED METHODS FOR ACTUAL EVAPOTRANSPIRATION IN UTTAR PRADESH, INDIA

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ABSTRACT:

Evapotranspiration is an important indicator in hydrology, agriculture, and climate. The classical methods to compute the evapotranspiration incorporate climate data of temperature and precipitation. Thornthwaite and Budyko approaches, therefore called here TBA, are the most applied methods for monthly potential evapotranspiration (ET0) respective actual evapotranspiration (AET0). In this study, we have compared the differences between ET0 and AET0 carried out with TBA methods with the crop evapotranspiration (ETc) and actual crop evapotranspiration (AETc) carried out with new methods of TBA applied at spatial scale (TBSS) including the land cover data. Mean monthly rainfall and mean monthly air temperature from 24 meteorological stations located in the Uttar Pradesh State from India were analyzed together with the land cover data to observe and analyse the spatial distributions and differences in evapotranspiration pattern. The study was conducted for 1951 – 2000 period including seasonal analysis. The results indicates that during the mid-season, the ET0 reaches highest values (856.25 mm) while in the same period, the ETc indicates values about 1343.44 mm. The differences between seasonal ET0 and ETc were observed also for the initial and end seasons, with significant increases in evapotranspiration (about 200 mm). Interestingly, during the cold season, the ET0 has higher values than ETc with about 20 mm. As consequences of seasonal increases of the ETc, the annual ETc and AETc indicate higher values than annual ET0 and AET0. These aspects may imply the reduction of runoff and water availability in the study area. Moreover, these findings highlight the importance of land cover pattern in the calculation of evapotranspiration and water balance. The results are illustrates that the applied methodology including the land cover data is more reliable for regional scale and water management investigation rather than the classic methods.

Key-words: *Climate change, Water balance, Evapotranspiration, Crop coefficient, Land cover, Uttar Pradesh.*

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1. INTRODUCTION

Evapotranspiration plays an essential role in the water balance and estimation of water renewals. Climatic components are often used in the studies regarding water availability, recharge of groundwater, and drought periods. Surface waters and groundwater represent precious resource that depend by precipitation regime. Climate change effects on different natural systems are an uncontested mater. Mostly, the impact of climate has negative (Parmesan & Yole, 2003; Kløve et al., 2014; Cox et al., 2013; Kløve et al., 2014; Prăvălie, 2014) consequences on the main resource of the Globe: water. However, the climate change affects directly and indirectly the hydrological cycle and groundwater resources as well. The main problems of freshwaters which occurs due to climate variations include the decrease of groundwater recharge, surfaces waters runoff reductions, melting of glaciers, decreased recharge of karst aquifers and decreased groundwater levels (Collins, 2008; Aguilera & Murillo, 2009; Hidalgo et al., 2009; Piao et al., 2010; Jiménez Cisneros et al., 2014). The Global and regional climate changes were claimed in many scientifically papers (Haeberli et al., 1999; IPCC, 2001; Oerlemans, 2005; IPCC, 2007; Cheval et al., 2014; IPCC, 2014; Čenčur Curk et al., 2015; Constantinescu et al., 2016; Nistor et al., 2016). The climate warming and high water consumptions may lead to reduction of spring's flow discharge in many regions of the Globe (Yustres et al., 2013; Kløve et al., 2014).

Up to present, in different countries and regions of the world, the scientists approve several methods to determine the evapotranspiration, including original or modified methods. The effects of climate change on evapotranspiration is mainly related to temperature regime and the water renewals are depending much by precipitation regime. Evapotranspiration in a certain territory may be estimated through calculations by empirical formula or by in-situ measurements. However, the last method is useful in particular locations and due to it's limits, the large territories should be estimates by formulas. During the last decades, numerous scientist estimated the evapotranspiration including the crops and land cover. Allen et al. (1998) proposed the standard methodology of ETc using crop coefficients (Kc) calculated for various types of vegetation and crops, in different zones of the Globe. One of the simplest and high applicability approach is Thornthawaite method (1948) for monthly ET0. In the end of 1990s, Grimmond & Oke (1999) examined the Kc in urban areas from United States. They have calculated the Kc not only for green areas, but also for urban, bare soil, and impervious lands. More recently, Nistor & Porumb-Ghiurco (2015) combined the Thornthwaite (1948) and Allen et al. (1998) methods to analyse the ETc at spatial scale for four seasons. Further, their method have been successfully applied for different regions from Europe and for Turkey (Nistor et al., 2017, Nistor et al., 2019). In the Grand Est region from France, Haidu & Nistor (2019a) used the ETc and precipitation for water availability calculation. The agriculture is the main function of the region and the study of evapotranspiration and water resources is necessary in the region.

The objective of this paper is to compare the classical evapotranspiration method of TBA with the new method TBSS carried out by climate data and land cover. As an example, in this study the spatial distribution of the climate variables over the Uttar Pradesh

State from India were used. The comparison consists in seasonal and annual maps of ET0, ETc, AET0, and AETc over 1951-2000 period.

2. STUDY AREA

Uttar Pradesh State is located in the North of India, close to the tropic zone (Figure 1). During the period 1951-2000, the mean annual temperature of the study area ranges between 24.41 °C and 26.16 °C, indicating the higher values in the eastern part of the region (Figure 2a). The annual precipitation regime varies from 253 mm to 1050 mm, with the much humid values in the East and South-East parts (Figure 2b).

According to Köppen-Geiger climate classification, the area has a warm temperate climate with warm summers (Cfb). Kottek et al. (2006) characterize the Cfb climate type as fully humid.

The land cover of the study area is mainly composed by crop lands, plantations and grass land. The northern and southeastern parts are covered by forest. I the region are presents numerous cities and artificial areas, while the surface water resources are present mainly by two long rivers Ganga and Yamuna and lakes in the southern part. The fallow and barren lands are extending much in the southern part.
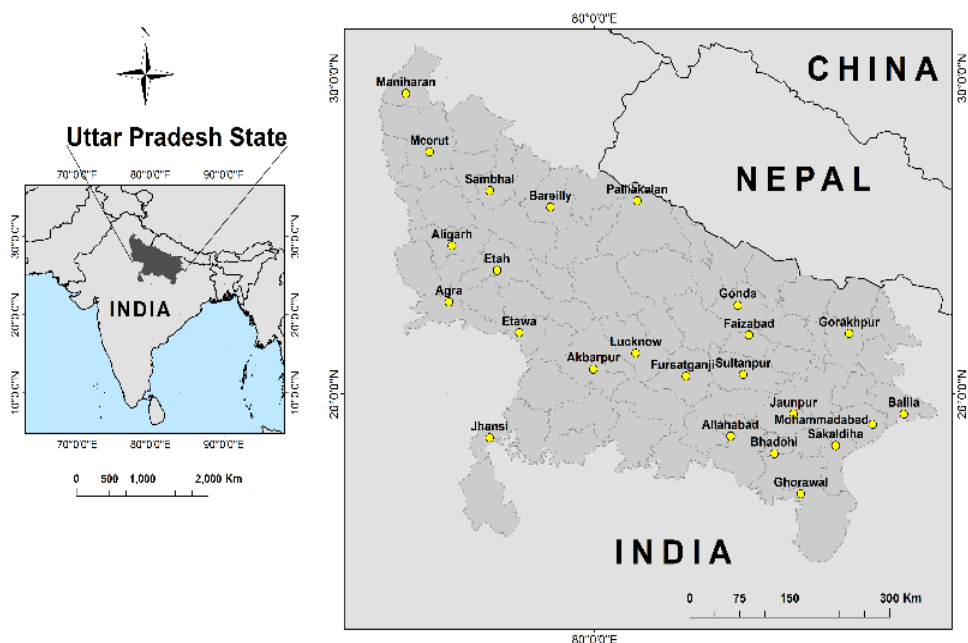

Fig. 1. Location of Uttar Pradesh State on the map of India.

3. MATERIALS AND METHODS

3.1. Overview of the methodology

This work is focusing on spatial procedures to estimate the distribution of evapotranspiration using different methods. Two methods (TBA and TBSS) were applied to for evapotranspiration using climate data from 24 meteorological stations.

In order to obtain the continuous surface of groundwater table over Singapore, Ordinary Kriging (OK) was used as it is recognized in the geostatistical analyses as one of the most important interpolator (Setianto & Triandini, 2013).
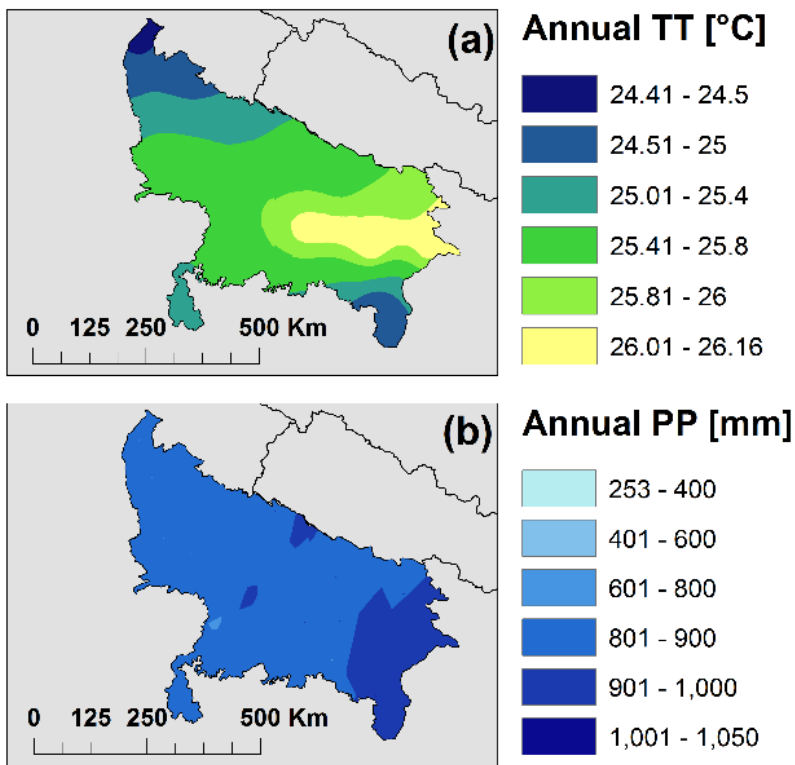

Fig. 2. Spatial variation of mean annual temperature and mean annual precipitation in Uttar Pradesh State. a. Temperature variation 1951-2000. b. Precipitation variation 1951-2000.

3.2. Climate data

Mean monthly air temperature and monthly precipitation from 1951-2000 were used in this study to calculate the ET0, ETc, AET0, and AETc. The climatic data belong to 24 meteorological stations located in the Uttar Pradesh State and these data are courtesy from Indian Meteorological Department at Pune, India (http://www.imdpune.gov.in/). The stations are well distributed in the territory and the data were homogenized and corrected for the long-term period. Table 1 shows the characteristics of climatological stations used in this study.

3.3. Land cover data

Land cover data in 12 classes was used to set up the seasonal Kc at spatial scale for each land cover type in Uttar Pradesh State. The data belong to Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) and has a resolution of 100 m (Roy et al., 2015). Landsat data from 2005 was used as support for the land cover extraction. By supervised classification method, the land cover pattern was prepared.

Table 1.
The meteorological stations and their corresponding geographical co-ordinates (latitude and longitude) and elevations.

Station	Latitude N (decimal degrees)	Longitude E (decimal degrees)	Altitude above mean sea level (m)
Agra	27.17	78.03	169
Aligarh	27.88	78.07	187
Allahabad	25.45	81.73	698
Ballia	25.75	84.17	64
Bareilly	28.37	79.4	172
Sakaldiha	25.35	83.25	79
Etah	27.57	78.68	172
Etawa	26.78	78.98	197
Faizabad	26.75	82.08	102
Mohammadabad	25.62	83.75	77
Gonda	27.13	81.93	110
Gorakhpur	26.77	83.43	84
Juanpur	25.75	82.68	81
Jhansi	25.45	78.58	249
Akbarpur	26.32	79.98	200
Palliakalan	28.45	80.57	148
Lucknow	26.52	80.55	111
Meerut	29.07	77.77	237
Sambhal	28..58	78.58	293
Bhadohi	25.25	82.42	78
Fursatganji	26.23	81.23	88
Maniharan	29.81	77.45	264
Ghorawal	24.74	82.78	303
Sultanpur	26.25	82	96.8

3.4. Evapotranspiration

3.4.1. Potential evapotranspiration (ET0)

Thornthwaite (1948) method (Eq. (1)) was used to calculate the ET0 for Uttar Pradesh State during 1951-2000. This method implies the mean monthly air temperature data. Even if is old, this methods is used often in hydrology and climate studies at regional scale and for long period (Zhao *et al.*, 2013; Čenčur Curk *et al.*, 2014; Cheval *et al.*, 2017). Based on monthly ET0, the seasonal ET0 was calculated and further, the seasonal ETc was determined.

$$ET_0 = 16bi(\frac{10T_i}{I})^\alpha \quad \text{[mm/month]} \tag{1}$$

where:

ET$_0$ = potential evapotranspiration;

bi = radiation parameter for specific latitude (Table 2);
T$_i$ = monthly air temperature;
I = annual heat index (see Eq. 2);
α = complex function of heat index (see Eq. 3)

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514} \tag{2}$$

where: T$_i$ = monthly air temperature

$$\alpha = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.7912 \times 10^{-2}I + 0.49239 \tag{3}$$

where: I = annual heat index

Table 2.

Sunshine parameter (expressed in units of 30 days of 12 h).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
bi (25° N latitude)	0.93	0.89	1.03	1.06	1.15	1.14	1.17	1.12	1.02	0.99	0.91	0.91

Source: Thornthwaite (1948)

3.4.2. Seasonal and annual crop evapotranspiration (ETc)

In order to calculate the seasonal ETc, the ET0 of each season was multiplied by Kc of the respective season (Eqs. (4-7)). The annual ETc represents a sum of all seasons (Eq.(8)). The calculations were completed using raster grid data in ArcGIS environment. In this study were are using the standard Kc values following growth stages (Allen *et al.* 1998).

Therefore, four developmental stages of crop growth in one year were used in this present study and for each land cover type was assigned a specific value of Kc for that season. For the evapotranspiration rate in the areas with bare soil, open water and urbanization, the values of Kc were chosen accordingly to Grimmond and Oke (1999). They have calculated the Kc in base of studies in several cities from United States.

The seasons were divided as follow: initial season from March to May, mid-season from June to August, end season from September to November and cold season during January, February, and December. Table 3 reports the specific Kc for the land cover types from the study area. Figure 3 illustrates the spatial distribution of the seasonal Kc over Uttar Pradesh State.

$$ET_{c\ ini} = ET_{0\ ini} \times K_{c\ ini} \tag{4}$$

$$ET_{c\ mid} = ET_{0\ mid} \times K_{c\ mid} \tag{5}$$

$$ET_{c\ end} = ET_{0\ end} \times K_{c\ end} \tag{6}$$

$$ET_{c\ cold} = ET_{0\ cold} \times K_{c\ cold} \tag{7}$$

$$Annual\ ET_c = ET_{c\ ini} + ET_{c\ mid} + ET_{c\ late} + ET_{c\ cold} \tag{8}$$

Table 3.
Land cover classes and representative seasonal Kc coefficients for the Uttar Pradesh State

Corine Land Cover	Kc ini season	Kc mid season	Kc end season	Kc cold season
Land cover description	Kclc	Kclc	Kclc	Kclc
Built-up land	0.2	0.4	0.25	-
Wasteland	0.16	0.36	0.26	-
Plantation	0.3	1.05	0.5	-
Cropland	1.1	1.35	1.25	-
Deciduous broadleaf forest	1.3	1.6	1.5	0.6
Mixed forest	1.2	1.5	1.3	0.8
Grassland	0.3	1.15	1.1	-
Shrubland	0.8	1	0.95	-
Fallow land	0.4	0.6	0.5	-
Barren land	0.1	0.15	0.05	-
Permanent wetlands	0.15	0.45	0.8	-
Water bodies	0.25	0.65	1.25	-

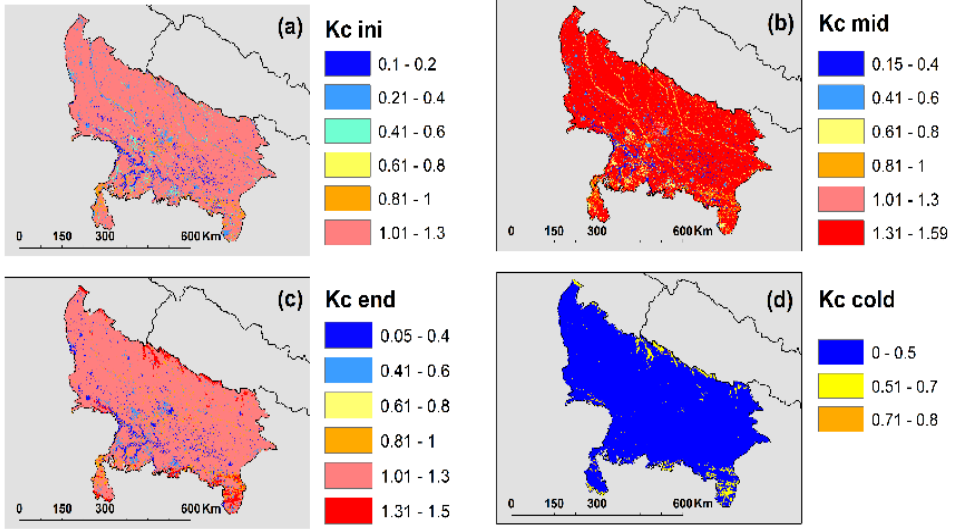Source: From Allen et al. (1998); Nistor and Porumb-Ghiurco (2015); Nistor (2017); Nistor et al. (2017)

Fig. 3. Spatial distribution of crop coefficient (Kc) in Uttar Pradesh State. (a) Kc for initial season (Kc ini). (b) Kc for mid-season (Kc mid). (c) Kc for end season (Kc end). (d) Kc for cold season (Kc cold).

3.4.3. Determination of AET0 and AETc

The AET0 and AETc were calculated by Budyko (1974) approach (Eq. (9)). The method consists in aridity index φ calculation (Eq. (9)) and further in annual AET0 incorporanting also precipitation data. In case of AETc, the ETc was used instead of ET0 for the aridity index φ calculation. The Budyko's formula contributes to water balance determination and in the same time, it indicates if the heat energy is enough to produce the evaporation from the precipitation data (Gerrits *et al*., 2009; Cencur Curk *et al*., 2014). Recently, Haidu & Nistor (2019b) used Budyko approach to determine the climate change effect on groundwater resources in the Grand Est region, France.

$$\varphi = \frac{ET0}{PP} \tag{9}$$

$$\frac{AET0}{PP} = [\left(\varphi tan\frac{1}{\varphi}\right)(1 - exp^{-\varphi})]^{0.5} \tag{10}$$

where:

AET0   actual land cover evapotranspiration [mm]

PP   total annual precipitation [mm]

φ   aridity index (Eq. (9))

4. RESULTS

4.1. Variation of seasonal and annual ET0 and Etc

Overall, the results carried out with the TBSS methods indicates higher maximum values in comparison with the TBA method both for seasonal and annual ETc. Thus, during the initial season, the ET0 ini shows values from 511.12 mm to 757.31 mm (Figure 4a). In the same season, the ETc ini indicates values between 56.32 mm to 968.61 mm (Figure 4b). For both ET0 ini and ETc ini, the high values were depicted in the South-central part of the region, while the low values were depicted in the northwestern part (ET0 ini) and in most of the urban and settlements areas.

The ET0 mid indicates values between 702.8 mm to 856.25 mm while the ETc mid shows values between 117.7 mm to 1343.44 mm. In this season, the higher values of ET0 mid were identified in the central and West-central parts of the Uttar Pradesh State (Figure 4c). The ETc mid recorded high values in the northern and northwestern parts of the region, mainly in the areas deciduous broadleaf forest (Figure 4d).

During the end season, the ET0 end values are ranging from 301.9 mm to 395.55 mm. In the same season, ETc end values varies from 15.19 mm to 588.99 mm. The ET0 end has high values in the West and East parts of the region (Figure 4e), while the ETc end shows higher values in the North and North-West of the region (Figure 4f).

Interestingly, the values of the ET0 cold are varying from 62.05 mm to 95 mm and the ETc cold vary from 0 mm to 75 mm. The higher values of ET0 cold were depicted in the eastern and southeastern part of the Uttar Pradesh State (Figure 4g), while the higher values of the ETc cold were depicted in few locations from the northern and southern parts (Figure 4h).

The annual ET0 varies from 1751 mm to 2003 mm, indicating higher values in the West, central, and East parts of the region. The lower values were identified in the North-West and South-East, but still these values are exceeding 1700 mm (Figure 5a). The variation of annual ETc is between 193 mm and 2869 mm, with most of the territory in the range of 2000 mm and 2500 mm. The higher values were identified in the northern and southern parts of the region. The lower values were depicted in the urban areas and wastelands (Figure 5b).

4.2. Variation of aridity index, AET0, and AETc

As ratio between evapotranspiration and precipitation, the aridity index indicates the drought and leak of water for the higher values of the index. In the Uttar Pradesh State, the aridity index was calculated as the basis for deriving the AET0 and AETc values. Thus, the aridity index calculated for AET0, incorporates the annual ET0 and it shows values between 1.7 and 7.6, but most of the territory has values between 2 and 3. For the AETc, the annual ETc was used in the ratio formula. The aridity index carried out for AETc shows values between 0.2 and 5.2.
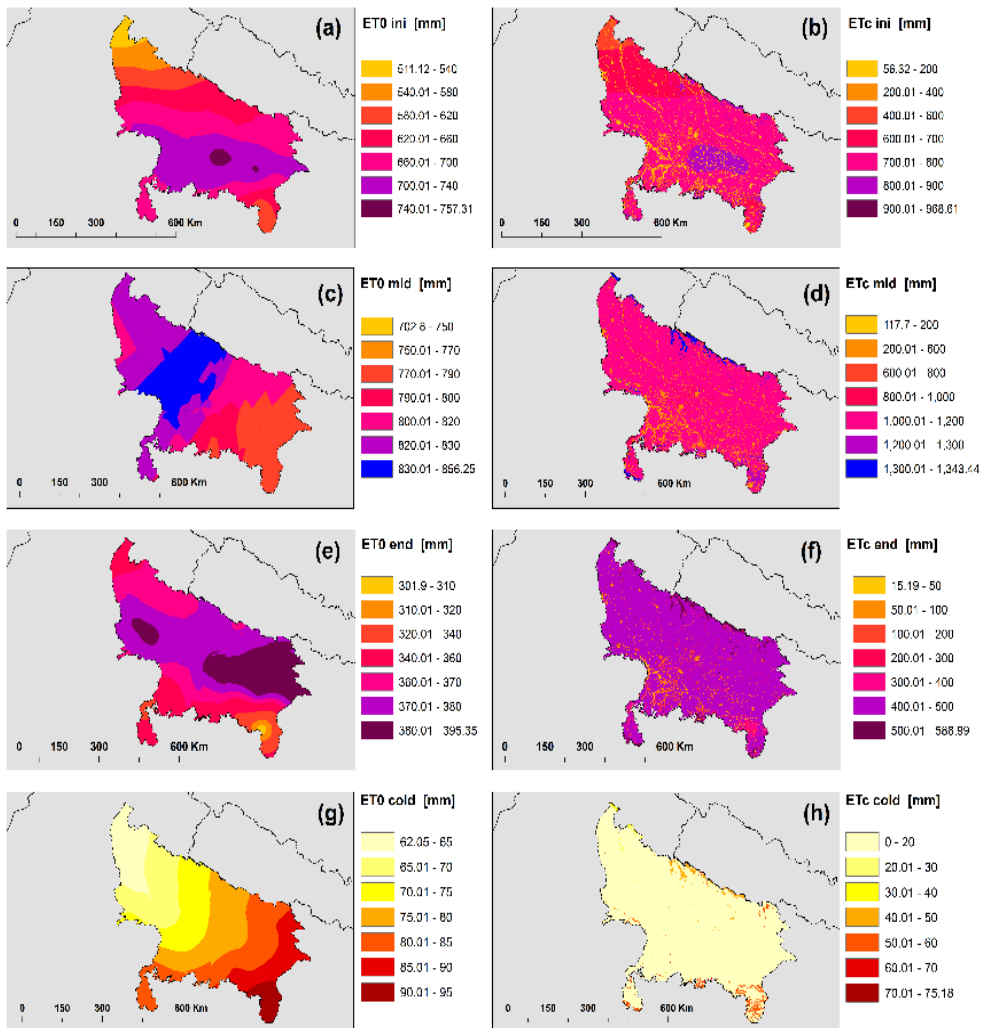
Fig. 4. Spatial distribution of seasonal potential evapotranspiration (ET0) and potential crop evapotranspiration (ETc) in Uttar Pradesh State. (a) ET0 for initial season (ET0 ini). (b) ETc for initial season (ETc ini). (c) ET0 for mid-season (ET0 mid). (d) ETc for mid-season (ETc mid). (e) ET0 for end season (ET0 end). (f) ETc for end season (ETc end). (g) ET0 for cold season (ET0 cold). (h) ETc for cold season (ETc cold).

The AET0 varies from 253 mm to 906 mm, indicating higher values in the eastern and central parts of the region. The lower values were identified in the northwestern and southwestern parts (Figure 6a). The variation of AETc is between 183 mm and 923 mm (Figure 6b). The higher values were identified in the northern and southern parts of the region. The lower values were depicted in the urban areas and wastelands.
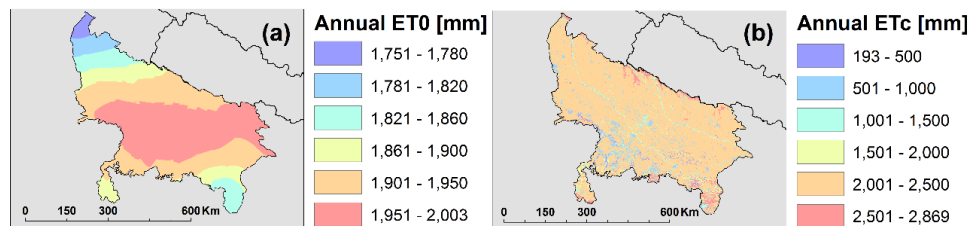

Fig. 5. Spatial distribution of annual potential evapotranspiration (Annual ET0) and annual potential crop evapotranspiration (Annual ETc) in Uttar Pradesh State. (a) Annual ET0. (b) Annual ETc.
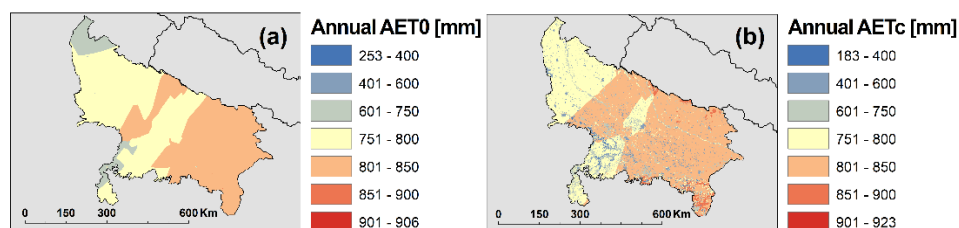

Fig. 6. Spatial distribution of annual actual evapotranspiration (AET0) and annual actual crop evapotranspiration (AETc) in Uttar Pradesh State. (a) Annual AET0. (b) Annual AETc.

5. DISCUSSION

The applied complex methods based on TBA and TBSS integrate the climate and land cover data for determination of seasonal and annual ET0 and ETc, and for annual AET0 and AETc. Based on the climatological data from the 1951-2000 recorded in Uttar Pradesh State, the application of the two methods for evapotranspiration was completed. Firstly, the TBA includes only the temperature and precipitation data, while the TBSS includes the vegetation pattern. The difference in findings of the two methods is obviously not only at numerical results but also at spatial scale. In fact, the TBSS method is much useful at the spatial scale analyses. Secondly, the last method (TBSS) returns values higher and lower for the maxima and minima with respect to the TBA method. For this reason, the seasonal ETc indicates higher values for ETc ini, ETc mid, and ETc end in comparison with the seasonal ET0. In contrast, due to the reduced plants activities during the cold season, the ETc cold has lower values in comparison with the ET0 cold. The contribution of another

three seasons (ETc ini, ETc mid, and ETc end) for evapotranspiration are influencing the higher values of the annual ETc in comparison with annual ET0.

Thus, according to the TBA the values of evapotranspiration are not reaching the maximum and are not fall to the minimum that the TBSS method are given. The performance of the TBSS may help better in the agriculture studies, in varies types of land cover and crops. In this way, the areas with high Kc and low precipitation, could be in deep investigated and, if necessary, prepared for irrigation. Looking in much details, the TBSS method could be also be used for the water resources investigations. In this sense, the runoff and water availability could be calculated at spatial scale and the areas with low runoff and water availability could be protected by some activities (i.e. water exploitation, intense agriculture).

The results of this study underline the importance of continuously improving the traditional methods (i.e. TBA) with much current approaches that cover nowadays requirements (i.e. spatiality analysis with TBSS). In addition, the groundwater resources recharge at spatial scale could be estimated and further, different groundwater models could be set up.

The analysis of the original maps that we provided here can be a substantial way to evaluate the proprieties of the evapotranspiration and water resources in a single locations, focusing on a single type of land cover. For instance, the variations of evapotranspiration by TBA and TBSS indicate higher values of the maximum calculations for the TBSS due to the incorporation of Kc. The Kc values contribute to the increases of evapotranspiration for ETc ini, ETc mid and ETc end because the plants and crops plantations are active during these seasons. Regarding the cold seasons, only forest and threes are consuming heat energy.

The present research demonstrates how the same methods could return different results if the land cover pattern is included in the analysis. Due to the specific Kc for various seasons, the TBSS method could be more useful in the applicability of agriculture and water resources pressure under the climate change. Thus, our work become an important task not only in the climatology, hydrology and agriculture, but also for the regional administration of the environment. As an example, the delimitation of protection areas with respect of low water resources could be done using the present results. In addition, the groundwater vulnerability and future planning strategies could be drawn based of the original maps developed in this study.

6. CONCLUSIONS

This paper aimed in the comparison of the TBA and TBSS methods for the evapotranspiration. The application of these methods was completed on the Uttar Pradesh State from India using the land cover and climate data from 24 stations. By comparing the results of both methods, the following conclusions could be drawn:

- The procedures and calculations of the four seasons ET0 and ETc were applied on the Uttar Pradesh State from territory. Further, the AET0 and AETc were carried out using both TBA and TBSS methods.
- For the spatial analysis of ETc and AETc, the specific Kc was assigned for each land cover types. In base of this, the contribution of vegetation pattern for evapotranspiration was taken into consideration.
- Both TBA and TBSS methods return reasonable results with respect to the evapotranspiration at seasonal and annual temporal scales. As the findings confirmation, the evapotranspiration reach higher values in the mid-season.
- The maximum values of evapotranspiration, were found for ETc and AETc by using TBSS method.
- TBA method is much consistent with the climate data, while the TBSS follows the climate data but the results are controlled by the Kc values. However, both methods could be useful for hydrological, climatological, and agricultural studies.

This comparison represents a contribution for the existing approaches with respect to the evapotranspiration. The methodology can be widely used for investigations at spatial scale. The results indicate that the TBSS method is much realistic due to the incorporation of the land cover data. Based on the findings of this paper and the spatial calculations of ET0, ETc, AET0, and AETc in the Uttar Pradesh State, the environmental plans for management could be implemented in this region.

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