Field-scale spatial variability of physical properties of black soils of Purna Valley, India, using Geostatistical Approach

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ABSTRACT

The analysis of the spatial variability of soil properties is important for precision agriculture, land use planning and environmental modelling. Soil texture (sand, silt and clay) and soil hydraulic properties like available water capacity and hydraulic conductivity are most important soil physical properties that govern nearly all of the soil attributes. The objective of the study was to determine the degree of spatial variability of sand, silt, clay, bulk density, hydraulic conductivity and available water content at field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC) of salt affected black soils of Purna valley. Data were analyzed both statistically and geostatically to describe the spatial distribution of soil physical properties. Soil physical properties showed large variability with greatest variation was observed in hydraulic conductivity (54%). Spherical and gaussian models were fit well for the soil physical properties. The nugget/sill ratio indicates that hydraulic conductivity, clay, silt content and soil water content at field capacity were strongly spatially dependent and all other soil physical properties were moderate spatially dependent. Cross validation of the kriged map shows that prediction of the soil physical properties using semivariogram parameters is better than assuming mean of observed value for any unsampled location. The spatial distribution of hydraulic conductivity and bulk density followed the distribution pattern of clay and exchangeable sodium content. These maps will help to the planners in site-specific management/precision farming by application of the correct measures for improving the physical properties of these degraded shrink-swell soils through application of gypsum, FYM and green manuring through variable rate techniques.

Key words: Soil physical properties, Spatial variability, Geostatistics, Semivariogram, Cross-validation, Purna valley

INTRODUCTION

Soil variability is the outcome of many processes acting and interacting across a continuum of spatial and temporal scales and is inherently scale dependant (Trangmar et al., 1985). Spatial variability is an inherent and dynamic feature of soil. It may be both vertical (within a pedon) and horizontal (across the landscape). Variability in soil properties results mainly from the complex interactions between geology, topography, climate, as well as soil use (Quine and Zhang, 2002). Variability may also occur as a result of land use and management strategies. As other environmental variables, soil water and soil texture changes in space and time. The soil variability has been of great concern to the researchers in the past as it plays an important role in design of field experiments, management of soils and in evaluation of productivity potential. Soil texture, the relative percentage of sand, silt, and clay; soil water, bulk density and saturated hydraulic conductivity are the most important soil physical properties that governing nearly all of the other attributes of soils. Soil water and texture are two soil physical properties which control plant growth and influence a variety of soil processes including, leaching and erosion potential (Adhikari et al., 2009), plant nutrient storage (Kettler et al., 2001), organic-matter dynamics (Kong et al., 2009). Knowledge of spatial variation of soil properties is important in precision farming and environmental modeling (Santra et al., 2008).

Therefore, understanding of spatial variation of soil properties is very essential for refining farm management practices, modeling at landscape level...

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and assessing the impact of agriculture on environment. The application of parametric statistics is inadequate for analysis of spatially dependant variables because, they assume that measured observations are independent in spite of their distribution in space. The recently available techniques like GIS and GPS enables successful application of these technologies for management and conservation of natural resources at varied levels of scale i.e. from village to country level (Dean, 1994). Geostatistics provide a tool for improving sampling design by utilizing the spatial dependence of soil properties within a sampling region and useful to illustrate the spatial interrelationship of soil data which reduces error, biasness and increase the accuracy of data for interpolation (Oliver, 1987). Geostatistics is a technology for estimating the soil property values in non-sampled areas or areas with sparse samplings (Yao et al., 2004). These non-sampled areas can vary in space (in one, two, or three dimensions) from the sampled data (Zhu et al., 2005). Geospatial techniques are also useful assessing land uses and development of sustainable agricultural land use plans (Farooq et al., 2008; Sharma et al., 2018).

Vertisols and associated soils are the most widely distributed soils in the world and can be found under varied climatic condition. In India, shrink-swell soils are found mostly in the peninsular region and these soils are developed on alluvium derived from weathering of Deccan Basalt (Murthy et al., 1982). The Vertisols occupy about 26.62 m ha in India of which 5.6 m ha is in Maharashtra (Bhattacharyya et al., 2009). They are mainly confined to lower topographic positions, such as the river valleys. One such valley is the Purna valley, which covers a large area of 1,900,000 ha in the district of Amravati, Akola and Buldhana of Maharashtra, India. The earlier studies conducted in the region reveal that the soils of the Purna valley have problems like the native salinity/sodicity, poor drainability and poor quality ground water. The unique feature of salt affected soils of Purna valley is that though salinity is widely reported in this tract, presence of salts on surface is hardly seen (Balpande et al., 1996). Thus these soils are deteriorated in their soil physical properties and resulted in poor drainability and hence for the sustainable agricultural production it is essential to understand the spatial distribution of their physical properties for better management options and strategies for restoration of these problem soils. The information on spatial variability of soil properties at village or watershed level, particularly, in soils of basaltic terrain is meagre. Therefore, the present study has been planned to quantify the spatial variability of physical properties of soils in Ramagarh village of Amravati district of Maharashtra.

MATERIALS AND METHODS

Study area

The study area comprises central part of the Purna valley in Vidarbha region of central India. Ramagarh village was selected for present study which is located between 77°12′36″ to 77°13′50″ E longitude and 20°52′46″ to 20°53′59″ N latitudes in Daryapur tehsil of Amravati district of Maharashtra covering an area of 324 ha (Fig. 1). The mean elevation of the village ranges from 250 to 286 m above the mean sea level (MSL). The area is characterized by hot summer and a dry weather conditions except, during the south west monsoon season and thus represents a tropical sub humid dry to semi-arid dry climate. The study area has monsoonal climate, beginning from June or July through September which receives 85-95% of the total annual rainfall of 700-975 mm. However, the district experiences an erratic rainfall pattern with low as 600 to as high as 1100 mm. This is followed by a dry season from October to May or June. April and May are the hottest months with mean monthly temperature of 32.5 and 35.2°C, respectively.
December and January are the coolest months with monthly temperature of 22°C. The length of growing period in the area is 152 days. The soils have a Typic Troposolic moisture regime (Van Wambeke, 1985). The soil temperature regime is hyperthermic. There are two broad soil subgroups in the study area according to Soil Taxonomy (USDA) namely – Typic Haplusterts and Sodic Haplusterts. Majority percentage of cultivated land in kharif is under Soybean (Glycin max), greengram (Phaseolus aurens) and cotton (Gossypium spp.) as principal crops. Legumes like pigeon pea (Cajanous cajan), black gram (Phaseolus mungo) and cowpea (Vigna catiang) are also grown. Chickpea (Cicer arietinum) is dominant crop in rabi season under residual soil moisture and/or with some protective irrigations. The natural vegetation of the area comprises of dry deciduous tree species and grasses. The dominant tree species are babul (Accacia arabica), ber (Ziziphus jujube), palas (Butea frondosa), neem (Azadiracta indica), rui (Calotropic giganda), kans (Saccharum spontaneum) and dub (Cynadon dactylon).

Soil sampling, processing and analysis

The information about land resources of the Ramagarh village was interpreted and studied from the collateral maps. The cadastral map of the village on 1:8,000 scale showed the field boundaries with survey number of each field, the other permanent details like habitation, roads, farm ponds, community ponds and stream etc. were also obtained from the same. In addition to this the Survey of India (SOI) toposheet No. 55 H/1 (1:50,000 scale) was used to collect topographic information for landform analysis. Simultaneously the latitude and longitude of the study area was recorded using portable hand held Garmin GPS instrument for georeferencing of the study area. Then the cadastral map georeferenced with the toposheet using maximum GCP and digitized in Arc GIS Ver. 10.1 GIS software. Grid size of 250×250 m was superimposed on cadastral map of the village on 1:8000 scale using Arc GIS software (Fig. 2). Further, the locations of sampling points in the village acquired using the GPS was converted to point attribute feature class in Arc GIS. In the entire study area, a total of 84 grid soil samples were collected within 0–20 cm soil depth at identified locations. Collected soil samples were air-dried and passed through 2 mm sieve for laboratory analysis.

The processed soil samples were analyzed for its particle size distribution was determined as per the international pipette method. Soil was treated with H2O2 (30%) for the removal of organic matter and further treated with HCl (1N) to remove CaCO3 using sodium hexametaphosphate as dispersing agent. Sand (2.0-0.05mm), silt (0.05-0.002mm), clay (<0.002mm) were separated using the procedure described by Jackson (1979). The bulk density was determined by clod coating technique as described by Blake and Hartge (1986). Air dried clods collected from soil profiles were weighed and their bulk volume was determined by water displacement by clod coated with melted paraffin wax. The bulk density (Mg m⁻³) was expressed on oven dry basis. The saturated hydraulic conducti-vity was determined by constant head method described by Klute and Dirksen (1986). Moisture retention was determined at FC (-33 kPa) and PWP (-1500 kPa) using Pressure Plate Apparatus and available water capacity was determined as the difference between water content at PWP – FC (Klute,1986).

Geostatistical analysis of soil properties

Spatial interpolation and GIS mapping techniques were employed to produce spatial
distribution maps for the investigated basic soil properties, and the software used for this purpose was ArcGIS v.10.1 (ESRI Co, Redlands, USA). In ArcGIS, kriging can express the spatial variation and allow a variety of map outputs, and at the same time minimize the errors of predicted values (González et al., 2014). Moreover, it is very flexible and allows users to investigate graphs of spatial autocorrelation. Kriging, as applied within moving data neighbourhoods, is a nonstationary algorithm which corresponds to a nonstationary random function model with varying mean but stationary covariance (Deutsch and Journal, 1992). In kriging, a semivariogram model was used to define the weights of the function (Webster and Oliver, 2001), and the semivariance is an autocorrelation statistic defined as follows (Mabit and Bernard, 2007):

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

Where, $z(x_i)$ is the value of the variable $z$ at location of $x_i$, $h$ the lag, and $N(h)$ is the number of pairs of sample points separated by $h$.

During pair calculation for computing the semivariogram, maximum lag distance was taken as half of the minimum extent of sampling area. Anisotropic semivariograms did not show any differences in spatial dependence based on direction, for which reason isotropic semivariograms were chosen. Spherical, exponential, and Gaussian models were fitted to the empirical semivariograms. Best-fit model with minimum root mean square error (RMSE) were selected for each soil property:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [z(x_i) - \hat{z}(x_i)]^2}$$

The spherical and gaussian models were best fitted to all the soil physical properties. Expression for different semivariogram models used in this study is given below:

**Spherical model**

$$\hat{\gamma}(h) = C_0 + C \left[ 1.5 \frac{h}{a} - 0.5 \left( \frac{h}{a} \right)^3 \right], \text{ if } 0 \leq h \leq a$$

$$\hat{\gamma}(h) = C_0 + C, \text{ otherwise}$$

**Gaussian model**

$$\hat{\gamma}(h) = C_0 + C \left[ 1 - \exp \left( -\frac{h^2}{a^2} \right) \right]$$

for $h \geq 0$

Using the semivariogram model, basic spatial parameters such as nugget ($C_0$), sill ($C + C_0$) and range ($A$) was calculated which provide information about the structure as well as the input parameters for the kriging interpolation. Nugget represents variation caused by stochastic factors, such as error in measurement, sill is the lag distance between measurements at which one value for a variable does not influence neighboring values, and range is the distance at which values of one variable become spatially independent of another (Lopez-Granados et al., 2002).

**Accuracy assessment**

Accuracy of the maps was evaluated through cross-validation approach (Davis 1987). Among the three evaluation indices used in this study, mean absolute error (MAE) and mean-squared error (MSE) measure the accuracy of prediction, whereas goodness of prediction (G) measures the effectiveness of prediction. MAE is a measure of the sum of the residuals (Voltz and Webster, 1990).

$$MAE = \frac{1}{N} \sum_{i=1}^{N} [z(X_i) - \hat{z}(X_i)]$$

Where $\hat{z}(X_i)$ is the predicted value at location $i$. Small MAE values indicate less error. The MAE measure, however, does not reveal the magnitude of error that might occur at any point and hence MSE will be calculated.

$$MAE = \frac{1}{N} \sum_{i=1}^{N} [z(X_i) - \hat{z}(X_i)]^2$$

Squaring the difference at any point gives an indication of the magnitude, for example, small MSE values indicate more accurate estimation, point-by-point. The G measure gives an indication of how effective a prediction might be relative to that which could have been derived from using the sample mean alone (Schloeder et al., 2001). If $G = 100$, it indicates perfect prediction, while negative values indicate that the predictions are less reliable than using sample mean as the predictors. The comparison of performance between interpolations was achieved by using MAE.

**RESULTS AND DISCUSSION**

**Descriptive statistics of soil physical properties**

The variability of soil properties can be described by descriptive statistics such as minimum, maximum, mean, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis. Measured variables in the data set were
analyzed using Arc GIS software to obtain the descriptive statistics (Table 1). There was a difference in the CV of the soil physical properties. Wilding (1985) described a classification scheme for identifying the extent of variability for soil properties based on their CV values in which CV values 0-15, 16-35, and >36 percent indicate little, moderate, and high variability, respectively. Among the particle size separates, the clay and silt content of soil had lowest variability (CV of 2% and 5%, respectively), and sand contents which made moderate variability (CV of 26%). While studying black soils Gore et al. (2012) reported lower CV values for sand and higher CV values for silt and clay, respectively. Average bulk density was recorded as 1.62 Mg m\(^{-3}\) with a range of 1.35 to 1.88 Mg m\(^{-3}\) (CV= 7%). Hydraulic conductivity found not normally distributed and range from 0.72 to 13.77 mm h\(^{-1}\) with average value of 4.98 mm h\(^{-1}\) having largest variation among the physical properties (CV=54). Moisture retention at 33 kPa and 1500 kPa varied from 33.27 to 48.97 and 15.76 to 32.06 per cent with mean value of 41.07 and 24.47 per cent, respectively. The moisture retention at 33 kPa and 1500 kPa were found little variable with CV of 9 and 12%, respectively. Moisture retention at 33 kPa and 1500 kPa were found normal with lower skewness and kurtosis values. Although these statistical studies provide useful information about the soil physical properties distribution, they do not describe the spatial continuity of the data, that is, the relationship between the value for a property in one location and the values for the same property at other location through the landscape. Hence, geostatistical techniques were applied to better understand of spatial distribution pattern of the studied variables. Besides, normality may not be strictly required in geostatistical analyses but normal distribution may lead to more reliable results (Webster and Oliver, 2001). Therefore, each soil physical property was checked for normality.

Semivariogram analysis of soil physical properties

Semivariogram parameters (nugget, sill, and range) for each soil physical properties with best fitted modal were identified based on minimum RMSE. Analysis of the isotropic variogram indicated that the sand, silt, and clay contents semivariograms were well-described by spherical model, with the distance of spatial dependence being 2500, 1230, and 479 m, respectively and bulk density and hydraulic conductivity also best described by spherical model, with the distance of spatial dependence being 1882 and 1183 m, respectively. The longer spatial dependence of BD and HC is due to the variation in these properties owing to the clay dominated by exchangeable sodium under the prevailing semi-arid climate and basin topography of the valley soils and also due to variation in management (Nimkar et al., 1992; Kadu et al., 1993; Balpande et al., 1996; Kadam et al., 2013). While the FC, PWP, and AWC semivariograms were well described by guassian model, with the distance of spatial dependence being 479, 814, and 1013 m, respectively (Table 2). Within the study area, the soil particles displayed slight difference in the distance of spatial dependence. Such differences in the distance of spatial dependence for soil particles were reported in other studies (Cambardella et al., 1994; Safari et al., 2013). The ratios of nugget and sill between 0.25 and 0.75 represented moderate spatial dependence; those below 0.25 represented strong spatial dependence (Cambardella et al., 1994). The resulting semivariograms indicated that except clay, hydraulic conductivity, water content at field capacity and silt, all other soil physical properties were moderate spatially dependent (47.3-68.5%).
imprinted by intrinsic factor (soil forming process), and extrinsic factors (tillage operation and cultivation practices) (Cambardella et al., 1994). The semivariogram parameters of the physical properties of soils showed that the zone of influence (range) of clay and moisture retention at 33 kPa found to be relatively very less (479 m) indicating strong spatial dependence over a short distance as the clay content is the inherent property of soil. All these soils are developed from the basalt and obviously the clay content is more than the sand and silt. Some other researchers had also found the moderate spatial dependence of soil physical properties (Iqbal et al., 2005; Safari et al., 2013).

### Table 2. Geostatistical parameters of the fitted semivariogram models for soil physical properties

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Semivariogram model</th>
<th>Range (m)</th>
<th>Nugget (C₀)</th>
<th>Partial sill (C)</th>
<th>Sill (C₀+C)</th>
<th>Nugget/Sill Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Spherical</td>
<td>2500</td>
<td>0.85</td>
<td>0.039</td>
<td>1.24</td>
<td>68.5</td>
</tr>
<tr>
<td>Silt</td>
<td>Spherical</td>
<td>1230</td>
<td>0.53</td>
<td>1.76</td>
<td>2.29</td>
<td>23.1</td>
</tr>
<tr>
<td>Clay</td>
<td>Spherical</td>
<td>479</td>
<td>0.14</td>
<td>1.06</td>
<td>1.2</td>
<td>11.7</td>
</tr>
<tr>
<td>ln (Bulk density)</td>
<td>Spherical</td>
<td>1882</td>
<td>0.0032</td>
<td>0.0026</td>
<td>0.0058</td>
<td>55.2</td>
</tr>
<tr>
<td>Hydraulic Conductivity</td>
<td>Spherical</td>
<td>1183</td>
<td>0.016</td>
<td>0.162</td>
<td>0.178</td>
<td>9.0</td>
</tr>
<tr>
<td>Moisture retention -33kPa</td>
<td>Gaussian</td>
<td>479</td>
<td>2.74</td>
<td>9.60</td>
<td>12.34</td>
<td>22.2</td>
</tr>
<tr>
<td>Moisture retention -1500kPa</td>
<td>Gaussian</td>
<td>814</td>
<td>2.90</td>
<td>3.23</td>
<td>6.13</td>
<td>47.3</td>
</tr>
<tr>
<td>AWC (%)</td>
<td>Gaussian</td>
<td>1013</td>
<td>1.48</td>
<td>1.60</td>
<td>3.08</td>
<td>48.05</td>
</tr>
</tbody>
</table>

Spatial distribution map and cross-validation

The parameters of the spherical and gaussian models were used for kriging to produce the spatial distribution maps of soil physical properties of the study area. Spatial maps of silt and clay (Fig. 3 & 4) showed that overall sand content in the soils of Purna valley is also reported to be below 10 percent (Balpande, 1996), 5 to 10% sand content was found uniformly distributed all over the region except in NE corner. The silt content varied from 30 to 40% and the majority of the area fall in the range of 30 to 35% except in SW, SE and NE quadrant, and the clay content ranged from 55 to 65%, the spatial map of clay content indicates that 50% each area falls in to the 55-60 and 60-65% category and higher content...
of clay found in the centre of the study area. The silt and clay contents were spatially correlated. Areas with higher clay content corresponded with lower silt content.

The spatial variability map of bulk density was reclassified into 2 classes viz. 1.47-1.60 and 1.60-1.80 Mg m\(^{-3}\). It is evident from the map that most of the area, 95% of TGA of the village is under high BD class (1.60-1.80 Mg m\(^{-3}\)) remaining 5% area of TGA in the SW quadrant is under medium (1.47-1.60 Mg m\(^{-3}\)) category. It means that maximum area of the village is facing problem of compaction which inhibit emergence of young plants. The hydraulic conductivity varied from 1.55 to 8.87 mm/hr. The spatial variability map of hydraulic conductivity was reclassified into 2 classes viz. very slow (1.0-5.0 mm/hr) and slow (5.0-10.0 mm/hr). The spatial variability map of hydraulic conductivity (Fig. 5) shows that 87% TGA of the village with a continuous patch extending from NE to SW is suffering from slow permeability and on the other hand 13% TGA of the village had very slow hydraulic conductivity problem. The result indicates that high values of BD are due to low soil organic carbon and heavy farm mechanization. On the other hand, decrease in hydraulic conductivity owing to high ESP and removal of calcium from the surface soils and its precipitation in subsoil resulting into subsoil sodicity. The study has importance in efficient utilization of agricultural inputs with respect to spatial variation of soil properties.
Spatial maps of FC, PWP and AWC (Fig 6–8) indicated that soils in the NW and SW part of the study area have low water retention at FC and PWP, as well as lower AWC. As expected, a negative relationship was obtained of sand content with FC (–0.115), PWP (–0.048), and AWC (–0.097) and positive relationship of clay with AWC (0.157, two-tailed) and PWP (0.75), and highly significant positive relationship of OC with FC (0.42) and PWP (0.73).

In summary, the distribution maps of various soil physical properties across the study area have implications for variable rate application of chemical amendments like gypsum, FYM, fertilizer, water, seed rate, and management strategies in terms of crop rotation and green manuring. For instance, the spatial distribution of hydraulic conductivity and bulk density closely followed the distribution of pattern of silt, clay and exchangeable sodium percentage in these soils. These maps will help to planner to develop the variable rate of technology (VRT) for the study area. The VRT plan for the study area would not only optimize yield of crops by avoiding crop water stress in highly prone areas, but would also reduce ESP and improves the hydraulic properties and surface water stagnation in the 

Table 3 showed the evaluation indices resulting from cross-validation of spatial maps of soil physical properties. It was observed that, bulk density, sand content, hydraulic conductivity, and clay content had low MAE however, bulk density, clay and sand content had relatively low MSE than other soil physical properties. For all the soil physical properties, the G value was greater than 0, which indicates that spatial prediction using semivariogram parameters is better than assuming mean of observed value as the property value for any unsampled location. This also shows that semivariogram parameters obtained from fitting of experimental semivariogram values were reasonable to describe the spatial variation of all the studied soil physical properties.

**CONCLUSIONS**

The classical and geostatistical method on a large scale could be accurately used to evaluate spatial variability of soil physical properties. The raw data of hydraulic conductivity strongly positively skewed and the application of log transformation was effective in normalizing the data. Among the three models selected, the
spherical model fits the experimental semivariogram for soil particles, bulk density and hydraulic conductivity while for soil hydraulic properties, the gaussian model was found the best to fit the experimental semivariogram. Semivariograms for soil properties indicated that hydraulic conductivity, clay, silt content and soil water retained at field capacity were strongly spatially dependent and all other soil physical properties were moderate spatially dependent. Spatial maps of sand content showed that in the soils of Purna valley sand is below 10 percent, 5 to 10% sand content was found uniformly distributed all over the region except in NE corner. Majority of the area fall in the range of 30 to 35% silt content except SW, SE and NE quadrant and clay contents showed that 50% each of the area falls in to the 55-60 and 60-65% category and higher content of clay found in the centre of the study area. It is evident from the map that most of the area, 95% of TGA of the village is under high BD class whereas very little area (5%) of TGA in the SW quadrant is under medium BD category. The spatial variability map of hydraulic conductivity revealed that 87% TGA of the village is suffering from low permeability and on the other hand 13% TGA of the village had very low hydraulic conductivity problem.

Cross validation of kriged map shows that spatial prediction of soil physical properties using semivariogram parameters is better than mean of the observed value for any unsampled location. Spatial variability maps of various soil physical properties will help in site-specific management/precision farming by application of the correct properties will help in site-specific management/


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