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Research Article

Digital Mapping of Soil Water Retention at Field Capacity and Permanent Wilting Point, Two Key Soil Indicators for Assessing Sustainability of Agricultural Production System in Arid Western Rajasthan

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ABSTRACT

Soil water retention at field capacity (FC) and permanent wilting point (PWP) are two critical soil moisture constants that define the availability of soil moisture for sustainable crop growth and yield. The tedious and time-consuming measurement process in the laboratory limits the information on these two soil moisture constants. In this study, digital maps of soil water retention at FC and PWP were prepared using digital soil mapping (DSM) and pedotransfer function (PTF) approach. Through the DSM approach, digital soil maps of sand, silt and clay content were prepared through ordinary kriging (OK). For this purpose, data on soil particle size distribution for 705 locations within western Rajasthan was used. Among these, data for 230 locations were collected from report on legacy soil data, while the remaining data for 475 locations were developed by collecting soil samples from field followed by analysing them in laboratory. A semivariogram of the content of sand, silt, and clay was computed, followed by fitting it to a standard model using the weighted least squares technique. Ordinary kriging was used for estimating sand, silt, and clay at unsampled locations in a 1 km grid in western Rajasthan, which covers a territory of approximately 20 million hectares. The k-fold cross-validation of the developed maps revealed that they were accurate for sand (R^2 = 0.41) and silt (R^2 = 0.46), but not for clay content. Instead, the clay content map was prepared by subtracting the (sand and silt) content from 100. Using the PTF approach, soil water retention at FC and PWP were prepared by combining the maps of sand and clay content using PTF equation. A digital map of FC and PWP could help farmers select the appropriate crops and apply the correct amount of irrigation water for sustainable land management in western Rajasthan.

Key words: Digital soil mapping (DSM), Pedotranfser function (PTF), Ordinary kriging (OK), Field capacity (FC), Permanent wilting point (PWP), Western Rajasthan

Introduction

Natural resources in arid regions are highly fragile and poor in terms of their availability and quality (Chaudhari *et al*., 2024). Most of the soils in the arid region are coarse textured, which causes poor retention of nutrients and water. The biological productivity of the soil is maintained by limiting support for soil biota in the high soil temperature regime in the arid region. The surface soil temperature of the region reaches 60–70° C during summer months and remains >50°C for most periods

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of the year. To maintain a conducive environment for plant growth, most biological processes are suppressed due to this high thermal regime. Soils with low soil organic carbon (SOC) status have a tendency to have loose structural attributes due to their 80–90% sand content. Moreover, these loose surface soils are highly prone to erosion both by wind and water. The addition of organic matter alone does not lead to an improvement in SOC due to its low biological activity. The physical environment of very hot and dry soil in arid regions becomes more serious due to global climate change scenarios, particularly warming scenarios. Availability of both surface water and groundwater resources is also limited in the arid region of India. Groundwater depth below ground level is increasing at a very fast rate due to continuous withdrawal and less recharge of rainwater. The quality of scarce groundwater resources is again a limitation because of inherent salinity in most parts of the region.

Despite experiencing frequent droughts, the region sustains a predominantly agricultural economy. For example, human population in arid western Rajasthan has been increased by > 250% over a period from 1961 to 2011, while the animal population has been increased by about 125.2% between 1956 and 2012 census. Irrespective of frequent droughts, the region has a dominant agricultural economy. An estimate of changes in agricultural activity in arid Rajasthan between 1982–83 and 2005–06 indicated an increase in net-irrigated (128%) and double cropped area (70%), whereas a decline in culturable waste. The problem has been made worse by the rapid rate of land conversion in recent times. To sustain the livelihood of the continuously increasing population pressure, a clear change to an arable farming system is necessary. Reversely, suitable on-farm technologies need to be developed to tackle the problem of sustainable production in the region.

Regular monitoring and assessment of the natural resource base of the region and taking corrective measures is necessary to ensure sustainable agricultural production in the future under such circumstances. Monitoring and mapping the soil resources through sensitive soil indicators may help to assess the sustainability of agricultural production system. Several literatures reported the soil quality index (SWI) as an approach for integrated assessment of soil resources in which several soil parameters are combined together to a single value through principal component analysis (Bastida *et al*., 2008; Mukherjee and Lal, 2014; De *et al*., 2022). In addition to these SQI, there are also a few soil indicators that have a significant impact on crop growth and yield that can be utilized. However, such soil indicators should be easily measurable, able to measure changes in soil functions, encompass chemical, biological, and physical properties, accessible to many users and applicable to field conditions and sensitive to variations in climate and management. These indicators may be measured in terms of the intensive pressure of agricultural activity on soil resources, the current state of soil resources, and the response of soil resources to crop yield. The sustainability of agricultural production in arid regions can be assessed through two critical soil moisture constants, soil water retention at field capacity (FC) and permanent wilting point (PWP). By mapping these two indicators, stakeholders can make efficient use of scarce water resources in the agricultural production system. Surveying efforts followed by laboratory analysis have traditionally been used to map soil properties. Soil maps developed by the conventional approach are generally hard copy maps, which are not easily accessible to end users. Moreover, mapping units of these maps are delineated based on soil profile data and surveyor’s field experience. These mapping units sometimes represent quite large area in field and thus soil properties of interest vary considerably within a unit. With advancement of geostatistics and abundant availability of digital information on earth features, there is a possibility to map soil properties utilizing available soil data and auxiliary information on earth features and environmental variables. In the digital soil mapping (DSM) methodology, soil class or properties at unsampled locations are estimated using information on spatial variation of soil properties and environmental covariates affecting soil formation process. The importance of digital soil mapping has recently increased in various parts of the world, including India (Minasny and McBratney, 2016; Santra, 2017a; Santra *et al*., 2017b; Santra *et al*., 2020). There are three main approaches followed in

DSM: geostatistical approach, state-factor (clorpt) approach and PTF approach. In the geostatistical approach, spatial variation parameters (nugget, sill and range) are identified from a spatial soil database using a semivariogram followed by making unbiased estimate of soil properties at an unsampled location through kriging. In the state-factor (clorpt) approach the soil formation theory proposed by Dokuchaev (1883) and Jenny (1941) is the backbone. Climate (CL), organism (O), relief (R), parent material (P), and time (T) are considered the five major factors that influence soil in this approach. The PTF approach is used to develop digital soil maps of complex and difficult to measure soil properties using maps of basic soil properties. Keeping in background the abovesaid DSM approaches and the importance of soil water retention at FC and PWP as key soil indicators, it has been hypothesized that (i) whether the DSM methodology can be applied to prepare digital soil map of FC and PWP in a regional scale e.g. western Rajasthan and (ii) if successfully applied, what will be the accuracy and uncertainty of the developed maps and its dependency on spatial distribution of soil sampling locations.

Materials and methods

Study area: western Rajasthan

The study was carried out in western Rajasthan, India. Sixty two per cent areas of hot arid ecosystem in India lies in western Rajasthan consisting of twelve districts e.g. Jaisalmer, Barmer, Jalore, Pali, Jodhpur, Bikaner, Nagaur, Sikar, Churu, Ganganagar, Hanumangarh, Jhunjhunu and Sikar and covers about 20 million ha. In western Rajasthan, soils are mainly classified under two soil orders; Entisol and Aridisol, which constitute about 61% and 38% of the total area of western Rajasthan, respectively. Torripsamments are the major great groups under Entisol, covering 87.7% of the area, while Haplocambids are the major great groups under Aridisol, covering 71.1% of the area (Santra *et al*., 2017a). High aeolian activity in western Rajasthan is common where soils under entisols are generally found. Average soil depth of soil profiles under Entisols is 118 cm and bulk density of these soils is 1.58 Mg m^{-3}. Surface horizon is rich in sand content in comparison to subsurface horizons. Aridisols are more prevalent than Entisols in parts of arid regions with less aeolian activity. The average depth of this type of soil is 100 cm, with well-defined horizons and an average bulk density of 1.43 Mg m^{-3}. Calcite concretes below the soil profile are a common feature of these soils.

Development of soil database on particle size distribution in western Rajasthan

Database on sand, silt and clay content in western Rajasthan was developed through two efforts; (a) Compilation of available legacy data from published reports and literaures, hereinafter referred as legacy data. and (b) Collection of soil samples followed by laboratory analysis, hereinafter referred as primary database. Legacy data on sand, silt and clay content in 230 locations of western Rajasthan was collected from following three sources; (i) Soil series data of Rajasthan published by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur (Shyampura *et al*., 2002) (N=48); (ii) Soil resource atlas of Rajasthan state published by State Remote Sensing Application Centre (SRSAC), Jodhpur (2010) (N=85) and (iii) data on soil particle size distribution reported in Santra *et al*. (2015) (N=97). Primary database on sand, silt and clay content was developed by collecting surface soil samples (0-15 cm) from 475 locations in western Rajasthan covering Jodhpur (N= 186), Nagaur (N= 143), Hanumangarh (N= 3), Ganganagr (N= 132), Bikaner (N=4), Churu (N=1) and Jaisalmer district (N=7). Collected soil samples were air-dried and passed through 2 mm sieve to determine sand (0.02-2 mm), silt (0.002-0.02 mm) and clay (<0.002 mm) content following international pipette method (Piper, 1966). Spatial locations of these database in western Rajasthan for both legacy and primary database (N=705) are presented in Fig. 1.

Descriptive data analysis

The descriptive statistics of soil properties were computed using the R programming environment (R Core Team, 2021). Normality of the data was checked through histogram plot and Q-Q plot. In case, probability density function of the measured data deviated from theoretical normal distribution, data transformation e.g. logarithm transformation was carried out to fit the data into normal distribution.

Spatial variation and kriging

Semivariogram

The spatial variation of soil properties was investigated using geostatistical techniques. In the following, the soil properties at observed locations are denoted as $z(s_1)$, $z(s_2)$, $z(s_3)$, ...$z(s_n)$, where $s_i = (x_i, y_i)$ is observed location and x_i and y_i are the coordinates of the location and n is number of observations. Spatial variability of soil properties was determined through a semivariogram $\gamma(h)$, which measures the average dissimilarity between the data separated by a vector (h). It was computed as half of the average squared difference between the components of the data pairs:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(s_i) - z(s_i + h)]^2 \quad (1)$$

where $z(s_i)$ represents the value of the variable z at s_i, h represents the lag distance or separation distance and $N(h)$ is the number of pairs of sample points separated by h. The experimental semivariograms $\gamma(h)$ derived from Eq. (1) were fitted in standard models using weighted least square approach, and three standard spatial variation parameters viz. nugget (C_0), partial sill (C) and range (a) were determined. While fitting the experimental variogram to the standard model using the weighted least square technique, weights were assigned as inversely proportional to the lag distance and directly proportional to number of pairs for each lag. Half of the diagonal distance of the sampling extent was used as the maximum lag distance to decrease the impact on the border. The best fit model among different standard semivariogram models was identified by minimizing the residual sum of squares. Below are the mathematical expressions for four standard semivariogram models that were used to fit the experimental semivariograms

Exponential model

$$\gamma(h) = C_o + C_1 \left[1 - exp\{-\tfrac{h}{a}\}\right] \; for \; h \geq 0 \quad (2)$$

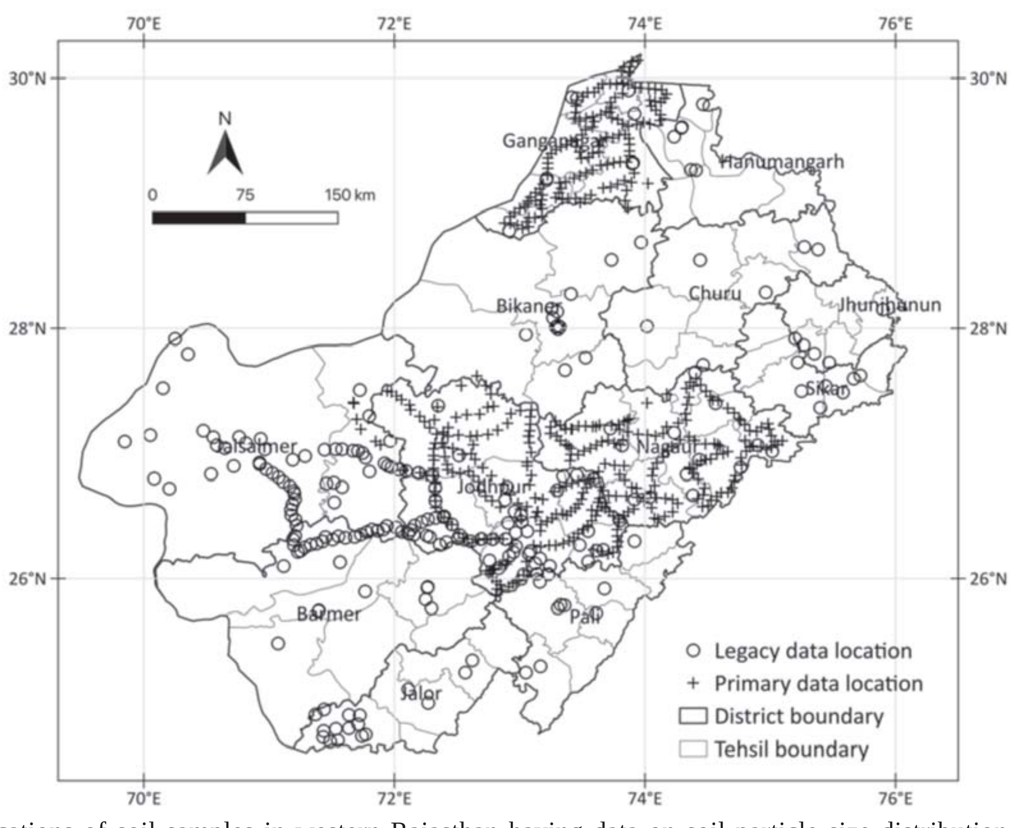

Fig. 1. Locations of soil samples in western Rajasthan having data on soil particle size distribution (sand, silt and clay)

Spherical model

$$\gamma(h) = C_o + C\left[1.5\frac{h}{a} - 0.5(\frac{h}{a})^3\right]$$

$$for\ 0 \leq h \leq a \text{ otherwise } C_o + C \quad (3)$$

Gaussian model

$$\gamma(h) = C_o + C\left[1 - exp\left\{\frac{-h^2}{a^2}\right\}\right]\ for\ h \geq 0 \quad (4)$$

Linear model

$$\gamma(h) = C_o + C_1\left[\frac{h}{a}\right]\ if\ h < a \text{ otherwise } = C_o + C_1 \quad (5)$$

Ordinary kriging (OK)

Fitted semivariogram parameters corresponding to best fit model were further used to prepare surface maps of soil properties through ordinary kriging (OK). Estimates of soil properties at unsampled locations, $z(s_0)$, were derived using a weighted linear combinations of known soil attributes $z(s_i)$ located within a neighborhood $W(s_0)$ centered around s_0, using the OK technique.

$$z(s_0) = \sum_{i=1}^{N} \lambda_i\, z(s_i) \quad (6)$$

where γ_i the weight assigned to datum $z(s_i)$ located within a given neighborhood, $W(s_0)$ centered on s_0. Weights for N number of neighborhood points were chosen as such to minimize the estimation or error variance, $z(s_0) = \sum_{i=1}^{N} \lambda_i\, z(s_i)$ under the constraint of no-bias of the estimator. When the kriging equations are solved to obtain the weights, γ_i, large weights are assigned to those sampled points near to the point or block to be kriged. The larger is the nugget variance, the smaller are the weights of the points that are nearest to the target point or block. Clustered points are lighter than isolated ones at the same distance in terms of weight. All geostatistical analyses including semivariogram fitting and kriging were performed with 'gstat', 'sp', 'sf' and other relevant auxiliary packages of R (R Core Team, 2021) and a detailed description on this aspect may also be found in Santra *et al*. (2017a).

In case, the data on soil properties are transformed log-normally to fit it in normal distribution, the predicted values through ordinary kriging are back-transformed to original data through following transformation:

$$\hat{z}_{bt}(s_0) = \exp\left[\hat{z}_{OK}(s_0) + 0.5\, var\{\hat{z}_{OK}(s_0)\}\right] \quad (7)$$

Where, $\hat{z}_{bt}(s_0)$ is the back transformed value of soil properties at unsampled location, $\hat{z}_{OK}(s_0)$ is the predicted log-transformed value of soil properties through ordinary kriging and $var\{\hat{z}_{OK}(s_0)\}$ indicates variance in predicted value through ordinary kriging. Similar to back-transformation of predicted value to original data, there is also requirement of back-transformation of variance of prediction, which was carried out through following equation

$$var[\hat{z}_{bt}(s_0)] = \exp\left[2\,\hat{z}_{OK}(s_0) + var\{\hat{z}_{OK}(s_0)\}\right] \times (\exp[var\{\hat{z}_{OK}(s_0)\}] - 1) \quad (8)$$

Cross-validation

The kriging approach was tested by using the k-fold cross-validation method. In our study, value of *k* as 10 was used. The kriging cross-validation was done using krige.cv() function of the 'gstat' package of R. Lin's concordance correlation coefficient (LCCC), R^2, mean square error (MSE), root mean square error (RMSE), and bias were used to evaluate the performance of each spatial interpolation method.

$$LCCC = \frac{2\rho\sigma_{obs}\vartheta_{pred}}{(Z_{obs} - Z_{pred}) + \sigma_{obs}^2 + \sigma_{pred}^2} \quad (9)$$

$$R^2 = 1 - \frac{\sum_{i=1}[z(s_i) - \hat{z}(s_i)]^2}{\sum_{i=1}^{N}[z(s_i) - \bar{z}(s_i)]^2} \quad (10)$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}[z(s_i) - \hat{z}(s_i)]^2 \quad (11)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[z(s_i) - \hat{z}(s_i)]^2} \quad (12)$$

$$bias = \frac{1}{n}\sum_{i=1}^{n}[z(s_i) - \hat{z}(s_i)] \quad (13)$$

where $z(s_i)$ is the represents the variable's observed values at the location s_i, $\hat{z}(s_i)$ represnets varaiable's predicted values with variance σ^2 at the location s_i, and n represents the number of sampling location. The accuracy and precision of the relationship was estimated through LCCC. The orthogonal distance from the 1:1 line of observed and predicted values passing through origin has been used to compute the LCCC. The LCCC values were in the range of -1 to +1.Having a direct agreement between observed and predicted values is indicated by an LCCC value of

1, while perfect negative agreement is represented by an LCCC value of -1. When the LCCC value is zero, it means that the observed and predicted values do not match. The R^2 is a measure of the relationship's accuracy. The RMSE is a measure of prediction accuracy (e.g. larger RMSE values indicate less accuracy of prediction). The mean error of prediction is represented by bias, and a value of zero implies that the prediction is unbiased.

Pedotransfer function of soil water retention at field capacity (FC) and permanent wilting point (PWP)

The soil moisture retention at FC and PWP are essential factors in determining irrigation water application in the field. In the case of a rainfed production system, adopting field management practices to maintain the rhizosphere soil moisture regime in between these two soil moisture constants plays a major role in obtaining sustainable crop yield. Therefore, knowledge on soil water retention at FC and PWP helps farmers to choose the right crop, to adopt suitable soil water conservation technology and to apply the right amount of irrigation water at the right time. However, measuring these two soil moisture constants is a tedious task due to the time and cost involved in its laboratory measurement procedure. Alternatively, soil water retention at FC and PWP can be estimated using the pedotransfer (PTF) function approach.

PTFs are generally a statistical model, which translates easily measurable basic soil properties to complex and difficult to measure soil properties. Several PTFs for different complex soil properties have been developed at different parts of the world, which are available in literature. Most of these PTFs perform better if applied in a the similar agro-climatic region from where it was developed than others. These PTFs may be used to create digital soil map of complex soil properties from the digital soil map of easily measurable basic soil properties (Santra *et al*., 2008). Such type of PTF equations have also been developed for estimating soil water retention at FC and PWP in arid ecosystem of India by Santra *et al.*(2018), which are given below:

$$\theta_{FC}\ (\%,\ g/g) = 29.79 - 0.264 \times Sand\ (\%) + 0.207 \times Clay\ (\%)\ (R^2 = 0.87) \quad (14)$$

$$\theta_{PWP}\ (\%,\ g/g) = 5.04 - 0.0385 \times Sand\ (\%) + 0.232 \times Clay\ (\%) - 0.00057 \times Sand\ (\%) \times Clay\ (\%)\ (R^2 = 0.92) \quad (15)$$

Where, θ_{FC} and θ_{PWP} are soil water retention at FC and PWP, respectively.

Here, these two PTF equations were used for preparing digital soil maps of FC and PWP in western Rajasthan where digital soil maps of sand, silt and clay prepared through OK approach were used as inputs in the equations.

Results and Discussion

Descriptive statistics on soil particle size distribution in western Rajasthan

The descriptive statistics for soil particle size distribution at a depth of 0-15 cm in western Rajasthan are displayed in Table 1. Across the database, sand content ranges from 17.1% to 99.0%, with an average of 72.2% (CV= 21.7%). This suggests that the soil predominantly consists of sand, which can impact its water-holding capacity and available moisture. The silt content varied from 0.01% to 68.8%, with a mean of 22.1% (CV= 71.5%). This indicates a moderate variation (Seyedmohammadi *et al*., 2019) in silt content across the database. Clay content influences soil structure, nutrient retention, and water availability. The average clay content was 5.60% and varied from 0.5% to 35.8% (CV= 77.5%). The relatively low clay content suggests that the soil may have good drainage but might require organic matter or other amendments to improve its fertility and water-holding capacity. Li, *et al*. (2024) observed that clay and silt concentrations were highly variable throughout all depth layers, with coefficients of variation (CV) ranging from 0.34 to 0.66, but sand content was less variable, with CVs ranging from 0.08 to 0.13.

Histogram of soil particle size distribution in western Rajasthan at 0-15 cm layer has been depicted in Fig. 2. It has been found that sand content and silt content followed near normal distribution whereas clay content did not follow normal distribution, for which logarithmic transformation has been carried out to fit it in normal distribution.

Table 1. Descriptive statistics of soil properties (0-15 cm) in database of western Rajasthan

Soil properties	Number of data locations	Minimum	Maximum	Mean	Standard deviation	Coefficient of Variation (%)
Sand (%)	705	17.1	99.0	72.2	15.7	21.7
Silt (%)	705	0.01	68.8	22.1	15.8	71.5
Clay (%)	705	0.5	35.8	5.6	4.34	77.5

Spatial variation of sand, silt and clay in western Rajasthan

Semivariogram of soil particle size distribution has been plotted in Fig. 3 along with the corresponding spatial variation parameters of best fitted model. From the semivariogram plots, it has been observed that calculated semivariograms were fitted well among four standard models. Exponential model was found the best fitted model for all three particle size classes. Nugget component in total sill or variation was low (41-45% of total sill) in case of sand and silt content whereas high (65% of total sill) in clay content. Range parameters of sand (209 degree) and silt (56 degree) content was comparatively higher than for clay content (55 degree) (1 degree ~ 1 km). Long range parameter indicates large spatial continuity of soil parameters whereas short range indicates local variation influenced by different management practices and short-range soil processes.

Digital soil maps of sand silt and clay in western Rajasthan

Spatial maps of soil properties in western Rajasthan prepared through OK approach are presented in Fig. 4. Sand content (Fig. 4) map shows variation from 50 to almost 100%. Western part of western Rajasthan shows high sand content (85-100%) covering mostly Barmer and Jaisalmer. At north-eastern part of western Rajasthan covering part of Churu, Sikar and Jhunjhunu district, sand content was found higher (~80-90%). Sand content was found lower (~50-60%) in northern part of western Rajasthan covering Ganganagar and Hanumangarh district and at southern part covering Jalore district. Conversely, silt content was found higher (35-45%) in northern part of western Rajasthan covering Ganganagar and Hanumangarh district and found lower (<10%) in western part of the region covering Barmer and Jaisalmer (Fig. 5). Clay content (Fig. 6) was found very low (<6%) in most part of western Rajasthan except at few pocketed locations in southern part covering Pali district, where clay content was found high (~8-16%).

Cross-validation of digital soil maps of sand, silt and clay

Spatial maps of sand, silt and clay contents prepared through ordinary kriging approach were cross-validated through k-fold cross-validation

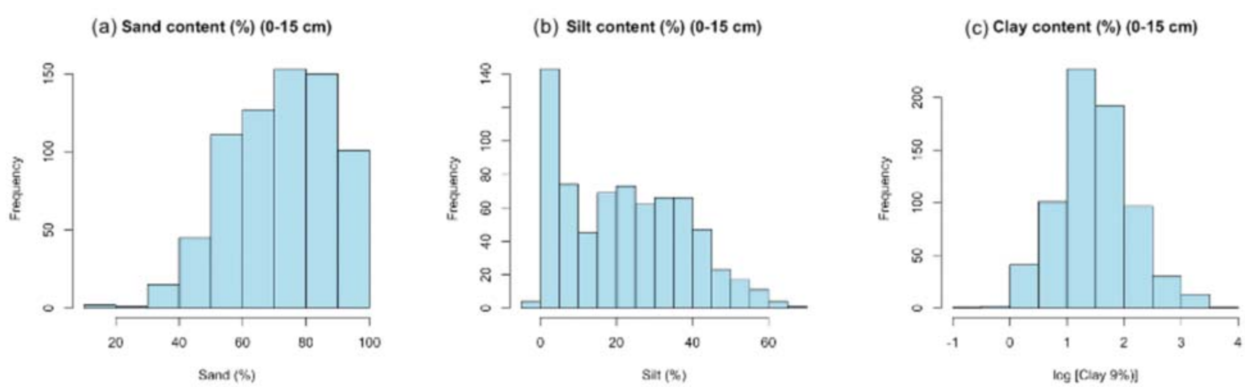

Fig. 2. Histogram of data on soil particle size distribution from western Rajasthan; (a) sand (0.02-2 mm) content, (b) silt (0.002-0.02 mm) content and (c) clay (<0.002 mm) content

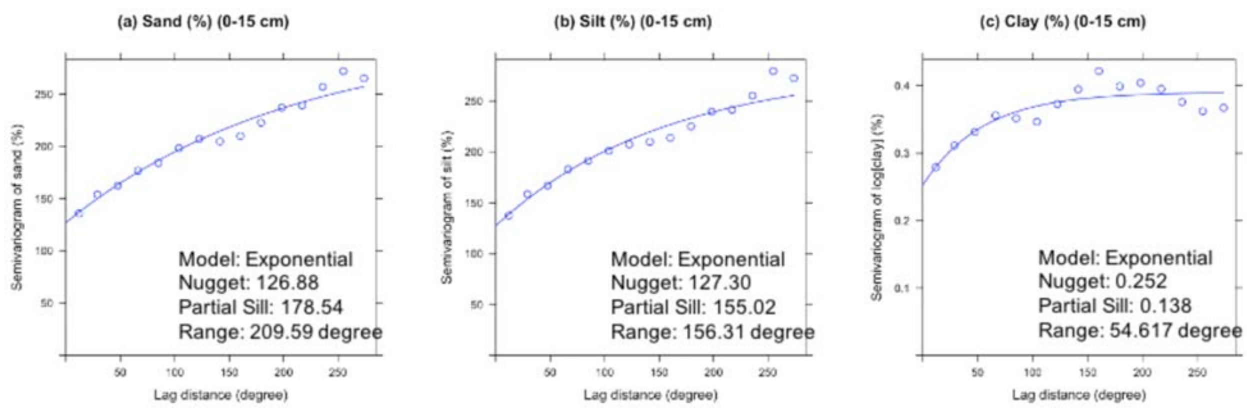

Fig. 3. Semivariogram of spatial variation of soil particle size distribution in western Rajasthan; (a) sand content, (b) silt content and (c) log[clay] content

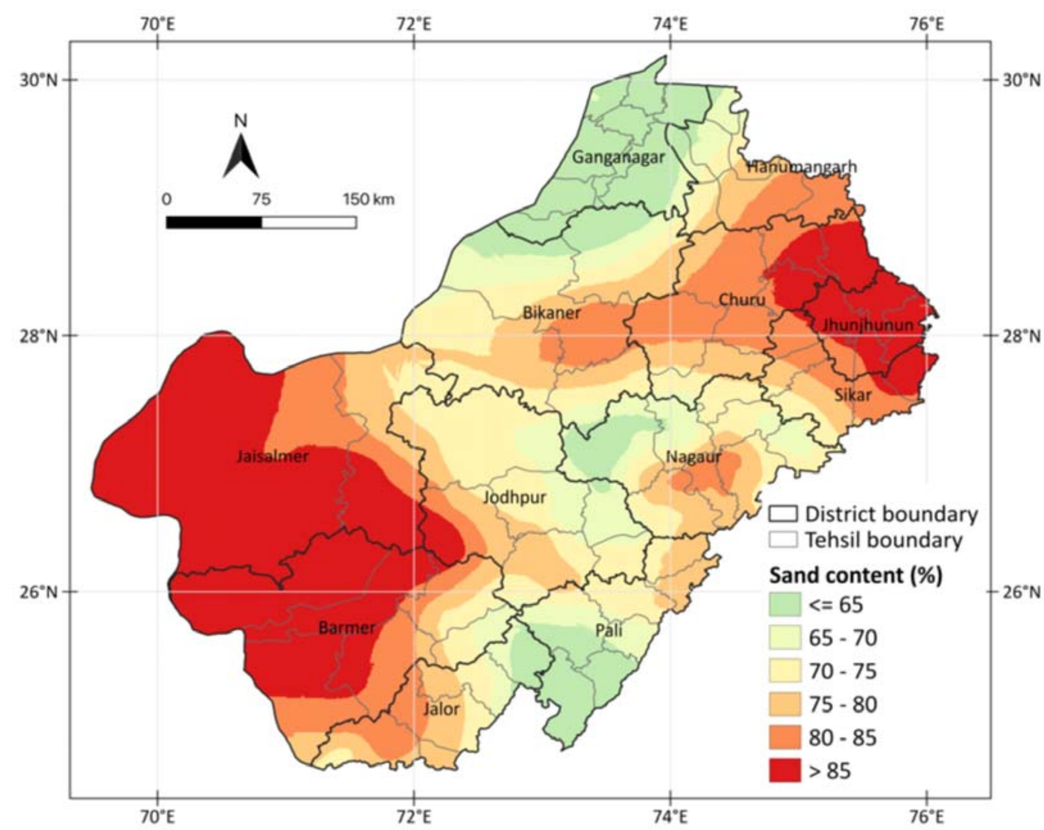

Fig. 4. Digital map of sand (0.02-2 mm) content of surface soil layer (0-15 cm) in western Rajasthan

(k=10) approach. Scatter plot of observed and predicted values of soil properties along with validation statistics (LCCC, R^2, RMSE and bias) are presented in Fig. 7. Best performance was observed for silt content ($R^2 = 0.46$) followed by sand content ($R^2 = 0.41$) and clay content ($R^2 = 0.17$).

Digital soil maps of soil water retention at field capacity (FC) and permanent wilting point (PWP)

Using these PTFs and the digital soil maps of sand, silt and clay (refer Fig. 7), digital maps of soil water retention at FC and PWP were prepared and

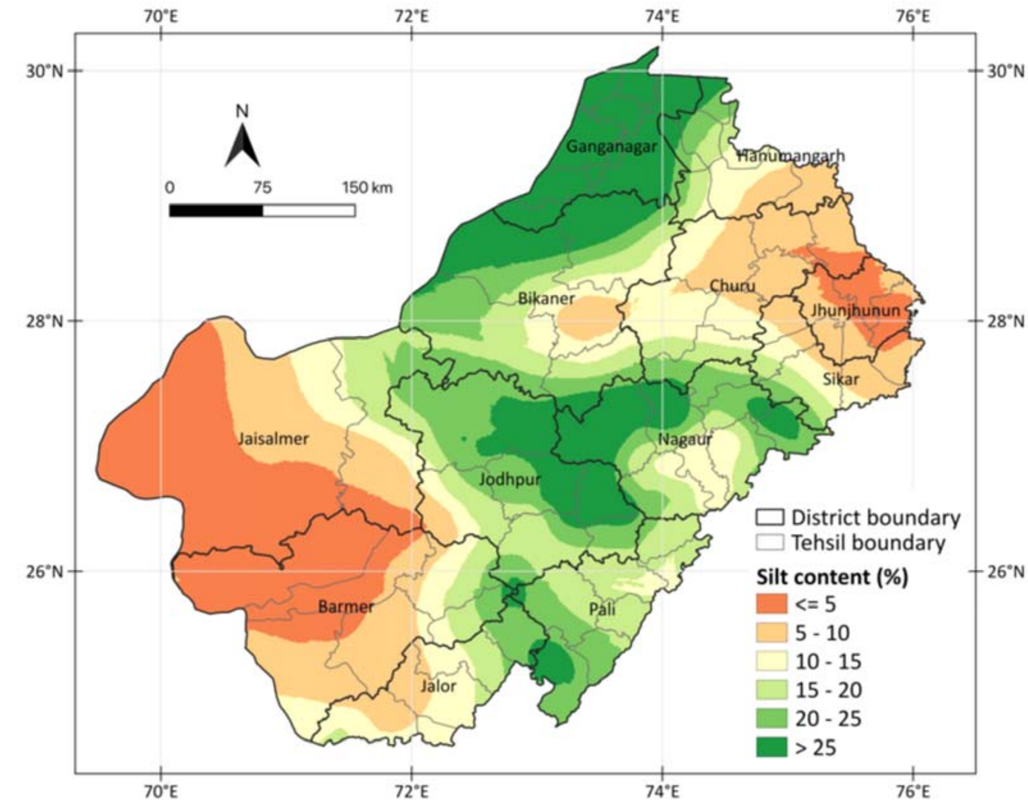

Fig. 5. Digital map of silt (0.002-0.02 mm) content of surface soil layer (0-15 cm) in western Rajasthan

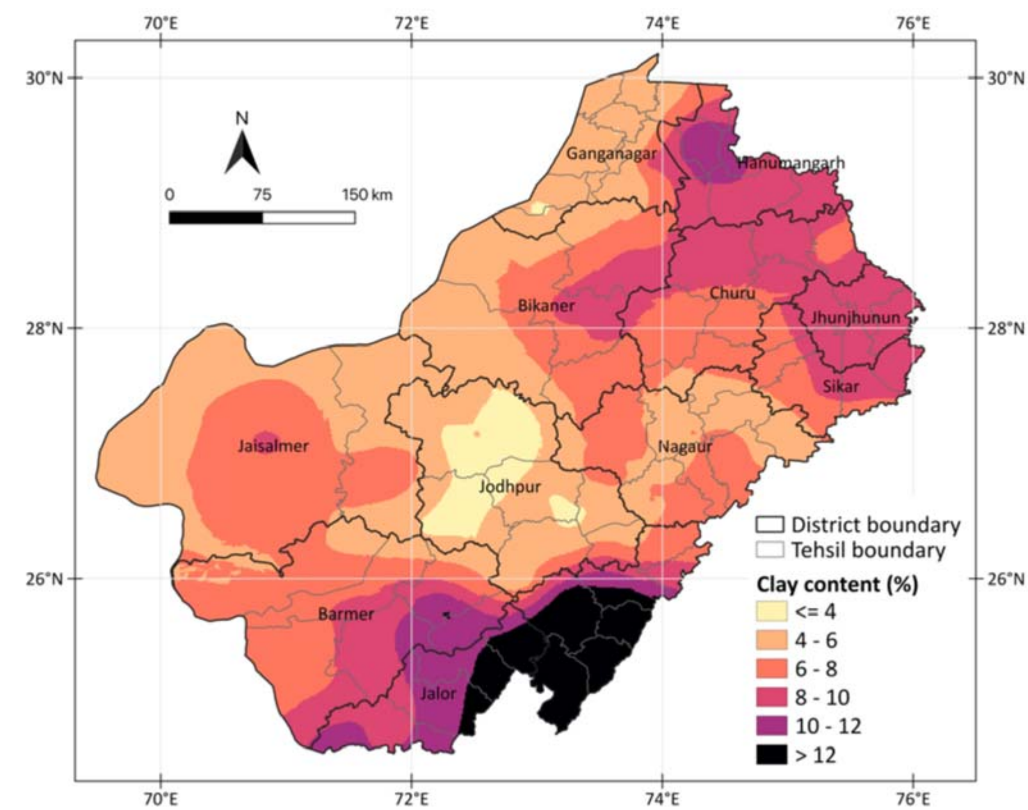

Fig. 6. Digital map of clay (<0.002 mm) content of surface soil layer (0-15 cm) in western Rajasthan

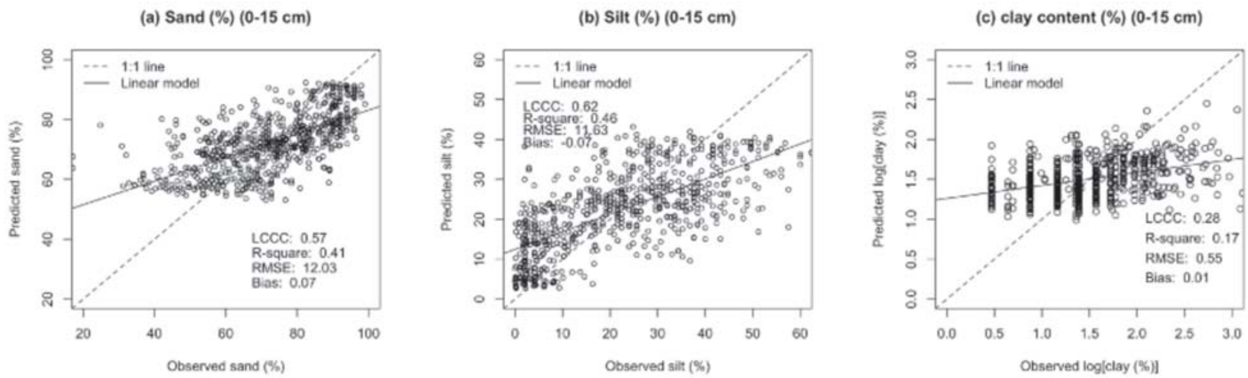

Fig. 7. Scatter plot of observed versus predicted values of particle size distribution in western Rajasthan; (a) Sand content (b) Silt content and (c) clay content

presented in Fig. 8. Spatial pattern of FC is almost similar with the pattern of sand content since sand content is the dominant factor in governing the soil water retention at FC, which is also evident from high coefficient for sand content in PTF for FC. According to Reddy and Das (2023), higher sand content in the western parts of the country may have contributed to lower FC and PWP values in western Indian desert ecosystems. Spatial pattern of PWP follows the pattern of clay content in to some extent although it is affected by both sand and clay content and their interaction (Srinivasarao *et al*., 2009). The map on FC (Fig. 9) shows very low soil water retention (8-10%, g/g) at south-western and north-eastern part of the region covering most part of Jaisalmer, Barmer, Churu and Jhunjhunu. Similarly, soil water retention at PWP is also very low (2.5-3.5%, g/g) in the most part of Jaisalmer, Barmer, Churu and Jhunjhunu. Therefore, sustainable crop growth in these districts in western Rajasthan is very difficult prepositions and only drought tolerant crops and varieties may the suitable option. In contrast, soil water retention is comparatively high in Ganganagar and Hanumangarh located at northern

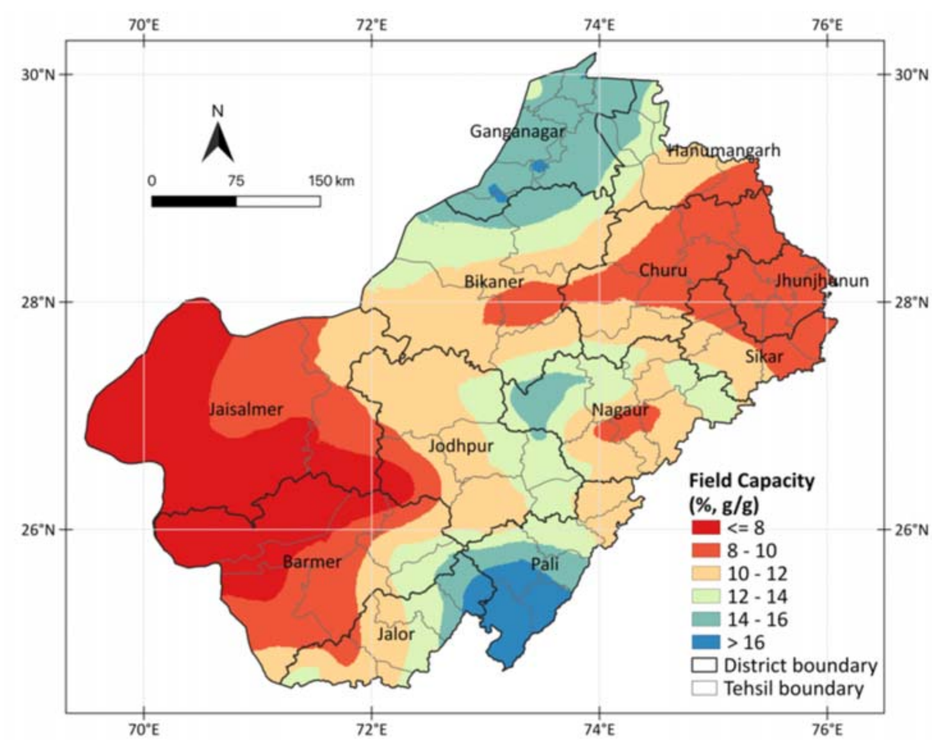

Fig. 8. Digital soil map of soil water retention at field capacity of surface soil layer (0-15 cm) in western Rajasthan

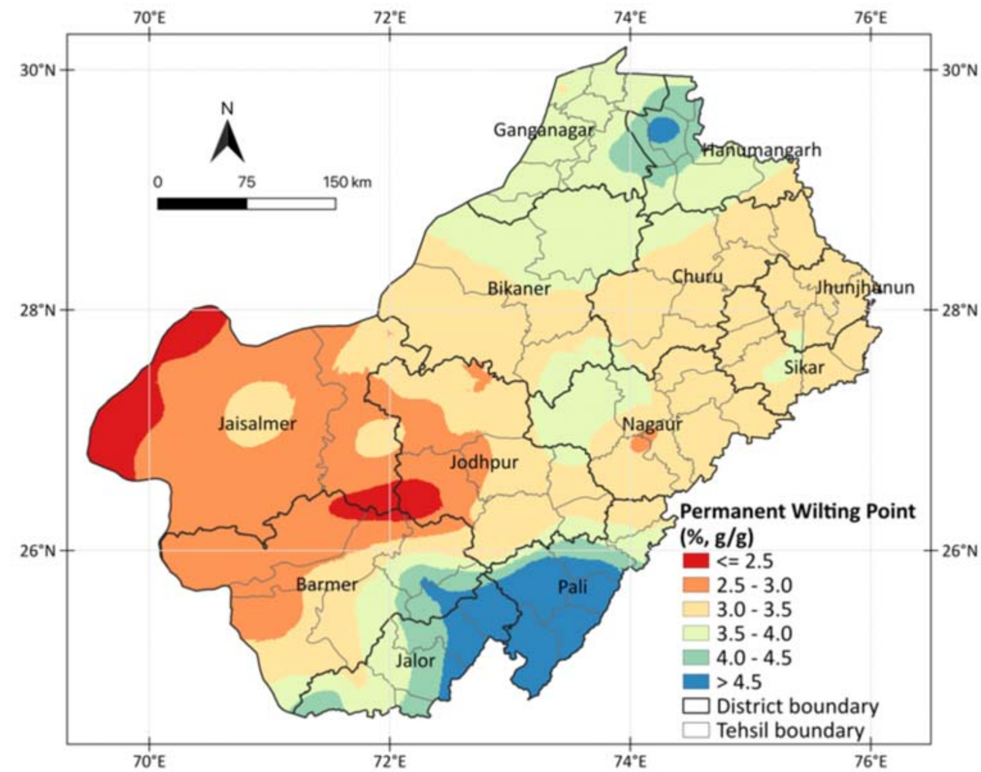

Fig. 9. Digital soil map of soil water retention at permanent wilting point of surface soil layer (0-15 cm) in western Rajasthan

part and in Pali district located at southern part of the region and crops with medium to high water requirement may be selected for sustainable agricultural production in the region.

One advantage of preparing digital map of soil properties through OK is the availability of map on standard deviation of kriged estimate at ach pixel of the map. Knowing the standard deviation of prediction, it is possible to measure uncertainty of the developed digital soil map, which is otherwise ignored in most cases. Here, the regression based PTF on FC and PWP were used to convert digital soil map of sand, silt and clay. Therefore, the uncertainty associated with each input map in PTF equation was propagated to map on FC and PWP. As standard deviation is invariant with origin and changes with scale, standard deviation of predicted θ_{FC} and θ_{PWP} were calculated using the following equation

$$\sigma_{\theta FC} = \sqrt{(0.264 \times \sigma_{sand})^2 + (0.207 \times \sigma_{clay})^2} \quad (16)$$

$$\sigma_{\theta PWP} = \sqrt{\begin{array}{c}(0.0385 \times \sigma_{sand})^2 + (0.232 \times \sigma_{clay})^2 \\ +(0.00057)^2\left[(\sigma^2_{sand} + \hat{z}_{sand})(\sigma^2_{clay} + \hat{z}_{clay}) - (\hat{z}_{sand})^2(\hat{z}_{clay})^2\right]\end{array}} \quad (17)$$

Where $\sigma_{\theta FC}$, $\sigma_{\theta PWP}$, σ_{sand}, σ_{clay}, represent standard deviation of prediction on θ_{FC}, θ_{PWP}, sand and clay, respectively; $\hat{z}_{sand}$ and $\hat{z}_{clay}$ are kriged estimate (mean) of sand and clay, respectively at each pixel of the digital soil map. It is to be noted here that in OK, sand and clay were assumed to follow independent normal distribution, therefore, the covariance component in the above equations were considered as zero. Prepared standard deviation map of estimated θ_{FC} and θ_{PWP} are presented in Fig. 10 and 11, respectively. It has been found from Fig. 10 that standard deviation of estimated θ_{FC} at central and north west pocket of western Rajasthan is low (<4.8%) as compared to rest part of the region, thus the kriged estimates are more reliable in these pocketed areas. This was due to more sampling density in these pocketed parts than rest part of the region (please refer Fig. 1). Hence, it indicates that

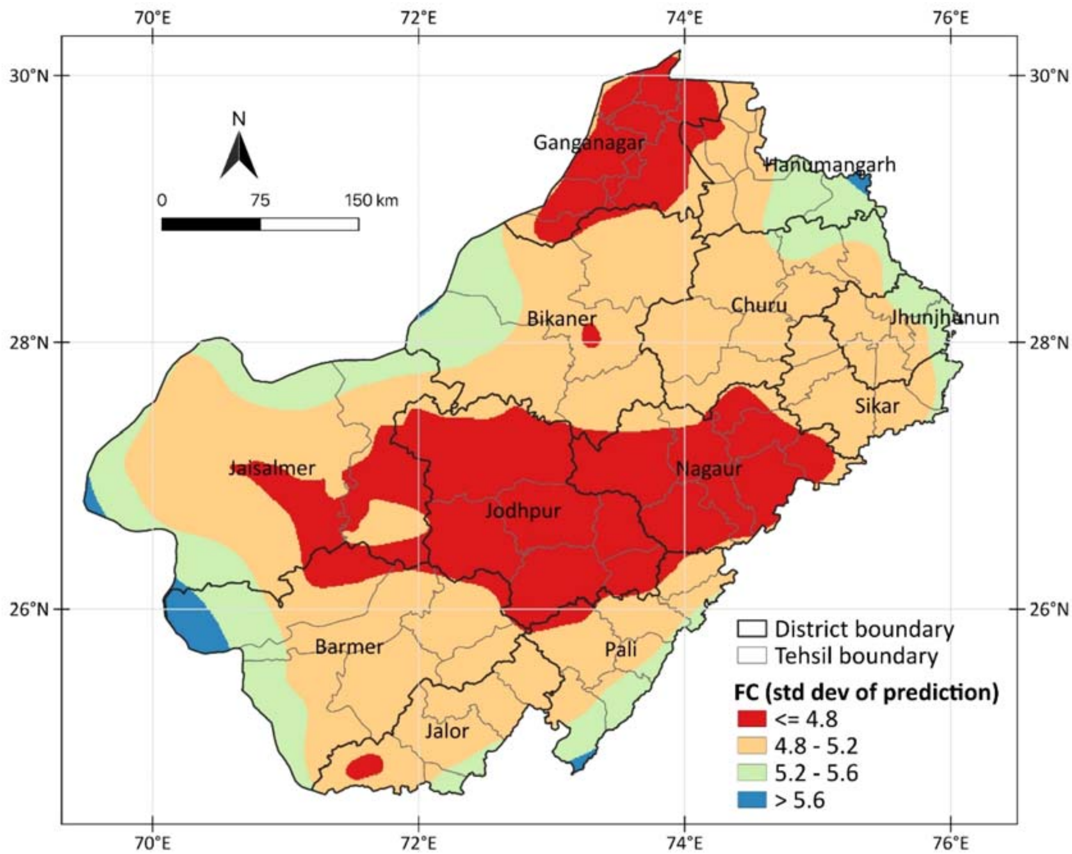

Fig. 10. Standard deviation of predicted digital map on soil water retention at field capacity (FC) of surface soil layer (0-15 cm) in western Rajasthan

the uncertainty of the developed map may be reduced by increasing sampling density. Overall, the standard deviation of estimated θ_{FC} was <5.2% in about 80% of the region.

Similarly, standarad deviation of estimated q_{PWP} was <4.5% in about 80% of the region in western Rajasthan (Fig. 11). However, the coefficient of variation (kriged estimate divided by standard deviation) of kriged estimate was comparatively higher in θ_{PWP} than θ_{FC}. It may be due to more number of input variables in the PTF equation for θ_{PWP} than for θ_{FC}, which lead to propagation of multiple variation in the final predicted value (please refer Eq 14-7).

Another big advantage of preparing the standard deviation of prediction map is the estimation of confidence interval of prediction at a desired significance level. For example, confidence interval of predicted θ_{FC} or θ_{PWP} can be calculated as follows:

Confidence Interval at 90% significance level = kriged estimate ± 1.64 × Standard deviation of prediction (18)

Confidence Interval at 95% significance level = kriged estimate ± 1.96 × Standard deviation of prediction (19)

Similar to these two soil indicator maps, other soil indicator maps e.g. soil erodibility, soil hydraulic conductivity, infiltration rate, soil fertility, soil quality index etc can also be prepared following the digital soil mapping and pedotransfer function approach (Van Looy *et al.*, 2017). Few such soil indicators for assessing sustainability of agricultural production system in arid region are mentioned in Table 2.

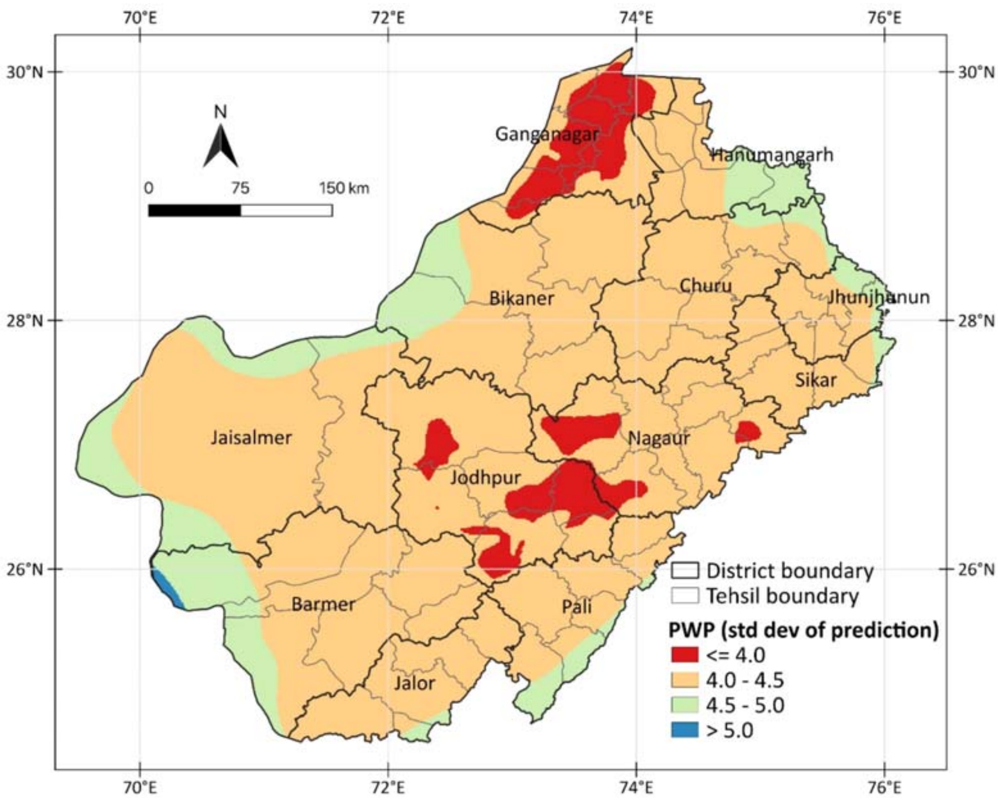

Fig. 11. Standard deviation of predicted digital map on soil water retention at permanent wilting point (PWP) of surface soil layer (0-15 cm) in western Rajasthan

Table 2. Field level soil indicators for assessment of sustainable agricultural production in arid region

Indicator type	Field level soil indicators	
	Indicators	Measurable unit
Pressure indicator	Water holding capacity	% (m^3 m^{-3})
	Freely available $CaCO_3$ content	%
	Infiltration rate	mm h^{-1}
State indicator	Soil grain size distribution index	-
	Soil organic carbon content	g kg^{-1}
	Fine sand (0.02-0.25 mm) content	%
	Soil nutrient content	kg ha^{-1}
	Soil loss rate	t ha^{-1} y^{-1}
	Salt build up (EC, ESP, SAR)	dS m^{-1}
Response indicator	yield loss	Rs ha^{-1}

Conclusion

Digital maps of soil water retention at FC and PWP in western Rajasthan were successfully developed by combining digital soil mapping (DSM) and pedotransfer function (PTF) approach. Spatial data on sand, silt and clay content for 705 locations in western Rajasthan with a geographical area of 20 million ha was used to prepare digital map of sand, silt and clay followed by combining these maps through PTF equation to digital map of FC and PWP. Following major conclusions are drawn from the present study:

(i) The integration approach of DSM and PTF is very much suitable to prepare map of complex soil properties, which are difficult to measure and time consuming. Digital map of basic soil properties are otherwise easy to prepare through soil sampling in a quick time. Moreover, complex soil properties are highly heterogeneous and thus is very difficult to capture the spatial pattern to prepare digital soil map by directly applying the DSM methodology.

(ii) Accuracy and uncertainty of the developed digital maps on FC and PWP is reasonable specifically if compared with the cost involved in direct measurement of these properties at multiple locations. Both accuracy and uncertainty of digital maps on complex soil properties depends on how best the spatial pattern of the basic soil properties are captured through a well distributed soil sampling approach. Accuracy of the prepared map on complex soil properties also depends on the accuracy of the PTF models . Here, the accuracy of digital map of sand, silt and clay in terms of R^2 were about 0.41-0.46, whereas the accuracy of PTF models in terms of R^2 were about 0.87-0.92. Therefore, accuracy of the developed map of complex soil properties may be improved by increasing accuracy of both the approaches. A big advantage of the ordinary kriging approach to prepare digital soil map is the quantification of standard deviation of predicted values of soil properties at each pixel of the digital map. However, when the individual maps are combined through PTF equations, standard deviation propagates through PTF equations. Thus more complex is the PTF equation, more propagation and multiplication of error in the final map. It has also been observed that uncertainty of prediction was low at those pocketed areas where sampling density was high. Thus, high sampling density and uniformly distributed sampling locations has a great contribution on improving the accuracy and reducing the uncertainty (increasing reliability) of the developed maps.

(iii) Soil water content at FC and PWP are two important soil indicators in western Rajasthan. These two soil water constants greatly influence the amount of irrigation water to be applied in agricultural field. Most of the time, knowledge on these soil parameters are not available which pose a serious limitation in judicious use of scare water resources. Thus, digital soil map on FC and PWP may greatly help farmers and other stakeholders for sustainable management of both soil and water resources. Such digital maps have a great opportunity to cater the need of several stakeholders by making it available in different digital platforms.

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