Pedotransfer function for predicting the soil hydraulic properties in semi-arid region of Karnataka Plateau

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Abstract

Soil hydraulic properties are important for irrigation scheduling and preparation of proper landuse planning. Field capacity, permanent wilting point and infiltration rate are the three vital hydraulic properties which determine the availability and retention of the water for crop growth. These properties are difficult to measure and time consuming but it can be easily predicted from the available soil information like soil texture, bulk density, organic carbon content etc through pedotransfer functions. Pedotransfer function (PTF) was developed for Field capacity and permanent wilting point for two different regions of Karnataka viz. Northern Karnataka Plateau (512 soil samples) and Southern Karnataka Plateau (228 soil samples) separately. PTF for infiltration rate was developed using 100 soil samples for whole Karnataka. Cross validation techniques was used to validate the PTFs and the results are satisfactory with low RMSE and higher R^2. The developed PTFs are useful in determining soil hydraulic properties of semi arid region of south India.

Keywords: Pedotransfer functions, Field capacity, Permanent wilting point, Infiltration rate, Karnataka Plateau

Introduction

Growth of plants mainly depends on available water content of the soil. The quality and quantity of water available for plant growth is determined by the soil hydraulic properties. When the water content reduces beyond 15 bar (1500 kPa), most of the crops starts wilting. Hence, knowing about the soil water regime is important for judicial planning of irrigation[1]. Soil moisture constants viz., Field capacity, wilting point and infiltration rate are the most important soil hydraulic properties which decide the application and frequency of irrigation. Field capacity refers to the soil water content retained in soil micropores and macropores at a tension of -0.033 MPa whereas permanent wilting point is the soil water content at a tension of -1.5 MPa. The difference in field capacity and permanent wilting point is the water available to the plants. Infiltration is defined as the process by which a fluid passes through or into another substance travelling through pores and interstices[2] which widely influences irrigation, contaminant transport, groundwater recharge, and ecosystem viability[3]. Determination of the availability of these hydraulic properties of soil is important as it access the soil moisture content and suitability of land for crop production.

In large areas measuring the field capacity, wilting point and infiltration rate even within an agricultural field, is time-consuming and expensive[4] and also impossible to perform enough measurements as these properties varies at each sampling point. Several methods have been proposed to estimate soil hydraulic properties[5-7] from easily measured soil properties, *e.g.*, texture and bulk density (BD), and/or limited data collected during soil surveys. An equation or model developed for indirect estimation of particular soil property is termed as pedotransfer function (PTFs)[8]. PTFs are alternative method for estimation of hydraulic properties using available soil parameters since field measurement of soil hydraulic properties consumes time, tedious and costly affair. Practically most of the PTFs use the soil's particle size distribution data, or its derived parameters, and other easily measurable soil properties, e.g. soil texture, bulk density, calcium carbonate content, pH value[9-10], etc. PTFs add value to this basic information by translating them into estimates of other more laborious and expensively determined soil properties[11].

Several pedotransfer functions were developed in India[7,12-14] to estimate the soil hydraulic properties. But the PTFs developed for particular agroecological region may not be useful for other region. Cornelis *et al.* (2001) showed that a PTF yields more accurate estimates when it is applied to the geographical region for which it was developed[15]. In India, inter-relationships between soil texture, water retention and transmission characteristics have been worked out in the past[7,13,16-17]. PTFs were developed for Indo-Gangetic plains (IGP)[7,18], Black soil region (BSR)[18] and arid western India[1]. PTFs developed for particular region has limited applicability in another region[12]. For southern India Deccan plateau (Semi arid region), no comprehensive PTFs were available. In this context, the present study was aimed to develop Pedo-transfer functions for field capacity, permanent wilting point and infiltration of Karnataka plateau (North Karnataka Plateau and South Karnataka Plateau) representing semi arid regions of Southern India.

Materials and methods

Study area

The present study was carried out in two different regions of Karnataka Plateau viz. Northern Karnataka Plateau and Southern Karnataka Plateau. The study area extends from 11°30' North and 18°30' North latitudes and 74° East and 78°30' East longitude (Fig.1). **Northern Karnataka Plateau (**Koppal, Raichur, Yadgir and Gulburga districts): The soils are experiencing hot-semi arid climate and having rainfall range of 600-750 mm with PET of 1600-1700 mm. The average annual rainfall is 672 mm. The LGP ranged between 90-120 days. The major area comes under rainfed cultivation with rainfed crops like Sorghum, Pigeon pea and Pearl millet. The north Karnataka comes under Krishna and Godavari basins and having topography of 300-600 m with sporadic hills. Substantial area is by underlined by basalts with continuation of deccan trap of Maharashtra. The major soils represented by shallow to deep black soils, red loam soils, red clay soils, alluvio-colluvial soils and laterite gravelly soil[19]. **Southern Karnataka Plateau** (Tumkur and Chamarajanagar districts): South Karnataka comes under hot-semi arid climate and having rainfall range of 600-900 mm with mean annual rainfall of 735 mm. The LGP ranged between 120-150 days. The major crops cultivated under rainfed cultivation are Finger millet, Pigeon pea and Groundnut. Under Irrigated condition the major landuse is paddy and sugarcane. The southern Karnataka comes under Cauvery basins and having topography of 600-900 m with residual hills. Most of the area is underlined by granite and granite gneiss. The major soils represented by red gravelly loamy soils, red loam soils, red gravelly clay soils, red clay soils, laterite soils and aluvio-colluvial soils.

Datasets used for study

Soil physical properties such as sand, silt, clay, organic carbon, pH, EC, CEC and ESP, field capacity (FC) and permanent wilting point (PWP) for major soil groups in study region under SUJALA III project[20] (www. http://watershed.kar.nic.in/SujalaIII_Doc.htm) was used for development of PTFs. Totally 512 soil samples (106 profiles) in Northern Karnataka Plateau (NKP) and 228 samples (43 soil profiles) in Southern Karnataka Plateau (SKP) were collected and the samples were analysed at ICAR- NBSS&LUP as per standard protocol. Infiltration rate was measured at field using double ring infiltrometer[21] by the University partners under Sujala III project.

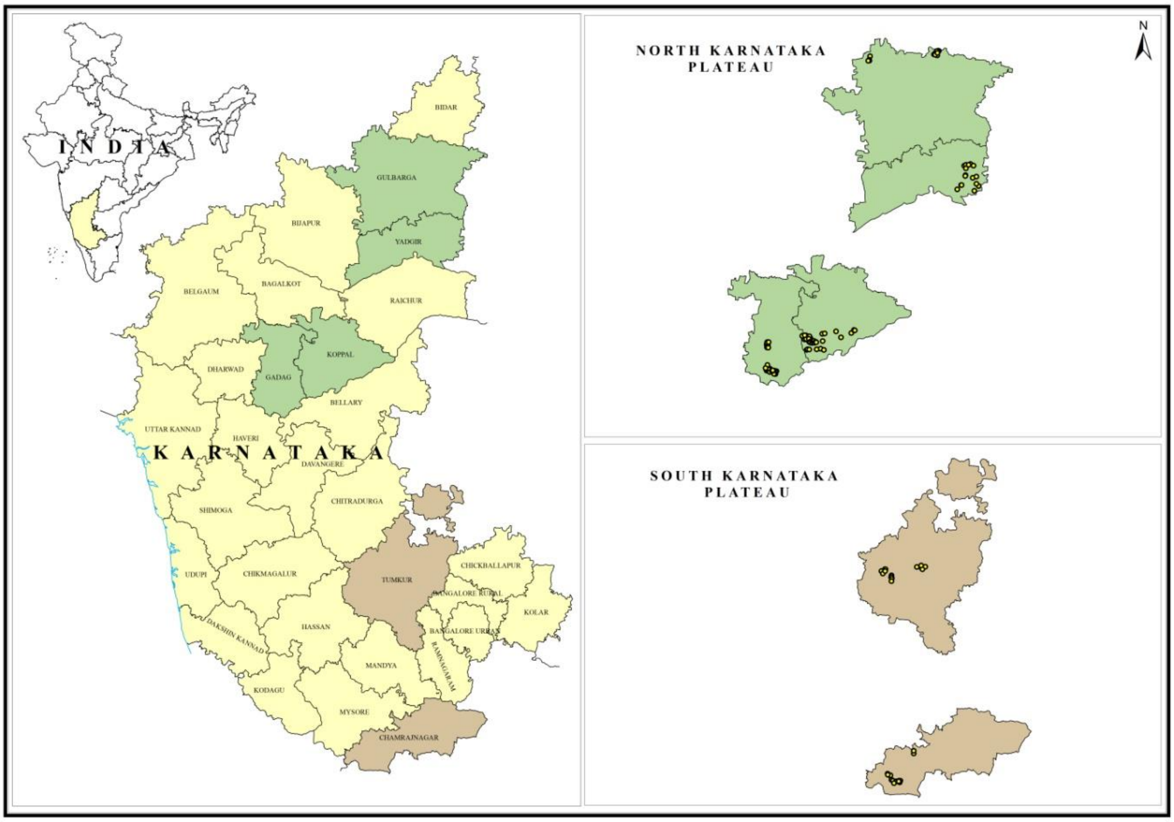


Fig.1. Study area

Selection of most important variables

Random Forest 4.6 package[22] in R environment was used to identify the most important variables or predictors. Random forest model (RFM) which works based on assemblage of a number of classification and regression trees by using two levels of randomization for every tree in the forest[23] and the relatively important variables identified based on number of times variable was used in nodes[24-25]. Three top most important variables were used for PTF development using multiple regression technique.

Development of PTFs

Multiple regression technique was used for developing PTFs in R environment (RStudio**10.0**). The PTFs for FC and PWP were developed separately for soils of the Northern Karnataka plateau and South Karnataka plateau since, soils and climate of these regions are significantly differed. The results were validated using cross validation techniques. Selected top most important variables was used for estimating Field capacity at –33 kPa and permanent wilting point at -1500 kPa. In addition, clay content (%) alone was used as independent variable to relate field capacity and permanent wilting point. The relationship between clay content and hydraulic properties is evaluated since amount of clay in the soil sample is one of the easily measurable properties compared to others. Similarly, PTFs were developed to predict infiltration rate for Karnataka from the database of 100 observations/soils.

Cross-Validation of PTFs

Cross-Validation was carried out to the analyse performance of PTF models. Ten folds cross validation techniques with 20 times repetition was used to evaluate the performance by using indicators such as Coefficient of determination (R^2), Root Mean Square Error (RMSE) and mean error (ME). Coefficient of determination (R^2) is defined by percentage of variation explained by the model. The good models have Coefficient of determination is equal or close to 1 and root mean square error close to 0.

$$\text{Coefficeint of determination (R2)} = 1 - \frac{\sum_{i=1}^{n}(pi - oi)^2}{\sum_{i=1}^{n}(oi - \overline{oi})^2}$$

$$\text{Bias (M}E) = \frac{1}{n}\sum_{i=1}^{n}(oi - pi)$$

$$\text{Root mean squared error (R}MSE) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(oi - pi)^2}$$

Where, pi and oi are predicted and observed values, $\overline{pi}$ and $\overline{oi}$are means of predicted and observed values

Results and discussion

Statistics of soil properties

Northern Karnataka Plateau: Descriptive statistics of soil properties of Northern Karnataka Plateau (NKP) soils are given in Table1. The pH of the soils ranged from very strongly acidic to very strongly alkaline with the mean pH of 8.1. The electrical conductivity of the soil also varied from 0.0 to 6.5 dSm^{-1}. Organic carbon was ranged between 0.03 and 1.6 % with mean of 0.5 %. The clay, sand and silt contents varied between 1.2 and 80.8 %, 2.7 and 94 % and 2.4 and 40.7 % respectively. Cation exchange capacity in NKP soils are ranged from 1.7 to 80.9 C mol p+ Kg^{-1}. The maximum exchangeable sodium percentage recorded in NKP soils is 68.5 %. The field capacity and permanent wilting point ranged from 3.2 to 62.1% (mean 29.9 %) and 0.9 to 43.7% (mean 19.0%) respectively with high coefficient of variation (Fig.2). Except pH and clay, other parameters are positively skewed.

Table 1. Statistics of physio chemical soil properties in Northern Karnataka Plateau (N=512)

Properties	pH	EC (dS/m)	OC (%)	SAND (%)	CLAY (%)	SILT (%)	FC (%)	PWP (%)	CEC (C mol p^+ Kg^{-1})	ESP (%)
Mean	8.1	0.4	0.5	39.8	43.2	17.1	29.9	19.0	33.6	7.0
Max	10.4	6.5	1.6	94.0	80.8	40.7	62.1	43.7	80.9	68.5
Min	4.7	0.0	0.03	2.7	1.2	2.4	3.2	0.9	1.7	0.0
SD	1.0	0.6	0.3	24.3	19.6	7.7	13.3	10.9	21.0	11.9
Kurtosis	0.4	38.0	0.3	-1.0	-0.9	-0.3	-0.9	-0.9	-1.2	7.9
Skewness	-0.8	5.4	0.6	0.3	-0.2	0.4	0.1	0.3	0.3	2.7
CV(%)	12.4	177.3	48.2	61.2	45.4	45.2	44.6	57.4	62.3	170.7

South Karnataka plateau: Descriptive statistics of soils of South Karnataka Plateau (SKP) soils are given in Table. 2. The pH of the soils ranged from very strongly acidic (4.5) to Very strongly alkaline (9.1) with the mean of 7.6. The electrical conductivity of the soil also varied from 0.02 to 0.48 dSm^{-1}. Organic carbon content is ranged from 0.08 and 2.0 % with mean value of 0.4%. The clay, sand and silt contents varied between 5.8 and 67.8, 4.4 and 92.3 % and 2.0 and 36.0 % respectively. The field capacity in SKP soils are ranged from 4.1 to 70.9% with a mean of 22.2% and permanent wilting point ranged from and 2.1 to 41.0% with a mean of 11.4 %. Cation exchange capacity (C mol p^+ kg^{-1}) of the soil varied from 1.2 and 52.6 with mean value of 14.7. Except pH and sand content, other parameters are positively skewed and among the soil properties, soil pH showed least variability with 12% CV.

Table 2 . Statistics of physio chemical soil properties in Southern Karnataka Plateau (N=228)

Properties	pH	EC (dS/m)	OC (%)	SAND (%)	CLAY (%)	SILT (%)	FC (%)	PWP (%)	CEC (C mol p^+ Kg^{-1})	ESP (%)
Mean	7.6	0.10	0.40	53.5	31.5	15.0	22.2	11.4	14.7	3.0
Min	4.5	0.02	0.08	4.4	5.8	2.0	4.1	2.1	52.6	33.1
Max	9.1	0.48	2.00	92.3	67.8	36.0	70.9	41.0	1.2	0.0
SD	0.9	0.08	0.23	16.5	13.1	6.4	9.5	6.3	9.5	3.4
Kurtosis	0.1	2.98	10.49	0.7	-0.2	0.7	5.4	3.1	2.9	28.3
Skewnes s	-0.8	1.57	2.22	-0.6	0.3	1.0	1.8	1.5	1.6	4.2
CV (%)	12.0	81.7	57.81	30.9	41.5	42.8	43.1	55.4	65.1	115.1

2. Correlation analysis

The results of correlation studies shows that Field capacity in NKP soils are significantly positively correlated with CEC (.867**), clay (.848**) and silt (0.549**) and negatively correlated with sand (-0.857**). Permanent wilting point in NKP soils are significantly positively correlated with CEC (.902**), clay (.898**), silt (0.526**), pH (.335**) and negatively correlated with sand (-0.890**). Like NKP soils, field capacity and permanent wilting point in SKP soils are significantly correlation with all the soil properties except soil organic carbon. Adhikary et al. (2008) also recorded that no significant relationship found between soil organic matter and corresponding FC and PWP in 800 samples studied across the country[26].

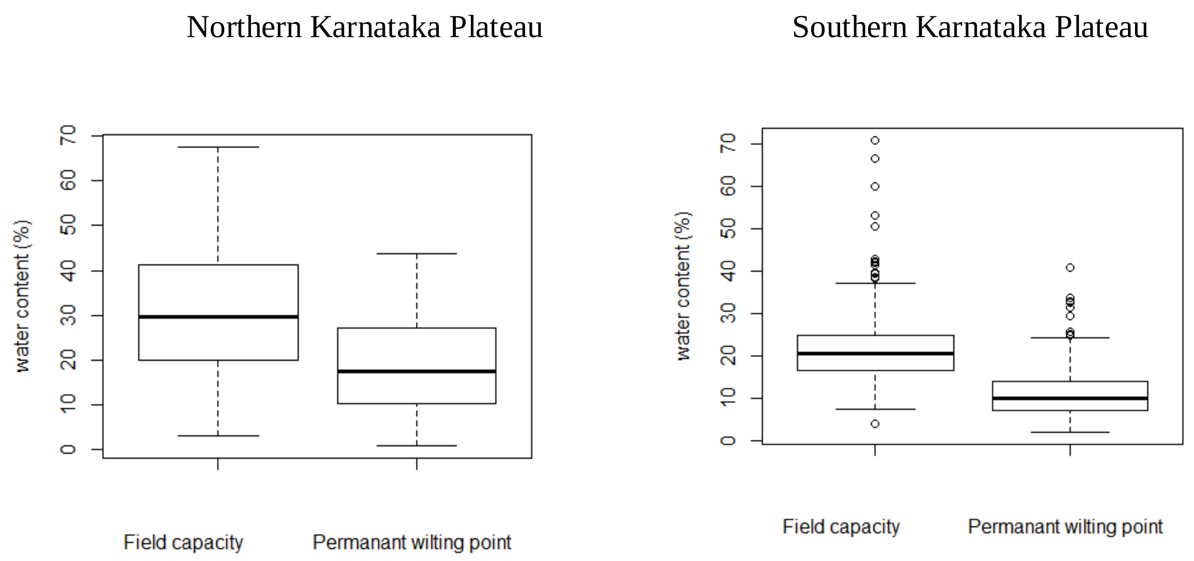


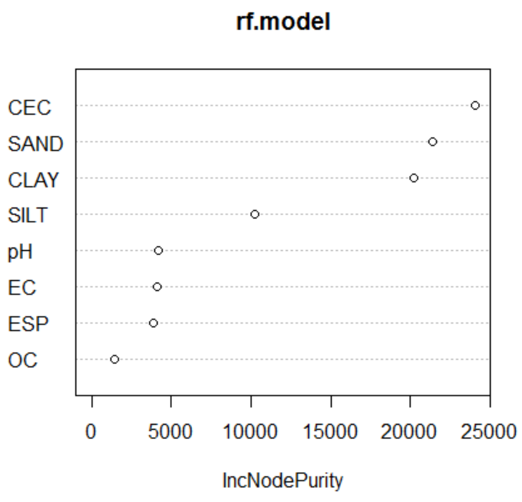
Fig.2. Distribution of Field capacity and permanent wilting point in Northern and Southern Karnataka Plateau

3. Selection of most important variable

Random Forest model has an advantage that model help to identify the importance of each predictor variables on prediction[24-25]. The analysis showed that CEC, sand and clay are the top three most important variables for prediction of Field capacity and permanent wilting point in both regions (Fig.3). The order of important variables are CEC>Sand>Clay for Field capacity and CEC> Clay > Sand for Permanent wilting point in NKP soils. Sand>CEC>Clay for Field capacity and Sand> Clay > CEC for Permanent wilting point in case of SKP soils.

Field capacity **Permanent Wilting point**

Northern Karnataka



Southern Karnataka

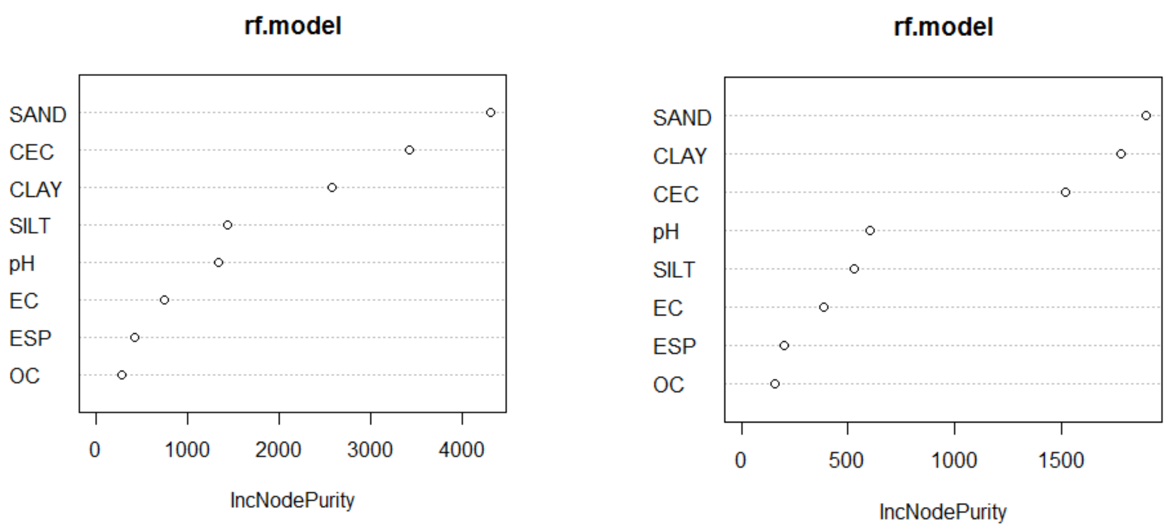


Fig.3. Variable importance rankings of variables in predicting soil moisture constants in Northern and Southern Karnataka Plateau

4. Prediction of Field capacity Permanent wilting point and infiltration rate

The PTFs were developed using the selected soil properties viz., CEC, Sand and Clay as independent variables. The FC and PWP of soil is determined by the equations:

FC = a + b(CEC) + c(Sand)+ d(Clay)

PWP = a + b(CEC) + c(Sand)+ d(Clay)

Where a, b, c and d are regression coefficients. The PTFs of soil hydraulic properties (Field capacity and PWP) were developed separately for both the regions viz., North and South Karnataka. In case of Infiltration rate, PTFs were developed for entire Karnataka as a whole due to availability limited datasets. Developed PTFs were cross-validated by 10 folds cross validation techniques. Criteria of 1 and 5% level of significance were used for acceptance or rejection of a predictor variable in these models. The prediction of field capacities and PWPs through developed PTFs were satisfactory with low RMSE values and high R^2 (64-88%) except PTF for infiltration rate which has poor and acceptable R^2 (41%).

4.1 Northern Karnataka Plateau:

PTFs of field capacity and Permanent wilting was developed using 512 soil layer observations of 100 profiles collected in Gulburga, Gadag, Yadgir and Koppal districts. Table. 3 summarises the results of PTFs developed for estimating the water retention at field capacity and permanent wilting point in NKP soils. The equations are

FC= 13.82 +0.205 (Clay)-0.088 (Sand)+ 0.316 (CEC)

PWP = -5.78 +0.315 (Clay)+0.050 (Sand)+ 0.271 (CEC)

Clay with its very large adsorption surface and CEC which reflects the negative charge of clays greatly influence the soil water content due to adsorption of di-polar water molecules. The performance of PTF models in terms of R^2 value was higher for PWP (R^2 = 88%) than for FC (R^2 =83%) which indicates that variables used in PTF model explained 88% variation for PWP and 83% for FC. Sand negatively influence for prediction of FC whereas positive influence for prediction of PWP. Tiwary et al. (2014) developed PTFs for soil moisture contents for Basaltic region (black soil region) which are similar to NKP soils using CEC, ESP and Clay content of 75 soil layer observations of 14 soil profiles[18]. The performances of PTFs are similar to present results with R^2 of 0.82 and 0.71, respectively for Field capacity and Permanent wilting point. The errors of estimations, RMSE also found very low for both FC (5.2 %) and PWP (3.7%) in NKP soils. Bias (mean error) of the estimated values of FC and PWP was found smaller for this regression model than other established PTFs in India[1]. Negative bias in the NKP soils indicates that predicted values are larger than observed values.

When only clay data available

Among the soil properties, clay content can be easily measured or judged by different methods. When only clay content available, the following equation can be used to predict the field capacity and permanent wilting point in NKP soils

$$FC= 4.97+0.586\ (Clay)$$

$$PWP=-2.44+0.50\ (Clay)$$

The performance of regression model showed that R2 value was higher for PWP (80%) than FC (71%). RMSE values for FC (7.05 %) and PWP (4.74 %) which is comparatively higher than PTFs developed using Clay+CEC+Sand models.

Table.3. Multiple regression analysis of water content at Field capacity and Permanant wilting point in Northern Karnataka Plateau

Properties	**Field capacity**		**Permanent Wilting point**	
	Estimate	Std.error	Estimate	Std.error
Intercept	13.82	3.823***	-5.776	2.724*
Clay	0.205	0.046***	0.315	0.033***
Sand	-0.088	0.042*	0.050	0.030
CEC	0.316	0.025 ***	0.271	0.018***

*** Significant at 0.001, * significant at 0.05

Table.4. Regression analysis of water content at Field capacity and Permanent wilting point using clay content in Northern Karnataka Plateau

Properties	**Field capacity**		**Permanent Wilting point**	
	Estimate	Std.error	Estimate	Std.error
Intercept	4.968	0.789***	-2.443	0.520***
Clay	0.586	0.017***	0.500	0.011***

*** Significant at 0.001

4.2 Southern Karnataka Plateau:

Table. 5 summarises the results of PTFs developed for estimating the water retention at field capacity and permanent wilting point for SKP soils. The equations are

FC= 39.18 -0.041(Clay)-0.371(Sand)+ 0.257 (CEC)

PWP = 8.227 +0.168 (Clay)-0.101(Sand)+ 0.217 (CEC)

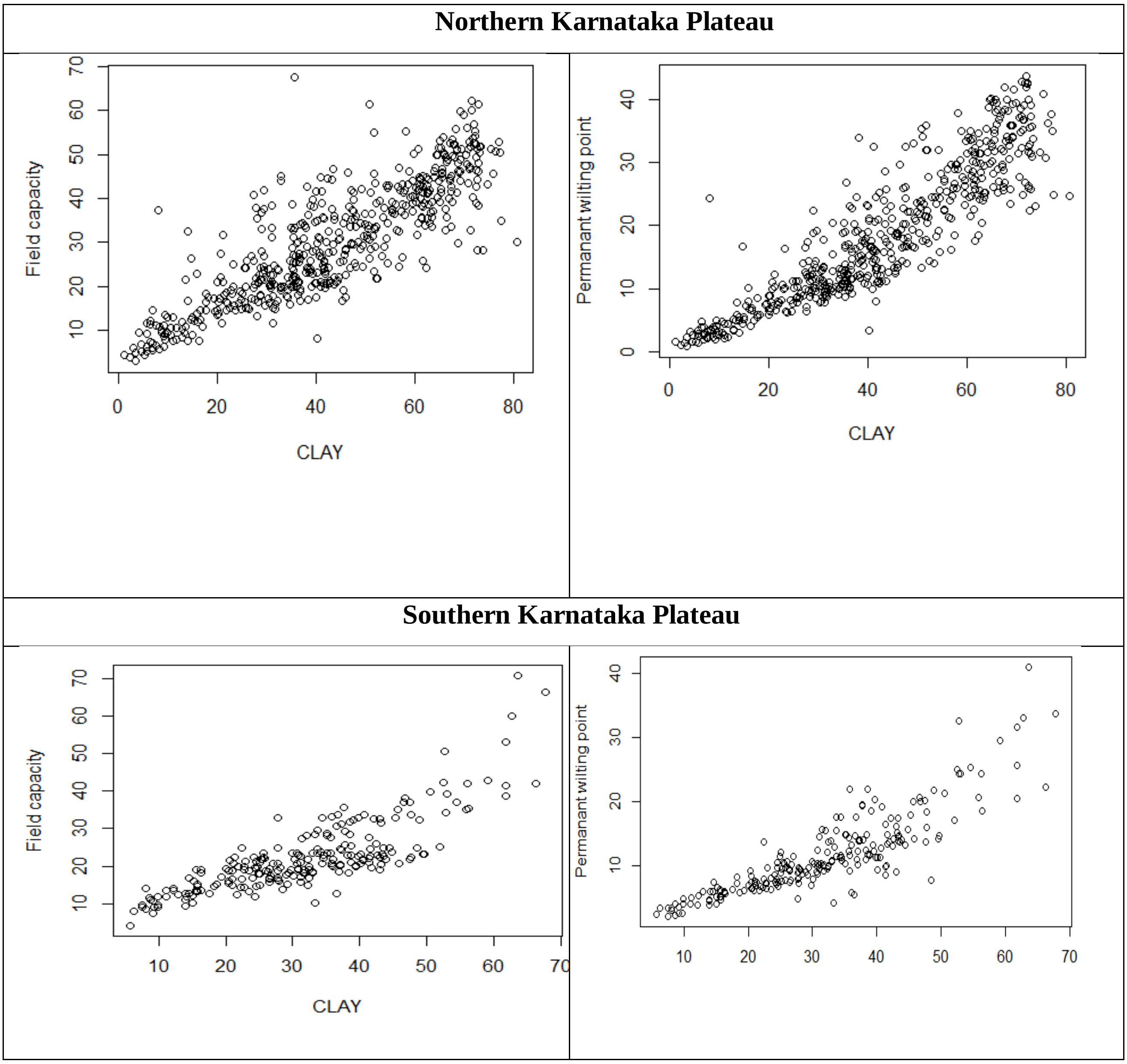


Fig.4. Relationship between soil moisture constants and clay content in Northern and Southern Karnataka Plateau

Like NKP soils, the performance of PTF models (Table 5) in SKP soils in terms of R^2 value was higher for PWP (88%) than FC (84%) which indicates that variables explained more variation for PWP than FC. Similar results were recorded by different researchers in India[18,27-28] (Tiwary et al., 2014; R2=67%-82%; Mohanty et al., 2014, R2= 85%; Dabral and Pandey, 2016, R2= 80%). In contrast to NKP soils, sand has negatively influence for prediction of both FC and PWP.RMSE values also comparatively lower for both FC (3.05 %) and PWP (2.17%) than NKP soils. Positive bias (mean error) was found for prediction of PWP whereas negative bias was observed in prediction of FC.

When only clay data available

The following equation can be used to predict the soil moisture constants in SKP soils when only clay content available

FC= 3.72+0.581(clay)

PWP=-1.98+0.43 (clay)

Like NKP soils, less performance was recorded for FC~clay (R^2=64%) and PWP~clay (R2=73%) models comparatively to FC/PWP~ Clay+CEC+Sand model.

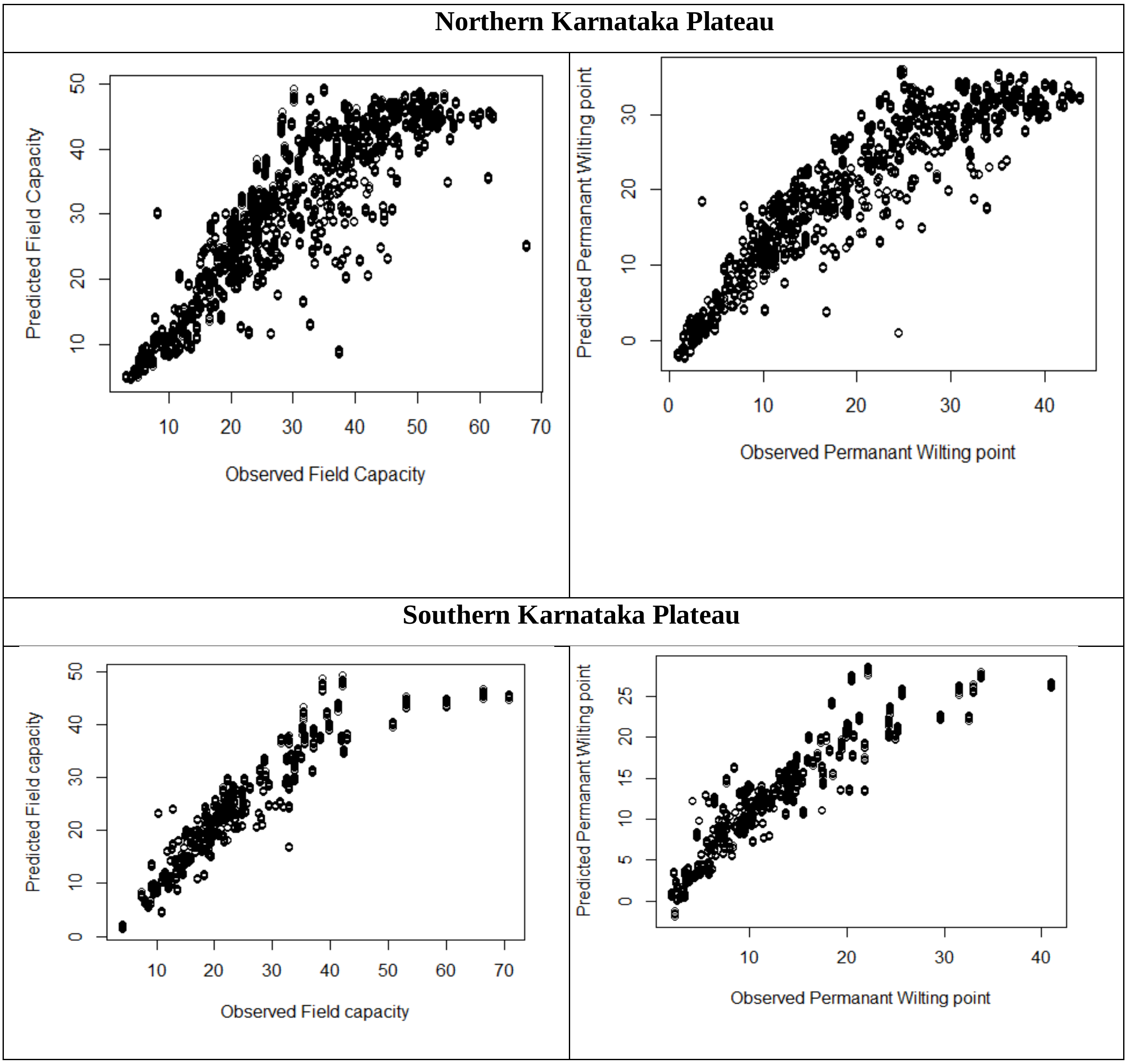


Fig.5. Observed and predicted soil moisture constants in Northern and Southern Karnataka Plateau

Table.5. Multiple regression analysis of water content at Field capacity and Permanent wilting point in Southern Karnataka Plateau

Properties	Field capacity		Permanent Wilting point	
	Estimate	Std.error	Estimate	Std.error
Intercept	39.179	3.618***	8.227	2.635**
Clay	-0.041	0.045	0.168	0.032***
Sand	-0.371	0.040***	-0.101	0.029***
CEC	0.257	0.035***	0.217	0.025***

*** Significant at 0.001, ** significant at 0.01

Table.6. Performance of PTFs in predicting water content at Field capacity and Permanent wilting point.

Properties	Northern Karnataka		Southern Karnataka	
	FC	PWP	FC	PWP
R^2 (%)	83±5.4	88± 4.2	84±9.4	83±8.6
Mean error	-0.004±0.76	-.0002±0.54	-.002±0.65	0.001±0.5
RMSE	5.25±0.80	3.71±0.61	3.05±0.84	2.17±0.53

Table.7. Regression analysis of water content at Field capacity and Permanent wilting point using clay content in Southern Karnataka Plateau

Properties	Field capacity		Permanent Wilting point	
	Estimate	Std.error	Estimate	Std.error
Intercept	3.724	0.993***	-1.979	0.559***
Clay	0.581	0.029***	0.428	0.016***

*** Significant at 0.001, ** significant at 0.01

Table.8. Performance of PTFs developed using clay content in predicting water content at Field capacity and Permanent wilting point.

Properties	**Northern Karnataka**		**Southern Karnataka**	
	FC	PWP	FC	PWP
R^2 (%)	71±8.2	80± 4.9	64±14	73±10.7
Mean error	0.001±1.0	0.002±0.71	0.012±1.3	0.006±0.7
RMSE	7.05±1.01	4.74±0.54	5.39±1.2	3.13±0.68

Clayey soils retain more water than sandy soils. In both region (NKP and SKP), higher $R^2$was recorded for permanent wilting point than field capacity. Shwetha and Varija (2013) reported that water retention at lower tension (FC) is not mainly depends on soil texture[29] like clay but depends on soil structure, but at higher tension (PWP) depends on particle-size distribution and soil mineralogy.

5. Infiltration rate:

Infiltration rate mainly depends on pore size and particle size. The PTFs for prediction of Infiltration was developed from soil particle viz., sand, silt and clay datasets of 100 observations of Karnataka (Fig.6). Infiltration rate is varied from 2.3 to 35 mm/hr with a mean and standard deviation of 15.69 and 8.75 mm/hr. Infiltration rate increases with decreasing clay content (Fig.7) (clay (7.25 mm/hr) < sandy clay (14.69 mm/hr) < sandy clay loam (17.32 mm/hr) < sandy loam (18.80 mm/hr) < loamy sand (25.42 mm/hr)). The regression model developed for this purpose has the minimum RMSE 6.71% and acceptable R^2 value (41%).

Infiltration rate= 177.55-1.47(sand)-1.80(clay)-1.58(silt)

Adhikary et al. (2008) found the infiltration rate has the power function relationship with clay content (R^2= 42 %)[26]. The rate of decrease of infiltration rate is maximum till it reaches 20 % clay after that the rate reduces and becomes negligible. Mahdian et al. (2009) developed PTFs for infiltration rate using silt, clay, sand, bulk density, field capacity and wilting point as input variables[30]. The performance of PTF is highly significant with R^2 of 74 %. Unlike soil moisture constants, only limited research was carried out on soil infiltration rate which might be due to the complex process and high variance.

Table.9. Multiple regression analysis of infiltration rate in Karnataka

Properties	Estimate	Std.error
Intercept	177.55	73.1*
Clay	-1.80	0.75*
Sand	-1.47	0.75*
Silt	-1.58	0.69 *

* significant at 0.05

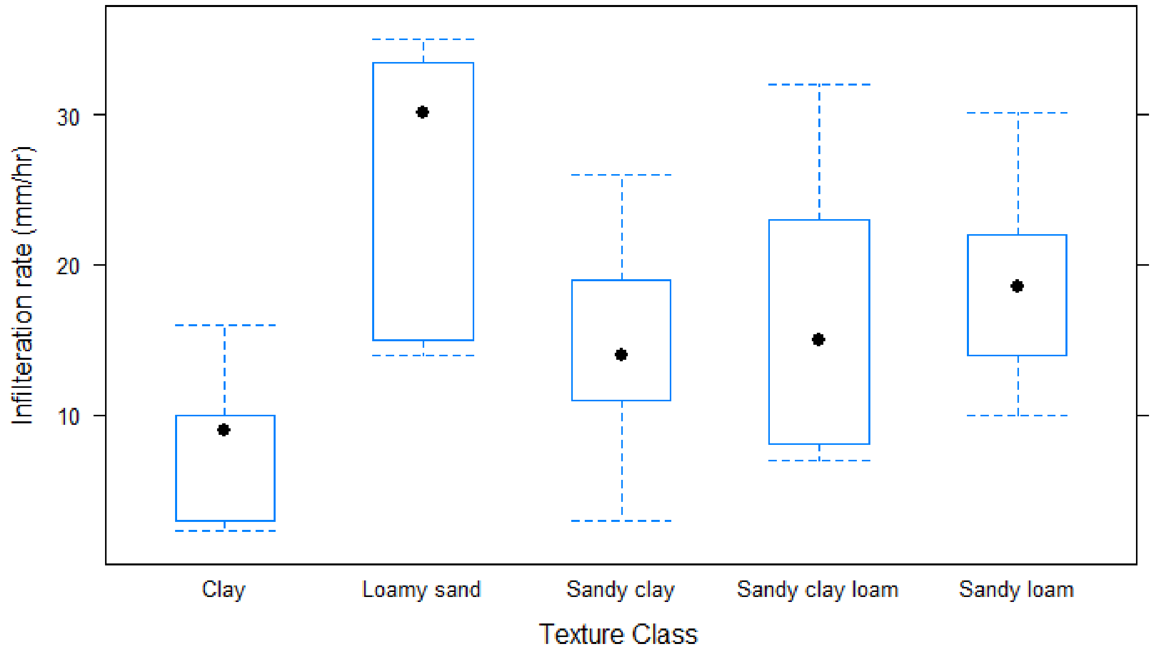


Fig.6. Infiltration rates under different texture classes in Karnataka

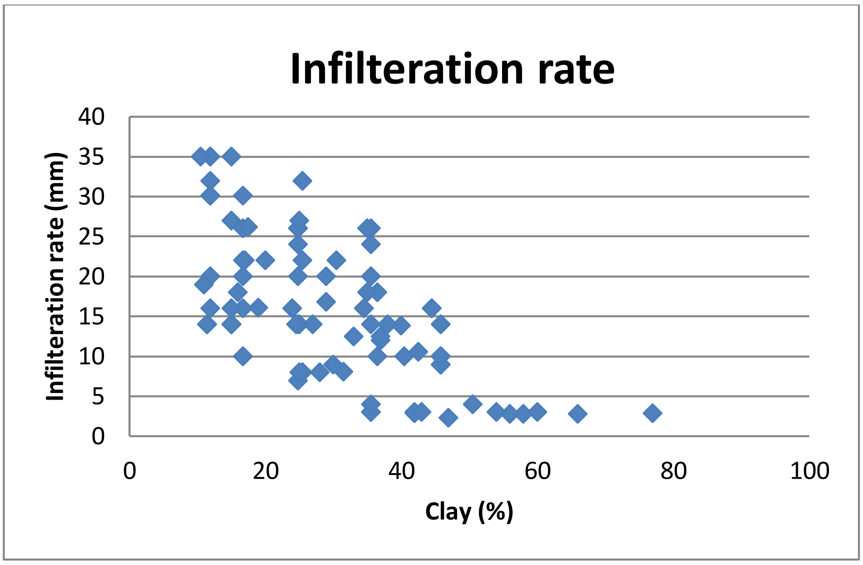


Fig.7. Infiltration rates Vs clay content in Karnataka

Conclusion:

Characterising soil response to hydrology is a challenging problem, particularly because of the difficulty in quantifying soil hydraulic properties and their spatial variability. To make the application of PTFs for practical usage, we need approaches that provide for hydraulic information in a cost-effective way, minimizing requirements for direct measurement of soil hydraulic properties. The PTFs developed in this study are improvised hydrologic prediction of Semi arid regions of Southern India. Regular updation of PTFs with increased number of observations as well as increased number of independent variables like bulk density, aggregate stability will improve the results.

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