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Short Communication

Computation of reference evapotranspiration, its variability and trends in different agroclimatic regions of Punjab

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Reference evapotranspiration (ET_o) is an important climatic variable, which drives other regional climatic parameters including turbulence, formation of clouds and convection etc. (Vergopolan and Fisher, 2016) and is an important component of hydrological cycle. Mao *et al.* (2015) reported that about 2/3rd of the precipitation is expended by evapotranspiration globally as worldwide rainfall is 98.5 x10^3 km^3 $year^{-1}$ and evapotranspiration is 65.5 x 10^3 km^3 $year^{-1}$).Evapotranspiration is significantly affected byclimatic parameters (Hussain *et al.,* 2013; Fares *et al.,* 2016). Qian *et al.* (2007) concluded that precipitation changes dominated the ET trend rather than temperature. Shan *et al.* (2015) observed that wind speed contributed more to evapotranspiration. Djaman *et al.* (2018) observed that annual evapotranspiration was lowest in the regions with high precipitation and highest in the regions with dry climate.

The north-west India is facing dual challenge of climate variability and limiting water availability (Kingra *et al.*, 2017).Singh and Park (2018) reported that in 92% of agricultural land of the central Punjab,water table had drained by more than 0.6 m $year^{-1}$ between 2000 and 2010.Although FAO-Penman Monteith method (FAO-PM) is globally accepted for computing ET_o (Allen *et al.*, 1998), but limited availability of weather data restricts its use for many locations. Thus, other methods need to be validated with reference to FAO-Penman method (Kingra *et al.,* 2002; Kingra and Hundal, 2005; Kukal and Irmak, 2016). Keeping this in view, the present study was conducted to identify most appropriate methods to compute ET_O in different agroclimatic regions of Punjab for judicious water management in future.

Study area

The study area included Ballowal Saunkhari in sub-humid north-east region, Ludhiana in semi-arid central plain region and Bathinda in arid south-west region. As per the availability, the long-term records on open pan evaporation, maximum temperature, minimum temperature, mean relative humidity, wind speed and sunshine hours were collected from agrometeorological observatories located at these sites. The data of Ballowal Saunkhari was from 1984 to 2018, Ludhiana from 1970 to 2018 and Bathinda from 2000 to 2018.

Computation of reference evapotranspiration (ET_o)

*ET_o*was calculated using FAO-PM (Allen *et al.,* 1998) and HS (Hargreaves and Samani, 1985). The variability and trends in long-term ET_o were studied using non-parametric (Mann-Kendall test and Sen's slope estimator) tests (Kingra *et al.*, 2018). Relation between open pan evaporation and ET_o was studied.Since FAO-PM is used globally for computing ET_o, therefore ET_o computed using HSmethod was related with FAO-PM method.

Spatio-temporal variability in annual and seasonal Pan-E and ETo

The annual as well as seasonal Pan-E in different agroclimatic regions of Punjab increased from sub-humid to arid region. The annual, *kharif* and *rabi* season Pan-E was observed to be 1577.1$\pm$223.1, 996.8$\pm$153.6 and 576.2$\pm$82.4mm in the sub-humid region, 1703.9$\pm$240.9, 1124.2$\pm$164.8 and 575.3$\pm$97.3mm in semi-arid region and 1990.9$\pm$291.9, 1328.4$\pm$200.7 and 666.6$\pm$118.0mm in the arid region. Whereas annual, *kharif* and *rabi* season FAO-PM ET_o was observed to be 1593.5$\pm$120.5, 984.1$\pm$81.1 and 611.2$\pm$50.1mm in the sub-humid, 1417.2$\pm$72.5, 930.3$\pm$58.6 and 486.9$\pm$24.7mm in semi-arid region and 1404.0$\pm$115.8, 917.9+82.3 and 488.8+38.2mm in the arid region. Almost similar trend was observed in annual and seasonal ET_o computed by HS method.

Annual open pan evaporation significantly decreased in sub-humid (@ 16.4mm $year^{-1}$) and semi-arid region (@ 5.6mm $year^{-1}$). For FAO-PM method, annual ET_o decreased @ 7.6mm $year^{-1}$ in sub-humid, 5.6mm $year^{-1}$ in semi-arid and

Table 1: Variability in annual and seasonal reference evapotranspiration (ET_o) computed with different methods and open pan evaporation (Pan E) in different agroclimatic regions of Punjab

Month	Test	Pan E	FAO-PM	HS
		Sub-humid region (Ballowal Saunkhari)		
Annual	Mean±SD	1577.1±223.1	1593.5±120.5	1628±51.5
	Z	-4.8***	-4.9***	2.2*
	Q	-16.4	-7.6	2.4
Kharif	Mean±SD	996.8±153.6	984.1±81.1	992.1±39.9
	Z	-4***	-3.9***	1.6
	Q	-10.6	-5.0	1.2
Rabi	Mean±SD	576.2±82.4	611.2±50.1	635.5±26.6
	Z	-3.9***	-3.7***	0.7
	Q	-5.0	-3.9	0.4
		Semi-arid region (Ludhiana)		
Annual	Mean±SD	1703.9±240.9	1417.2±72.5	1594.3±55.6
	Z	-4.3***	-6.6***	-6.8***
	Q	-5.6	-10.7	-10.1
Kharif	Mean±SD	1124.2±164.8	930.3±58.6	983.6±45.9
	Z	-4.3***	-6.0***	-6.8***
	Q	-4.7	-8.9	-8.3
Rabi	Mean±SD	575.3±97.3	486.9±24.7	610.2±25.3
	Z	-2.8**	-6.2***	-5.1***
	Q	-2.2	-4.6	-5.4
		Arid region (Bhatinda)		
Annual	Mean±SD	1990.9±291.9	1404±115.8	1732.7±55.2
	Z	1.7	-3.5***	-4.4***
	Q	22.5	-13.6	-5.6
Kharif	Mean±SD	1328.4±200.7	917.9±82.3	1081±41.7
	Z	1.3	-3.3**	-4.7***
	Q	14.3	-9.8	-4.8
Rabi	Mean±SD	666.6±118	488.8±38.2	651.7±29
	Z	1.0	-2.4*	-3.4***
	Q	5.8	-4.7	-2.0

Z: Mann-Kendall test, Q: Sen's slope estimator.

N Statistically significant trends at the 5% significance level, N N Statistically significant trends at the 1% significance level, N N N N Statistically significant trends at the 0.1% significance level

Table 2: Variability in monthly reference evapotranspiration (ET_o) computed with different methods and open pan evaporation (Pan E) in sub-humid region (Ballowal Saunkhari)

Month	Test	Pan E	FAO-PM	HS
January	Mean±SD	44.9±10.3	54.7±8.4	66.8±4.5
	Z	-4.0***	-4.7***	-1.6+
	Q	-0.7	-0.6	-0.1
February	Mean±SD	72.2±15.6	75.9±10.9	84.4±6.5
	Z	-3.1**	-2.4*	1.2
	Q	-0.7	-0.5	0.1
March	Mean±SD	129.4±25.3	129±14.1	136.3±10.4
	Z	-2.9**	-2.0*	1.4
	Q	-1.2	-0.4	0.2
April	Mean±SD	215.9±36.1	195.8±19.9	188.1±12
	Z	-3.7***	-2.4*	1.6
	Q	-2.3	-0.9	0.3
May	Mean±SD	287.6±55.7	243.3±23.1	225.2±12.8
	Z	-3.6***	-2.9**	0.8
	Q	-3.4	-1.0	0.1
June	Mean±SD	239.4±53.8	207.5±32	201.7±17.2
	Z	-3.7***	-2.5*	0.0
	Q	-3.2	-1.6	0.0
July	Mean±SD	149.5±47.3	144.1±21.6	159.9±14.4
	Z	-1.7+	-1.5	1.4
	Q	-1	-0.4	0.3
August	Mean±SD	113.5±20.4	131.3±13	145.4±10.9
	Z	-4.0***	-3.8***	2.0*
	Q	-1.1	-0.7	0.3
September	Mean±SD	107.4±15.2	127.4±12.1	133.7±10.2
	Z	-3.3***	-3.5***	0.9
	Q	-1.0	-0.7	0.1
October	Mean±SD	99.5±24.6	130.5±20.4	126.3±7.4
	Z	-2.5*	-3**	1.3
	Q	-0.5	-0.9	0.2
November	Mean±SD	69.6±10	91.3±12.6	90.6±4.4
	Z	-2.7**	-3**	1.1
	Q	-0.5	-0.5	0.1
December	Mean±SD	48.3±8.8	62.7±8.6	69.9±5.1
	Z	-3.1**	-2.9**	1.0
	Q	-0.4	-0.4	0.1

Z: Mann-Kendall test, Q: Sen's slope estimator.

N Statistically significant trends at the 5% significance level, N N Statistically significant trends at the 1% significance level, N N N N Statistically significant trends at the 0.1% significance level

Table 3: Variability in monthly reference evapotranspiration (ET_o) computed with different methods and open pan evaporation (Pan E) in semi-arid region (Ludhiana)

Month	Test	Pan E	FAO-PM	HS
January	Mean±SD	48.1±15.8	46.7±4.6	62±5.1
	Z	-4.6***	-5.2***	-3.8***
	Q	-0.5	-0.2	-0.2
February	Mean±SD	67.9±17.2	62.8±5.8	77.9±6.1
	Z	-2.3*	-2*	-0.3
	Q	-0.3	-0.1	0
March	Mean±SD	119.5±20.8	108.1±6.7	129.4±10.1
	Z	-0.9	1.2	0.9
	Q	-0.3	0.1	0.1
April	Mean±SD	214.7±37.1	162±12.7	187.5±12
	Z	-0.6	-1.7+	-0.5
	Q	-0.3	-0.2	-0.1
May	Mean±SD	305.7±64.1	208.5±18.8	224.2±14.1
	Z	-2.8**	-3.9***	-1.8+
	Q	-1.4	-0.7	-0.3
June	Mean±SD	269.3±63.9	197.9±22.5	199±16.6
	Z	-2.7**	-3.2**	-2.8**
	Q	-1.3	-0.8	-0.5
July	Mean±SD	172.3±58.8	157.4±16.3	156.7±15.2
	Z	-1.9+	-2.1*	-3**
	Q	-0.6	-0.3	-0.5
August	Mean±SD	132.8±19.7	140.3±12.3	142.5±9
	Z	-1	-0.7	-3.9***
	Q	-0.2	-0.1	-0.3
September	Mean±SD	128.2±18.2	126.4±9.4	134.5±10.9
	Z	-2.5*	-4.1***	-4.6***
	Q	-0.5	-0.4	-0.5
October	Mean±SD	115.9±21.6	100±9.1	126.7±7.7
	Z	-5.0***	-6.6***	-3.2**
	Q	-0.9	-0.5	-0.2
November	Mean±SD	77.3±19.8	62.5±6.5	88.4±4
	Z	-4.9***	-5.2***	-1.1
	Q	-0.7	-0.3	-0.1
December	Mean±SD	52.2±20.6	44.8±5.6	65.5±5.5
	Z	-4.0***	-5.4***	-1.3
	Q	-0.4	-0.3	-0.1

Z: Mann-Kendall test, Q: Sen's slope estimator.

N Statistically significant trends at the 5% significance level, N N Statistically significant trends at the 1% significance level, N N N N Statistically significant trends at the 0.1% significance level

Table 4: Variability in monthly reference evapotranspiration (ET_o) computed with different methods and open pan evaporation (Pan E) in arid region(Bhatinda)

Month	Test	Pan E	FAO-PM	HS
January	Mean±SD	48.2±14.8	41.9±5.5	67.9±7.2
	Z	-0.3	-1.6	-4.6***
	Q	-0.2	-0.3	-0.4
February	Mean±SD	66.4±19.2	61.1±5.2	83.9±7.4
	Z	2+	-0.8	-1
	Q	2.2	-0.1	-0.1
March	Mean±SD	129.9±30.2	114.1±8.6	137.2±11.1
	Z	1.7+	-1.2	0.9
	Q	2.1	-0.6	0.1
April	Mean±SD	256±83.2	164.5±18	194.2±13.4
	Z	3.1**	-2.1*	0.7
	Q	7.6	-1.3	0.1
May	Mean±SD	346.9±67.6	209.8±28.9	238.6±13.6
	Z	3.5***	-2.4*	-0.7
	Q	9.8	-2.2	-0.1
June	Mean±SD	298.6±55.1	185.4±23.2	221.2±14.6
	Z	2.0*	-2.1*	-0.9
	Q	4.2	-1.8	-0.2
July	Mean±SD	207.3±45.7	159.2±18.6	179.1±13.5
	Z	0.5	-1	-0.4
	Q	2.4	-0.9	-0.1
August	Mean±SD	175.5±44.9	141.1±15	159.4±16.4
	Z	-0.2	-3.7***	-2*
	Q	-0.7	-2.3	-0.3
September	Mean±SD	152.8±39.7	124.8±10.9	147.5±12.6
	Z	0.8	-3**	-3.2**
	Q	1.4	-0.9	-0.5
October	Mean±SD	147.2±24.2	97.5±10.4	135.2±8.9
	Z	0.1	-2.9**	-3**
	Q	0.3	-1.5	-0.3
November	Mean±SD	93.0±19.9	59.2±8.8	96.3±5.3
	Z	-1.5	-2.7**	-2.6**
	Q	-1.4	-1.1	-0.2
December	Mean±SD	68.9±15.4	45.3±7.2	72.3±6
	Z	-2.3*	-3.1**	-2.7**
	Q	-1.6	-0.7	-0.2

Z: Mann-Kendall test, Q: Sen's slope estimator.

N Statistically significant trends at the 5% significance level, N N Statistically significant trends at the 1% significance level, N N N N Statistically significant trends at the 0.1% significance level

Table 5: Relationship of open pan evaporation with ET_o computed by different methods

Month /Season	Pan E &FAO-PM		Pan E & HS		FAO-PM & HS	
	R^2	RMSE	R^2	RMSE		
			Sub-humid region(Ballowal Saunkhari)			
Annual	0.30[a]	188.8	0.18[a]	248.8	0.41[a]	127.0
Kharif	0.30[a]	130.7	0.13[c]	165.2	0.06	73.6
Rabi	0.51[a]	70.2	0.07	102.3	0.33[a]	49.7
			Semi-arid region(Ludhiana)			
Annual	0.22[a]	360.5	0.63[a]	229.2	0.37[a]	187.0
Kharif	0.25[a]	242.1	0.55[a]	194.2	0.53[a]	67.1
Rabi	0.42[a]	124.5	0.67[a]	91.1	0.26[a]	125.0
			Arid region(Bhatinda)			
Annual	0.40[a]	447.1	0.06	216.9	0.42[a]	333.0
Kharif	0.31[b]	423.8	0.21[c]	302.2	0.11	148.0
Rabi	0.52[a]	205.1	0.04	116.1	0.22[c]	159.0

a, b, c and d: significant at 1%, 2%, 5% and 10% level of significance, respectively

13.6mm $year^{-1}$ in arid region. However, for HS method, annual ET_o increased @ 2.4mm $year^{-1}$ in sub-humid region, whereas it decreased @ 10.1mm $year^{-1}$ in semi-arid and at 5.6mm $year^{-1}$ in arid region (Table 1). Han *et al.* (2015) also reported variability in annual evapotranspiration during 1956-2011 in China.

Spatio-temporal variability in monthly Pan-E and ETo

In the sub-humid region, the open pan evaporation ranged from 44.9±10.3mm in January to 287.6±55.7mm in May. FAO-PM and HS methods estimated minimum of 54.7±8.4 and 66.8±4.5mm during January and maximum of 243.3±23.1 and 225±12.8mm during May. Trend analysis of monthly Pan-E and FAO-PM ET_o indicated significant decrease in Pan-E during eleven months (except July) in sub-humid region @ 0.4 to 3.4 mm $year^{-1}$, however there was no significant change in ET_o computed by the HS method (Table 2).

In semi-arid region, the monthly Pan-E ranged from 48.1±15.8mm to 306±64.1mm. The HS ET_o ranged from 62.0±5.1mm to 224±14.1mm, and by FAO-PM method ranged from 44.8±5.6mm to 209±18.8mm. The Pan-E decreased significantly during eight months (except March, April, July and August) in semi-arid region. FAO-PM ET_o decreased during January (0.2 mm $year^{-1}$), May (0.7 mm $year^{-1}$), September (0.4 mm $year^{-1}$), October (0.5 mm $year^{-1}$), November (0.3 mm $year^{-1}$) and December (0.3 mm $year^{-1}$) r and HS ET_o during January (0.2 mm $year^{-1}$), August (0.3 mm $year^{-1}$) and September (0.5 mm $year^{-1}$) (Table 3).

In the arid region, monthly Pan-E ranged from 48.2±14.8mm to 347±67.6mm. The HS ET_o ranged from 67.9±7.2mm to 239±13.6mm and, FAO-PM ET_o from 41.9±5.5mm to 210±28.9mm. Monthly PAN-E showed increasing trend in three summer months (April to June) but decreasing trend in December. The HS ET_o showed a decreasing trend during January, August and September and FAO-PM ET_o during April to June and August to December (@2.3 mm $year^{-1}$) (Table 4). The variations in monthly Pan-E and ET_o may be attributed to the variability in climatic parameters in all the regions.

Relation between Pan-E and ET_o

Annual and seasonal Pan-E was observed to be significantly related to FAO-PM ET_o in all the regions with highest coefficient of determination (R^2) in sub-humid (R^2 = 0.30, 0.30 and 0.51) and arid (R^2 = 0.40, 0.31 and 0.52) regions but with HS ET_o in semi-arid region (R^2 = 0.63, 0.55 and 0.67) (Table 5). FAO-PM also showed high R^2 value with HS method in all the regions. These results indicate that FAO-PM method could be used to compute ET_o with highest accuracy in all the regions followed by HS method.

CONCLUSION

A significant decrease has been observed in Pan-E as well as ET_o in all the regions along with large year-to-year variations.Therelationships betweenPan-Eand ET_oshowed that both FAO-PM performed better for estimating ET_othan HS method in different regions, but as the FAO-PM method requires more detailed weather data, hence the HS method can also be used quite successfully under limited data availability.

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