Generation of monthly irrigation maps for India using spatial interpolation techniques

A. Bhadra[1], N. S. Raghuwanshi[2] & R. Singh[2]
[1]*Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology, India*
[2]*Department of Agricultural and Food Engineering, Indian Institute of Technology Kharagpur, India*

Abstract

Considering the current water resources problems and rapid increase in its demand, the importance of effective utilization of water resources cannot be underestimated if India has to remain self reliant in food production. Point ETc (crop evapotranspiration) can be calculated by multiplying point ETo (reference evapotranspiration with appropriate k_c (crop coefficient) values on a monthly temporal scale. Subtracting the monthly point effective rainfall values from corresponding monthly cumulative point ETc, the point net monthly irrigation requirements can be estimated. Spatially interpolating the point net monthly irrigation requirements by kriging, monthly net irrigation requirement (NIR) maps can be generated. Such maps, although readily available for most of the developed countries, have not yet been developed for developing countries like India. This kind of readily available standard net irrigation requirement maps can be very useful in obtaining reliable irrigation demands in new areas. Therefore, in this paper, an attempt has been made to develop monthly net irrigation requirement maps for India. To grasp the spatial distribution characteristics of the net irrigation requirement for the dominant crop of the season and agro-ecological region (AER), geostatistical analysis was performed on the normal monthly NIR derived from 32 years (1971-2002) data of 133 IMD (India Meteorological Department) stations uniformly distributed over the country. It was observed that ordinary kriging produced best results and hence was used to produce the final net monthly irrigation requirement surfaces for all the months.
Keywords: net irrigation requirement, geostatistics, spatial interpolation, ordinary kriging, agro-ecological region.

WIT Transactions on Ecology and The Environment, Vol 168, © 2012 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SI120251

1 Introduction

The quantum of water used for irrigation by the last century was of the order of 300 km^3 of surface water and 128 km^3 of groundwater, leading to a total of 428 km^3. The estimates indicate that by the year 2025, the water requirement for irrigation would be 561 km^3 for low-demand scenario and 611 km^3 for high-demand scenario. Accurate estimation of evapotranspiration (ET) is of great importance for hydrologic water balance, irrigation system design and management, water resources planning and management, etc. A number of indirect methods for estimation of reference ET (ETo) have been developed by several researchers in the past decades. Many scientists have found the Penman-Monteith family of models most reliable for estimation of ETo [1–3]. A major study conducted by ASCE Committee on Evapotranspiration in Hydrology and Irrigation (formerly ASCE Committee on Irrigation Water Requirements) [4] evaluated the performance of 20 different ETo methods using a set of lysimeter data from 11 stations around the world under widely variable climates. The study confirmed the superior performance of the PM method in all climatic conditions. Similar comparative studies [5–7] performed after the evolution of FAO-56 PM method [8] recognized FAO-56 PM as the international standard ETo estimation method.

Based on the crop grown and its stage of growth on a monthly temporal scale, point ETc (crop evapotranspiration) can be calculated by multiplying point ETo (reference evapotranspiration), as estimated by the DSS_ET model [9], with appropriate k_c (crop coefficient) values. Allen *et al.* [8] listed the k_c values for different crop growth stages of various crops and the correction procedure to use these values in non-ideal conditions. In some of the cases actual k_c values are significantly different from those suggested by the Food and Agricultural Organization of the United Nations, indicating the need for generating these values at the local/regional level [10, 11]. However, measured crop coefficients agreed with those obtained using the FAO-56 methodology for a field of linseed in central Italy [12] and for rice field in Japan [13]. Allen *et al.* [14] described the development of the procedure and figures for estimating crop coefficient during the initial stage of crop growth ($k_{c\ ini}$).

The point net monthly irrigation requirements can be estimated by deducting the monthly point effective rainfall values from corresponding monthly cumulative point ETc. To obtain monthly net irrigation requirement maps, the point net monthly irrigation requirements should be spatially interpolated by geostatistical techniques, kriging. The readily available standard monthly net irrigation requirement maps can help in selecting reliable irrigation demand in new areas for the dominant crop of the season and particular region. This will also avoid adoption of empirical approach (e.g., ratio of irrigation water to cumulative pan evaporation, IW/CPE) to determine irrigation water requirement for water management related projects leading to under- or over-estimation. Such maps, though available for most of the developed countries, have not yet been developed for India. So, present study was taken up with an attempt to generate monthly net irrigation requirements maps for India.

2 Theoretical considerations

2.1 Estimation of ETo using FAO-56 Penman-Monteith

Allen *et al.* [8] simplified the basic Penman-Monteith equation [15] by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m, having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing, and adequately watered. With standardized height for wind speed, and temperature and humidity measurements at 2.0 m, latent heat of vaporization = 2.45 MJ kg^{-1}, and specific gas constant = 0.287 kJ kg^{-1} °C^{-1}, the FAO-56 PM equation, for 24 h time step, was given as:

$$\text{ETo} = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \dfrac{900}{(T_{mean} + 273)} \cdot u_2 \cdot (e^o{}_z - e_z)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{1}$$

where, R_n = net radiation at the crop surface, MJ m^{-2}; G = soil heat flux density ≈ 0 (for daily basis calculation); T_{mean} = mean air temperature, °C; $e^o{}_z$ = saturation vapour pressure at mean air temperature, kPa; e_z = actual vapour pressure at mean air temperature, kPa; Δ = slope of saturation vapour pressure-temperature curve, kPa °C^{-1}; γ = psychometric constant, kPa °C^{-1} and u_2 = mean wind speed at 2 m above ground, m s^{-1}.

2.2 Estimation of ETc, effective rainfall and net irrigation requirement

Point ETc can be calculated by multiplying point ETo with appropriate k_c (crop coefficient) values. The k_c values were calculated following the single crop coefficient approach of Allen *et al.* [8]. The k_c values for initial ($k_{c\ ini}$), middle ($k_{c\ mid}$), and end ($k_{c\ end}$) growth stages of different crops under typical irrigation management and soil wetting are given in Allen *et al.* [8]. Among these, use of the $k_{c\ ini}$ values is recommended for estimating ETc during preliminary or planning studies. However, the $k_{c\ mid}$ and $k_{c\ end}$ values given in Allen *et al.* [8] are for RH_{min} = 45% and u_2 = 2 m s^{-1}. Hence, the standard table values ($k_{c\ Table}$) of $k_{c\ mid}$ and $k_{c\ end}$ were corrected for normal RH_{min} other than 45% and normal u_2 larger or smaller than 2 m s^{-1} in the respective month as [8]:

$$k_c = k_{c\,Table} + \left[0.04 \cdot (u_2 - 2) - 0.004 \cdot (RH_{min} - 45)\right] \cdot \left(\frac{h_c}{3}\right)^{0.3} \tag{2}$$

where, h_c = average crop canopy height, cm.

Effective rainfall (R_e) is that part of the total rainfall (R_t), which satisfies evapotranspiration requirements of crop. The normal monthly total point rainfall values were thus converted to effective rainfall using the following relationship presented by the USDA Soil Conservation Service [16]:

$$R_e = \left(1.25 \cdot R_t^{0.824} - 2.93\right) \cdot \left(10^{0.000955 \cdot \text{ETc}_m}\right) \tag{3}$$

where R_e and R_t are the monthly total values in mm; and ETc$_m$ is the monthly total crop evapotranspiration in mm.

The monthly total point effective rainfall values were deducted from corresponding monthly cumulative point ETc to determine the net monthly irrigation requirement at each point.

2.3 Kriging of point net monthly irrigation requirement

Point net monthly irrigation requirement values were spatially interpolated by kriging (geostatistical methods) to create monthly net irrigation requirement maps. The spatial interpolation technique, kriging, measures the degree of spatial dependence among the known points in terms of semivariance (γ) given by:

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left[z(x_i) - z(x_i + h)\right]^2 \tag{4}$$

where, h is the distance between known points called lag; n is the number of pairs of known points separated by h; and z is the attribute value at location x_i or $x_i + h$.

A semivariogram is the semivariance plotted in y-axis against the distance between known points in x-axis. To use the semivariogram as an interpolator in kriging, the five standard models (Spherical, Exponential, Gaussian, Rational quadratic and Hole effect) were considered to fit the sample semivariograms in this study. Mainly three kriging methods were attempted in this study, viz., ordinary kriging, simple kriging, and universal kriging.

3 Data and methodology

3.1 Meteorological data

Monthly meteorological data (maximum and minimum air temperature, mean relative humidity, wind speed, solar radiation or sunshine hour, and rainfall) for the period of 32 years (1971–2002) were procured from India Meteorological Department (IMD), Pune, for 133 selected stations evenly distributed over 19 out of 21 agro-ecological regions (AERs) of India [17]. The AER 21, i.e., Islands of Andaman-Nicobar and Lakshadweep was excluded from this study for spatial discontinuity, whereas, suitable IMD station could not be located within AER 1, i.e. Western Himalayas (Cold Arid). Elevation and latitude-longitude of the stations were taken from the IMD stations list [18]. The cropping pattern of the country was prepared based on data provided in Ministry of Agric. [19], Sharma [20], Oxford Atlas [21], and through personal communication with Misri [22]. To obtain the spatial distribution of the stations within each of the 19 agro-ecological regions, the agro-ecological map of India (Sehgal *et al.* 1990) was digitized and was overlaid on the point locations of the selected stations (Fig. 1). Out of the 131 IMD stations (excluding Patna and Kota due to data scarcity), 10% (i.e. 13) stations were randomly picked up as validation stations (Ahmedabad, Anantapur, Balurghat, Bhopal, Hazaribagh, Jagdalpur, Jaipur, Ludhiana, Rentachintala, Salem, Satna, Shillong and Solapur) in such a manner that they were distributed over different agro-ecological regions (Fig. 1). These validation stations were not included in the kriging exercise. These were used to

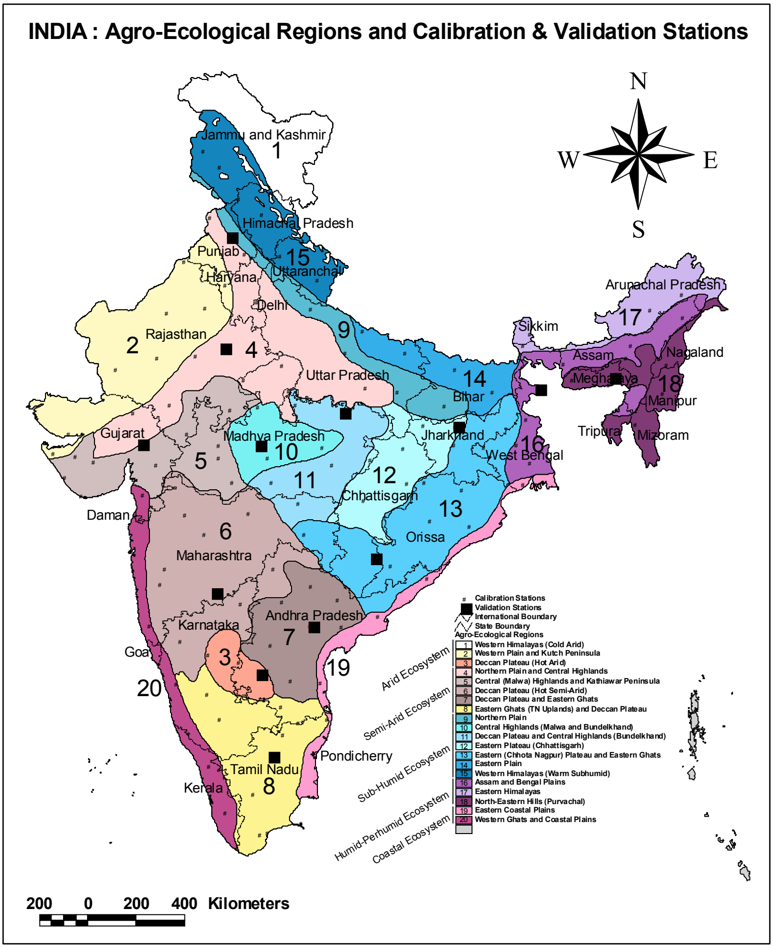

Figure 1: Selected control/calibration and validation stations for kriging.

compare the performance of different semivariogram models and kriging methods. The rest 118 stations were used as the control/calibration stations (Fig. 1) for kriging.

3.2 Description of DSS_ET model

The DSS_ET model [9] was developed in Microsoft Visual Basic 6.0. This model supports a total of 22 well-established and widely used ET methods including FAO-56 Penman-Monteith. The graphical user interface of the model provides a friendly link between data and the model and better interaction between the model and its user. The user does not need a prior knowledge on ET estimation for using the menu/toolbar driven windows based DSS_ET model meaningfully. Extensive options were provided to view input data and results, and to compare ETo estimates obtained by different methods both in tabular and graphical formats. This model includes options for estimating the required intermediate parameters, each by a number of equations available in the literature, providing more control/information on ETo calculation procedure and enhancing the flexibility of the model. It also provides options for estimation of missing data – particularly missing solar radiation data from air temperature extremes, direct import of data from standard IMD file format and good documentation for user.

The ASCE Standardization of Reference Evapotranspiration Task Committee [5] also recommended the use of FAO-56 PM method for daily estimation of ETo. It was found that solar radiation and sunshine hour data were missing for most of the IMD stations. However, either of these two data is mandatory for FAO-56 PM method. Therefore, missing solar radiation was estimated from difference between air temperature extremes [23] using DSS_ET model. A detailed report of the above exercise may be found in Bandyopadhyay *et al*. [24].

3.3 Determination of normal monthly point ETc

Based on 32 years (1971-2002) monthly data, normal monthly ETo values were obtained using the FAO-56 PM ETo method. At each IMD station, the normal monthly point ETo were multiplied by appropriate k_c values depending on the area-wise main crop grown in the respective agro-ecological region (AER) and its stage of growth in a particular month to get monthly point ETc. While preparing the cropping pattern for each of the AER (Table 1), if the growing

Table 1: Cropping patterns of different agro-ecological regions.

AER	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AER 2	Bengal Gram	Bengal Gram	Bengal Gram	Maize	Maize	Maize	Pearl Millet	Pearl Millet	Pearl Millet	Bengal Gram	Bengal Gram	Bengal Gram
AER 3	Sorghum	Black/ Green Gram	Black/ Green Gram	Black/ Green Gram	Black/ Green Gram	Maize	Maize	Maize	Maize	Sorghum	Sorghum	Sorghum
AER 4	Wheat	Wheat	Wheat	Wheat	Rice	Rice	Rice	Rice	Rice	Rice	Wheat	Wheat
AER 5	Wheat	Wheat	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton	Wheat	Wheat	Wheat
AER 6	Sorghum	Sorghum	Bengal/ Green Gram	Bengal/ Green Gram	Cotton	Cotton	Cotton	Cotton	Sorghum	Sorghum	Sorghum	Sorghum
AER 7	Rice	Rice	Rice	Rice	Maize	Maize	Maize	Maize	Rice	Rice	Rice	Rice
AER 8	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice
AER 9	Wheat	Wheat	Black/ Green Gram	Black/ Green Gram	Black/ Green Gram	Rice	Rice	Rice	Rice	Rice	Wheat	Wheat
AER 10	Wheat	Grams/ Pea	Grams/ Pea	Grams/ Pea	Grams/ Pea	Rice	Rice	Rice	Rice	Rice	Wheat	Wheat
AER 11	Sorghum	Bengal/ Green Gram	Bengal/ Green Gram	Bengal/ Green Gram	Bengal/ Green Gram	Rice	Rice	Rice	Rice	Rice	Sorghum	Sorghum
AER 12	Wheat	Wheat	Grams/ Pea	Grams/ Pea	Grams/ Pea	Rice	Rice	Rice	Rice	Rice	Wheat	Wheat
AER 13	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice
AER 14	Wheat	Wheat	Pea	Pea	Pea	Rice	Rice	Rice	Rice	Rice	Wheat	Wheat
AER 15	Wheat	Wheat	Wheat	Wheat	Maize	Maize	Maize	Rice	Rice	Rice	Wheat	Wheat
AER 16	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice
AER 17	Potato	Potato	Maize	Maize	Maize	Maize	Sorghum	Sorghum	Sorghum	Potato	Potato	Potato
AER 18	Potato	Potato	Maize	Maize	Maize	Rice	Rice	Rice	Rice	Potato	Potato	Potato
AER 19	Rice	Rice	Rice	Rice	Ground-nut	Ground-nut	Ground-nut	Ground-nut	Rice	Rice	Rice	Rice
AER 20	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice	Rice

periods of two or more main crops of a region were found overlapping in some month, the crop with the highest k_c at that month was selected. This was done to prevent the crops with high water demand from facing water stress at their critical growth stages. Hence, the crop selected may not always be the one which is grown in maximum area of a region. However, the water demand of the area-wise main crop will certainly be fulfilled with the calculated net irrigation requirement since it is based on a crop which is having more water demand.

3.4 Kriging using geostatistical software

The kriging exercises were performed by the Geostatistical Analyst tool of ArcGIS 9 [25]. Different kriging methods were attempted to interpolate normal net irrigation requirement for each month of the year varying different parameters (transformation, order of trend removal, semivariogram model, anisotropy, number of lags and lag spacing, direction and extent of search, etc.). The ArcGIS Geostatistical Analyst provides four performance indicators for comparing different kriging models and selecting the best alternative model. These are standardized mean prediction error, root-mean-squared prediction error, average standard error, and standardized root-mean-squared prediction error. The best model is the one that has the standardized mean prediction error nearest to zero, the smallest root-mean-squared prediction error, the average standard error nearest the root-mean-squared prediction error, and the standardized root-mean-squared prediction error nearest to one [25]. Based on the above performance indicators, kriging method and parameters to be used in each case were selected.

Finally, the surfaces created by the selected kriging method and parameters were validated in terms of modelling efficiency (ME), coefficient of residual mass (CRM), standard error of estimates (SEE), and coefficient of determination (r^2) at the validation points. The value of ME would be 1.0 when all the estimated values match perfectly with the observed ones. A lower value (close to zero) of ME indicates poor performance of the estimation method used and a negative value indicates that the estimated values are worse than simply using observed mean. CRM indicates overall under- or over-estimation. For perfect estimation, the value of CRM would be zero. A positive value of CRM indicates the tendency of the estimation method to under-estimate the observed values, whereas, a negative CRM indicates a tendency to over-estimate the observed values.

4 Results and discussion

4.1 Estimation of point net monthly irrigation requirement

As discussed earlier, the point net monthly irrigation requirements were calculated by deducting the monthly point effective rainfall values from corresponding monthly cumulative point ETc. The monthly normal ETc, and the net irrigation requirement values, averaged over the agro-ecological regions, are given in Table 2. It can be seen that, for most of the regions, ETc requirement is highest during April to June, whereas, the net irrigation requirement is highest during March to May. However, the high net irrigation requirement stretches from December to June, i.e., almost the entire non-rainy season, in some regions. On the other hand, for almost all the regions which produce rice as the main kharif crop (AERs 4, 9, 10, 11, 12, 13, 14, 16, 18, 20), the total monthly evapotranspirative demand can mostly be met from rainfall during the monsoon months of July to September. However, some irrigation may be required to avoid water scarcity during the critical stages of crop growth since these may coincide with comparatively drier days depending on the distribution of rainfall within a month. Rain water harvesting practices may be helpful to some extent in avoiding such situations. Again, extra water in the form of irrigation will be necessary to maintain the required ponding depth in paddy fields and to meet the enhanced deep percolation rate thereof.

4.2 Generation of net monthly irrigation requirement maps

To interpolate normal point net irrigation requirements for each month of the year, the performances of different kriging techniques with varying parameters (transformation, order of trend removal, semivariogram model, anisotropy, number of lags and lag spacing, direction and extent of search, etc.) were compared in terms of accuracy of estimation (standardized mean prediction error, root-mean-squared prediction error, average standard error, and standardized root-mean-squared prediction error) at 13 validation points. Ordinary kriging produced best results for all the months except July and hence it was used to produce the final net monthly irrigation requirement surfaces of all the months (among 12 produced maps, only one map i.e., net irrigation requirement map of May is shown in Fig. 2). Table 3 shows the performance indicators of the kriged surfaces at the 13 validation stations. From these performance indicators, it can be said that the kriged surfaces performed satisfactorily and can be used to get an idea of the monthly total net irrigation requirement at unknown stations for the dominant crop of the season and AER.

5 Conclusions

For most of the agro-ecological regions, ETc requirement is highest during April to June, whereas, the net irrigation requirement is highest during March to May. The high net irrigation requirement stretches from December to June, i.e., almost the entire non-rainy season, in some regions. On the other hand, for almost all the regions which produce rice as the main kharif crop (AERs 4, 9, 10, 11, 12, 13, 14, 16, 18, 20), the total monthly evapotranspirative demand can mostly be met from rainfall during the monsoon months of July to September. However, some irrigation may be required to avoid water scarcity during the critical stages of crop growth since these may coincide with comparatively drier days depending on the distribution of rainfall within a month. Rain water harvesting practices may be helpful to some extent in avoiding such situations. Again, extra water in the form of irrigation will be necessary to maintain the required ponding

Table 2: Monthly normal ETc (mm d^{-1}) and net irrigation requirement (mm) values in different agro-ecological regions.

AER	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR	ETc	NIR
AER 2	2.12	57.90	3.80	102.17	5.26	159.89	6.05	173.62	8.21	236.81	8.94	223.69	5.48	80.92	4.77	77.37	1.39	15.99	2.10	53.43	1.61	44.07	1.30	38.18
AER 3	4.29	121.78	5.04	141.06	6.39	195.42	7.34	197.23	3.62	72.38	5.85	122.08	5.62	126.08	5.83	121.35	2.17	0.00	4.09	55.84	3.96	90.46	3.92	115.89
AER 4	2.17	58.56	3.32	82.41	4.96	143.51	2.23	59.30	7.56	215.52	7.53	156.78	5.64	16.77	4.76	14.87	4.85	72.97	3.44	90.51	1.97	53.89	1.75	49.46
AER 5	3.94	121.29	1.62	45.01	5.44	168.39	6.76	202.59	7.91	239.32	7.08	111.48	4.95	7.56	4.26	12.85	2.29	12.33	3.01	67.31	3.62	98.64	4.08	117.91
AER 6	3.93	118.23	2.81	77.40	5.02	152.64	8.41	239.91	7.69	206.69	6.05	76.34	4.73	41.63	4.20	31.73	3.99	22.84	4.17	65.67	4.00	97.25	3.79	113.88
AER 7	3.94	118.06	5.28	144.48	6.63	196.93	4.87	130.78	7.00	178.94	6.45	114.08	5.53	58.35	5.16	51.27	4.95	56.14	4.53	64.85	4.08	89.60	3.46	103.10
AER 8	4.06	113.75	5.20	133.07	6.47	186.02	5.93	141.94	6.49	143.25	6.53	147.15	5.32	98.91	5.52	104.46	5.49	79.49	4.81	38.79	4.18	36.54	2.53	33.10
AER 9	2.16	54.18	3.15	71.29	4.55	128.37	6.74	191.90	3.55	95.02	6.64	115.92	5.02	4.32	4.62	6.34	4.37	24.14	2.51	53.35	1.86	46.70	1.86	48.86
AER 10	3.26	91.13	1.89	42.01	4.60	134.28	8.56	252.83	9.65	288.25	7.19	95.76	4.71	0.00	3.99	0.00	4.53	29.64	4.77	120.51	3.13	82.12	3.22	93.69
AER 11	2.76	72.22	1.76	33.49	4.17	119.55	7.66	223.53	8.51	247.70	6.48	85.74	4.48	0.00	3.90	0.00	4.18	13.61	4.34	98.06	3.25	85.34	2.72	77.95
AER 12	3.00	79.79	3.99	95.55	4.08	113.46	7.44	207.10	7.94	216.71	6.34	44.68	4.56	0.00	4.21	0.00	4.18	0.33	2.56	42.59	2.16	55.90	2.39	69.24
AER 13	3.37	96.04	4.65	115.20	6.28	176.77	6.69	167.11	7.41	173.50	6.36	39.86	4.66	0.00	4.17	0.00	4.21	2.52	4.11	61.61	2.89	69.22	2.99	88.99
AER 14	2.21	58.59	3.26	82.15	3.72	109.39	6.88	188.59	6.86	168.79	5.78	58.84	4.61	0.00	4.47	0.00	4.11	1.82	2.33	25.55	1.93	54.27	1.98	57.19
AER 15	1.37	8.14	2.10	12.58	3.19	30.41	1.34	8.38	5.06	98.78	5.58	75.56	5.00	42.58	4.64	32.11	4.20	48.59	2.14	34.25	1.32	20.89	1.11	11.65
AER 16	2.66	74.81	3.56	77.57	4.94	111.70	4.21	44.55	2.75	5.89	4.84	7.48	4.54	0.00	4.50	0.00	4.08	0.00	3.66	25.97	2.98	74.63	2.57	68.77
AER 17	2.00	31.88	1.55	6.25	3.24	41.82	3.97	2.19	4.30	0.00	1.36	0.00	3.93	0.00	3.97	0.00	3.43	0.00	2.96	8.77	2.60	46.31	2.11	45.04
AER 18	2.49	69.10	2.18	37.22	3.90	64.76	4.71	28.52	4.80	13.67	4.03	0.00	3.97	3.59	4.09	0.56	2.26	0.00	3.08	15.73	2.82	54.07	2.54	66.26
AER 19	3.85	108.69	4.84	121.19	5.84	169.63	4.25	97.41	6.23	138.53	6.42	107.13	5.90	80.37	5.62	63.65	5.41	49.98	4.80	7.06	4.25	36.78	3.58	71.57
AER 20	4.57	139.25	5.25	140.76	6.00	177.34	5.56	138.27	5.71	99.52	4.84	0.00	4.21	0.00	4.04	0.00	2.58	0.00	4.29	47.16	4.80	90.54	5.17	147.38

Table 3: Performance indicators of the kriged surfaces at the 13 validation stations.

	Ahmedabad	Anantapur	Balurghat	Bhopal	Hazaribagh	Jagdalpur	Jaipur	Ludhiana	Rentachintala	Salem	Satna	Shillong	Solapur
ME	0.0941	0.776	0.897	0.841	0.911	0.918	0.891	0.960	0.745	0.815	0.902	0.938	0984
CRM	-0.007	0.103	0.157	0.242	-0.166	-0.121	0.056	0.044	0.097	0.201	0.089	0.106	0.031
SEE	19.661	29.074	14.728	43.815	17.861	18.329	22.852	8.769	21.000	24.201	26.470	8.284	11.535
R^2	0.962	0.843	0.976	0.981	0.947	0.939	0.900	0.971	0.884	0.980	0.950	0.961	0.972

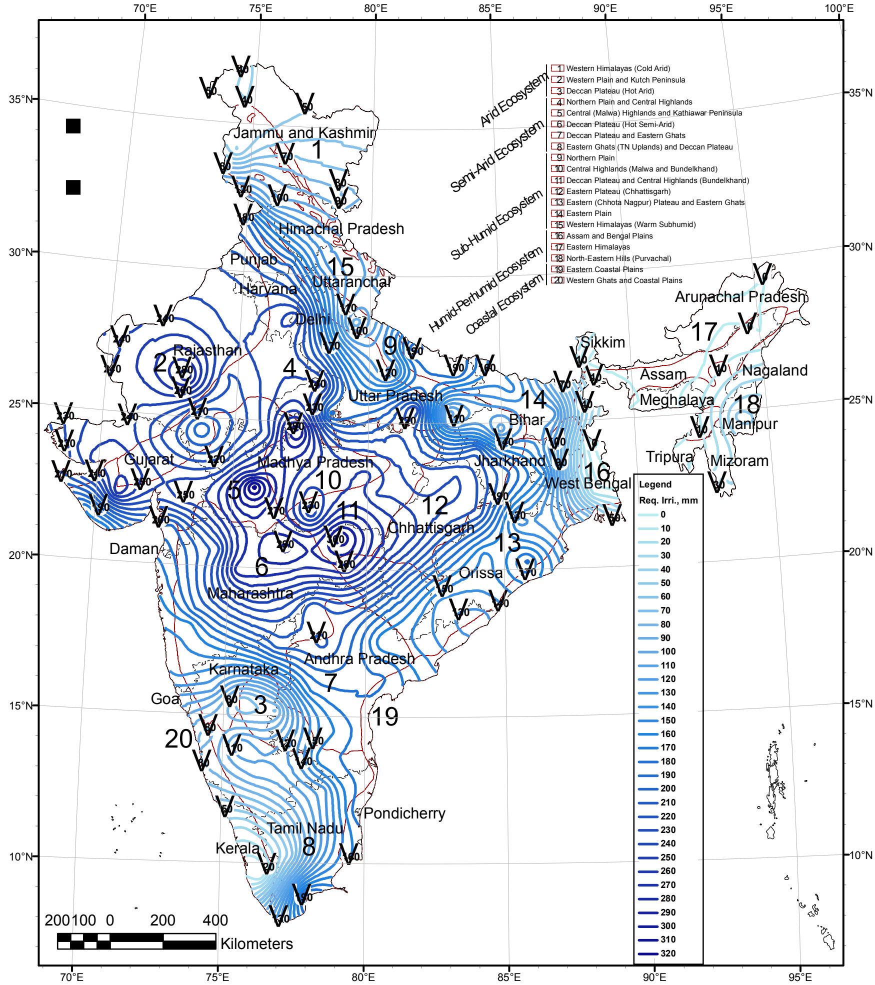

Figure 2: Net irrigation requirement map of May.

depth in paddy fields and to meet the enhanced deep percolation rate thereof. Among different kriging techniques tried in this study for spatial interpolation, ordinary kriging produced best results for all the months except July and hence it was used to produce the final net monthly irrigation requirement surfaces for India at monthly interval. These surfaces also produced satisfactory results at the 13 validation stations and can be used to get an idea of the monthly total net irrigation requirement at unknown stations for the dominant crop of the season and AER.

References

[1] Allen, R.G., Jensen, M.E., Wright, J.L. & Burman, R.D., Operational estimates of reference evapotranspiration. *Agron. J.*, **81(4)**, pp. 650–662, 1989.

[2] Chiew, F.H.S., Kamaladassa, N.N., Malano, H.M. & McMahon, T.A., Penman-Monteith, FAO-24 reference crop evapotranspiration and class-A pan data in Australia. *Agric. Water Mgmt.*, **28**, pp. 9–21, 1995.

[3] Lunardi, M.A., Lunardi, D.M.C. & Cavaguti, N., Comparison between evapotranspirometric measurement and FAO methodologies in determination of potential evapotranspiration. *IRRIGA*, **4(1)**, pp. 52–66, 1999.

[4] Jensen, M.E., Burman R.D. & Allen, R.G., (eds). *Evapotranspiration and irrigation water requirements*, ASCE Manuals and Reports on Engrg. Practice No. 70, Am. Soc. Civil Engrs. (ASCE), NY, USA, 1990.

[5] Itenfisu, D., Elliot, R.L., Allen, R.G. & Walter, I.A., Comparison of reference evapotranspiration calculations across a range of climates. *Proc. of the 4th National Irrig. Symp.*, Am. Soc. Agric. Engrs. (ASAE), St. Joseph, Mich., USA, pp. 216–227, 2000.

[6] Itenfisu, D., Elliott, R.L., Allen, R.G. & Walter, I.A., Comparison of reference evapotranspiration calculations as part of the ASCE standardization effort. *J. Irrig. Drain. Engrg.*, **129(6)**, pp. 440–448, 2003.

[7] Temesgen, B., Eching, S., Davidoff, B. & Frame, K., Comparison of some reference evapotranspiration equations for California. *J. Irrig. Drain. Engrg.*, **131(1)**, pp. 73–84, 2005.

[8] Allen, R.G., Pereira, L.S., Raes, D. & Smith, M., *Crop evapotranspiration – Guidelines for computing crop water requirements*, Irrig. and Drain. Paper 56, Food and Agric. Organization of the United Nations (FAO), Rome, Italy, 1998.

[9] Bandyopadhyay, A., Bhadra, A., Swarnakar, R.K., Raghuwanshi, N.S. & Singh, R., Estimation of reference evapotranspiration using a user-friendly decision support system. *Agric. For. Met.*, In press, doi: 10.1016/j.agrformet.2011.10.013.

[10] Tyagi, N.K., Sharma, D.K. & Luthra, S.K., Evapotranspiration and crop coefficients of wheat and sorghum. *J. Irrig. Drain. Engrg.*, **126(4)**, pp. 215–222, 2000.

[11] Bandyopadhyay, P.K. & Mallick, S., Actual evapotranspiration and crop coefficient of wheat (Triticum aestivum L.) under varying moisture levels of humid tropical canal command area. *Agric. Water Mgmt.*, **59**, pp. 239–254, 2003.

[12] Casa, R., Russell, G. & Cascio, B.L., Estimation of evapotranspiration from a field of linseed in central Italy. *Agric. For. Met.*, **104**, pp. 289–301, 2000.

[13] Vu, S.H., Watanabe, H. & Takagi, K., Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan. *Agric. Water Mgmt.*, **76(3)**, pp. 195–210, 2005.

[14] Allen, R.G., Pruitt, W.O., Raes, D., Smith, M. & Pereira, L.S., Estimating evaporation from bare soil and the crop coefficient for the initial period using common soils information. *J. Irrig. Drain. Engrg.*, **131(1)**, pp. 14–23, 2005.

[15] Monteith, J.L., Evaporation and surface temperature. *Quart. J. Roy. Meteorol. Soc.*, **107**, pp. 1–27, 1981.

[16] SCS, *Irrigation water requirements*, Technical Release 21 (TR-21), Soil Conservation Service (SCS), USDA, Washington, D.C., USA, 1970.

[17] Sehgal, J.L., Mondal, D.K., Mondal, C. & Vadivelu, S., *Agro-ecological regions of India*, Tech. Bull., NBSS Pub. 24, National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Indian Council of Agric. Res. (ICAR), Nagpur, India, 1970.

[18] IMD, *Climatological tables of observatories in India (1931-1960)*, India Meteorological Department (IMD), Govt. of India Press, New Delhi, India, 1983.

[19] Ministry of Agric., *Agricultural statistics at a glance*, Directorate of Economics and Statistics, Dept. of Agric. and Cooperation, Ministry of Agric., Govt. of India, New Delhi, India, 2000.

[20] Sharma, R.P., (ed). *Handbook of agriculture*, Indian Council of Agric. Res. (ICAR), New Delhi, India, 2000.

[21] Oxford Atlas, *A social and economic atlas of India*, Oxford, NY, USA, 1987.

[22] Misri, B.K., *Personal communication*, Regional Res. Centre, Indian Grassland and Fodder Res. Inst., Palampur, India, 2007.

[23] Hargreaves, G.H., Simplified coefficients for estimating monthly solar radiation in north America and Europe. *Dept. Paper*, Dept. of Biol. and Irrig. Engrg., Utah State Univ., Logan, Utah, USA, 1994.

[24] Bandyopadhyay, A., Bhadra, A., Raghuwanshi, N.S. & Singh, R. Estimation of monthly solar radiation from measured air temperature extremes. *Agric. For. Met.*, **148**, pp. 1707–1718, 2008.

[25] ESRI, *ArcGIS 9 – Using ArcGIS Geostatistical Analyst*, Environ. Sys. Res. Inst., Inc. (ESRI), Calif., USA, 2004.