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Topographic Appraisal for Irrigation Suitability in a Part of Jayakwadi Command Area, Parbhani District, Maharashtra

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Land evaluation for cotton-based cropping systems was carried out based on detailed soil survey data in part of Jayakwadi command area under irrigation. The study of soil-landscape relationships showed that the variations in micro-relief have a marked influence on the soil profile characteristics, internal drainage and degree of sub-soil sodicity. The shrink-swell sodic soils (Parbhani series-P5) with hard, angular blocky aggregates over middle slopes (<6%) retained only 7.5% plant available water in the root zone thus reducing both productivity and irrigation efficiency. The irrigability analyses showed that land grading and levelling were prerequisite for designing surface irrigation systems in cracking clay soils over middle slopes. The irrigation analyses for cotton showed that the soils on middle slopes require an irrigation frequency of 14 days for deep and 9 days for shallow black soils. The present study showed the limits of soil–topography-yield variations in interpreting site-specific data for irrigation.

Key words: Land evaluation for irrigation, topographic appraisal, Jayakwadi command, basaltic clay soils

Irrigable lands produce 40% of food supply in the world (Hargreaves and Mekley 1998). Even by optimistic estimates, the global irrigation base is unlikely to grow faster than 0.6% in a year over the next 25 years (Postel 1999), but the extent of per capita irrigated area is declining. The area under irrigation in India has increased from 21 million hectares (Mha) in 1950 to more than 71 Mha in 1990 (Navalawala 1992), but the rise in food production was only 10% (World Commission on Dams 2000). The major challenge to Government of India (GOI) is to meet the ninth plan target of 4.5% growth rate per annum for agriculture (GOI 1999; World Bank 1998) in the face of land degradation and expanding biotic stresses. The severe problem facing Indian irrigation system is rising incidences of waterlogging, soil salinity and lower water use efficiency (Thakkar 1999).

Maharashtra has the irrigation potential of 13%, which is far below the national average of 33%. The state has the gross irrigated area of 1.93 Mha, out of which 21% is irrigated by canals, 14% by tanks, 58% by wells and 7% by other sources (Sawant *et al*. 1999). The distribution of soil subgroups of Vertisols and vertic intergrades in the Deccan trap was mainly characterized by high smectitic clay, low hydraulic conductivity and high exchangeable magnesium (Mg) and sodium (Na) in the region (Balpande *et al.* 1996). The formation of sodic soils in micro-highs along the side of non-sodic Vertisols in micro-lows were reported in Purna valley of Maharashtra (Vaidya and Pal 2002). Further, the soil resource inventories in Maharashtra have shown that 1.5% total geographical area (TGA) in command areas of Godavari, Ghod, Purna, Manar, Mula, Pravara, Nira and Krishna river basins was occupied by moderately to strongly saline/sodic soils (Challa *et al*. 1995). Slope, texture and soil depth were the severe limitations for irrigation as reported in basaltic terrain of Ethopia (Gebrekidan *et al.* 2005), whereas drainage, salinity and soil depth were the limitations reported in Vertisols of India (Bhattacharjee 1979).

The Jayakwadi command area covers 0.276 Mha of cultivable land having problems of shallow water table and salinization (Abhange *et al.* 1986). At present the information on microtopographical variations and their influence on irrigation in command area is scarcely available. Therefore, the present study was carried out to characterize the soil-topography-yield relationships and to evaluate the soils for their suitability to irrigated-cotton-based cropping systems in a part of Jayakwadi command area.

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Materials and Methods

Study Area

The study was carried out in a part of Jayakwadi command area (18°50' N latitude and 76°59' E longitude) which lies over the basaltic terrain in Porwad village of Parbhani district. The climate is hot subhumid with a mean annual rainfall (MAR) of 960 mm and complete dryness from November to May. The length of growing period is 120 to 150 days with more probability of moisture stress at critical stages of *kharif* cotton and experiences water deficit during winter (Fig. 1). The water deficit in semi-arid tropics could be compensated by irrigation (Ramasastri and Ramana Murthy 1975; Subramaniam and Sambasiva Rao 1987)

Field Survey and Land Evaluation

Detailed soil survey was carried out in 459 ha of irrigated command area using a map of 1:8000 scale. The elevation varies from 378 to 408 m above mean sea level (amsl). Forty-five soil pedons were morphometrically examined and were classified in the subgroups of Entisols, Inceptisols and Vertisols (Soil Survey Staff 1998). The samples were collected horizon-wise for the determination of physical and chemical properties (Black *et al*. 1965; Jackson 1973). Soil-site suitability for cotton with irrigated *jowar* and wheat for each mapping unit was worked out (FAO 1985). The soil interpretations were made for irrigation suitability (USBR 2005), parametric evaluation of land classes (Sys and Verheye 1974) and limiting symbol formulae (Sys *et al.* 1991). The soil water holding characteristics were used to determine the frequency of irrigation for cotton-based irrigation systems (FAO 1979). The relative yield index was calculated as $(y_i \times 100)/y_t$ (Soil Survey Staff 1995), where y_i = yield of crops in each soil type and y_t is mean yield of crops in the transect.

Results and Discussion

Soil Topography

Progressive increase in thickness of solum in Vertisols and vertic intergrades with distinct structural development in subsoils over middle slope indicated the influence of pedomorphic surfaces on morphogenetic characteristics of shrink-swell soils in basaltic landscape (Bhaskar *et al*. 2001a). This landscape is characterized as midcycle matured land (hypsometric integral of 0.36) with rectilinear slopes. The soil profile thickness was significant and negatively correlated with elevation (r =-0.66*) and expressed in an exponential form as:

Soil profile thickness (cm) = 8326.99 –1380.95 (*ln* elevation, m).

where, *ln* = natural logarithm and elevation is 378 to 408 m. The pedons over summit (P1) were Typic Ustorthents with Ap-r horizon sequence but gradually changed to Ap-Bw-Cr horizon sequence on middle slopes to Ap-Bw-Bss in Typic Haplusterts (P9) on foot slopes (Fig. 2). The Chromic Haplusterts on middle slopes (P7) have dark gray to brown matrix with chroma of less than 3, whereas, Typic Haplusterts (P9) on foot slopes have yellowish gray Bss horizons. The texture is clay loam in summit

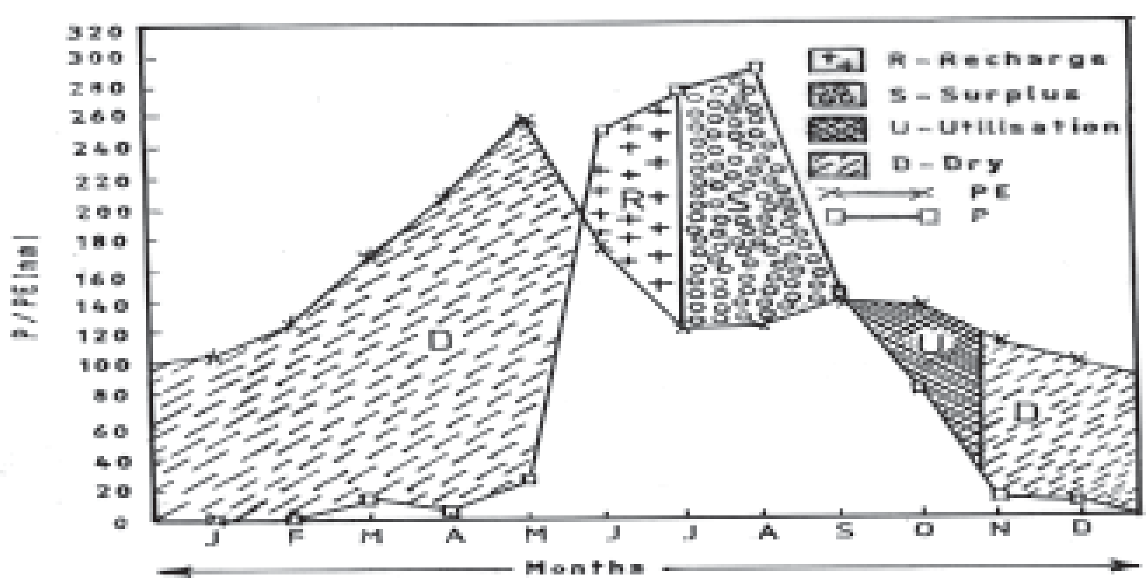

Fig.1. Water balance diagram

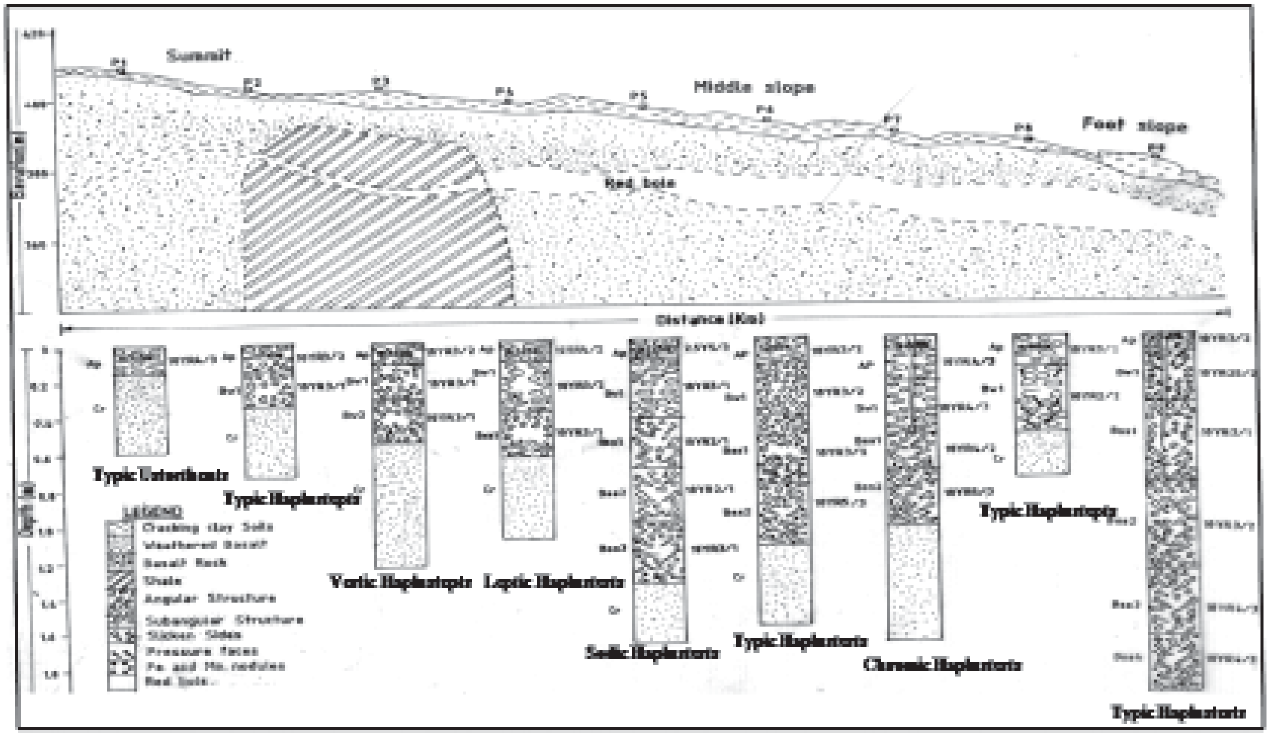

Fig.2. Landscape-soil relationship in Minor -4 of Jayakwadi Irrigation Project

soils (P1) but uniformly clay in soils over middle and foot slopes. The extent and distribution of soils show that Typic Haplusterts on the foot slopes (below 390 m) occur in association with vertic intergrades. The spatial distribution of soils with respect to elevation show that Thola series (P9) on foot slopes covers 32.1% of area followed by Brahmapuri (P6, 15.3%), Lohgaon (P4, 13.6%) and Porwad series (P2, 11.5%).

Soil Characteristics Related to Irrigability

The nine soil series are grouped into three depth classes *viz.*, very deep (>90 cm) [Parbhani series (P5), Brahmapuri (P6), Dhampuri (P7) and Thola (P9)], deep [45-90 cm), Ambetak (P1), Pokhad (P3), Lohgaon (P4) and Malsonna (P8)] and moderately deep [(22.5 to 45 cm), Porwad (P2)] (Soil Survey Manual 1970). The very deep soils were associated with deep and moderately deep soils commonly occurred at an elevation ranging from 375 to 395 m. These soils have sand content of 10.3 (P9) to 21.7% (P7). The deep soils have mean sand content of 17.1% with a variation of 12.2%, where as very deep soils have mean sand content of 15.4% with coefficient of variation of 31%. The silt content varies from 12.2% in P2 to 27.9% in P9. The deep soils have mean silt content of 21.4% with a variation of 29% whereas very deep soils have 26% silt with a variation of 7.9%. The soils over summit (P1 and P2) to middle slopes (from P3 to P7) have clay content of 51 to 58% and were defined as fine and in soils of P1, P6 and P9, the clay content of more than 60% were defined as very fine at family level (Table 1). The clay content increases with depth with a coefficient of variation of 6.5% in Bw and Bss horizons. These soils have bulk density of 1.32 to 1.50 Mg m^{-3} and porosity of 44 to 50%. These soils are calcareous with calcium carbonate content varying from 61.9 (P2) to 164.6 g kg^{-1} (P5), which shows distinct variations with depth and slope along the transect. The $CaCO_3$ content improves the water retention capacity in soils by promoting stable microstructure (Shainberg and Gal 1982). The exchangeable sodium content is high (23.9%) in P5. The available water holding capacity (AWC) of shrink-swell soils ranges from 11.4 (P4) to 15.7% (P9). These soils are slightly to strongly alkaline (pH of 8.1 to 9.2) with low electrical conductivity (0.08 to 0.87 dS m^{-1}) and have organic carbon content that decreases from 7.4 g kg^{-1} in summit to 3.9 g kg^{-1} in foot slopes. The low content of organic carbon in soils of foot slopes could be attributed to erosion of litter by runoff and imperfect internal drainage. Similar observations at lower landscape positions were reported from a hill slope of north-west Florida by Day *et al.* (1987).

Table 1. Soil properties related to irrigability

Soil series	Depth (cm)	Particle size distribution (% of < 2mm)			AWC (%)	BD (Mg m^{-3})	Porosity (%)	pH	ESP	Organic carbon (g kg^{-1})	$CaCO_3$ (g kg^{-1})
		Sand (2-0.5)	Silt (0.5-0.002)	Clay (<0.002)							
Ambetak	60	14.2	24.0	61.8	12.5	1.50	44	8.4	1.30	6.9	115.9
Porwad	34	13.2	27.3	59.5	11.9	1.43	46	8.2	1.00	9.9	61.9
Pokhad	56	16.9	12.2	53.9	14.4	1.39	48	8.8	10.40	7.4	113.2
Lohgaon	65	18.7	22.8	58.5	11.4	1.37	48	8.2	2.60	7.3	138.2
Parbhani	136	15.7	26.5	57.8	14.8	1.45	45	9.0	23.90	5.6	164.6
Brahmapuri	115	14.2	23.1	61.6	12.7	1.36	49	8.4	1.20	6.9	118.3
Dhampuri	105	21.7	26.9	51.3	12.5	1.32	50	8.2	0.70	6.8	72.2
Malsonna	53	18.5	26.7	54.8	13.3	1.41	47	7.9	1.20	9.0	86.1
Thola	167	10.3	27.9	60.8	15.7	1.38	49	8.9	9.30	3.2	135.4

Suitability Classification for Irrigation

Land suitability units were derived (Sys *et al*. 1991) to identify land development requirements. This frame work permits definition of limitation with symbols and their degree of suitability for pre-irrigated cotton, *jowar* and wheat. The Malasona (P2) and Pokhad (P7) units with heavy topsoil texture and moderate erosion on 3 to 5% slopes were evaluated as suitable. The Porwad (P8) and Ambetak (P9) were unsuitable with moderate subsoil permeability, heavy texture and moderate salinity (Table 2). The Thola, Dhampuri, Brahmapuri and Lohgaon land units were evaluated as slightly suitable because of strong subsoil alkalinity and strong micro-relief. It was estimated that 233.4 ha land (50.81 % TGA) on middle slopes (P4, P6, P7 and P8) requires grading and levelling (t^1) for efficient irrigation management (w). The land units of Parbhani, Porwad and Ambetak cover 10.3% of area with sodicity (Y), long-term erosion hazard (e) and alkalinity (Z) limitations.

Saturated Hydraulic Conductivity Class in Control Section

The saturated hydraulic conductivity (K_{sat}, Table 2) class for each soil series was evaluated on the basis of morphology (McKeague *et al.* 1988) which encompassed structure, texture, channels and cracks. The medium to high K_{sat} class was observed for fine textured Haplusterts on middle and foot slopes with 40 to 45% porosity, slow to moderate permeability, strong angular blocky structure and wide cracks but very low K_{sat} class was observed for Sodic

Table 2. Suitability subclass, irrigation frequency (days) and crop yields

Soil series	Suitabilit subclass*	Symbol formulae	K_{sat} class in control section (25-100 cm)	Irrigation frequency (days)			Yield (t ha^{-1})			Soil productivity index
				Cotton	*Jowar*	Wheat	Cotton	*Jowar*	Wheat	
Ambetak	N2rt	3H2S/cd3e3	M1	9	11	11	1.15	1.29	1.54	107
Porwad	N1rt	3H3S/Ba3e3	M3	7	9	9	1.09	1.35	1.54	104
Pokhad	S3r(e)	3H2S-A2/Ba2e3	M3	11	14	14	1.17	1.00	1.43	102
Lohgaon	S2t"(e)	3V2S/Bc2e2	M1	11	14	14	1.35	1.12	1.58	103
Parbhani	N1ZX'Y'a'	4VSS2-A3/Aa1e2	L1	11	14	14	1.10	1.40	1.20	85
Brahmapuri	S2wt'	4V1S/Ac1e1	M2	11	13	13	1.14	1.06	1.31	97
Dhampuri	S2wt'	3H1S/Bb2e2	M1	11	14	14	1.00	1.06	1.31	98
Malsonna	S3r(t')	3H2S/Bb2e2-01f1	M2	12	15	15	1.09	1.35	1.54	104
Thola	S3d1(Y)	5VSA3/Ab1e1-w1P01f1	H1	14	17	17	1.14	1.06	1.31	97

Note. S2,moderately suitable; S3, marginally suitable; N1, marginally not suitable; N2, permanently not suitable; d, drainage; Y, sodicity; r, rooting depth; t, land grading and leveling; w, water application management; Z, pH; X, leaching; a,' amendments; e, long-term erosion hazard;Soil limitations (in numerator) Subsoil permeability 3, moderate; 4, slow; 5, very slow; Top soil texture V, very heavy (SC, SiC, C);, H, heavy (CL, SiCL,SCL); Soil alkalinity A2,moderate; A3,severe; Soil salinity S2,moderate; Depth limiting layers S, soft weathered rock; Soil depth class 1, deep; 2, moderately deep; 3, shallow; Topographic, Erosion and Drainage limitations (in denominator) Slope (%) A, 0; B, 2-5; C, 5–8; Transversal slope (%) a, 1-2; b,2-5; c, 5-8; d, 8-12; Micro relief 1, slight; 2, moderate; 3, strong; Erosion status e1, slight; e2, moderate; e3, severe; Flooding f1, slight; Groundwater depth w1, slight; Drainage e1,presence of mottling between 1.2 – 2 metres; Ponding hazard 01,slight.

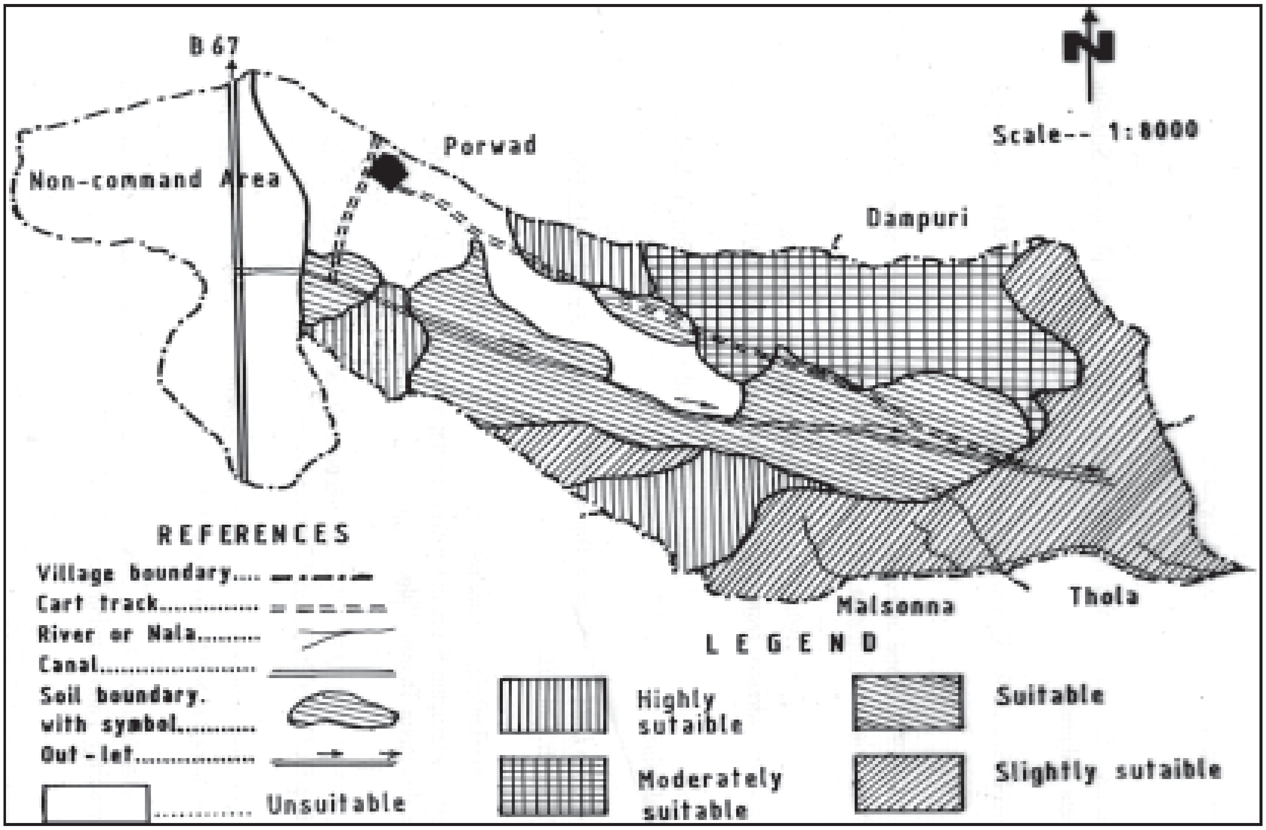

Fig.3. Soil suitability map for gravity irrigation in Minor- 4

Haplusterts on middle slopes (P5) due to the presence of hard, compact clay layer with prismatic to angular blocky aggregates and a few macropores (Canada Soil Survey Committee 1978). These fine textured moderately deep to deep soils present in high run-off sites with hard substratum cause impediment to drainage when saturated

Irrigation Frequency

Earlier, climatic index was proposed for irrigation scheduling for cotton-based systems in command areas of Maharashtra (Subramaniam and Sambasiva Rao 1987). In the present study, the soil water holding characteristics were used to estimate requirement for irrigation frequency (FAO 1979). The irrigation analyses for cotton (Table 3) indicated significant variation from 14 days in very deep Typic Haplusterts on foot slopes (P9) to 7 days in well drained moderately deep Typic Haplustepts on summits (P2). Similar soils require 17 to 9 days irrigation frequency for *jowar* and wheat. The suitability analyses were worked out to identify economically viable units for optimal utilization of water in command areas. The clay soils on middle slopes were classified as suitable for irrigation (Fig. 3) and cover 122 ha (26.7% of area) but clay soils on foot slopes (P9) were moderately suitable covering 24% of area (110 ha).

Topographic Factor in Irrigability Analysis

Microtopographical variation was a significant factor in evaluating irrigation efficiency in Vertisols and vertic intergrades in Jayakwadi command area. The development of shrink-swell soils in the catenary sequence were genetically interrelated and characterized by progressive thickening of cambic and slickensided B horizons. The suitability classification (FAO 1979) had clearly brought out site-specific topographic limitations as mentioned in the symbol formulae (Table 2). The soil over summits (P1 and P2) with strong micro-relief (80.8 ha, 17.6%, Table 3), heavy texture, shallow rooting depth and severe erosion were found to be unsuitable for irrigation. The soils over middle slopes with heavy texture, moderate salinity, slow to moderate subsoil permeability and moderate to deep soil depth with slight to moderate micro-relief (2 to 5%; B slope class) and slight to moderate erosion (P4 and P6, Table 3) were evaluated as suitable. The Pokhad series (P3; 31.25 ha) with shallow rooting depth and Thola soils (P9;

Table 3. Topographic factor in irrigability analyses

Landscape units	Summit		Middle slope				Foot slope		
Soil series/ soil subgroups	Ambatek (Typic Ustorthents)	Porwad (Typic Haplustepts)	Pokhad (Vertic Haplustepts)	Lohgaon (Leptic Haplusterts)	Parbhani (Sodic Haplusterts)	Brahmapuri (Typic Haplusterts)	Dhampuri (Chromic Haplusterts)	Malsonna (Typic Haplustepts)	Thola (Typic Haplusterts)
Extent (ha)	22.1	58.7	31.25	70.2	6.84	107.5	48.1	12.2	102.21
Land suitability for irrigation with limitations	Unsuitable **Soil limitations**: Moderate subsoil permeability, heavy texture, shallow depth **Topographic limitations**: 2–5% slopes, strong micro-relief and severe erosion		Slightly suitable/Suitable **Soil limitations** :- Moderate subsoil permeability, heavy in Pokhad series (P3) and very heavy in other soils, strong alkalinity in Parbhani series (P5, unsuitable)/ moderate salinity **Topographic limitations**: Slight to moderate micro-relief with moderate erosion.				Slightly suitable **Soil limitations**: Very slow subsoil permeability, strong alkalinity, very heavy texture and soft weathered rock **Topographic limitations**: 2 to 5% transverse slopes, slight micro-relief, moderate erosion and slight flooding		
Land management needs	Land levelling and grading is difficult due to hard root restricting layer below 40 cm. Irrigation frequency is 7 to 9 days for cotton		This unit needs land levelling and grading for efficient water application. Irrigation frequency varies from 11 to 14 days for cotton.				This unit needs drainage structures and amelioration for sodicity hazard through gypsum application. Irrigation frequency of 14 to 17 days for cotton.		
Topographic factor on crop yield	Cotton yield is 1.09 to 1.15 t ha^{-1}. Hybrid *jowar* and wheat yields are 1.5 to 1.7 t ha^{-1}. Soil productivity index is high.		The cotton performance in terms of yield is 1.4 t ha^{-1} in Lohgaon (P4) and 1.1 t ha^{-1} in Parbhani (P5). Soil productivity index is low for deep soils but high for moderately deep soils.				Cotton yield is around 1.0 to 1.1 t ha^{-1}. Hybrid *jowar*/wheat yields are 1.2 to 1.3 t ha^{-1}. Soil productivity index is low		
Topography-yield - weather relationships	**Subnormal seasons** Crop yields are low **Abnormal seasons** Crop yields are better		**Subnormal seasons** Crop yields are moderate and highly variable **Abnormal seasons** Crop yields are moderate and better than foot slopes				**Subnormal seasons** Crop yields are better than other sites. **Abnormal season** Crop yields are poor		

102.21 ha) with heavy texture, slow permeability and salinity problems were marginally suitable for irrigation. The development of subsoil sodicity was mainly attributed to micro-topographical variations (Vaidya and Pal 2002; Pal *et al*. 2003) and upward gradient of water potential and lateral upward fluxes of Na and Ca/Mg carbonate accumulations due to seasonal rains as is evident from the profiles of Parbhani (P5) and Thola series (P9) in the study area (Seelig *et al*.1990; Bhaskar *et al.* 2001a).

The soil depth and erosion are the two important criteria in Vertisols and vertic intergrades for evaluating cotton suitability (Sehgal 1991). However, microtopographic variations also have a significant influence on yield of cotton as evidenced from the present study wherein the cotton yield varies from 1.0 t ha^{-1} in P7 to 1.3 t ha^{-1} in P4. Similar yield-topography relationships was reported in lower plains of basaltic terrain in Amravati district, Maharashtra (Bhaskar *et al.* 2001b). The influence of precipitation and topography on yield of cotton is quite contradictory in semi-arid toposequence because of imperfect drainage in foot slopes during wet years and water deficit in uplands during prolonged dry spells that have resulted in lower yield. The prolonged dry spells and excess wet periods in the Jayakwadi command area have resulted in failure of *kharif* cotton (Ramakrishna Rao *et al.* 1986). The relative yield index based on crop yield data was worked out for arriving at relative soil productivity index. The indices showed that the Leptic Haplusterts and other vertic soil subgroups have yield index above mean (99.3%), whereas the yield index was below the mean value in Sodic Haplusterts (Bhaskar 1997).

Conclusions

The study indicated that land grading and levelling were prerequisite for designing surface irrigation for cotton-based cropping systems in deeply cracking clay soils. The irrigation analyses for cotton showed that irrigation frequency of 14 and 9 days, respectively were required for deep and shallow black soils over middle slopes. The topography-yield relationships showed that the variations in microtopography have significant influence on the yield of cotton, *jowar* and wheat. The soil productivity indices (SPI) indicated that the productivity potential of Leptic Haplusterts and Vertic Haplustepts were higher than the Sodic Haplusterts. The present land evaluation analyses signify the limits of soil–topography-yield variations in interpreting site-specific data for irrigation.

References

Abhange, G.V., Pisolkar, S.S., More, S.D., Bharambe, P.R. and Ghonsikar, C.P. (1986) Problems in Jayakwadi and Purna commands and their management. In *Agricultural Development of Jayakwadi and Purna Command Areas.* Marathwada Agricultural University, Parbhani, pp.155-165.

Balpande, S.S., Deshpande, S.B. and Pal, D.K. (1996) Factors and processes of soil degradation in Vertisols of the Purna valley, Maharashtra, India. *Land Degradation and Development* **7**, 313-324.

Bhaskar, B.P. (1997) Soils of Jayakwadi Irrigation Project, Minor-4. *Technical Report No*. **535**. NBSS&LUP Publication, Nagpur, pp. 89.

Bhaskar, B.P., Anantwar, S.G., Challa, O., Bharambe, P.R. and Velayutham, M. (2001a) Catenary variations in properties of shrink-swell soils in minor- 4 of Jayakwadi irrigation project in Parbhani district, Maharashtra. *Journal of Geological Society of India* **57,** 429 -434.

Bhaskar, K.S., Wasnik, S.M., Barde, N.P. and Mendhe, P. N. (2001b) Comparative performance of cotton-based systems in different toposequences on watershed basis for sustainable land use planning. *National Seminar on Developments in Soil Science 2001*, Indian Society of Soil Science, 179 p.

Bhattacharjee, J.C. (1979) *Land Evaluation Criteria for Irrigation. Report of Expert. World Soil Resources Report.* **50**. Soil Resources, Management and Conservation Services, Land and Water Development Division, FAO. Rome. pp. 38-52.

Black, C.A., Evans, D.D., Ensminger, L.E., White, J.L. and Clark, F.E. (1965) *Methods of Soil Analysis*, **Part 1**, American Society of Agronomy, Madison, Wisconsin, USA.

Canada Soil Survey Committee (1978) *The Canadian System of Soil Classification*, Canada Department of Agriculture Supply and Services. Canada, Ottawa, **1646**. pp. 164.

Challa, O., Vadivelu, S. and Sehgal, J. (1995) *Soils of Maharashtra for Optimising Land Use.* NBSS Publication, **54b**, NBSS&LUP, Nagpur, India, pp. 112.

Day, L.D., Collins, M.E. and Washer, N.E. (1987) Landscape position and particle size effects on soil phosphorus distribution. *Soil Science Society of America Journal* **51,** 1547-1553.

FAO (1979) Soil Survey Investigations for Irrigation. *FAO Soils Bulletin* **42,** FAO**,** Rome.

FAO (1985) Guidelines: Land Evaluation for Irrigated Agriculture. *FAO Soils Bulletin* **55,** FAO, Rome.

Gebrekidan, H., Mishra, B.B. and Aune, J.B. (2005) Productivity and irrigability classifications of some basaltic soils in toposequence: A case study of Amensis sub-catchment at Hirna watershed in Western Hararghe, Ethiopia. *Agropedology* **15**, 16-21.

GOI (1999) *Ninth Five Year Plan* 1997-2002 **Vol. I and II**, Planning Commission, Government of India, New Delhi.

Hargreaves, G.H. and Mekley, G.P. (1998) *Irrigation Fundamentals*. Water Resource Publication. LLC. pp. 200.

Jackson, M.L. (1973) *Soil Chemical Analysis*. Prentice Hall of India Pvt. Ltd. New Delhi.

McKeague, J.A., Wang, C. and Coen, G.M. (1988) Describing and interpreting the macro structure of mineral soils - A preliminary report. *Land Resource Research Institute Contribution No*. **8450**. Agriculture. Ottawa, Canada, pp. 47.

Navalawala, B.N. (1992) Indian perspective in water resource planning. *Seminar on Irrigation Water Management.* New Delhi. **1**, 18-42.

Pal, D.K., Srivastava, P., Durge, S.L. and Bhattacharyya, T. (2003) Role of microtopography in the formation of sodic soils in the semi-arid part of the Indo-Gangetic Plains, India. *Catena* **51,** 3-31.

Postel, S. (1999) *Pillar of Sand: Can the Irrigation Miracle Last*? New York & London. WW Norton & Company, pp. 313.

Ramakrishna Rao, G., Sondge, V.D. and Bhonsle, S.S. (1986) Climatic conditions in Jayakwadi and Purna commands with reference to water management. *Agricultural Development in Jayakwadi and Purna Command Areas.* Marathwada Agricultural University, Parbhani.

Ramasastri, K.S. and Ramana Murthy, B.H.V. (1975) Evaluation of soil moisture in dry farming area in India by climatic water balance. *Indian Journal of Agricultural Sciences* **45,** 452-462.

Sawant, S.D., Kulkarani, B.N., Achuthan, C.V. and Satya Sai, K.J.S. (1999) *Agricultural Development in Maharashtra - Problems and Prospects*. National Bank for Agriculture and Rural Development, Department of Economic Analysis and Research, Karnatak Orion Press, Fort, Mumbai. pp.1-173.

Seelig, B.D., Richardson, J.L. and Barker, W.T. (1990) Characteristics and taxonomy of sodic soils as a function of landform position. *Soil Science Society of America Journal* **54**, 1690-1697.

Sehgal, J.L. (1991) Soil site suitability evaluation for cotton. *Agropedology* **1,** 49-63.

Shainberg, I. and Gal, M. (1982) The effect of lime on the response of soils to sodic conditions. *Journal of Soil Science* **33,** 489-498.

Soil Survey Manual (1970) *All India Soil and Land Use Survey Organisation*, IARI, New Delhi.

Soil Survey Staff (1995) *Soil Survey Manual*. USDA. Hand book.No.18. Scientific Publishers. Jodhpur.

Soil Survey Staff (1998) *Keys to Soil Taxonomy.* Eighth Edition. SMSS, USDA, Washington, DC.

Subramaniam, A.R. and Sambasiva Rao, A. (1987) Scheduling irrigation based on some climatic indices for crops in Maharashtra of western peninsular India. *Irrigation and Water Allocation, Proceedings of the Vancouver Symposium*, August 1987. IAHS Publ. no. **169.** pp**.** 153-162.

Sys, C. and Verheye, W. (1974) Land evaluation for irrigation of arid regions by the use of the parametric method. *Transactions of the 10th International Congress of Soil Science. Moscow.* **10**, pp.149-155.

Sys, C., van Ranst, E. and Debaveye, J. (1991) Land Evaluation. Part II. Methods in Land Evaluation. *Agricultural Publications No.***7**. Univ. Ghent. Belgium.

Thakkar, H. (1999) Assessment of irrigation in India. Prepared for thematic view **IV-2**. *South Asia Network on Dams, Rivers and People, India*. World Commission on Dams, pp.1-129.

USBR (2005) *Technical Guidelines for Irrigation Suitability Land Classification*. Reclamation Managing Water in the West. Technical Service Centre. *Land Suitability and Water Quality Group*. Denver, Colorado. pp.1-236.

Vaidya, P.H. and Pal, D.K. (2002) Microtopography as a factor in the degradation of Vertisols in the Central India. *Land Degradation and Development* **13**, 429-445.

World Bank (1998) India. *Water Resources Management Sector Review: Irrigation Sector*. New Delhi: The World Bank.

World Commission on Dams (2000) *Dams and Development: A new frame work for decision making*. Earth Scan Publishers. London, UK.

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