

भौगोलिक सूचना तंत्र पर्यावरण में फसल अनुरूपण तकनीक का प्रयोग करते हुए मृदा के भौतिक गुणों पर आधारित किसी क्षेत्र के लिए अनुकूलतम फसल क्रमण का मूल्यांकन

**ASSESSMENT OF THE OPTIMUM CROPPING
SEQUENCE FOR A REGION BASED ON SOIL
PHYSICAL PROPERTIES USING CROP
SIMULATION TECHNIQUE IN GIS
ENVIRONMENT**

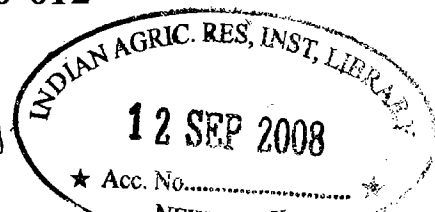
SANDHIR KUMAR



**DIVISION OF AGRICULTURAL PHYSICS
INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI-110 012**

2007

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**ASSESSMENT OF THE OPTIMUM CROPPING
SEQUENCE FOR A REGION BASED ON SOIL
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ENVIRONMENT**

By

SANDHIR KUMAR

A Thesis

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Indian Agricultural Research Institute, New Delhi,
in partial fulfilment of the requirements
for the award of the degree of

DOCTOR OF PHILOSOPHY

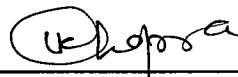
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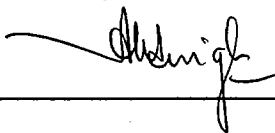
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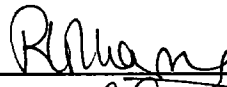
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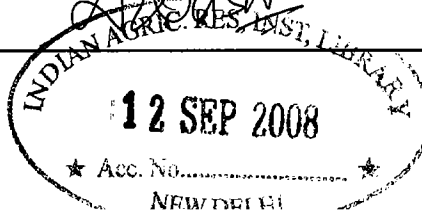
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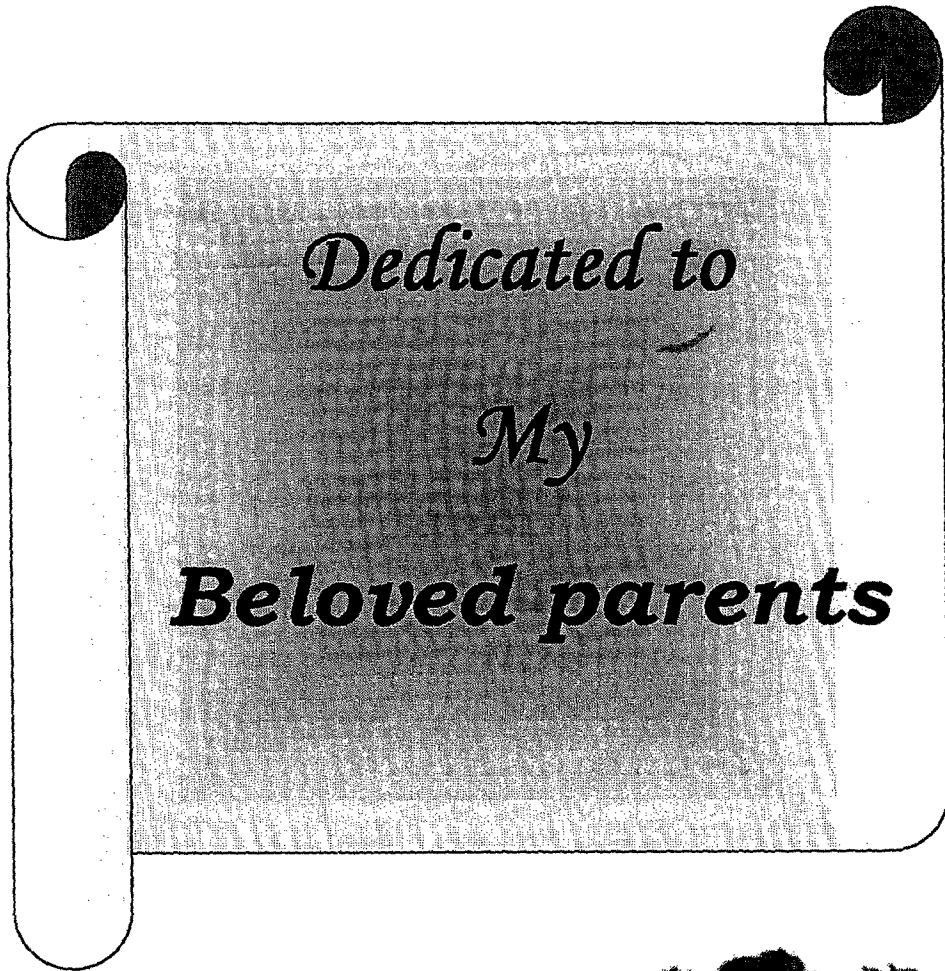
This is to certify that the thesis entitled “**Assessment of the optimum cropping sequence for a region based on soil physical properties using crop simulation technique in GIS environment**”, submitted to the Faculty of Post Graduate School, Indian Agricultural Research Institute, New Delhi, by **Sandhir Kumar** in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy in Agricultural Physics** embodies the results of *bona-fide* work carried out by him under my supervision and guidance. No part of thesis has been submitted by him for any other degree or diploma.

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Place : New Delhi

Date *July 31*, 2007


(U.K. Chopra)
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Dedicated to
My
Beloved parents



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1. INTRODUCTION

India, a home of 17 per cent of the world's population and over 15 per cent of the world's livestock has only 2 per cent of the land resource of the world to meet their basic requirements. To meet the demand of increasing population, it is estimated that our country requires about 340 million tons of foodgrain by 2020 (Rao, 2007) but the current pace of food grain production reflects that food grain production will increase from 216 MT in 2006-07 to about 240 MT in 2020 (Radhakrishna, 2002). To achieve these targets, foodgrain production must increase at the rate of 9 MT/yr over the next fourteen years. Therefore, maximising crop production becomes a national necessity for meeting the food requirements of a rapidly growing population.

However, the ability of the land to produce is limited and the limits to production are set by soils, climate and landform conditions, their intrinsic characteristics and agroecological settings. Therefore, promoting optimal land use and assessment of suitability of crops are essential for planning and achieving self reliance in food production. For efficient crop planning, information relating to soil suitability for cultivation of different crops is necessary.

Each crop requires a specific set of climatic and site specific soil characteristics for optimum production. But in the majority of cases, the soils are cultivated to different crops influenced by other factors including socio-economic conditions of farmers. Thus ignoring the soil-site requirements of a particular crop leads to sub-optimum yield or complete failure of crop.

Identification of suitable crops for specific regions will help the development agencies in land use planning and suggest alternate optimum crops to farmers for maximum utilisation of soil resource. Development of cropping system aims at increasing the resource use-efficiency for a given agro-climatic region with a selection of suitable crop calendar and thus securing maximum total returns from a number of crops grown in a region.

Forecasting crop yield is becoming an important tool for making future economic and management decisions (Las *et al.* 1993). The significance of crop yield forecasting is three fold. First, yield forecasts in advance of final harvest are necessary

for national food security including policy decisions of import/export plans and prices. Second, yield forecasts give farmers the advantage of beneficial marketing plans for their products. Third, crop management practices such as irrigation and application of fertilizers, are made on the basis of assessment of both current crop status and technology effects in terms of final yield (Horie *et al.*, 1992). Crop growth models have been helpful in making economically and environmentally correct decisions. They predict growth, development and yield of different crops as a function of soil, weather and crop management conditions (Hoogenboom *et al.*, 1995). These models draw knowledge from disciplines such as crop physiology, soil science, agronomy, climatology and plant protection. In these models various mechanisms of photosynthesis, respiration, dry matter production and crop phenology are dynamically linked to each other by various rate equations and each mechanism is defined by the value of its state variables at the end of simulation time scale of one day. They have good yield predictive capacity but are input data intensive. These models have been used for crop yield simulation at field scale and to evaluate various management options or to simulate potential yields in a region.

Though the crop simulation models are very useful in evaluating crop growth at field scale their implementation at larger scale is restricted by the input data availability at corresponding scale. To expand the application of crop models to large areas, the crop models have been combined with geographic information systems (Calixte *et al.* 1992). Various approaches have been used in developing capabilities for users to analyze the spatial variability of crop performance for a particular area (Papajorgji *et al.*, 1994). These combined tools can be used for characterizing the regions, locating high yielding and problematic areas and estimating their productivity under different management scenario.

Keeping this in view, a study was carried out in the watershed area of Shikohpur, Gurgaon district, Haryana. The area is a micro watershed of about 1000 ha including Krishi Vigyan Kendra of the Indian Agricultural Research Institute. Watershed area of Shikohpur is natural because it allows to manage soil and water resources without disturbing the harmony of natural habitats. In terms of its physical components watershed management is very nearly synonymous with soil and water conservation with emphasis on optimum production. Development is not confined to

the agricultural lands alone but involves a combination of practices for the overall development of the area. Now a days due to land use pattern and lack of latest technology, agricultural production in both *kharif* mainly, pearl millets and *rabi* season (wheat and mustard) are low to medium. Ameliorative measures, proper management and suitable cropping sequence are definitely needed to enhance productivity and sustainability of the soils, for which assessment of cropping sequence based on soil properties are absolutely necessary. Therefore, the present study is carried out with the following objectives:

1. To assess the variation in soil physical properties viz. soil moisture content, bulk density, saturated hydraulic conductivity, water retention properties etc. of the study area.
2. To identify the optimum cropping sequences of the study area based on variations in soil physical properties using GIS linked simulation technique.
3. To assess the long term performance of the identified optimum cropping sequences of the study area.

2. REVIEW OF LITERATURE

The review of literature on various aspects pertaining to the present study is presented in this chapter. An attempt has been made to cite relevant literature on studies on cropping sequence based on soil physical properties and crop modelling. However, due to paucity of adequate experimental evidence the similar work with related topics has also been reviewed where ever necessary. The literature has been reviewed under the following heads:

- ☞ Soil physical properties and plant growth
- ☞ Site specific soil characteristics and plant growth
- ☞ Cropping sequence
- ☞ Crop modelling

2.1 Soil physical properties and plant growth

2.1.1 Soil water retention and transmission characteristics

Soil water retention characteristics determine the amount of water that is retained in a soil. The amount of water remaining in the soil at equilibrium is a function of matric suction (Hillel, 1998). Thus water content of the soil at different levels of matric suction describes the retentivity of the soil for water. This function is usually measured experimentally and is represented graphically by a curve called the soil-moisture retention curve; also known as the soil moisture release curve or the soil moisture characteristic curve (Ghidyal and Tripathi, 1987).

Soil water-matric potential relationships of representative soil groups of India have been studied by a number of workers (Ali *et al.*, 1966; Sekhon and Arora, 1967; Abrol and Bhumbla, 1968; Biswas *et al.*, 1971; Mishra and Nanda, 1985 and Gajbhiye, 1990) using pressure plate and pressure membrane apparatus. Considerable information is available on water storage characteristics of benchmark soil profiles of differential groups from the work carried out under the All India Coordinated Research Improvement Project on "Improvement of Soil Physical Conditions to increase Crop Production in Problematic Areas" (Gupta *et al.*, 1984).

Soil water-matric potential relationships differ for different soils and are influenced by soil physical properties such as texture, structure, pore size distribution, bulk density, organic matter content, mineralogical composition, cation exchange capacity and thermal regimes (Post, 1981; Bhavanarayana *et al.*, 1986 and Das and Chopra, 1987).

Soils of different textures, when subjected to same force, retain varying amounts of water. Soil water retention both at -30 KPa and -1500 KPa was found to be negatively correlated with coarse sand and positively correlated with silt and clay fraction (Oswal and Khanna, 1981; Gupta *et al.*, 1986 and Gajbhiye, 1990). Thus fine textured soils have more retention of water than others. Not only the amount of clay but also the type of clay govern significantly the water retention characteristics of the soil (Ali and Biswas, 1968). The water retention curves of alluvial (illite), red and lateritic (Kaolinite), acid (illite and kaolinite) and black soil (smectite) reflect the role of respective clay minerals influencing soil water retention (Puri and Mahajan, 1962). Soil profiles with textural variation also effect water retention. Stratified soils having loamy layer overlying fine sand enhances water retention in comparison to homogeneous profiles due to restricted water movement at the interlayer boundary layer (Sharma and Felitsiant, 1983).

A well-aggregated soil may have lower water content except at low matric suction than a compacted soil due to greater volume of micro-voids in a compacted soil (Ghildyal and Tripathi, 1987). The same authors have also given the standards for performing water retention experiments. They recommend undistributed core samples for wet end values and sieved air-dry samples for dry end values of the retention curve.

Gupta *et al.* (1986) studied the soil-water functional relationship to obtain information on moisture retention and transmission coefficients of the soils of Rajasthan canal area. They reported high hydraulic conductivity (K) for sandy loam soils and highly significant correlation with coarse sand. Rakesh *et al.* (1992) observed significant correlation between available water and soil separates in command area of Sian Minor of Gandak project. Yadav *et al.* (1995) investigated the soil water retention and infiltration characteristics of north western Rajasthan command area which are

essential for any management plan for irrigation scheduling, methods of irrigation, drainage and solute migration. They concluded that sprinkler or drip irrigation might be suitable for desert plain and intralatitude soils due to their low water retentivity, low available water capacity and rapid infiltration rate.

Das and Datta (1997) studied water retention and transmission characteristics of different sub-tropical soils developed on varying materials in Bihar and West Bengal for management planning of irrigation scheduling, methods of irrigation and prevention of water and nutrients loss through drainage. They reported that, irrespective of parent materials, saturated hydraulic conductivity (K_s) of these sub tropical soils have a large bearing on soil coarse fraction and bulk density. Sprinkler or drip irrigation was found to be suited for one group of soils due to their low water retentivity, low available water capacity and high (K_s) and relatively low $K(\theta)$ and $D(\theta)$. In order to increase the water use efficiency and minimize the water and fertilizer nutrient losses through drainage, surface irrigation to these soils was preferred to be avoided while in other group of soils surface irrigation was recommended apart from drip/sprinkler irrigation because of their high water retention, high available water capacity, relatively low K_s and high $K(\theta)$ and $D(\theta)$. Further, the soils have the capacity to supply sufficient water at high degree of saturation and hence depending upon the crop and its water requirements, frequency of irrigation may be restricted for higher water use efficiency.

Structure particularly pore size distribution and continuity of pores, are related to water transmission and hydraulic characteristics. Variation in pore size distribution influences infiltration (Edwards et al., 1979 and Grismer, 1986). Sood and Choudhary (1980) observed that with large initial clod size of 95 mm Mean Weight Diameter (MWD), infiltration increased by 33 per cent as compared to that with initial clod size of 46 mm MWD.

Ploughing of soil increases macro-porosity of the surface leading to improved soil structure and reduction in bulk density. Higher infiltration rates in ploughed surface layer as compared to those on unploughed layer have been reported as a result of high suction gradient in relatively dry ploughed layer (Steichen and Nail, 1979 and Ambegaonkar *et al.*, 1984). Infiltration of labeled water was greater and more rapid in sub-soiled soil than where sub-soiling was not done (Schroder and Schapenseel, 1975). While ploughing increases infiltration, puddling drastically reduces infiltration

rate (Jaggi and Bisen, 1986) due to reduction in macro soil porosity. Porosity of a soil layer is directly related to bulk density. With higher bulk density of the surface layer due to compaction, infiltration rate decreases (Gupta *et al.*, 1984).

Initial moisture content in the soil profile also determines water entry into soil (Talsma, 1974; Malik *et al.*, 1987 and Hino *et al.*, 1988). Subramanyam and Kar (1976) reported a curvilinear relationship between initial moisture content and infiltration rate for a lateritic sandy loam soil. However, the relationship was linear between 6 and 20 percent moisture. In sandy loam soil, Joshi and Das (1977) found that increase in bulk density or initial moisture content decreased the sorptivity with a concomitant decrease in infiltration rate.

Knowledge of the pertinent transmission properties of soil such as saturated and unsaturated hydraulic conductivity and soil water diffusivity is essential for study of water movement through soil, root water extraction, contribution of groundwater table, crop water use and computation of soil water balance. Such properties are often determined in the laboratory using disturbed and sieved soil samples. However sample disturbance causes significant variation in hydraulic properties and the need for their measurement under field conditions has received considerable attention (Nielsen *et al.*, 1973; Das and Jat, 1984 and Patro and Mishra, 1985). Field measurement of hydraulic properties provides information on complex natural variation in the soil both in space and time, but is expensive as well as time consuming. Earlier researches in India on transmission properties of soils have been reviewed by Ghildyal *et al.* (1971). Khosla *et al.* (1982) and Das and Chopra (1987). Some pertinent literature on transmission characteristics is reviewed here.

The transmission characteristics are greatly influenced by the soil water content. Increase in soil water content increases the values of both hydraulic conductivity and soil water diffusivity (Rolston *et al.*, 1976; Joshi *et al.*, 1977; Das *et al.* 1977 and Gupta and Agrawal, 1980) but the extent of increase decreased with rise in soil moisture tension (Dhanpal and Varade, 1976 and Gupta *et al.*, 1986). Joshi *et al.* (1977) reported dependence of soil water diffusivity on initial soil water content of sandy loam soil at moisture contents less than saturation.

While conducting research on retention and transmission characteristics of Mahi right bank canal command area of Gujarat, Singh and Nayak (1999) found that water retention at various suctions correlated negatively with sand and silt and positively with clay, organic carbon, EC and pH. At any given suction, magnitude of water retention followed the order Vertic Halaquepts > Typic Halaquepts > Vertic Ustochrepts > Fluventic Ustochrepts > Fluventic Ustorthents > Typic Ustorthents. The available water capacity was categorized as high in Vertic Halapuepts, Typic Halaquepts and Vertic Ustochrepts, medium in Typic Ustochrepts and lower in Flueventic Ustochrepts, Typic Ustorthents and Fluventic Ustothernts. They also observed that there was wide variation in saturated hydraulic conductivity (K_s) of the soils, the highest was observed in Typic Ustorthents and the lowest in Vertic Halaquepts. Similar study carried out by Singh *et al.* (1994a) showed that water retention, water content and water storage capacity were more in Typic Chromusterts followed by Vertic Ustochrepts, Typic Ustochrepts and Typic Ustorthents. Mapa and Pathmarajah (1995) reported that available water of Alfisol in Sri Lanka increased downslope from 97 mm m^{-1} in the Rhodustalfs (upper slope) to 106 mm m^{-1} in the Haplustalfs (middle slope) and 122 mm m^{-1} in the Tropaqualfs (down slope).

2.1.2 Soil texture and structure

Soil texture, structure and organic matter content have been shown to cause significant changes in hydraulic conductivity (Dakshinamurthi and Pradhan, 1966; Pharanade *et al.*, 1969; Sur *et al.*, 1981 and Gupta and Ranade, 1987). Gupta *et al.* (1986) reported that saturated hydraulic conductivity maintained a highly significant correlation with coarse sand. However, medium textured soil with continuous transmission pores exhibit higher water conductivity as compared to coarse texture sandy soils (Mundra *et al.*, 1989).

The effect of soil texture, aggregate size and initial moisture content on soil water diffusivity $D(\theta)$ followed the order, loamy sand > sandy loam > clay loam. The effect of initial soil moisture content increased with the decrease in aggregate size with the increase being more pronounced below the size of 1 mm.

Mishra and Nanda (1985) stated that available water holding capacity, significantly correlated with silt plus clay fraction; within textural groups, it was still

more closely related to silt plus clay in coarse and moderately coarse textured, to silt in medium textured and to the proportion of silt to clay in fine textured soils. Water retention is largely influenced by the nature of the dominant clay mineral. Ram *et al.* (1987) observed that the clay was the major factor contributing towards the moisture content at 1500 kPa and the silt plus clay towards the moisture content at 33 kPa.

Nagar *et al.* (1995) studied soil water characteristics of different soil series in Chambal Command, Rajasthan and reported that field capacity, moisture equivalent and permanent wilting point were negatively correlated with sand fraction whereas field capacity was correlated with clay, moisture equivalent and wilting point. The above correlations were found to be nonsignificant with silt fraction. Sharma *et al.* (1990) reported that available water was significant and positively influenced by clay, silt, CEC and organic carbon while negatively by sand and bulk density.

Yadav *et al.* (1995) reported that derived soil climatic parameters viz. plant available water capacity (PAWC), soil effective rainfall and the length of growing period (LGP) were directly associated with soil depth and clay content. Similar conclusion was given by Siderius (1994) that plant available water capacity increase from sandy soil to fine loamy textured soil.

In watershed area in Kabbalanala, Karanataka, Murthy *et al.* (1995) found that forest and pasture soils had higher organic matter and mean-weight diameter value than dryland and irrigated soils. Forest soil had an aggregate stability coefficient near one which is conducive for root development.

2.1.3 Bulk density

Bulk density is the most fundamental soil property and it has a major impact on soil water relationship and crop root development and consequently on crop growth and yield (Unger and Cassel, 1991). Mallik and Nagarajarao (1972) found that on sandy loam soil ploughing decreased bulk density upto 1.2 g/cm^3 with mould board ploughing and 1.3 g/cm^3 with desi ploughing. At subsurface layer the saturated hydraulic conductivity decreased because of compaction by wheel traffic during or after tillage operation (Unger and Cassel, 1991).

Change in bulk density of soil brings variation in pore geometry, which influence pathways of water through the soil. Reduced hydraulic conductivity due to

high bulk density has been reported by several workers (Ghildyal and Satyanarayana, 1965; Joshi *et al.*, 1977 and Gupta *et al.*, 1984). The bulk density is less effective in reducing the water conductivity in alluvial, red and lateritic soils as compared to that in black soils. The hydraulic conductivity is also influenced by interaction of bulk density and soil moisture content. Higher values of transmission parameters are attained at higher bulk density as compared to low bulk density at soil moisture content near saturation, whereas, at low moisture contents, these values are reduced with increase in bulk density (Joshi *et al.*, 1977). Puddling of soil for cultivation and compaction of soil decrease saturated hydraulic conductivity of soil (Reddy and Hukkeri, 1983 and Nimmo *et al.*, 1988). The use of compaction technology in reducing the saturated hydraulic conductivity of coarse textured sandy to sandy loam soils have been reported (Gupta *et al.*, 1984 and Anonymous, 1991).

Several authors have found that loosening of soil by tillage operations increased saturated hydraulic conductivity of surface layer (Mallik and Nagarajarao, 1972; Pelgrin *et al.*, 1990; Gupta and Abrol, 1993). But, Benjamin (1993) observed that under no tillage system hydraulic conductivity values was 30 to 60 per cent greater than either chisel or MB ploughing system.

Soil texture, as well as type of clay mineral and organic matter content of the soil, greatly influenced the other physical properties of the soil.

Murthy *et al.* (1982) reported that the bulk density in shrink-swell soils changes with moisture content. Such soils have high (1.80 Mg m^{-3}) bulk density when dry and low (1.55 Mg m^{-3}) when wet. Depending on the soil moisture content, the bulk density of Vertisols varies from 1 to 2 Mg m^{-3} . Sharma *et al.* (1994a) characterized Soam river soils in lower Siwalik. He suggested that higher bulk density values (1.51 Mg m^{-3}) for those soils could be attributed to coarse texture and low organic matter content. Within the same textural class, Virmani *et al.* (1982) reported that there was increase of bulk density values of Vertisols along with the soil depth due to soil compaction.

Challa and Gaikawad (1987) studied the water retention characteristics of soils Dadra and Nagar Haveli and reported that the quantum of available water in Vertisols and vertic intergrade soils profile is higher and uniformly distributed than Entisols,

possibly due to the high clay content and its uniform distribution in the profiles of the former soils. It was also reported that Vertisol and Inceptisols retained more amount of moisture than in Entisols, indicating thereby drought to occur in former soils at identical level moisture.

Radder and Doddamani (1994) studied the moisture characteristics of major soil series of Malaprabha Command in Karnataka and found that moisture content at 33 kPa tension was generally twice the moisture held at 1500 kPa in all the black soils. The mixed black and red soils and the red soils did not hold this relationship. They also reported that available water in black soils was more (33.03 cm m⁻¹) than in mixed black and red (21.95 cm m⁻¹) and red soils (16.9 cm m⁻¹).

2.1.4 Soil physical environment and plant growth

Pearlmillet (*Pennisetum typhoides* L.) an important crop among the cereals is traditionally a component of dryland system. Out of the world area of 20 m ha under Pearlmillet 11m ha is in India. The annual grain production of Pearlmillet in India is very low *i.e.* around 10m ton. Pearlmillet has tolerant upto 75% depletion of available water from 0-30 cm depth of soil on heavy black clay soils in Karnataka (Patil and Ganjal, 1989) and on sandy loam soils of Delhi (DARE, 1975), on the sandy loam soils of AP, however, best yields were obtained with irrigation at 50% depletion level (APAU, 1975).

Pandey *et al.* (1988) reported that Pearlmillet grown in rainfed trials with different moisture conservation practices at a density of 1,00,000 and 2,00,000 plant ha⁻¹ gave average grain yield of 1.87 and 2.28 t/ha and water use efficiency at 5.95 and 6.78 kg grain/mm, respectively.

Growing of bajra in paired row is far superior as compared to single row planting which resulted in 38% increase in yield (Anonymous, 1974). Singh *et al.* (1978) reported yield increase due to paired row planting of bajra was 2.7 g/ha over its uniform row planting. Significantly higher yield of Pearlmillet grain was reported from paired rows than uniform rows percent increase being 29.9 (Anonymous, 1976).

Working on Pearlmillet at ICRISAT, Jarwal and Singh (1990) reported that the final above ground dry matter followed the pattern of cumulative intercepted PAR.

They further observed that radiation conversion efficiency ranged from 1.87 g/MJ to 2.82 g/MJ in different cultivars sown at different spacing.

Shankarnarayan and Mehta (1967) studied the effect of enzyme in rotation with cereal in Chambal area of Rajasthan. Rotations which included legume, gave better soil aggregation both in the surface and sub soil than rotations having cereal crops only. The soils, in the rotation in which chickpea was included (maize-chickpea-fallow-wheat) had higher organic carbon percentages, nitrogen percentage and water stable aggregates (2.5 mm) as compared to pure cereal rotation of maize wheat.

Gautam *et al.* (1964) working at IARI, New Delhi reported that maize grown with soybean give slightly higher yields of maize under intercropping. Nair (1964) reported that mixed cropping to maize with soybean had favourable effect on the growth characters such as no. of functionary (green) leaves, dry matter production per plant length and weight of cob, test wt. of grains of hybrid maize, although the differences were not statistically significant.

Hague *et al.* (1966), Hanwey and Weber (1971) associated soybean yields with the length of bean growth period and concluded that major yield difference between varieties and years were due to differences in the length of bean growth duration and not much dependent on bean growth rate.

Zapata *et al.* (1987) working on soybean reported that the increase in dry matter was small prior to 55 days of flowering but increased rapidly thereafter, 20% of final crop dry matter was accumulated before flower initiated and more than 74% during 40 days between flower initiation and physiological maturity.

Chickpea is a quantitatively long day plant (Summerfield *et al.*, 1980). Several environment factors *viz.* temperature, soil moisture, photoperiod etc. affect the duration and occurrence of different phenophases (Minchin *et al.*, 1980; Saxena, 1984 and Roberts *et al.*, 1980, 1985).

Summerfield *et al.* (1980) at ICRISAT, Hyderabad studied the effect of air temperature on days to 50% seedling emergence. They found that with increase in mean air temperature from 19.5 to 24.5°C the days for 50% emergence reduced from 9 to 6 in cultivar Rabut and from 6.5 to 4.0 days in chaba. Roberts *et al.* (1980) also

observed reductions in no. of days to seedling emergence with the increase in average air temperature.

Muchow (1985) studied the response of phenology to prolonged water deficit in soybean, green gram, black gram, lablab bean and pigeon pea in a semi arid tropical environment in Australia. He observed that water deficit had little effect on the date of flowering, although there was a tendency for flowering to be accelerated in all grain legumes except pigeon pea cv. Royes where flowering was delayed. He also reported that the duration of flowering was significantly reduced by water shortage in all grain legumes except soybean cv. Buchanan.

Singh (1991) observed that water deficit during all growth phases decreased foliage growth but the reduction was greater when the crop was stressed prior to flowering. Maximum reduction in green LAI occurred when the crop was continuously stressed throughout the season.

Kumar (2000) at IARI, reported that in chickpea the LAI increased upto 105 DAS and decreased thereafter. Maximum LAI of 4.33 was observed in Annegiri under irrigated condition and 4.07 in ICC 4958 under rainfed condition. Under rainfed conditions there was a significant reduction in LAI compared to the irrigated control.

The soil and water management hold the key of crop production with regard to yield and dry matter production in relation to irrigation or water stress. A ten fold increase were observed by Shieldrake and Saxena (1979) in yield and dry matter, production of chickpea with irrigation while moisture stress results in earlier senescence and maturity while in turn results in lower dry matter and yield. Singh and Rai (1980) while evaluating two varieties of chickpea for their drought resistance, reported growth inhibition in both the varieties by the imposed water stress. Soil moisture is an important factor in triggering senescence also, which is delayed by irrigation (Saxena and Sheldrane, 1980). Early growth may not also be positively related to grain yield in stress conditions (Brown *et al.*, 1987).

Singh *et al.* (1988) reported that chickpea (*C. arietinum*) yields were 2.3 and 2.6 t/h in single row (45 cm between rows) and double rows (45 cm between paired rows and 60 cm between pairs) respectively. Similarly, Manjunath and Sheelavantai

(1988) found that when *C. arietinum* was grown in rows 22.5, 30.0 37.5, 45.0 cm apart it gave yields of 2.32, 2.63, 2.50 and 2.6 t/ha, respectively.

Chickpea is grown in diverse eco-geographical conditions (Saxena, 1984: Khanna-Chopra & Sinha, 1987). Khanna-Chhopra and Sinha (1987) also reported that plants though, deep rooted, are affected adversely by soil moisture stress. At the same time they are highly sensitive to excessive soil moisture, high humidity and cloudy weather (Kay, 1979: Bejiga and Tullu, 1982).

Singh and Bhushan (1980) found that application of one irrigation after 45 days of sowing gave significant increase in yield of gram compared with no irrigation and one irrigation either at 75 days after sowing or, at early pod filling stage. Maximum water use efficiency (185.56 kg/cm/ha) was found in no post sowing irrigation treatment.

The biomass accumulation, which represents net photosynthesis of the crop is one of the major physiological parameters controlling crop productivity.

According to Khanna-Chopra and Sinha (1987) the pattern of dry biomass accumulation in chickpea shows a typical sigmoid curve with a slow vegetative phase, a log phase after flowering and a decline during the pod development phase.

Dahiya *et al.* (1976) observed that in dryland farming, late maturity varieties produced more dry matter but poor grain yields because of soil water stress in reproductive phase of growth. Reduction in yields upto 17% due to limited irrigation at critical stages in chickpea has been reported by Nanda and Saini (1992) and Yadav *et al.* (1994).

Yusuf *et al.* (1980) observed that water use efficiency in chickpea responded favourably upto two irrigations only. Thereafter, increase in irrigation number decreased the grain yield.

Beech and Leach (1989), reported that Safflower extracted more water (375 mm) from top 2 m of the soil profile than wheat (212 mm) and chickpea (195 mm). Wheat had highest water use efficiency than chickpea and Safflower. On the basis of market price, economic return was highest for chickpea, followed closely by Safflower and then wheat.

Studies on biomass production and its partitioning assume greater importance to crop management because grain yield is greatly dependent on the partitioning of photosynthates towards grain filling after anthesis. The division of assimilates among different parts of the plant termed partitioning, affect both productivity and survival of the plants (Gardner *et al.*, 1985). In *Brassica* species, though the major part of the biomass is accumulated in the post flowering period when the leaf area is on decline unlike most of the cereals, levels of accumulation before and after flowering were reported to have varied with species and varieties (Richards and Thurling, 1978). Under Delhi conditions, Rao (1992) reported that in mustard about 12 to 17 per cent dry matter was accumulated before flowering and remaining was accumulated after flowering. The relationship of total dry matter to yield at maturity is highly significant and accounted for 96 per cent of total variation in seed yield of oilseed *Brassica* (Bhargava, 1996).

Gunasekera *et al.* (2001) studied effect of variation in sowing conditions on dry matter production and yield of Indian mustard in Mediterranean environment and reported that final above ground dry matter production differed significantly among sowings and was the greatest in the early sown (2nd June) and the lowest in the very late sown (14th July) crop.

From the field experiments in semi arid conditions of Delhi in two *rabi* seasons, Kar and Chakravarty (2001) reported that biomass production and its partitioning in *Brassica* crop were highly affected by thermal environment during crop growth period. They reported that in *Brassica* (cv. B.O. 54 and Pusa Bold) the reduction in biomass production in the crop sown on 1st week of November and 3rd week of November over the crop sown on 3rd week of October was about 6 and 22 per cent, respectively.

Chauhan and Bhargava (1984) reported that seed yield in crop *Brassica* was positively and significantly associated with biomass production. Babu (1985) examined the morpho-physiological factors that caused reduction in yield in rapeseed. He observed that reduced plant height, inflorescence length, and number of branches, pod number, pod weight and 1000 seed weight accompanied yield reduction.

Rao (1992) conducted an experiment on *Brassica* species in semi arid climate of Delhi for two seasons and showed that seed yield was reduced by 36 per cent in

warmer season when maximum temperatures were higher by 5.2⁰C and minimum temperatures by 1.7⁰C than in the cooler season. He also concluded from simulation studies decrease in the radiation due to cloudy sky associated with passage of 'Western Disturbances' in Delhi region resulted in decrease in seed yield.

Kar (1996) reported that reduction in seed yield ranged from 7.6 to 23.3 per cent in different cultivars of *Brassica* (B.O. 54, Pusa Bold and Toria T-9) due to delay in sowing under Delhi conditions.

Bhargava (1996) sown seven cultivars of different growth duration belonging to four *Brassica* species at seven different sowing dates from 12th October to 11th December under field conditions in the 1988-89 *rabi* season. Comparison of results with optimal sowing date (20th October) indicated that early and all later sowings progressively reduced seed yield. The seed yields of cultivar Varuna were 431, 491, 275, 173, 138, 84 and 58 g/m², 22nd October, 1st, 11th, 21st November and 1st and 12th December sown crops, respectively.

Khushu *et al.* (2000) studied the impact of weather on growth and yield of *Brassica juncea* and found that minimum temperature between flower bud initiation and pod formation was negatively correlated with seed yield.

Giri (2001) from the field experiments conducted at IARI, New Delhi, during winter of 1995-96 and 1996-97, reported that in mustard cultivar Pusa Jaikisan, sowing in October gave higher dry matter accumulation, number of pods per plant, seed weight, and seed yield than the crop sown in November.

Mairan *et al.* (2005) after a 5 year long experiment for adopting sorghum sunflower cropping sequence in vertisols, found that value of pH, EC, Bulk density were significantly decreased with the treatment receiving 50% N through GM or FYM or PMC or wheat straw than N received through inorganic fertilizer.

Twomlow *et al.* (1994) found that as a result of soil loosening, the winter water content of the 0-0.5 m soil layer was increased by 8.5% the subsoil bulk density was reduced by 15% and shear strength was reduced by 23%. Bhatnagar (1992) also found that FYM application reduced the surface BD, increased porosity and increased the water retention capacity of soils under soybean-wheat-cropping system.

Wu-Yujun *et al* (1996) compared the green manure-maize-late rice, winter fallow-maize late rice; barley-maize late rice, and wheat rice in china. They found that green manure maize late rice cropping system produced the highest grain yields and net returns. This was largely related to improved soil physical properties and soil fertility.

Shaver *et al.* (2002) were studied the effect of cropping intensity and topography position on soil bulk density, porosity, sorptivity and aggregate stability in the surface soil. They compared the wheat-corn-fallow, wheat-sorghum-fallow, continuous cropping and wheat-fallow. They found that the cropping system that returned more crop residue decreased BD and increased total and effective porosities compared with wheat fallow. Macro-aggregates made up a higher percentage of total aggregates in continuous cropping and wheat-corn-fallow compared with wheat fallow in proportion to residue added and were also a function of clay content of the soil. These factors enhance the potential for greater infiltration and hence greater water availability for crops.

Patil and Sheelavantar (2004) evaluated the effect of cultural practices on soil moisture conservation soil properties, root growth and yield of sorghum. They found that *in situ* moisture conservation practices reduced Bulk density, increased infiltration rate, porosity, improved root growth and grain yield of winter sorghum. Among organic sources, incorporation of Leucaena lopping improved soil Physico-chemical properties, conserved high amount of moisture and increased winter sorghum yield to a greater extent than FYM and vermicompost.

2.1.5 Thermal environment and crop growth

Heat unit expressed as growing degree day (GDD) is a simple means to relate plant growth and development to temperature (Nuttonson, 1955). The biotic potential of any organism is dependent on heat requirement for its reproduction, growth and development which is expressed as degree days. The degree days are the summation of mean temperature over a base temperature. Base temperature is one below which internal metabolic activity of the organism ceases to function. For *Brassica* species base temperature worked out to be 5⁰C (Marrison *et al.*, 1989). Degree days concept has been widely adapted and used for cereal, legume crops (Chakravarty and Sastry,

1983; Chakravarty *et al.*, 1984) and mustard crop (Kar, 1996) to relate with crop growth, phenological development and yield.

Ramesh and Gopaldaswamy (1991) while working on heat unit requirement and prediction of development stages in soybean measured GDD, Photothermal units, heliothermal units. Photothermal units required for different stages showed lower coefficient of variability than cumulative day length or, heliothermal unit.

Singh *et al.* (1996) stated that the duration from commence of crop emergence to flowering could be best explained by photothermal units for different genotypes of wheat. Rao *et al.* (1999) observed that among wheat, GDDs and recorded lowest yield. On the other hand, wheat was able to produce highest yield while accumulating minimum GDDs.

2.2 Site specific soil characteristics and plant growth

The soil characteristics such as local elevation, slope, soil drainage, profile depth, soil texture, calcium carbonate content, gravel content, soil structure, salinity and alkalinity of soils, are the limiting factors for agricultural production (Khatter *et al.*, 1988). Hairston *et al.* (1989) found that soil depth, organic matter content and rainfall affected soybean yield in the Mississippi Blackland Prairi. The regression analysis revealed that differences from site to site were due to variation in soils organic matter and rainfall distribution, whereas differences within a site were influenced by organic matter, soil depth and other parameter such as pH and available K.

Khadse and Gaikwad (1995) evaluated yield influencing factors for different crops and reported that AWC appeared as the most yield influencing factor followed by CEC, clay, depth and CaCO_3 content for sorghum; AWC followed by depth, CaCO_3 content, CEC and clay content for cotton and clay content followed by AWC, CEC, depth and CaCO_3 for soybean. Sehgal (1991) stated that climate, depth, CaCO_3 content, texture, structure, drainage are the cotton yield determining factors. Rainfed cotton gives best yield on deep fine textured soils with a good structure. Cotton yield could be increased from 60 to 140 per cent by growing cotton on medium deep to very deep (45 to 90 cm) soils. He further reported that rainfall of 1000 mm, soil depth of 60-1000 cm, and CaCO_3 (nodular form) up to 20 cm per cent support good cotton crop.

Yadav *et al.* (1999) studied soil and site characteristics in relation to yield of cotton in Vidharbha region of Maharashtra. The soils site was situated in elevation of range between 465 m above msl on the summit and 320 m above msl on the valley floor. The result showed that elevation and coarse fragment did not affect the yield significantly. However, their impact was negative on the yield. The depth, clay content, PAWC and CEC significantly increased the cotton yield whereas influence of slope was observed to be negative. Furthermore, they observed that there was significant difference in cotton yield in different soils. The very fine, montmorillonitic hyperthermic Haplusterts occurring on interfluvial crest produced higher cotton yield followed by moderately well drained, Typic Haplusterts of valley floor soils. The clayey lithic Ustorthents of foot slope recorded the lowest yield.

Yadav *et al.* (1995) reported PAWC, soil effective rainfall and the LGP showed significant and positive 'r' values in all crops, i.e. cotton, pigeon pea, sorghum, groundnut and soybean in a watershed near Nagpur. Lime content also showed a significant contribution towards the yield of pigeon pea and groundnut. Simple regression equation of crops yield with PAWC, effective LGP showed linear relationships for cotton, pigeon pea and sorghum; soybean showed a quadratic relation with PAWC and linear relationship with effective rainfall.

Dry matter of the rice root and grain yield were significantly higher in clay loam than in loam or sandy loam soils which may be due to its greater nutrient supplying capacity (Sharma *et al.*, 1990). Soil texture, CEC, soil depth, soil drainage, stoniness and relief are the significant variables affecting the rice yield (Rondal, 1991). Sharma *et al.* (1994) found that rice yield was highest in the moderately well drained, deep fine textured soils with cambic or Arbillic Horizon.

Bhushan and Sharma (1999) reported that the root mass density (RMD) of wheat decreased by about 20% with every 0.1 Mg m^{-3} increase in bulk density above a value of 1.36 Mg m^{-3} . Root mass increased progressively and significantly with the increase in root-zone depth from 0.05 to 0.30 m, but decreased with the improvement in aeration status of root zone. Shoot growth was also affected significantly by depth, density and aeration status of root-zone but not in the same proportion and direction as the root growth. Hence, shoot/root ratio responded differently to root-zone parameter under study. Grain and straw yields of wheat increased with root-zone depth, straw

yield increased almost twice as the grain yield with every 0.05 m increase in root-zone depth. Aeration status affected the grain yield, but not the straw yield.

Prasad *et al.* (1990) modified the FAO frame work to evaluate the suitability of soils of Vellore Taluk, Tamilnadu. The soil site characteristics used for evaluation were climate, physiography, slope, drainage, flooding, texture depth, pH, CEC and base saturation. Sehgal (1991) applied the FAO land suitability approach to the soils of Khapri watershed and found that the soil site criteria considered for suitability classes were applicable under comparable situation.

Vadivelu *et al.* (1983) and Bhattacharya *et al.* (1989) observed that geomorphic unit influences land use pattern through their influence on soil-site and climatic characteristics. The hill ranges with shallow soils were mostly under forest with patches of rainfed crops, the pediment surfaces with shallow to deep soils were cultivated to sorghum, pearl millet and safflower and the soils occurring on piedmont plain and the flood plain were very deep and cultivated to sorghum, cotton and safflower under rainfed condition.

Gaikwad and Bhaskar (1988) concluded that under scientific management practices sorghum in Typic Ustochrepts and cotton in Typic Chromusterts are highly suitable.

Vadivelu and Sys (1993) evaluated the soils of Ahmednagar district and concluded that the soils of the Sindudi, Torkewadi, Pargaon and Dargaon series are marginally suitable for growing sorghum on the basis of rating of limitation characteristics, but on the basis of the parametric method these soils are unsuitable for sorghum. Topography, depth and coarse fragments are the major limitations.

Bhaskar *et al.* (1993) reported that deeper soils of Saongi catchment. Nagpur, were highly suitable for sorghum, cotton and wheat and the shallower soils were marginally suitable or not suitable. The ranking of suitability followed the given sequence : Udic Ustochrepts > Typic Chromusterts > Typic Ustochrepts > Lithic Ustochrepts > Lithic Ustorthents. Gabour *et al.* (1994) carried out the land suitability classification of El-Katta farm. Giza Governorate, Egypt. The results showed that the Typic Quartzipsamments were very suitable for carrot, potatoes and groundnuts, moderately suitable for beans, sunflowers, watermelons, tomatoes and millets and

marginally suitable for wheat, maize, sorghum, onions, citrus, olives, figs, grapes and trifolium.

Tamgadge *et al.* (1999) classified the suitability of soils of Madhya Pradesh. They reported that only 12.22% of the total area is highly suitable followed by 29.51 and 9.73% moderately and marginally suitable for rice crop. For wheat, gram and cotton, the highly and moderately suitable land constitute about 12 and 5% each, respectively, but for soybean the suitability is higher (20.9% moderately suitable).

Sidhu *et al.* (1989) evaluated Vertisols and associated soils in Jalgoan district of Maharashtra for banana cultivation and found that soils of Dhupa series on the piedmont plain were suitable, while Chahardi, Bhod and Khadki series developed over piedmont plain were marginally suitable and the Bhovad series on table land were unsuitable.

Das *et al.* (1997) examined the soils of Nadia, Murshidabad and Birbhum district of West Bengal for their suitability for sugarcane cultivation and reported that soils occurring in comparatively lower landforms (Aeric Endoaquepts and Vertic Ochraqualfs) and in rugged topography (Lithic Ustochrepts and Rhodic Paleustalfs) were marginally suitable and currently not suitable, while soils occurring on nearly level to gently sloping landform (Typic Ustochrepts, Typic Haplustalfs and Typic Ustifluvents) were moderately to highly suitable.

Anil *et al.* (1998) evaluated soil site suitability of Wunna catchment near Nagpur for major agricultural crops. They reported that Entisols which are dominant on the hill top were marginally suitable for sorghum and unsuitable for pigeon pea, while Vertisols which are dominant on toe and concave slopes of basaltic transect were very suitable for cotton, sorghum and pigeon pea. Inceptisols occurring on the toe slopes of sandstone transect were marginally suitable for sorghum and unsuitable for pigeon pea.

Singh and Mishra (1996) attempted land suitability classification of soil in a top sequence of alluvial fan of the Gandak command area of Bihar and reported that Entisols were suitable for maize, wheat and rice whereas Inceptisols were suitable for wheat and maize and moderately suitable for rice. Alfisols are suitable for rice, and moderately suitable for both wheat and maize.

Bhaskar *et al.* (1993) reported that deeper soils of Saongi catchment, Nagpur, were highly suitable for sorghum, cotton and wheat while the shallower soils were marginally suitable or not. The ranking of suitability followed the given sequence : Udic Ustochrepts > Typic Chromusterts > Typic Ustochrepts > Lithic Ustochrepts > Lithic Ustorthents.

Tamgadge *et al.* (1986) observed that the yield obtained from different types of soils at subgroup levels varied considerably. For wheat maximum yield was recorded from Udic Chromusterts followed by Entic Chromusterts = Typic Chromusterts > Typic Ustorthents > Vertic Ustochrepts > Lithic Ustorthents. Hajare *et al.* (1990) reported that the higher yield realisation in Typic Chromusterts and Vertic Ustochrepts over Lithic Ustorthents can be attributed to sufficiently deep solum to provide higher soil volume for nutrient and water extraction than Lithic Ustorthents. Available water capacity as well as total volume of water in the solum in former soils is higher as compared to Lithic Ustorthents.

Chary *et al.* (1995) studied the soils at Shesnagar Nagpur district and reported that Typic Ustochrepts were marginally suitable for cotton, moderately suitable for sorghum, groundnut and pigeon pea. Typic Ustorthents were marginally suitable for these crops whereas Lithic Ustorthents were potentially suitable for cotton, groundnut and pigeon pea.

Sitanggang (2001) studied the suitability of the soil of Shikohpur, Gurgaoan district for cotton, wheat, sorghum, soybean and Pearl millet. He compared the site specific soil characteristics with site specific requirements of crops. He found that 60% of total area are suitable for cotton cultivation. Climate, light texture, low organic matter and plant available water content (PAWC) were limitation for cotton cultivation. 80% of total area were found suitable for wheat cultivation with slight limitation induced by slope, stoniness, PAWC and excessive drainage. The climate was also suitable for growing sorghum in this area. Light texture low CEC, PAWC and high pH were limiting factors, which induce 30% of the soils to unsuitable levels. 50% of the soils were marginally suitable and rest 20% of soil were most suitable. He also found that 50% of total area were potential suitable for soybean crops, and 20% have slight limitation. Limitation for soybean growth were slope, stoniness, PAWC, CEC and ESP. In general alluvium derived soils in this area were suitable to marginal

suitable for pearl millet. The main constraints for pearl millet cultivation were climate particularly high temperature in growing period, which induces moderate limitation.

2.3 Cropping sequence

Several cropping sequences depending on agroclimatic conditions have been tested in different parts of the country. The Indian literature on this aspect is reviews here. Pearl millet has generally been rotated with *rabi* crops namely wheat, barley, mustard, safflower and chickpea in area which receive a well distributed rainfall of more than 600 mm and having limited irrigation facilities. Under the aegis of the All India Dryland Agriculture Project, bajra-mustard (Agra and Rath Dhiansar), bajra-rapeseed and bajra-safflower (Varanasi) and bajra-wheat (Rakh Dhiansar) have been found profitable (AICDLA, 1982). It was proposed that profitable bajra-based sequences in India viz. bajra-wheat, bajra-barley, bajra-potato-wheat, bajra-taramira, bajra-chickpea, bajra-sugarbeet, bajra-wheat-cotton (2 years) and bajra-groundnut-wheat etc.

Experiments were conducted by Patil *et al.* (1985) in four cropping sequences viz. bajra-wheat, bajra-wheat-onion, onion-wheat and groundnut-wheat-onion and the results showed that higher net returns were obtained from groundnut-wheat-onion sequence followed by bajra-wheat-onion. The input-output ratio was highest (1.92) for groundnut-wheat-onion followed by bajra-wheat (1.89). In field trails on sandy loam soil at Morena, Madhya Pradesh, the following cropping sequences were assessed, pearl millet-wheat, sorghum-toria, greengram-toria-wheat, toria-wheat, blackgram-mustard and fallow-mustard. The highest yield was obtained from blackgram-mustard sequence while cost of cultivation was highest for sorghum-toria-wheat sequence and lowest for fallow-mustard (Tomar and Gautam, 1992).

Giri and Saran (1983) found bajra-mustard sequence as a profitable one under dryland conditions (average rainfall 630 mm) at IARI, New Delhi after a three-year experiment during 1980-1983. A field trial in 1987-92 was conducted at Palampur, Himachal Pradesh consisting of 6 maize-based cropping sequences viz. maize-wheat, maize-toria potato, maize-peas potato, maize+soybean-wheat, maize-toria-wheat and maize-toria-potato-frenchbean. The results indicated that crop sequences including potatoes resulted in higher gross and net returns/ha. Maize-toria-potato and

maize+soybean-wheat sequences were the most stable. All the sequences, increased soil available nitrogen and phosphorus (Thakur *et al.*, 1994).

In order to find out the appropriate crop sequence with high productivity to suit the needs of semi-arid areas of Rajasthan a field experiment was conducted for five years during 1990-95 at the Agriculture Research Farm, Durgapura, Jaipur with six crop sequences viz. pearl millet-mustard and pearl millet-gram. The study revealed that clusterbean-barley and clusterbean-wheat crop sequences could be successfully followed under semi-arid areas of Rajasthan for higher productivity in terms of total grain yield and monetary returns (Manohar *et al.*, 1998).

Sarkar and Gangwar (1998) conducted field experiment during 1993-96 at different location viz. Siruguppa, S.K. Nagar and Banswara under semi-arid ecosystems with 4-6 cropping systems at each location. They concluded that the promising cropping systems for arid and semi-arid conditions are maize-wheat/mustard-green gram and pearl millet-potato-groundnut. A field experiment with 6 cropping sequences was conducted at Oilseed Research Farm, Kanpur (UP) during 1991-93, the cropping sequence were fallow-toria-wheat, green gram-toria-wheat, black gram-toria-wheat, cowpea-toria-wheat, green gram-toria-wheat and maize-toria-wheat. An extra early maturing variety of toria 'Bhawani' was sown as catch crop in between *kharif* and *rabi* seasons. The inference drawn from the experiments was that highest gross return of Rs 52,482 per hectare and net return of Rs 33,549 per hectare was found in maize-toria-wheat crop sequence at optimum level of N per hectare. From the same experiment it was concluded that Bhawani variety of toria resulted in highest seed yields in black gram-toria-wheat (Verma and Dixit, 1998). Santhi *et al.* (2001) revealed the effect of pearl millet (*Pennisetum glaucum*) crop residues on the yield of succeeding crops in pearl millet-based crop sequences. A sole cropping treatment with pearl millet was conducted. The crops sown in sequence with pearl millet were soybean, green gram, sesame. Succeeding crops performed better in terms of grain yield in the presence than in the absence of pearl millet residues. Among the different cropping sequences, pearl millet-green gram recorded the highest benefit:cost ratio. The cropping sequences were more productive than sole cropping of pearl millet.

A long term study on relative efficiency of legume-cereal (cowpea-wheat, groundnut-wheat, urdbean-wheat), cereal-legume (pearl millet-gram, maize-gram,

maize-cowpea) and cereal-cereal (pearlmillet-wheat, maize-wheat, maize-ragi) crop rotations were undertaken at varying fertility levels under All India Coordinated Agronomic Project on Cropping Systems Research with the objective to compare the productivity and economics of these rotations besides monitoring the soil properties. Six centres representing Hisar and Siruguppa under arid ecosystem and Junagarh, Rahuji, Kathalagere and Banswara from semi-arid. The analysis of five years data (1990-1991 to 1994-95) indicated that the highest productivity was observed from cereal-cereal sequence. However, as revealed from economic analysis, the cereal-cereal sequences were found to be beneficial only at Hisar and Siruguppa, while legume-cereal were markedly remunerative at all other locations except Junagarh (Shukla *et al.*, 2002).

2.4 Crop Simulation Model

This chapter reviews the work done nationally and internationally in the field of crop yield estimation/forecasting using methods of crop modelling and their use in a GIS (Geographic Information System) environment for regional applications. In this study, the definitions given by Bouman (1995) of yield forecasting and yield prediction are followed. Yield forecasting is defined as the estimation in advance what the yield of a crop will be at the end of the growing period, whereas yield prediction is the estimation of actually realized yields after harvest.

Crop simulation models are the principal tools needed to bring agronomic sciences into the information age (Ritchie, 1991). "Systems" approach successfully used by engineers to simulate physical systems provided an early anticipation that biophysical systems could also be simulated. According to systems approach, a system is a limited part of reality that contains interrelated elements. The totality of relations within a *system* is known as the 'system structure'. A *model* is a simplified representation of a system. The design of such models and the study of the model behaviour in relation to that of system is called simulation (Leffelaar, 1993). When the model includes change in system behaviour with time it is called dynamic simulation. A crop simulation model is simple representation of a crop and is explanatory in nature. It is used to study crop growth and to compute growth responses to the environment.

De Wit (1982) depending on the approach to model development categorized all models in two broad classes, namely, (i) descriptive and (ii) explanatory or mechanistic. He discussed the difference between descriptive models, which correlate observations, and explanatory models, which are created to explain a system. To create an explanatory model, the system is analyzed and its processes and mechanisms are quantified separately. The model is built by integrating these descriptions for the entire system. An explanatory crop growth model contains description of distinct processes such as photosynthesis, respiration, dry matter partitioning, leaf area expansion and tiller induction (Penning de Vries *et al.*, 1989). Further explanatory models have been divided into three types: preliminary, comprehensive and summary.

Most of the mechanistic dynamic crop simulation models are based on the "State-Variable Approach" (de Wit, 1982). These models are based on the assumption that the state of each system at any moment can be quantified, and that changes in the state can be described by mathematical equations. In such models, state, rate and driving variables are distinguished. State variables are quantities like biomass, amount of nitrogen in soil, plant, soil water content, which can be measured when time stands still. Driving variables, or forcing functions, characterize the effect of the environment on the system at its boundaries, and their values must be monitored continuously like meteorological variables. Each state variable is associated with rate variables that characterize their rate of change at a certain instant as a result of specific processes. These variables represent flow of material or biomass between state variables. Their value depends on the state and driving variables according to rules that are based on knowledge of the physical, chemical and biological processes that take place, and not on a statistical analysis of behaviour of the system that is being studied.

Dynamic crop simulation modelling was started in early 1960s when models were developed to estimate light interception and photosynthesis in crop canopies (Loomis and Williams, 1963, Duncan *et al.*, 1967). Later, the advent of computers and tremendous advances in equipment for field experimentation initiated modelling of many processes/factors that influence crop yield, such as weather, soils, crop genetics, plant physiology, and pest damage. The complexity of crop models increased as various details of plant, soil and environmental factors that alter plant growth were linked logically and hierarchically within the boundaries of system as defined by the

model objectives (Sinclair and Seligman, 1996). Several crop models of varying complexity now exist for major crops and a few are listed in Table 1. The plant processes typically simulated by various models are: photosynthesis, respiration, growth, transpiration, phenology, dry matter partitioning, senescence, soil water balance and plant and soil nitrogen balance (Whisler *et al.*, 1986). In some of the cases even pest simulation models are interlinked with crop models to simulate the effect of pest damage on crop growth and yield (Teng *et al.*, 1998).

Table 1. A list of some published simulation models for various crops

CROP	MODEL NAME	REFERENCE
Alfalfa	ALSIM	Fick (1981)
Barley	CERES-Barley	Ritchie <i>et al.</i> (1989)
Chickpea	CHIKPGRO Unnamed	Singh and Virmani (1996) Soltani <i>et al.</i> (1999)
Cotton	COTCO2 COTCROP COTTAM ELCOMOD GOSSYM KUTIN	Wall <i>et al.</i> (1994) Brown <i>et al.</i> (1985) Jackson <i>et al.</i> (1988) Marani and Baker (1981) Baker <i>et al.</i> (1983) Mutsaers (1984)
Dry bean	BEANGRO	Hoogenboom <i>et al.</i> (1994)
Maize	CERES-Maize CORNF CUPID GAPS	Jones and Kiniry (1986) Stapper and Arkin (1980) Norman and Cambell (1983) Buttler (1989)
Peanut	PNUTGRO	Boote <i>et al.</i> (1989)
Pearl Millet	CERES-Millet RESCAP	Ritchie and Alagarswamy (1989) Monteith <i>et al.</i> (1989)
Potato	POTATO SIMPOTATO Unnamed	Ng and Loomis (1984) Hodges <i>et al.</i> (1992) Fishman <i>et al.</i> (1985)

Rapeseed	BRASSICA Unnamed	Rao (1992) Gabrielle <i>et al.</i> (1998)
Rice	CERES-Rice IRRIMOD ORYZA-1 ORYZA-W RICEMOD SIMRIW	Ritchie <i>et al.</i> (1986) Angus and Zandstra (1980) Kropff <i>et al.</i> (1994) Wopereis <i>et al.</i> (1996) McMennamy and O'Toole (1983) Horie (1987)
Sorghum	CERES-Sorghum SORGF SORKAM RESCAP	Alagarwamy and Ritchie (1989) Arkin <i>et al.</i> (1976) Rosenthal <i>et al.</i> (1989) Monteith <i>et al.</i> (1989)
Soybean	GLYCIM SOYGRO SOYMOD	Acocki <i>et al.</i> (1983) Wilkerson <i>et al.</i> (1983) Curry <i>et al.</i> (1975)
Sugarcane	AUSCANE	Jones <i>et al.</i> (1989)
Wheat	ARCWHEAT1 ARCWHEAT2 CERES-Wheat MODWht3 ShootGro 2.0 SIRIUS SWHEAT WINTER WHEAT WTGROWS Unnamed Unnamed	Weir <i>et al.</i> (1984) Porter (1993) Ritchie <i>et al.</i> (1985) Rickman <i>et al.</i> (1996) Wilhelm <i>et al.</i> (1993) Jamieson <i>et al.</i> (1997) Van Keulen and Seligman (1987) Baker <i>et al.</i> (1985) Aggarwal <i>et al.</i> (1994) Sinclair and Amir (1992) Campbell and Diaz (1988)
General Models	CropSyst BACROS EPIC LINTUL MACROS SUCROS WOFOST WOFOST 6.0	Stockle <i>et al.</i> (1991) de Wit (1978) Williams <i>et al.</i> (1989) Spitters (1987) Penning de Vries <i>et al.</i> (1989) van Keulen <i>et al.</i> (1982) van Diepen <i>et al.</i> (1989) Hijmans <i>et al.</i> (1994)

Boote *et al.* (1996) has classified the uses of crop simulation into three primary categories: (i) for research knowledge synthesis, (ii) for crop system decision management, and (iii) for policy analysis. The foremost use of crop models have been in synthesizing research understanding by integrating up from a reductionist research process in the field of discipline and by integrating knowledge across disciplines (Whisler *et al.*, 1986). Crop models have been used to assist in genetic improvement of crops by (i) determining optimal genetic traits of plants for specific environment (Landivar *et al.*, 1983; Whisler *et al.*, 1986) and (ii) by predicting the performance of new cultivars for specific environments thus reducing the number of locations/seasons of multilocation breeding trials (Hunt, 1993; Palaniswamy *et al.*, 1993). Models are used for estimating climatic yield potential of crop and to analyse yield gap due to weather and other factors (Aggarwal and Kalra, 1994a). Many researchers have shown that models could be used for crop system management to find out optimum sowing date, row spacing, planting density, irrigation and fertilizer applications for different soil types (Aggarwal and Kalra, 1994a; Egli and Bruening, 1992, Bowen and Baethgen, 1998; Rao and Rees, 1992; MacRobert and Savage, 1998 and Chopra and Das, 1994). Using simulation models, effects of climate change and climatic variability on crop growth and yield have also been predicted (Lal *et al.*, 1998; Parry, 1991). Models have also been used in best management decisions to reduce fertilizer and pesticide leaching and soil erosion (Williams *et al.*, 1984). Some crop yield models have also been applied for large area crop yield forecasting (Horie *et al.*, 1992). Based on simulation models, decision support systems have been developed like DSSAT (Decision Support System for Agrotechnology Transfer) which is based on IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) crop growth models and has linkages to a GIS (Jones, 1993).

DSSAT

It is a decision support system for agrotechnology transfer which was a product of IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer. Project (1982-1993). It has four versions. Its first version 2.1 was introduced in 1989, second version 3.0 was released in 1994, third version 3.5 was released in 1998 and fourth version 4.0 was released in 2004.

It is a software application program that includes crop simulation models for more than 25 crops data base management programs for soils, weather, and crop management and experimental data and utilities and application programs. The crop simulation models simulate growth, development and yield and the soil and plant water, nitrogen and carbon balances. DSSAT and its crop simulation models have been used for a wide range of applications, including on farm and precision management to regional impact assessment of the climate change and variability. The data modules of system includes Background about place and people, details information about experiment, genotype crop-co-efficients, weather data on T_{\max} , T_{\min} , rainfall and radiation, soil file characterising soil properties, information on pest dynamics and information on input costs and returns. It has simulation models of more than 25 crops, which includes Ceres family of crops like wheat, maize, barley, sorghum and millet, Cropgro family of crops for legume crops, soybean, peanut, dry bean and chickpea, Root-crop models like potato and cassava. Various others like sugarcane, tomato, sunflower and pastures. It has applied in seasonal, sequential and spatial analysis.

2.4.1 Crop Simulation Modelling for Yield Estimation/Prediction

One of the greatest potential applications of crop modelling is yield estimation/forecasting. Timely and accurate crop yield prediction and forecasting on farm, regional, national and international scales is increasingly becoming important in both developing and developed countries (Bouman *et al.*, 1997). Singhi and Pariyar (1995) in their review of different methodologies of yield forecasting indicated the need for the introduction of new methods such as applying crop simulation models. Boote *et al.* (1996) encouraged the application of crop models to large-area yield forecasting.

2.4.2 Yield Prediction Components of Crop Models

Mechanistic simulation models use daily weather data, latitude, sowing date, nitrogen and irrigation applications and soil characteristics to predict development and growth and growth of crops, leading to a prediction of final economic yield. Ritchie (1991) has discussed in detail the specifications of the ideal simulation model for crop yield prediction. The minimum details needed in models include simulation of the duration of crop growth, biomass growth rate, the fraction of total biomass partitioned to the economic yield components, and a soil water balance. The ideal model should

evaluate phenophasic development of plants for details of sensitive growth stages, total growth duration, plant morphological development for evaluation of leaf number, leaf area, biomass growth rate, and economic yield components. The ideal crop model should also be linkable to pest models and other important factors related to management of crop productivity under risky environments. Penning de Vries and Spitters (1991) concluded that the accuracy of yield simulation depends on the adequacy of model structure, precision of parameters, and accuracy of environmental data. They argued that calibration could help improve the accuracy of the model significantly, if performed skillfully.

From crop simulation modelling point of view De Wit identified four levels of plant production based on growth limiting factors (Penning de Vries and van Laar, 1982). In order of decreasing crop yield, production levels are:

- (i) **Production Level 1:** This is an ideal situation in which crop does not suffer from any shortage of water and nutrients during the entire growing season. The crop growth and development depends on the current state of crop and current weather, particularly, radiation and temperature.
- (ii) **Production Level 2:** The growth rate of the crop is limited by the availability of water for at least part of the growing season. This situation is common in semi-arid regions and regions where the rainfall is inadequate and/or poorly distributed.
- (iii) **Production Level 3:** The growth rate of the crop is restricted by nitrogen shortage for at least part of the growing season and by water shortage or poor weather for rest of the season. This condition is very frequent in the agricultural systems all over the world.
- (iv) **Production Level 4:** Low phosphorus and other mineral nutrients in the soil restrict crop growth during the growing season. This situation occurs in heavily exploited areas with low fertilizer usage

2.4.3 Crop Simulation Models and Geographic Information System

Crop simulation models predict crop yield, plant growth and development, and nutrients and moisture dynamics based upon site specific characteristics such as weather, soil physical and chemical properties (Penning de Vries *et al.*, 1989). Most

process-based models have examined temporal variation using point data from a specific site, and model outputs thus are site specific. The scope of applicability of these simulation models can be extended to much broader scales for regional planning and policy analysis by combining their capabilities with a Geographic Information System (GIS) (Lal *et al.*, 1993). Several researchers have demonstrated or discussed the strengths of this concept for agricultural management decisions and planning at various scales (Curry *et al.*, 1990; Petersen *et al.*, 1995; Panesar and Gupta, 1996).

Burrough and McDonnell (1998) has defined GIS as a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes. The three major components of GIS are (i) computer hardware, (ii) computer software and (iii) digital geographic data. The advancements in GIS are directly related to the strides in the advancement of computer hardware and software technology. The information stored within a GIS can be divided into two distinct categories (Petersen *et al.*, 1995). The first category includes spatially referenced information that can be represented by points, lines, and polygons. This information is referenced to a geographic coordinate system and is usually stored in either raster (grid-cell) or vector (arc-node) digital format. The second category of information stored in a GIS is attribute data or information describing the characteristics of the spatial feature.

2.4.3.1 Interfacing Models and GIS

Besides conceptual considerations, interfacing of GIS and crop models has technological basis as both are implemented in the form of software on computer hardware. Hartkamp *et al.* (1999) has identified two basic issues in interfacing GIS with models (i) the level at which the software systems are combined and (ii) the logical structure of the interface. The first issue is essentially a problem of software development and management. Depending upon level, in literature three types of interfaces have been identified (i) linking, (ii) combining, and (iii) integrating (Tilley *et al.*, 1996; Hartkamp *et al.*, 1999). The second issue includes whether the model simulates all polygons or grid cells and whether dynamic attributes of one map unit affect attributes of other units like in water runoff and soil erosion models.

Simple linkage use GIS to display simulation results, usually with some form of spatial interpolation. More complex linkages use maps or combination of these to process the data to produce a data base containing inputs for a model. Linking requires little software modification and generally simple transfer of files in ASCII or a common binary file format is sufficient. This strategy has limitation that user cannot take full advantage of the functional capabilities of GIS. Example of linking is WOFOST (World Food Studies) model to ARC/INFO (van Laanen *et al.*, 1992).

Combining strategy also involves processing data in GIS and displaying model result, but the model is configured with interactive tools of the GIS, and data are exchanged automatically (Burrough, 1996). Use is made of macro languages of GIS, user callable routines or other programming languages (Tim, 1996). This approach usually requires more complex programming and data management than do simple linkages. Example of combining is AEGIS (Agricultural and Environmental GIS) with ArcView (Engel *et al.*, 1997).

Integration implies incorporating one system into the other. Either a model is embedded in a GIS, or a simple GIS system is included in a modelling system. This strategy usually involves automatic use of relational databses, expert systems, and statistical packages. Full integration implies system developed within the same or similar data structures. File transfer and format conversions are avoided or automated and thus are invisible to the user. A considerable programming effort is needed to develop these software systems. More often, integrated systems make use of simplified models (Tim, 1996). Example of integration is embedding TOPMODEL (Topographic Model) into SPANS (Stuart and Stocks, 1993).

Tim (1996) has used the terms loose coupling, close coupling and tight coupling for linking, combining and integration strategies, respectively. According to him a continuum exist from loose coupling to tight coupling of the software components. The choice of interfacing strategy depends upon the research problem, the application objectives, and the investment user is able to make.

Han *et al.* (1995) has identified two categories of simulation models which can be linked with a GIS: distributed parameter models and non distributed parameter models. A distributed paramter model reads model input parameters for all subareas

of a region before the model can be run. Thus, data exchange between the GIS and model occurs in one cycle. Many hydrological models, such as AGNPS (Agricultural Non Point Source) model (Young *et al.*, 1989), are distributed parameter models. However, the crop simulation models are normally nondistributed parameter models, which means that the models have to be run for each individual subarea in a region. The GIS database may need to be updated between model runs (time steps). The dynamic data exchange between the GIS and models requires that both the GIS and models be operated in batch mode and that the simulation model be stopped and restarted with new/adjusted input values after each model run (time step). Considerable amounts of computer memory and storage are required.

2.4.3.2. GIS Applications

The applications of interfaces of GIS and modelling have grown from primarily hydrological applications in the mid-80s to the current wide range of applications (Hartkamp *et al.*, 1999) such as spatial yield calculation (regional and global), precision farming, climate change studies, and agro-ecological zonation. The availability of many commercial and public domain GIS software has helped in developing large number of such applications. The name of few commonly available GIS software which run on a variety of operating systems are ARC/INFO (ESRI), ArcView (ESRI), IDRISI (Clark Lab.), MapInfo, SPANS (Tydac) GRASS (US Military), MicroStation (Bentley), TNTmips (Microlmages), Map2000 (Intergraph) and ILWIS (ITC). A list of model and GIS combinations and used of models for site specific studies is shown in Table 2.

Under the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project a computer software package called the Decision Support System for Agrotechnology Transfer (DSSAT) was developed which integrated 11 crop simulation models (CERES cereal, CROPGRO legume and other models) with a standardized input and output (Jones, 1993). Calixte *et al.* (1992) developed a regional agricultural decision support system, known as Agricultural and Environmental Geographic information System (AEGIS) that uses that DSSAT capabilities within ARC/INFO Gis for regional planning and productivity analysis. AEGIS allows the user to select various combinations of crop management practices over space, evaluate potential crop production, soil loss and other factors at regional scale, and build a land

Table 2. Model/Geographic Information System (GIS) combinations and uses of models for site-specific studies

Citation	System name, Model with GIS name, if used	Scale used
Berti <i>et al.</i> , 1986	n/a : CERES-Maize VI.0, No. GIS	Soil map unit, 1 : 1200
Sadler <i>et al.</i> , 1988	n/a: CERES-Maize, CERES-Wheat, SORKAM, no GIS	Soil map unit, 1: 1200
Ritchie and Amato, 1990	n/a: CERES-Maize, no GIS	Classed by plant extractable soil water
Calixte <i>et al.</i> , 1992	AEGIOS VI.0; DSSAT V2.1 with PC Arc/Info, dBASEIV	Region
Papajorgji <i>et al.</i> , 1993a	AEGISD_2; more generic version	Region
Lal <i>et al.</i> , 1993	AEGIS: DSSAT-BEANGRO VI.01 with PC Arc/Info	Region, 1:20,000
Hoogenboom <i>et al.</i> , 1993	IAEGIS: DSSAT V2.1 with PC Arc/Info V3.41	Soil map unit, ~ 0.5 ha min
Papajorgji <i>et al.</i> , 1993b	AEGIS_2.5:DSSAT V2.5 with PC Arc/Info	Farm
Wei <i>et al.</i> , 1994	IAEGIS:DSSAT V2.1 with Imox ArcInfo V6.1	Field
Papajorgji <i>et al.</i> , 1994	AEGIS+:DSSAT V3.0 with Unix Arc/Info V6.1	Field, map unit
Munster <i>et al.</i> , 1994	n/a: SOYGRO, no GIS	Soil map unit, 1:20000
deJong and Reynolds, 1995	n/a: LEACHM with IL WIS V1.3 (objective was atrazine loading)	Watershed
McCauley <i>et al.</i> , 1995	Unnamed: GOSSYM/COMAX with GRASS	Grid in field
Engel <i>et al.</i> , 1995	AEGIS/WIN: DSSAT with ArcView 2.0	field
Verhagen <i>et al.</i> , 1995	n/a: SUCROS87, no GIS	50-m grid
Verhagen <i>et al.</i> , 1995	n/a: WAVE, GIS not stated	50-m grid
Han <i>et al.</i> , 1995	Unnamed : SIMPOTATO with PC Arc/Info	12.2-m grid in 50-ha center pivot
Verhagen and Bouma, 1997	n/a: WAVE, GIS not stated	50-m grid

use and management plan for the region. A menu-driven interface permits the user to perform different processes in AEGIS without having to know the internal structure of the databases and GIS operating procedures. Lal *et al.* (1993) has analyzed the regional productivity of three sites in Puerto Rico using DSSAT-BEANGRO, the dry bean model and AEGIS. Engel *et al.* (1997) modified the AEGIS into AEGIS/WIN (AEGIS for Windows) which links the DSSAT (Version 3) with the geographical mapping tool ArcView-2 which is easy to use and low cost system available under Microsoft Windows. The AEGIS/WIN has been written in Avenue, an object-oriented macro scripting language. The system was applied to study the spacial yield variability of peanut for a research farm in Georgia. AEGIS/WIN was shown to be an effective tool for the spatial application of crop simulation model and for the analysis and visualization of simulated outputs.

Hoogenboom *et al.*, 1993. Counted our experiment whose crop simulation models for soybean, peanut-maize and wheat crops were used to study the spatial relationships between final crop yield, water use weather conditions and soil characteris the crop simulation models SOYGRD, PNUTGRO CERES-maize and CERES-wheat were linked with the Geographic information system PE-ARC/INFO. An interface was developed in PE-ARC/INFO to allow the user to select farms or fields and various crop management option. This information was exported from the GIS and used as input for the crop models the GIS crop model system was used to simulate crop growth and development for polygen or field with different soil characteristics. The crop models predicted yield and other related crop input and output-variables.

Thornton *et al.* (1997a) developed spatial analysis software for the most recent release of the DSSAT, Version 3.1. This software standardized the links between crop models and GIS software and this allowed developers to make use of whatever GIS software is most suitable for a particular purpose, while ensuring that basic links to the DSSAT system and the crop models are the same. The spatial analysis software has two modules: (i) a geostatistical module to interpolate maps and produce probability surfaces from a network of data points and (ii) a utility that calculates agronomic and economic output statistics from model simulations and maps the results as polygons.

Han *et al.* (1995) developed an interface between PC ARC/INFO GIS and SIMPOTATO simulation model to study potato yield and N leaching distribution

for site-specific crop management (precision farming) in a 50ha field. The GIS input layers, corresponding to important distributed input parameters for the model, were irrigated water/N layer, soil texture layers and initial soil N layers. For each unique subarea stored in the GIS database, the interface program extracts the attribute codes of that subarea from the GIS database, converts the attribute codes to the input parameters of the SIMPOTATO and sends them to the mode. After running the mode, the interface program retrieves the output data (potato yield and N leaching), converts them to the attribute codes and stores the output data in the GIS database.

Easterling *et al.* (1998) studied the effect of spatial aggregation of climate and soil data for use in site specific simulation models to estimate regional yields. They started with a scale of $2.8^0 \times 2.8^0$ and progressively disaggregated the climate and soils data to finer scales. Using EPIC simulation mode., observed crop yields of wheat and maize for the period 1984-1992 were compared with observed maize and wheat yield was greatly improved when climate data was disaggregated to approximately $1^0 \times 1^0$ resolution and further no improvement in agreement was observed at finer resolutions. Disaggregation of soil data gave no additional improvement beyond that of the disaggregation of climate data.

Aggarwal (1993) demonstrated the use of crop simulation model and GIS for agro-ecological zoning to characterize wheat environments of India. The model WTGROWS was used to estimate potential and water-limited wheat yield for 219 weather locations spread all over the country. Yield for each of the 434 district was derived by interpolation. The district boundaries (as polygons) and model input parameters of soil, weather stations and agroecological regions were stored in ARC/INFO GIS. The model outputs of potential and rainfed productivity were stored in GIS as polygon attribute data. Based on potential and rainfed productivity, the districts were classified into 10 iso-yield zones and represented as map using GIS.

Aggarwal *et al.* (1998) studied the agricultural land use option for the state of Haryana using symphonic use of expert knowledge, simulation modelling, GIS and optimization techniques. The study area was divided into agro-ecological land units by overlaying maps of soil, soil organic carbon and climatic normal rainfall in raster GIS IDRISI. The original soil mapping units based on 19 soil properties were reclassified based on soil texture, level and extent of salinity and sodicity, slope

water depth. The organic carbon and normal rainfall maps were generated by square interpolation of observed data points followed by segmentation.

Bacsi *et al.* (1991) studied the changes in wheat and maize production in Hungary as a result of future climate change. The GIS overlaying techniques were used for integration of climate, soil and crop production features maps to produce agro-climatic Zones of the country. Modified CERES crop models were run for each agro-climatic zone to simulate crop response to the climatic change derived from number of General Circulation Models (GCMs). Carter and Saarikko (1996) estimated regional crop potential in Finland under future climatic change using a geographical analysis system. The system comprised of a database and a wheat crop model which were combined in IDRISI GIS. The database included information on administrative boundaries, physiographic features, climate soils, land cover, agricultural land use and crop production at a resolution of 10×10 km regular grid across Finland. Simple growth model was employed to compute regional potential productivity with present-day climate and future climate scenario.

Lal *et al.* (1993) analyzed the regional productivity for three sites in western Puerto Rico using the DSSAT BENGROV1.01, the dry bean model and AEGIS. The analysis indicated that a considerable soil and weather variability exists within the three study sites. The optimum management factors such as cultivar selection, planting date irrigation strategy would significantly differ the productivity from one site to another.

An interface program between Arc-View GIS (grided surfaces) and IBSNT crop models (sequence simulations) was developed by Collis and Corbett (1999), to run crop rotations over a number of year. Climate profile files were obtained using climate surfaces and daily weather files were generated from these climate files. Soil profiles were set up based on soil taxonomy group. A simulation layer representing weather, soil and management information was developed. The model was then run for all the combinations of the simulation layer. Model output was processed statistically and variables were mapped in the GIS.

Satya *et al.* developed a spatial model "spatial-EPIC" in 1998, based on a simulation model EPIC. They proposed a method to generate fine resolution data from coarse resolution data, which are usually available at regional and national level. T

evaluated the impact of agricultural practices changes over temporal scale. Validation of spatial EPIC was conducted at different spatial scale i.e., national scale and regional scale in India. Results showed that at both resolution level crop yield varied significantly as a function of seasonal climatic variations, soil water retention characteristics and applied crop management strategies.

Chandra *et al.* (2002) linked Agro-informatics with simulation models for effective agro-advisory. Different databases like soil, sowing time and inputs, pests, pedigree management, socio economic aspects etc. were taken and linked with simulation technique. The models were used to determine potential yield of crops and yield gaps, assess impact of climate change on crop production and yield losses due to pests. They concluded that the linkage of agro informatics database with simulation modelling would be useful in assessing crop production on regional scale as well as devising site specific decision support system tools which would facilitate effective agro-advisory.

3. MATERIALS AND METHODS

The present investigation was carried out in the Shikohpur watershed of Gurgaon district, Haryana. A brief description of the materials used and methods followed are given below.

3.1 Study area - Shikohpur watershed

3.1.1 Location

The Shikohpur village is located at about 15 km from Gurgaon district of Haryana state on the Gurgaon Jaipur road (NH 8). It lies between 28°22'13" N latitude and 76°59'15" E longitude. The village is surrounded by Khidiki Danla in the north, Hasanpur and Sakatpur in the east and Sikandarpur in the west (Fig. 1).

3.1.2 Physiography

Two major physiographic units have been identified in the area viz. Aravalli range and the Piedmont ridge. The village is situated at the foothills of Aravalli range. The hills are almost barren devoid of soil and supports scanty vegetation. The Piedmont range is further subdivided into smaller units like piedmont plain modified by aeolian deposits. Aeolian deposits are common along the foothills as the Aravalli range act as a barrier to sand storm from the adjoining state of Rajasthan. Fluvio-Aeolian sediments are the colluvial washes from the Aravali ranges modified by the deposits. Small 'nalas' originate from the hill range and pass through the village area. The area used to be drained through these seasonal nalas through the large amount of run-off from the hill range and higher sloppes accelerating soil erosion in the foot slopes often leading to the formation of deep gullies.

3.1.3 Climate

The climate of the area is semi arid sub-tropical. The mean annual precipitation is about 450 mm around 90% of which is received during June to September months. Winter rainfall is very little and insufficient to meet the water requirement of *rabi* crops. The area is very hot in the summer with maximum temperature as high as 43.3°C during May and cold in the winter with lowest temperature of 3.0°C during January.

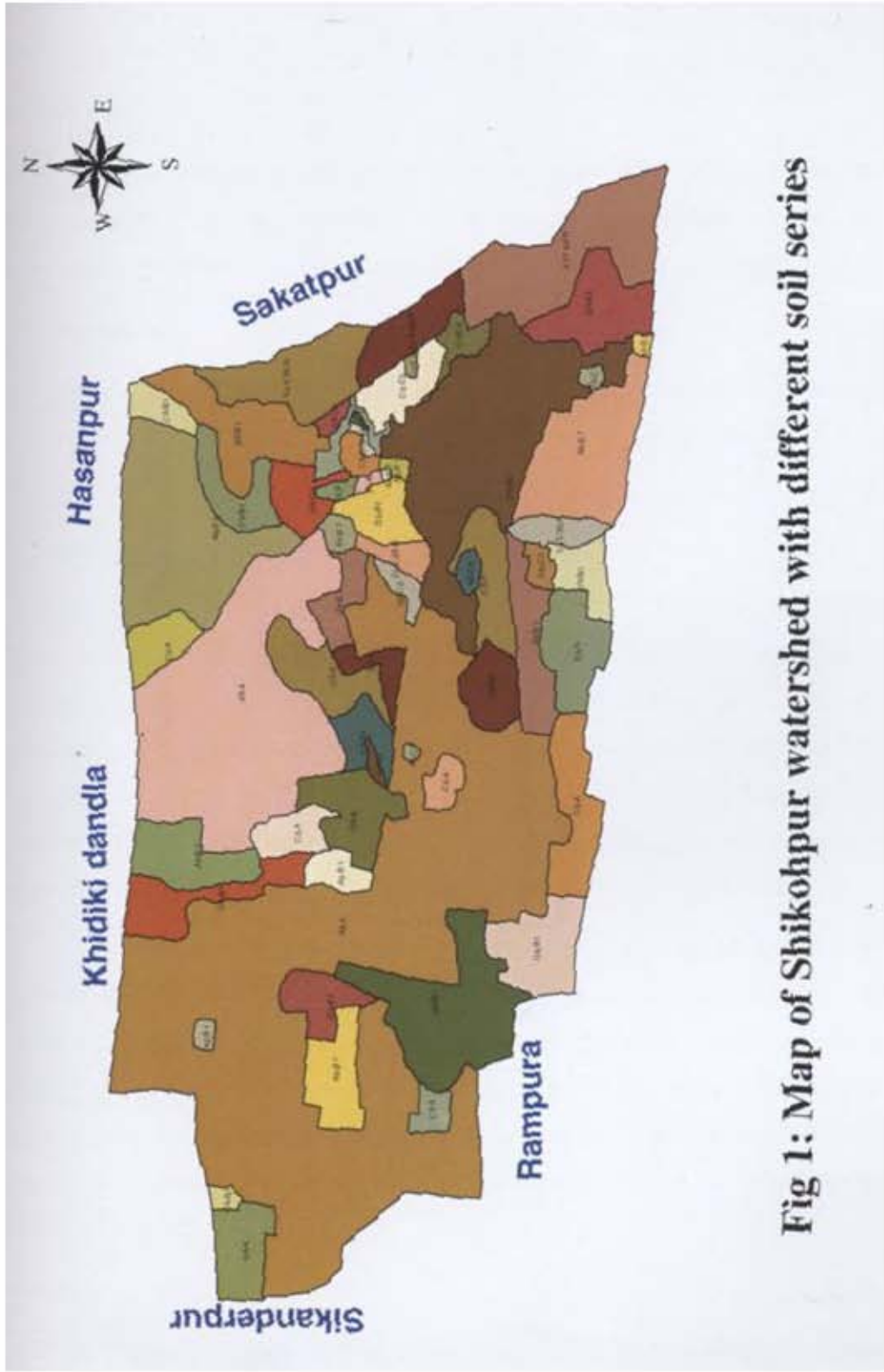


Fig 1: Map of Shikohpur watershed with different soil series

The mean annual temperature is 24.4°C. The mean maximum relative humidity is 84% in the month of July and the mean minimum relative humidity is 36.8% in the month of April.

3.1.4 Geology

Lithology of Aravali range shows a combination of different rocks like quartzite, sandstone and mica schist. The piedmont range is developed on alluvial deposits and substances modified by aeolian action especially near hills.

3.1.5 Vegetation

The vegetation in the village is thin and comprises of dry deciduous trees viz. babool, neem, dhak, khair, shisham, pepal and shrubs and grasses like Sharkeri mung doob, tinthins etc.

3.1.6 Land use and agriculture

Out of the total geographical area of 934 ha about 728 ha is under cultivation and the remaining 200 ha is occupied by habitats, hills (Aravallis), ponds etc. The earlier records show that at one time these hills were well covered by dense forests but they are now devoid of vegetation because the government of Haryana had then leased out the land for stone quarrying. Further, evergrowing and indiscriminate exploitation of vegetation cover have also added to the land degradation. Individual farm houses, stone crushers etc. have occupied some area of the village.

In *kharif* season, pearl millet is the main crop grown mixed with grass from chola and mung. This is followed by wheat, chickpea and mustard in *rabi*. Farmers are going for flower and vegetables in some areas for economic as well as commercial purposes. Tubewell is the main source of irrigation. There are about 450 tubewells which are deep bore because of very low ground water table (beyond 60-70 feet). Nearly 90 per cent of the farmers in the village use sprinkler irrigation system (NBSS&LUP, 2002).

3.1.7 Soils

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) Regional Centre, Delhi had conducted a detailed survey to map the soils of Shikohpur

village (Anonymous, 2000). Based on the investigations, they have prepared a soil map of the scale of 1 : 4000 comprising of six soil series and 16 soil mapping units. Out of 6 soil series only 4 soil series were cultivable. The percent sand, silt and clay of all the 4 soil series are shown in Table 3 (Sandau, 2001). The soil can be broadly classified under the orders Entisols and Inceptisols sub-orders orthents, Psamments and ustepts. Great groups are Ustorthents and Ustipsamments and family is Typic Ustipsamments and Typic Haplustepts.

3.1.8 Socio-economic aspects

The total population of the village is about 7635 of which about 3925 are male and about 3710 are female. About 29% population is literate who passed high school and above. The total number of household is 1035. Farmers are mostly marginal (69%) followed by small (25%) and big (6%) respectively. Regarding livestock, the number of animals is 2362 (Sharma *et al.*, 2005). The farmers attend regularly the training programmes, field level demonstrations etc. organised by the Krishi Vigyan Kendra of IARI. Farmers are adopting new technologies to cultivate commercial/cash crops but they want more incentives for the inputs like seeds, fertilizers etc.

3.2 Selection of representative sites for field and laboratory investigations

The study area is divided in to 26 grids of equal size (865 m x 865 m). Soil and plant samples were collected from each grid. Observations at different phenological stages of crops were taken from each grid during the year 2004-05..

3.3 Methodology

3.3.1 Selection of representative sites

The study area was digitized using Arc-view GIS software. The latitude, longitude and elevation of each location was determined with the help of GPS. The map of study area was geo-referenced by Arc view GIS software. The geo-referenced area was divided into 26 grids of equal size (size 865 m x 865 m) (Fig 2).

3.3.2 Field observations

Observations were collected from each grid on the following aspects :

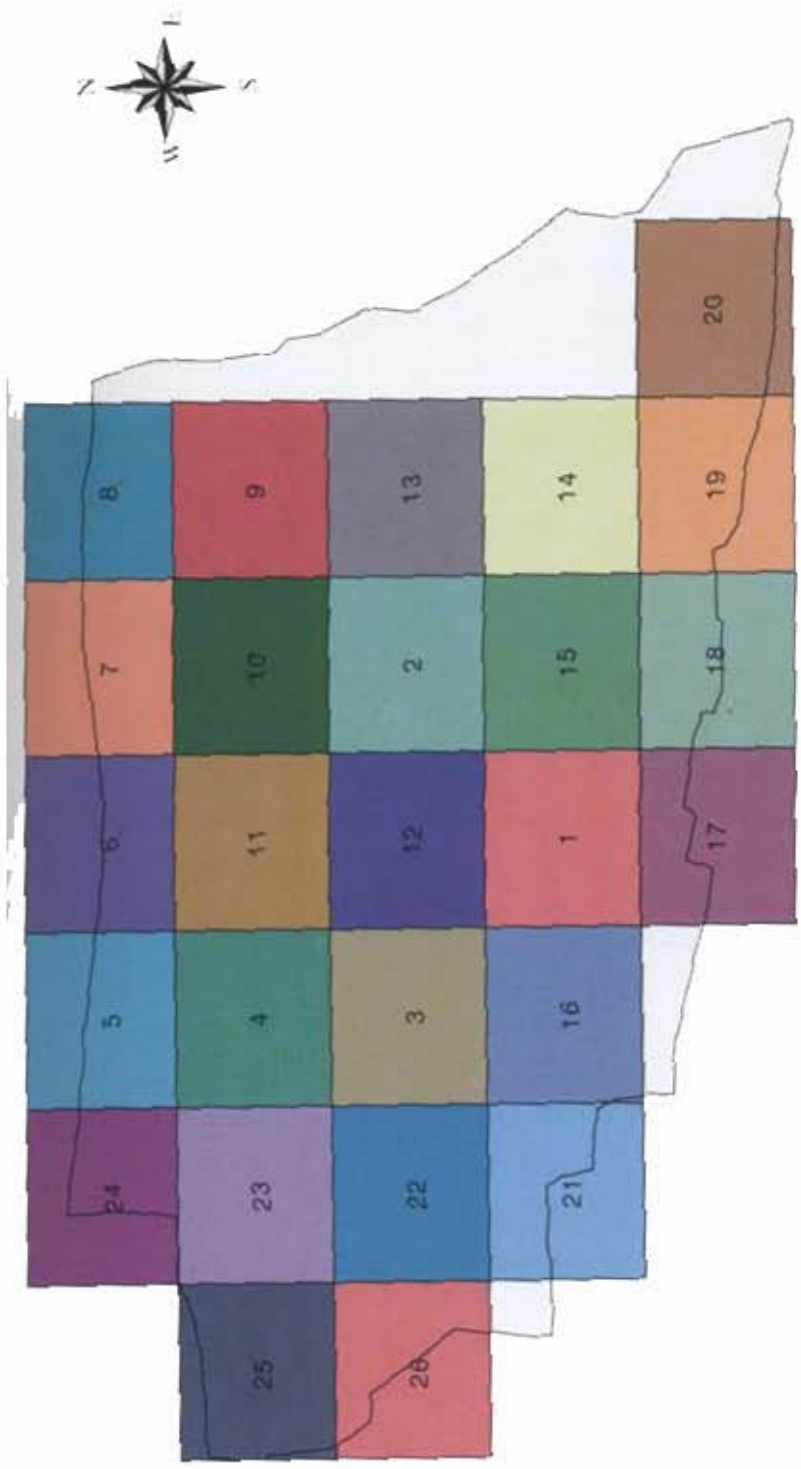


Fig 2: Grid ID map of Sikohpur watershed

Table 3. Physico-chemical characteristics of the soils of Shikohpur

Site No.	Soil Series	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	pH _{1:2} density (Mg/m ³)	EC _{1:2} (dSm ⁻¹)	Org. C (gKg ⁻¹)	ESP
1.	A	0-15	85.1	2.7	12.2	sl	7.32	0.7	1.0	3.2
		15-30	84.4	4.2	11.4	sl	7.42	0.7	1.0	3.4
		30-60	84.9	2.5	12.6	sl	7.35	0.7	1.0	3.2
		60-90	80.5	9.0	10.5	sl	7.44	0.6	0.9	3.2
		Av.	83.73	4.61	11.66		7.38	0.68	0.98	3.25
		SD	2.18	3.01	0.90		0.06	0.05	0.10	10.36
		% cv	2.60	65.34	7.75		0.77	7.41	5.13	3.08
2.	B	0-15	83.7	4.0	12.3	sl	7.62	0.6	1.0	4.5
		15-30	84.6	3.8	11.6	sl	7.68	0.6	1.0	4.8
		30-60	81.6	5.2	13.2	sl	7.63	0.6	1.0	4.2
		60-90	80.4	4.4	15.2	sl	7.66	0.6	1.0	4.4
		Av.	82.58	4.35	13.07		7.65	0.60	1.00	4.48
		SD	1.91	0.61	1.54		0.03	0.00	0.00	0.25
		% cv	2.32	14.07	11.81		0.36	0.00	0.00	5.59
3.	C	0-15	87.7	2.8	9.5	sl	7.36	0.6	5.2	3.7
		15-30	86.2	3.2	10.7	sl	7.45	0.7	3.3	3.9
		30-60	83.1	4.5	12.4	sl	7.65	0.7	3.1	4.1
		60-90	85.5	3.3	11.2	sl	7.60	0.7	3.3	3.9
		Av.	85.63	3.43	10.94		7.52	0.68	3.73	3.90
		SD	1.90	0.75	1.19		0.13	0.05	0.99	0.16
		% cv	2.22	21.81	10.84		1.78	7.41	26.52	4.19
4.	D	0-15	87.7	1.8	10.5	sl	7.68	0.6	4.60	2.7
		15-30	84.2	3.0	12.9	sl	7.72	0.6	3.30	3.8
		30-60	86.7	2.5	10.9	sl	7.76	0.6	1.00	3.4
		60-90	87.9	2.3	9.8	sl	7.63	0.6	0.70	4.2
		Av.	86.62	2.38	11.01		7.70	0.60	2.40	3.53
		SD	1.73	0.51	1.31		0.06	0.00	1.87	0.64
		% cv	1.99	21.41	11.87		0.72	0.00	77.95	18.15

'sl' denotes sandy loam texture

A - Coarse, loamy, mixed, hyperthermic family of Typic Haplustepts; B - Calcareous, mixed, hyperthermic family of Typic Ustipsamments; C - Coarse, loamy, calcareous and mixed hyperthermic family of Typic Haplustepts; D - Coarse loamy, mixed, hyperthermic family of Typic Ustipsamments.

3.3.2.1 Soil Sampling

Soil samples were collected from each of the 26 grids at three depths namely 0-15 cm, 15-30 cm and 30-60 cm with the help of screw auger and core sampler for estimation of bulk density, hydraulic conductivity and moisture retention at suction of 10, 30, 50, 100, 500 and 1500 kPa.

3.3.2.2 Plant sampling

Farmers in the study area were growing pearl millet in kharif and wheat, mustard and chickpea in rabi season of each cropping year. Plant samples for each crops at different phenological stages were collected to determine LAI and biomass at anthesis, biomass at harvest and yield. Other observations like date of sowing, cultivar grown, type, amount and date of fertilizer application, irrigation, incidence of pest and diseases were recorded, on the basis of information provided by the respective owners of the fields. The measurements of above ground crop biomass at anthesis and at harvest and yield were recorded manually by harvesting 2-3 sample plots of 1 m² area in each field. Local farmers helped in harvesting and threshing of sample plots.

3.3.2.3 Meteorological observations

The data on meteorological parameters during the crop season were recorded from the adjoining meteorological observatory at IARI, New Delhi for running the model DSSAT.V.3.5. The daily values of meteorological variables for the year 2004-05 recorded were maximum and minimum temperature (°C), rainfall (mm), bright sunshine hours (hr) and relative humidity (%). Monthly average data of above variables for last 20 years were also obtained. The recorded meteorological parameters are shown in Figure 3 and 4.

Figure 3 showed that during *kharif* season (June to September), the weekly maximum temperature varied from 40.1°C to 30.7°C. It was maximum in 1st week of June and minimum in last week of August. The *kharif* season's average weekly maximum temperature was 35.8°C and weekly average minimum temperature was 26.1°C. The minimum temperature decreased after last week of August from 26.3°C to 21.6°C in last week of September. The total *kharif* rainfall was 343.8 mm. Maximum rainfall of 164.4 mm occurred during 34th meteorological week i.e. between

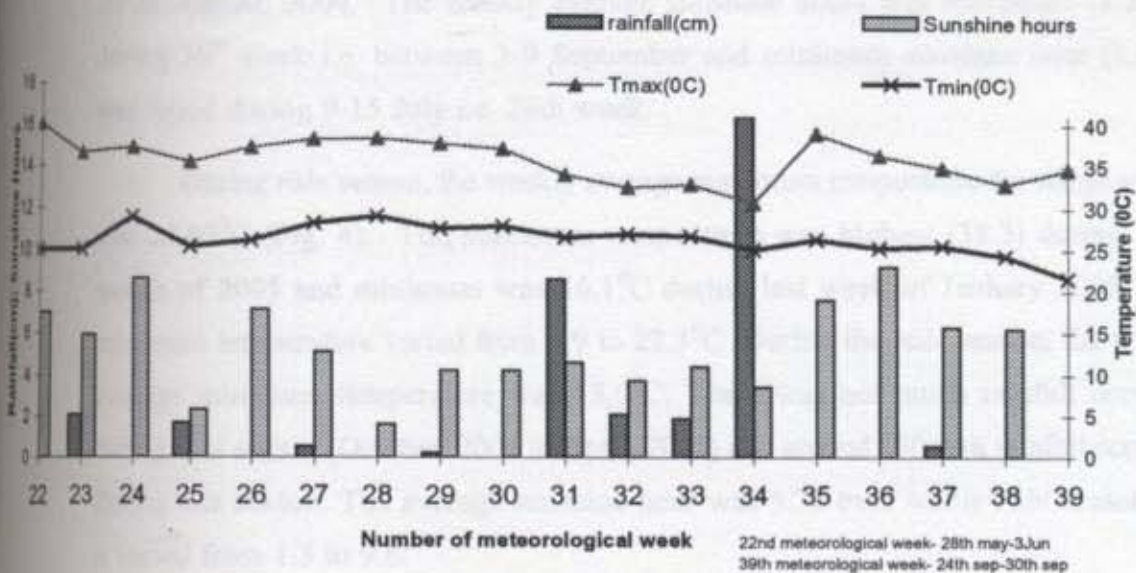


Fig 3: Weekly meteorological data during *kharif* season, 2004-05

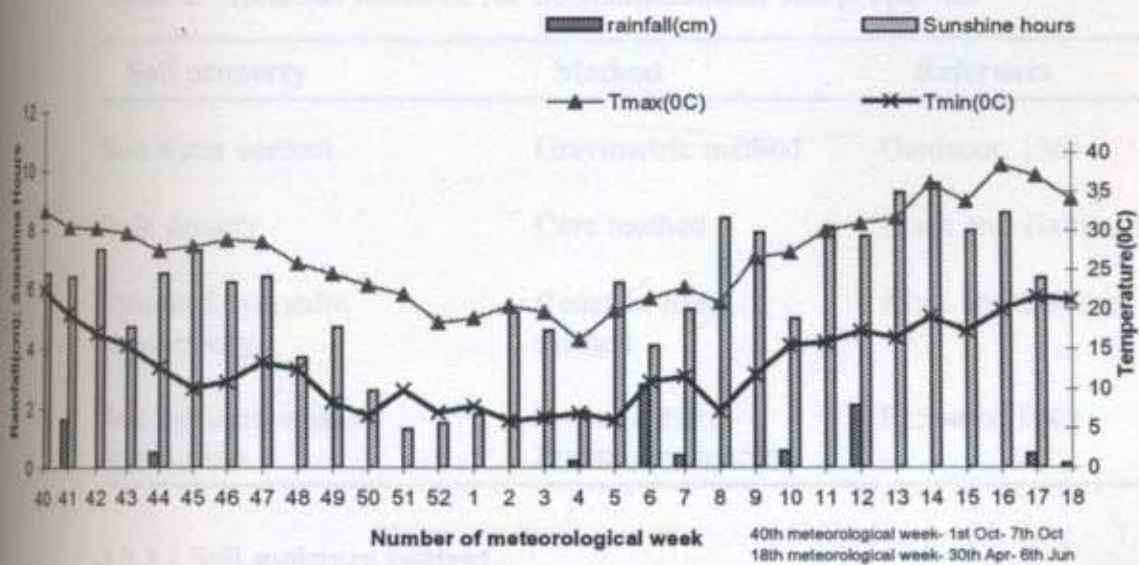


Fig 4: Weekly meteorological data during *rabi* season, 2004-05

20-26 August, 2004. The weekly average sunshine hours was maximum (9.2 hrs) during 36th week i.e. between 3-9 September and minimum sunshine hour (1.6 hr) was found during 9-15 July i.e. 28th week.

During *rabi* season, the weekly average maximum temperature for whole season was 24.80°C (Fig. 4). The maximum temperature was highest (38.3) during April month of 2005 and minimum was 16.1°C during last week of January 2005. The minimum temperature varied from 5.9 to 22.3°C. During the *rabi* season, the weekly average minimum temperature was 13.0°C. There was not much rainfall occurred during *rabi* season (October, 2004 to April, 2005) and around 150 mm rainfall occurred during this season. The average sunshine hour was 5.78 over whole *rabi* season and it varied from 1.3 to 9.6.

3.3.3 Measurement of soil parameters

Methods followed for the determination of different soil physical properties are listed in Table 4.

Table 4. Methods followed for determination of soil properties

Soil property	Method	Reference
Soil water content	Gravimetric method	Gardener, 1965
Bulk density	Core method	Black and Hartge, 1986
Saturated hydraulic conductivity	Constant head method	Klute and Dirkson, 1986
Soil moisture tension relationship	Pressure Plate - Pressure membrane	Richards, 1949

3.3.3.1 Soil moisture content

Soil moisture content was determined gravimetrically. The moist soil samples from field were weighed and then dried in oven at 105°C till they attained constant weight. Their dry weight was recorded. The moisture content in soil was expressed volumetrically by multiplying gravimetric moisture content with the bulk density.

3.3.3.2 Bulk density

Wet soil cores after hydraulic conductivity determination were dried at 105°C in oven and weighed. Bulk density (BD) was obtained by dividing the oven-dried mass by the core volume.

3.3.3.3 Saturated hydraulic conductivity

Measurement of the saturated hydraulic conductivity (HC) of saturated soils in the laboratory was based on the direct application of the Darcy's equation to a saturated soil column of uniform cross sectional area. A constant hydraulic head was imposed on the soil column and the resulting constant flux of water was measured. The saturated hydraulic conductivity was calculated as per Klute and Dirkson (1986).

3.3.3.4 Soil moisture tension relationship

Soil moisture tension relationship was found for core samples using pressure plate pressure membrane apparatus. Soil moisture content corresponding to six different tensions viz., 10, 30, 50, 100, 500 and 1500 kPa were determined gravimetrically. Available water capacity (%) was estimated by subtraction of soil moisture content at 1500 kPa from soil moisture content at 30 kPa. Available water capacity (AWC) was calculated for each of the three soil depths of each grids.

3.3.3.5 Preparation of thematic maps

The variations in soil physical properties of the whole watershed area were studied for each depth of soil of each grid. Thematic maps for each attributes e.g. BD, HC and AWC grids were prepared using Arc-view GIS software for the study area. These attribute values were classified into three categories on the basis of their values, which were arbitrarily named as Low, Medium and High.

3.3.3.6 Spatial variability map of soil physical properties

Spatial variability maps of BD, HC and AWC of soils of entire watershed were prepared with the help of surfer software, for each of the three depths (0-15 cm, 15-30 cm and 30-60 cm) of soil profile. Interpolation of the properties was done using spatial variability analysis (Krigging method) and contour lines at different values were drawn.

3.3.4 Measurement of plant parameters

For all the four crops, leaf area index and biomass at anthesis, biomass at harvest, 100 grain weight and grain yield were determined by bringing plant samples to laboratory.

3.3.4.1 Leaf area index (LAI)

Green leaf area (cm²) was measured for the purpose of computation of leaf area index (LAI) with the help of leaf area meter (LICOR 3100). Above ground portion of plant were removed and their green leaves were separated. The leaf area was determined by passing them through leaf area meter just after sampling. LAI was then calculated by the following equation :

$$\text{LAI} = \frac{\text{Total one sided green leaf area of plants (cm}^2\text{)}}{\text{Total ground area covered by the plants (cm}^2\text{)}}$$

3.3.4.2 Total above ground dry matter

Plant samples which were removed for estimating LAI were also used for estimating total above ground dry matter (TDM). The leaves, stem and spike (after anthesis) portions of plant samples were initially shade dried and later dried in an oven at 65°C for 72 hrs till constant weight was achieved. The dried samples were weighed on an electronic balance.

3.3.4.3 Grain yield and biomass at harvest

A net area of 1 m² in the centre of each plot was marked for the estimation of biomass and grain yield. The above ground part of this area was cut using sickle and bundled for weighing. Bundles were threshed manually and grains separated from chaff by winnowing. Grains from the 1 m² area were weighed to estimate grain yield. Small quantity of grains was kept in oven to estimate their moisture percentage. The grain yield was adjusted for expressing at 12% moisture level.

3.3.5 Crop simulation using DSSAT 35

Model input and initialization

Crop simulation technique was used to estimate yield of various crops for a given set of soil physical properties in the present investigation. A decision support

software DSSAT v 35 was used for various strategies evaluation through simulation technique. It is a decision support system from Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) released in year 1998. The main menu of DSSAT 35 is shown in Figure 5. The data bases required for running the DSSAT are :

Input files : It includes the sub modules on

- Background
- Experiment
- Genotype
- Weather
- Soil

3.3.5.1 Background

The information required in the submodule 'Background' is on name and site of experiment.

3.3.5.2 Experiment file

This file includes all the details of the experiment, treatments and management practices followed during the actual crop growth (Fig. 6).

3.3.5.2.1 Identifier

- ID
- Crop group
- Name

3.3.5.2.2 General

- Researcher
- Address
- Site

3.3.5.2.3 Plot information

- Plot area per replication
- Row per plot
- Plot length (m)
- Plot relative to drains (⁰)

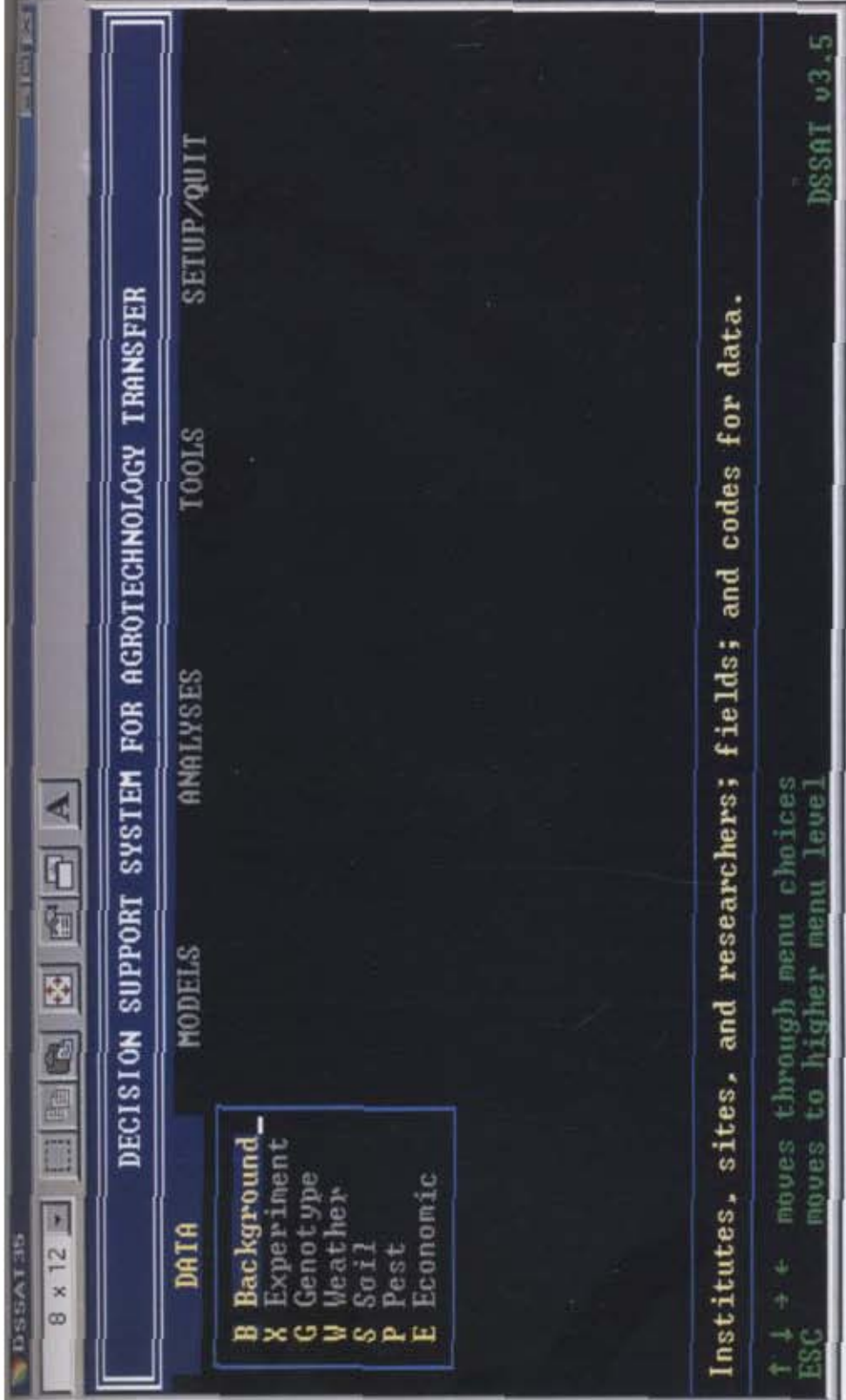


Fig 5: Main menu window of DSSAT 35



Fig 6: Experiment file for Pearl millet

- Plot spacing (cm)
- Plot layout
- Harvest area (m²)
- Harvest row number
- Harvest row length (m)
- Harvest method

Notes

3.3.5.2.4 Management : Information on the following aspects are required :

Treatments

Cultivars

Field — Field identifier, Weather station Identifier, slops(%), Obstruction to sun, drain type, drain depth, drain spacing, surface stone, soil texture, soil depth, soil identifier, elevation (m), area of field (m²), slope length, field length, slope aspect

Soil analysis — Analysis date, pH in buffer method code, phosphorus method code, potassium method code

Initial conditions — Measurement date, previous crop code, previous crop root weight, previous crop nodule weight, rhizobia number, rhizobia effectiveness, initial water table depth, initial crop residue at centre, initial residue P content, initial residue incorporation, initial residue incorporation depth (cm).

Planting — Planting date, emergence date, plant population at seedling, plant population at emergence, planting method, planting distribution, row space, row direction, planting depth, planting material (seed rate), transplant age, plants per hill, initial sprout length.

Irrigation — Irrigation application effect (fraction), management depth (cm), auto application, auto application end point, end of application, auto application method and amount per fixed irrigation (mm)

Fertilizer — Application date, method code applicate date, application depth, application of N in (kg/ha), P (kg/ha), K (kg/ha), application of Ca (kg/ha), other application (kg/ha), other element code.

Residue — Incorporation date, material code, amount, residue N concentration, P concentration, K concentration, incorporation %, Incorporation depth, residue incorporation method

Tillage — Tillage data, tillage implement code, tillage depth (cm)

Chemical — Date, code, application amount (kg/ha), method, depth, target code

Environment — Day length, radiation, maximum temperature, minimum temperature, rainfall, CO₂, humidity, wind

Harvest — Harvest date, harvest stage code, harvest component, code, harvest size group code, harvest %, harvest byproduct takeoff %.

3.3.5.2.5 Controls

- | | |
|---------|---|
| General | <ul style="list-style-type: none"> - Simulation name - Number of simulation year - Number of replication - Start of simulation code - Sim start date - Random number seed value |
| Options | <ul style="list-style-type: none"> - Water routine - Nitrogen routine - Symbiosis routine - Phosphorus routine - Potassium routine - Disease and pest routine - Chemical routine |

- Method
 - Tillage routine
 - Weather type
 - Initial soil condition
 - Light interception
 - Evaporation
 - Infiltration
 - Photosynthesis
 - Hydrology
- Management
 - Planting/Transplanting
 - Irrigation/Water management
 - Fertilization management
 - Residue application
 - Harvest
- Output
 - File name with Experiment code
 - Create overview file
 - Create summary file
 - Detail output taken
 - Detail output frequency
 - Create growth file
 - Create carbon file
 - Create water file
 - Create nitrogen file
 - Create mineral nutrients file
 - Create Diseases/pest file

T-7890



- Create long output file
- Create chemical file
- Create operational file

3.3.5.3 Genotype file

It includes information on crop genetic coefficients

Crop genetic coefficients were calculated with the help of Gencalc. Gencalc run the crop model for existing experiments a number of times, modified cultivar coefficients each time until simulated and observed values are in agreement. These final values of genetic crop coefficient were used for the simulation of yield. The genetic crop coefficients or genotype coefficient of different crops are shown in Table 5.

3.3.5.4 Weather file

- Maximum temperature (°C)
- Minimum temperature (°C)
- Rainfall (mm)
- Solar radiation (MJ/m²/day)

3.3.5.5 Soil file

- Lower and upper depth of the soil
- % sand, silt and clay measured
- Bulk density
- Organic carbon
- pH
- Soil classification

3.3.5.6 Observed data file

3.3.5.6.1 Average file — This file contains the observed data on the following aspects which is a one time measured data :

- Number/m²
- Maturity yield

Table 5. Genetic coefficient codes of different crops

Genetic Coefficient	Definition
Soybean and Chickpea	
CSDL	Critical short day length below which reproductive development progresses with no day length effect (hr)
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short day plants (1/ hour)
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)
FL-SH	Time between first flower and first pod (R3) (photothermal days)
FL-SD	Time between first flower and first seed (R5) (photothermal days)
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)
LFMAX	Maximum leaf photosynthesis rate at 30 ⁰ C, 350 vpm CO ₂ , and high light (mg CO ₂ /m ² -s)
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm ² /g)
SIZLF	Maximum size of full leaf (three leaflets) (cm ²)
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD	Maximum weight per seed (g)
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)
SDPDV	Average seed per pod under standard growing conditions (#/pod)
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)

Contd...

Table 5 contd...

Genetic Coefficient	Definition
Pearlmillet and Sorghum	
P1	Thermal time for seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 ⁰ C) during which the plant is not responsive to changes in photoperiod.
P20	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced.
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P20
P5	Thermal time (degree days above a base temperature of 8 ⁰ C) from beginning of grain filling (3-4 days after flowering to physiological maturity.
G1	Scaler for relative leaf size
G2	Scaler for partitioning of assimilates to the panicle (head)
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearance
Wheat	
PIV	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization is sufficient for all cultivars
PID	Relative amount that development is slowed when plants are grown in a photoperiod 1 hour shorter than the optimum (which is considered to be 20 hours)
P5	Relative grain filling duration based on thermal time (degree days above a base temperature of 1 ⁰ C), where each unit increase above zero adds 20 degree days to an initial value of 430 degree days.
G1	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (1/g).
G2	Kernel filling rate under optimum conditions (mg/day)
G3	Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g)
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances

- Irrigation
- LAI maximum
- Anthesis date
- Maturity date

3.3.5.6.2 Temporal file — The observed time series of the following variables are contained in this file.

- Leaf number
- LAI
- Grain number
- Grain weight
- Specific leaf area
- Unit grain weight

Four major crops cultivated in the study area are : Pearl millet, wheat, chickpea and mustard. Besides these crops, two more crops were identified which can be grown in this area as their agro-climatic requirement perfectly matched with the agro-climatic conditions of the water shed. These crops were soybean and sorghum which are kharif crops.

The observed data was partitioned into 2 sets. One set was used to calibrate the model and crop coefficient were calculated with the help of Gencalc. After calibrating the model, the other data set was used to validate the model.

Growth and yields of crops were simulated for each grid using DSSAT 35. The input soil file for each grid was prepared using the soil properties of that grid. As the soil properties varied spatially with grids, the input soil file also changed for each grid. The weather was same for the whole watershed, hence input weather file was same for each grid. With these soil and weather input files, yields were estimated for each crop using input crop file having crop genetic coefficients for that particular crop and variety. This procedure was carried out for each crop in each grid. The simulated yields for all the crops and for all the grids were divided into 3 classes for generation of thematic maps of yields. These classes were low, medium and high on the relative values of crop yields.

3.3.6 Spatial variability map for crop yield

Spatial variability of simulated yields of different crops of entire watershed were prepared with the help of Surfer version 6.2 software. The trends of variation in yields of crops were studied.

3.4 Economic analysis for major crops

Unit cost of cultivation/ha for all the six major crops was calculated considering all the input variables like expenditure on ploughing and harrowing, land levelling, seed sowing, fertilizer, irrigation, weeding, harvesting and threshing. The output price of all the crops were also calculated considering market prices of grain yield and fodder. The yield prices used were the minimum support price offered by the government. The fodder prices were the actual selling prices as told by the farmers. Difference in total output price and total input cost gave us net profit/ha.

$$\text{Net profit} = \text{Total output price} - \text{Total input cost}$$

3.5 Long term performance of cropping sequence

To evaluate the long term performance of crops, yield maps were prepared for watershed for all the crops, using simulated yields of last 20 years. Last 20 years weather data was used and yield were predicted for each crop in each grid. For these simulations, soil file, crop file and experiment file for each grid were same. The weather file changed for each of 20 run of the model for 20 years. This was done in each of 26 grids of water shed.

4. RESULTS AND DISCUSSIONS

The salient results of the present investigations are presented in the following three sections and sub sections and discussed critically for drawing inferences of practical significance :

- Variation of soil physical properties in the watershed.
- Assessment of crop growth and yield using crop growth simulation model.
- Long term performance evaluation of cropping sequences.

4.1 Variation of soil physical properties

4.1.1 Bulk density (BD)

The variations in soil bulk density of three depth layers of different grids of the watershed are shown in Table 6 and Fig. 7 (a, b, c and d)..

The BD of the surface soil (0-15 cm) was generally lower than the soil beneath (> 15 cm). It increased significantly depthwise for each grids. Average value of BD for all the grids changed significantly from 1.54 Mg/m³ in surface soil to 1.60 Mg/m³ in lower depths (30-60 cm). Statistical analysis showed that BD value increased significantly even at 1% level of significance from top layer to bottom layer (Table 6). However, on profile average basis, the soil BD in the entire watershed ranged from 1.50 Mg/m³ to 1.64 Mg/m³ and its average value was 1.58 Mg/m³.

There was a significant variation in soil BD among 26 grids of all the soil layers. In the surface layer BD value ranged from 1.44 Mg/m³ to 1.61 Mg/m³ which was equivalent to about 12% variation. Thematic map of BD of watershed for three depths were prepared using Arc view GIS software. These maps are shown in figure 8 (a, b and c). Out of the total area of watershed, 15% area showed soil BD value ranging between 1.44 to 1.49 Mg/m³ whereas 50% area had surface BD between 1.49 to 1.55 Mg/m³ and rest 35% of area showed BD value ranging from 1.55 to 1.61 Mg/m³ (Fig. 8a).

Table 6. Bulk density (Mg/m³) of 26 grids for the three soil layers

Grid ID	Bulk density (Mg/m ³)			
	0-15 cm	15-30 cm	30-60 cm	Average
1	1.53	1.59	1.58	1.57
2	1.55	1.61	1.62	1.59
3	1.59	1.63	1.63	1.62
4	1.49	1.53	1.52	1.51
5	1.56	1.59	1.61	1.59
6	1.52	1.61	1.59	1.57
7	1.53	1.58	1.59	1.57
8	1.54	1.58	1.61	1.58
9	1.53	1.57	1.58	1.56
10	1.61	1.66	1.66	1.64
11	1.59	1.62	1.63	1.61
12	1.55	1.59	1.59	1.58
13	1.51	1.59	1.58	1.56
14	1.46	1.52	1.55	1.51
15	1.53	1.57	1.58	1.56
16	1.56	1.61	1.63	1.60
17	1.52	1.56	1.61	1.56
18	1.56	1.63	1.66	1.62
19	1.52	1.58	1.56	1.55
20	1.44	1.52	1.53	1.50
21	1.51	1.59	1.57	1.56
22	1.59	1.65	1.65	1.63
23	1.53	1.57	1.58	1.56
24	1.59	1.64	1.63	1.62
25	1.56	1.59	1.63	1.59
26	1.49	1.56	1.59	1.55
Average	1.54	1.59	1.60	1.58

CD at 5% level of significance : 0.0209

CD at 1% level of significance : 0.0278

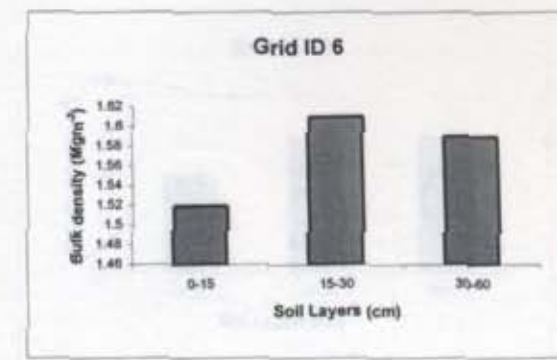
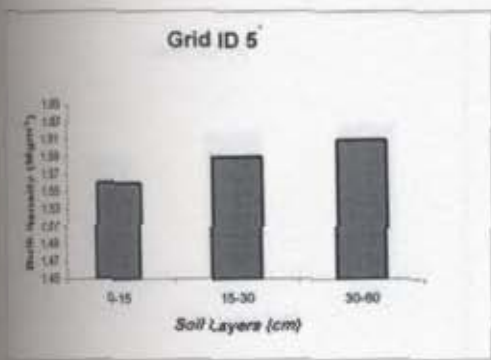
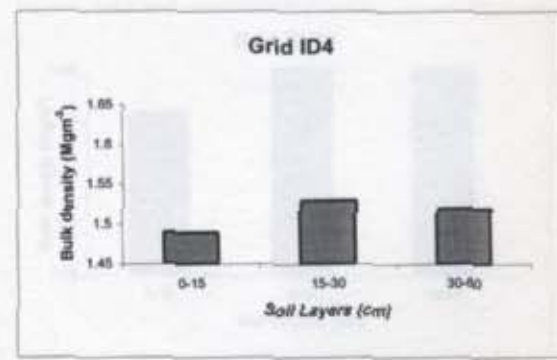
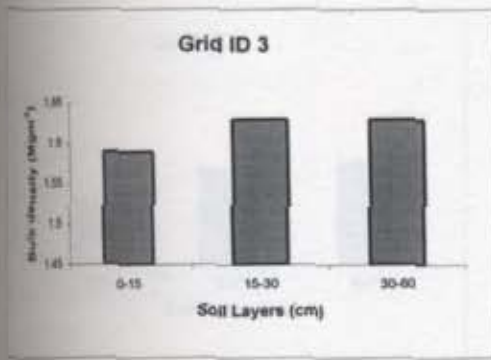
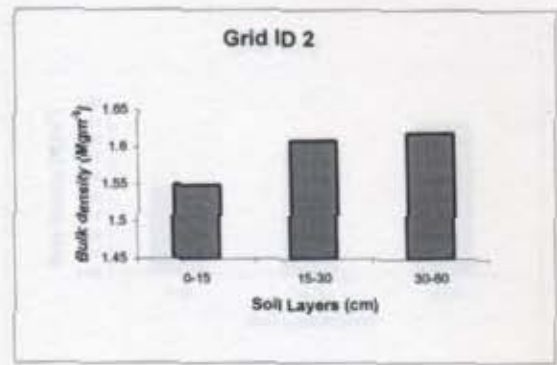
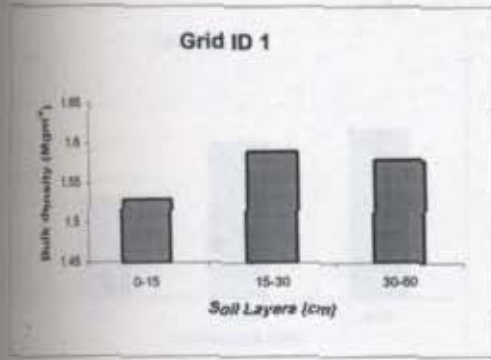


Fig 7(a): Bulk density (Mg m⁻³) of three soil layers (For Grid ID1-6)

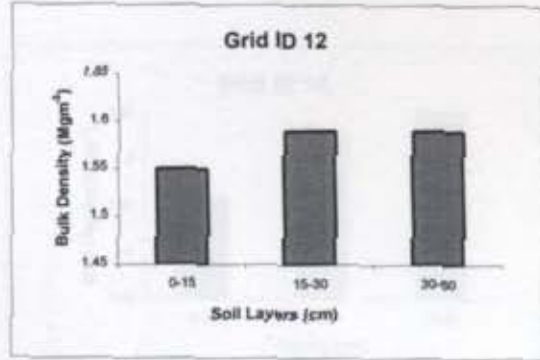
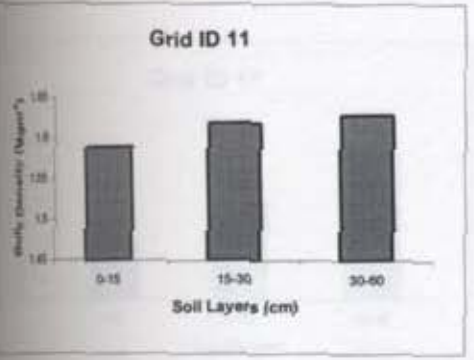
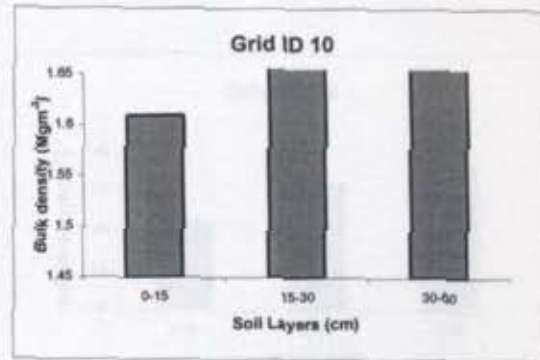
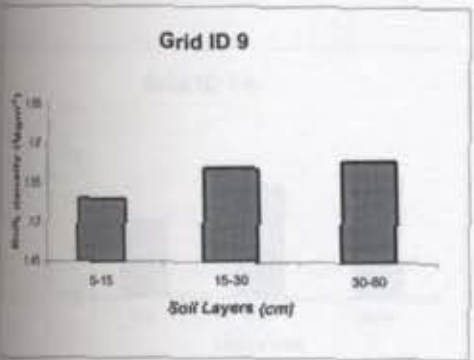
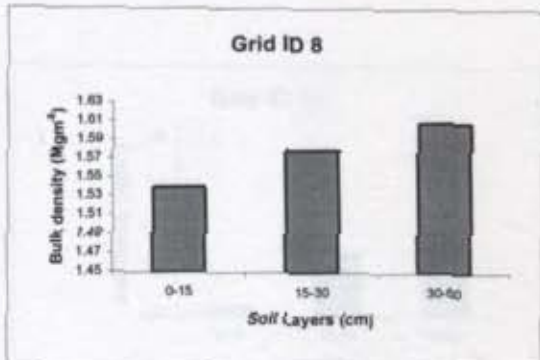
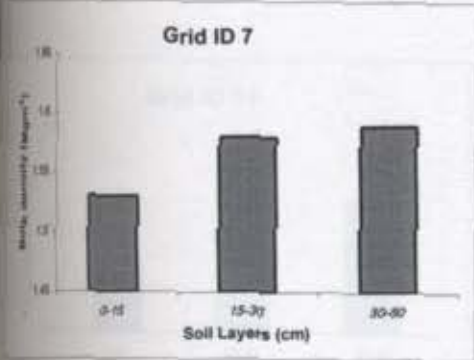


Fig 7(b): Bulk density (Mg m⁻³) of three soil layers (For Grid ID 7-12)

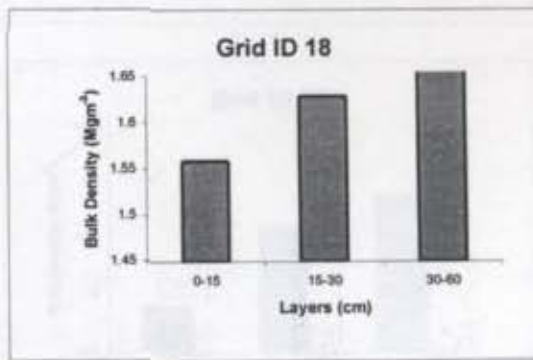
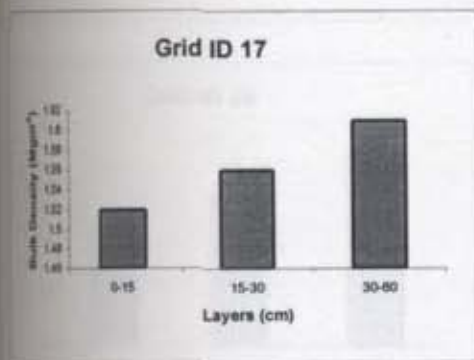
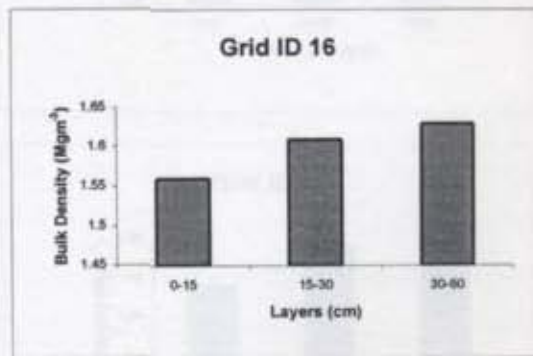
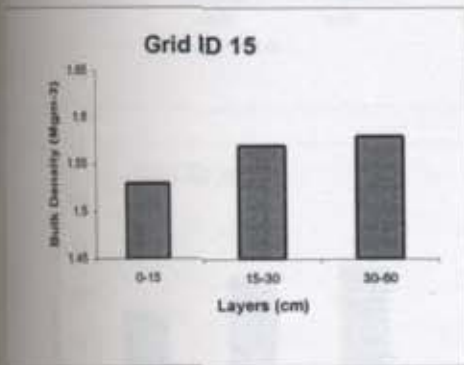
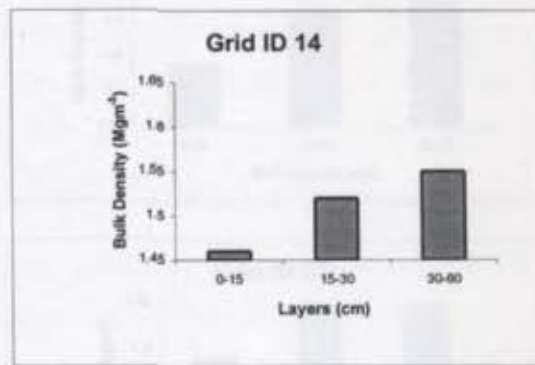
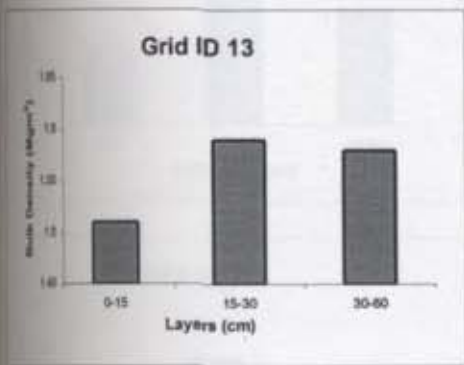


Fig 7(c): Bulk density (Mg m⁻³) of three layers (Grid ID 13-18)

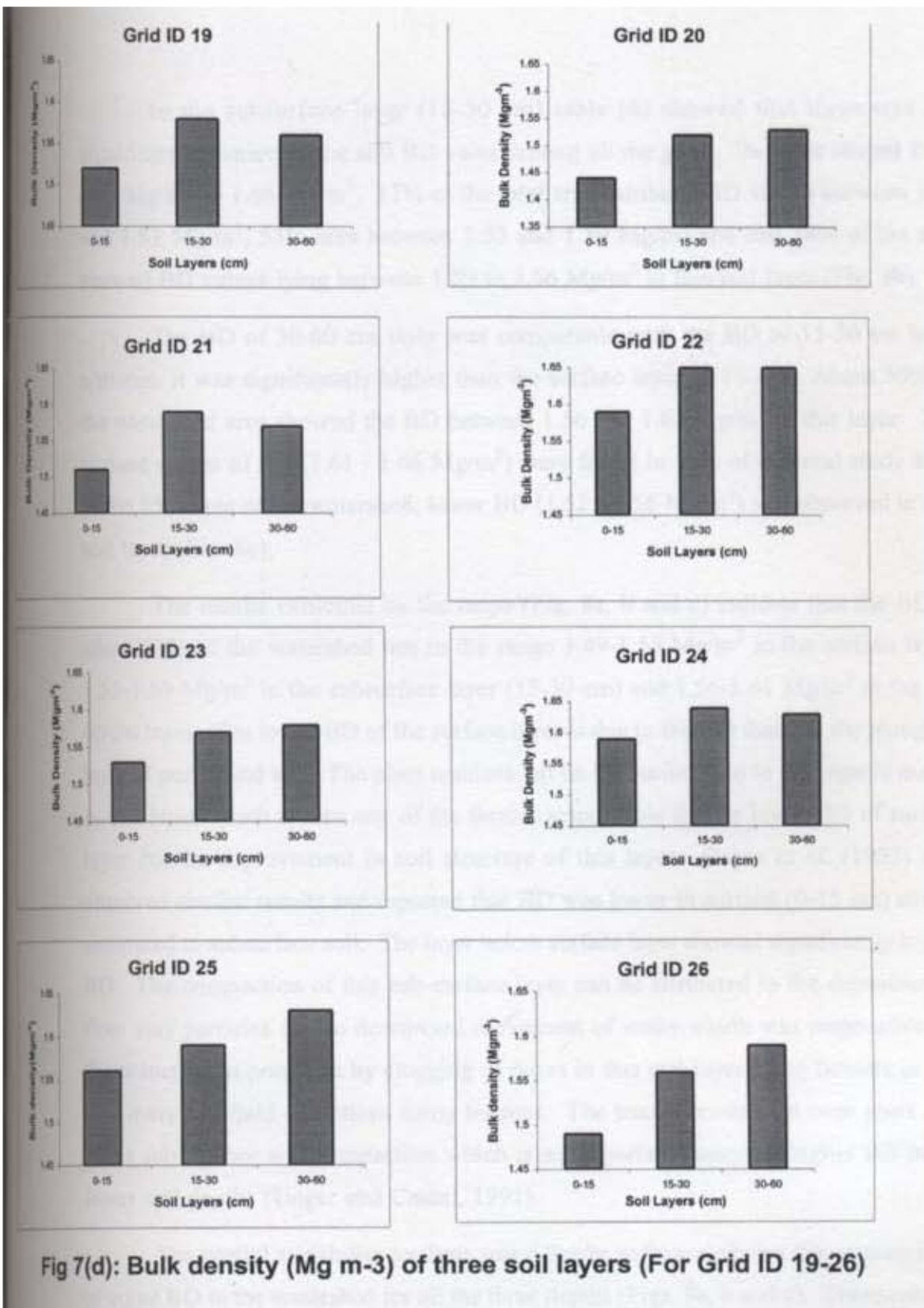


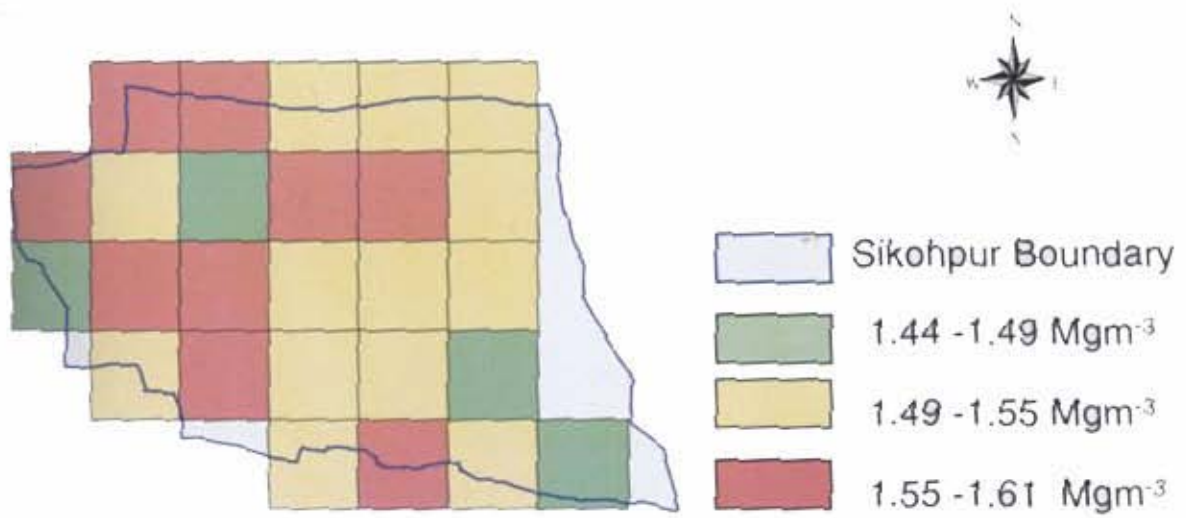
Fig 7(d): Bulk density (Mg m⁻³) of three soil layers (For Grid ID 19-26)

In the subsurface layer (15-30 cm) table (6) showed that there was 3% significant variation in the soil BD value among all the grids. Its value ranged from 1.52 Mg/m³ to 1.66 Mg/m³. 11% of the total area exhibited BD values between 1.52 and 1.53 Mg/m³, 55% area between 1.53 and 1.59 Mg/m³ and rest 34% of the area showed BD values lying between 1.59 to 1.66 Mg/m³ in this soil layer (Fig. 8b).

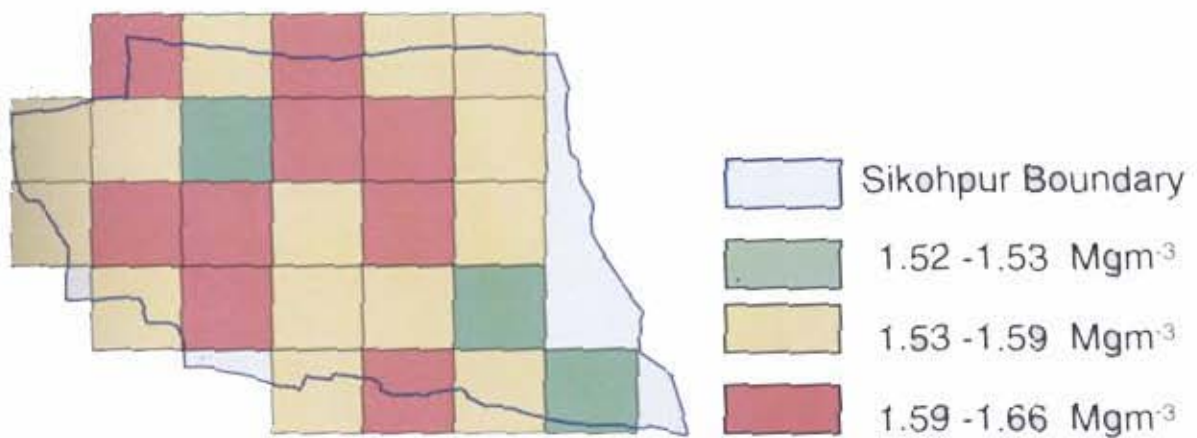
The BD of 30-60 cm layer was comparable with the BD of 15-30 cm layer although it was significantly higher than the surface layer (0-15 cm). About 50% of the watershed area showed the BD between 1.56 and 1.61 Mg/m³ in this layer. The highest values of BD (1.61 - 1.66 Mg/m³) were found in 35% of the total study area. In the 15% area of the watershed, lower BD (1.52 - 1.56 Mg/m³) was observed in this soil layer (Fig. 8c).

The results exhibited by the maps (Fig. 8a, b and c) indicate that the BD of about 50% of the watershed lies in the range 1.49-1.55 Mg/m³ in the surface layer, 1.53-1.59 Mg/m³ in the subsurface layer (15-30 cm) and 1.56-1.61 Mg/m³ in the 30-60 cm layer. The lower BD of the surface layer is due to the fact that it is the ploughed layer of pulverised soil. The plant residues left on the surface add to the organic matter in this layer which is also one of the factors responsible for the lower BD of surface layer due to improvement in soil structure of this layer. Gupta *et al.* (1993) also observed similar results and reported that BD was lower in surface (0-15 cm) soil as compared to subsurface soil. The layer below surface layer showed significantly higher BD. The compaction of this sub-surface layer can be attributed to the deposition of finer clay particles due to downward movement of water which was responsible for the reduction in pore size by clogging of pores in this soil layer. The farmers in this area carry out field operations using tractors. The tractor movement over years also cause sub-surface soil compaction which is an important reason of higher BD in the lower soil depths (Unger and Cassel, 1991).

The spatial variability analysis using Surfer software, shows the contour lines of equal BD in the watershed for all the three depths (Figs. 9a, b and c). These contour lines were obtained using the interpolation of BD values by Krigging method. These figures exhibit the regions of high BD and low BD on the horizontal surfaces of 0-15, 15-30 and 30-60 cm layers. These regions help in identifying the unsuitable areas of the watershed due to BD constraints.



(a) 0-15 cm

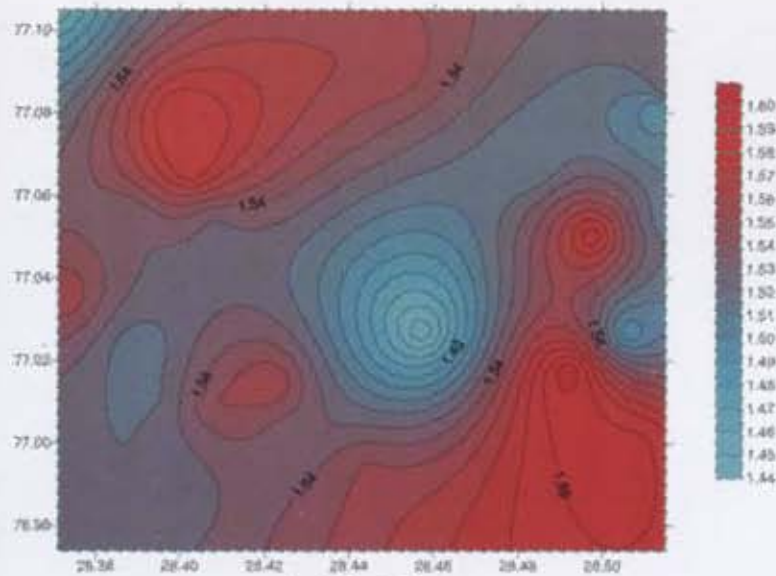


(b) 15-30 cm

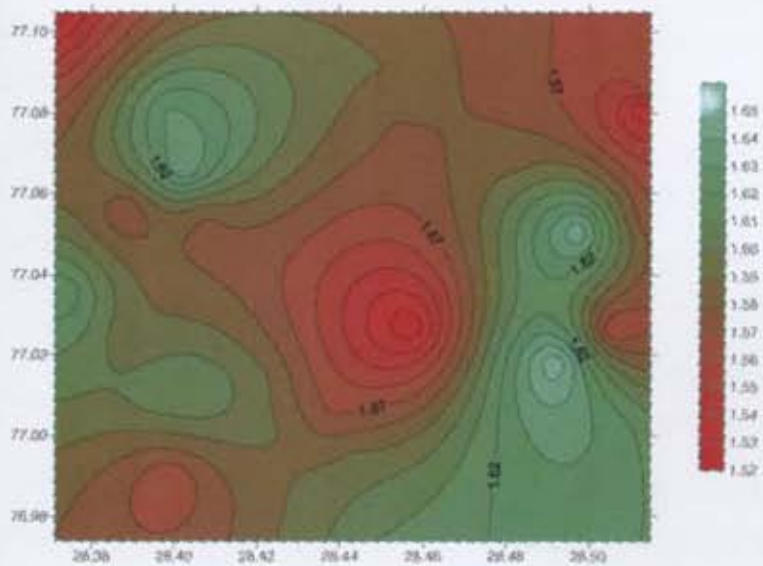


(c) 30-60 cm

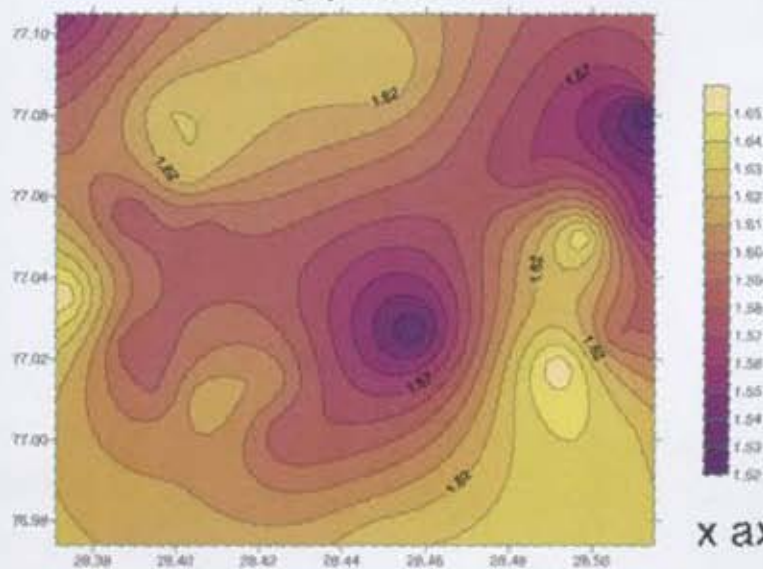
Fig 8: Thematic map of bulk density (Mgm^{-3}) for (a) 0 - 15 cm layer (b) 15 - 30 cm layer and (c) 30 - 60 cm layer



(a) 0-15 cm



(b) 15-30 cm



(c) 30-60 cm

x axis - longitude

y axis - latitude

Fig 9: Spatial variability of Bulk density (Mgm^{-3}) in watershed

All the results indicated that the BD value are in the higher in this watershed. The higher BD value of soil in the area can be attributed to the coarse texture of the soil having high % of sand, also reported by Sharma *et al.* (1994a).

4.1.2 Saturated hydraulic conductivity (HC)

The saturated Hydraulic Conductivity (HC) of the three soil layers for all the 26 grids are given in Table 7. The spatial variability of HC in this watershed is shown in HC map (Fig. 10 a, b, c and d).

The HC was highest for the surface layer and it decreased significantly with depth in all the grids (Table 7). The average, over grids HC decreased from 5 cm/hr in surface layer to 4.27 cm/hr in the sub-surface layer showing a significant reduction of 14.3%. The third layer (30-60 cm) HC (3.89 cm/hr) was statistically same as that of second layer. The average HC value showed a reduction of 6.8% from second (15-30 cm) to third layer (30-60 cm). However, HC of third layer was about 20% less than that of first layer which is a significant decrease at 5% as well as 1% level of significance. The overall average HC of watershed was 4.42 cm/hr indicating that the soils are well drained.

The spatial distribution of the magnitude of HC are shown in HC thematic maps (Fig. 11a, b and c) for the three depth layers thematic map. The map (Fig. 11a) shows that HC of surface layer was in the class of lower range of 2.5 to 4.4 cm/hr in about 34% area of the watershed, whereas 38% area of watershed had HC values in the middle range of 4.4 to 5.7 cm/hr. The higher range of HC which was 5.7-6.6 cm/hr existed in 28% of the surface area of the watershed.

In the sub-surface layer (15-30 cm), Fig. 11b indicate that the area corresponding to class having lower HC values ranging from 2.1-3.1 cm/hr was 23% whereas the area under the class having HC values 3.1-4.9 cm/hr was 38% and the area in the class of higher values (4.4-6.0 cm/hr) was 39%.

In the third layer of soil (30-60 cm) there was 38%, 38% and 24% of total area under the three classes ranging from 2.3-3.4 cm/hr, 3.4-4.7 cm/hr and 4.7 to 6.8 cm/hr, respectively (Fig. 11c).

Table 7. Saturated hydraulic conductivity (cm/hr) of 26 grids for the three soil layers

Grid ID	Hydraulic conductivity (cm/hr)			
	0-15 cm	15-30 cm	30-60 cm	Average
1	5.20	4.10	4.60	4.63
2	4.90	4.10	4.00	4.33
3	3.60	3.10	3.20	3.30
4	6.40	5.70	5.80	5.97
5	4.70	3.90	3.30	3.97
6	6.20	5.40	5.70	5.77
7	5.90	5.10	4.30	5.10
8	4.40	3.60	3.10	3.70
9	2.90	2.20	2.30	2.47
10	3.40	3.00	3.10	3.17
11	4.30	3.60	3.20	3.70
12	5.50	4.60	4.30	4.80
13	6.10	5.60	5.50	5.73
14	6.60	5.90	5.00	5.83
15	4.30	3.60	3.40	3.77
16	5.10	4.30	4.10	4.50
17	5.30	5.10	4.40	4.93
18	6.30	6.00	4.70	5.67
19	5.70	4.90	4.90	5.17
20	6.50	5.80	5.30	5.87
21	5.20	4.40	3.70	4.43
22	3.90	2.80	2.50	3.07
23	4.90	3.80	3.80	4.17
24	3.30	2.50	2.60	2.80
25	5.50	5.00	4.10	4.87
26	3.90	2.80	2.70	3.13
Average	5.00	4.27	3.98	4.42

C.D. at 5 % level of significance : 0.593

C.D. at 1 % level of significance : 0.787

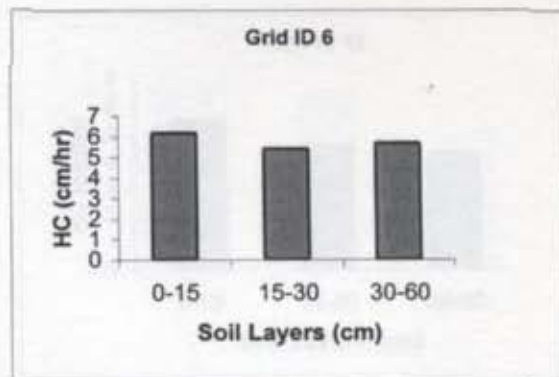
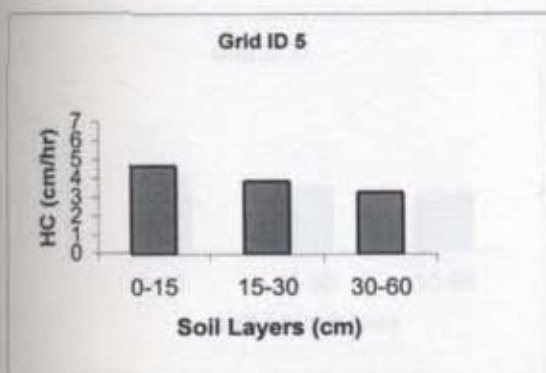
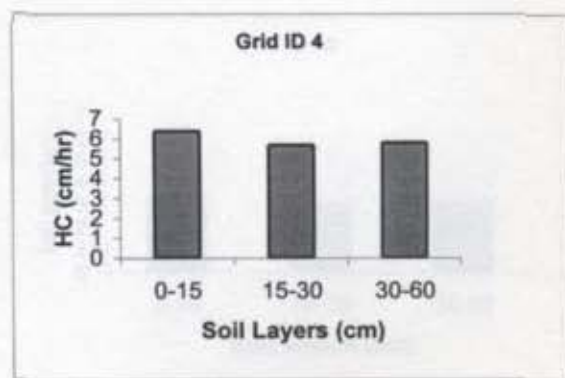
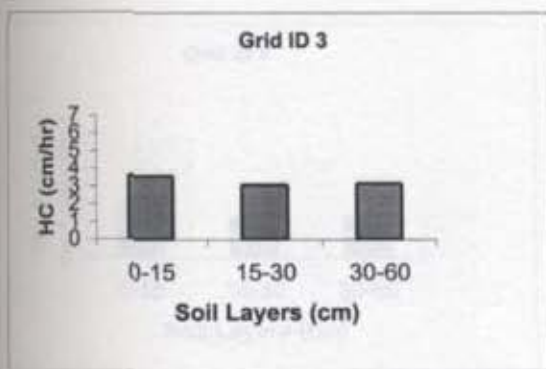
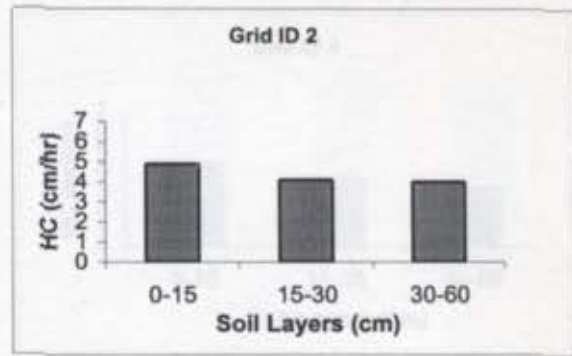
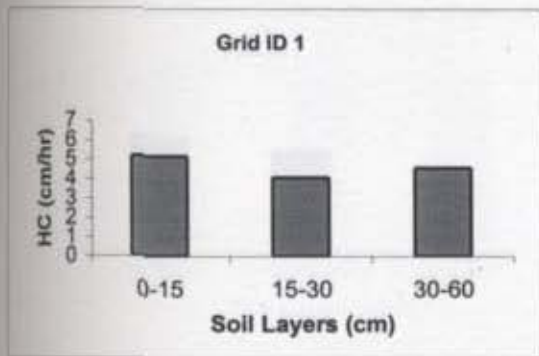
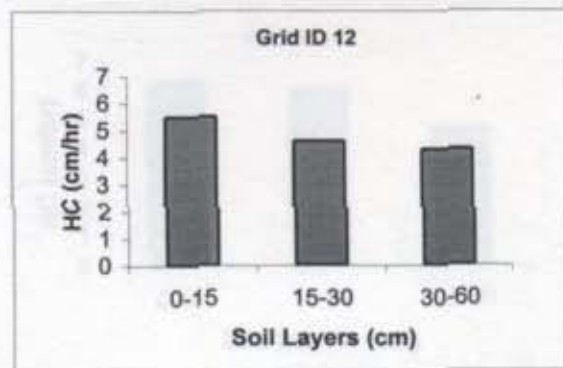
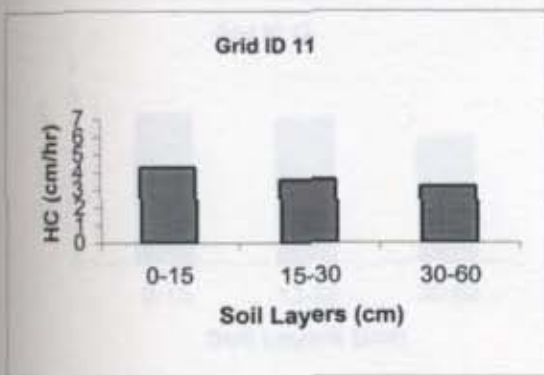
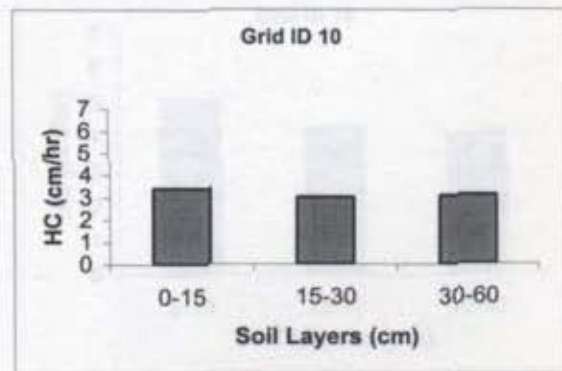
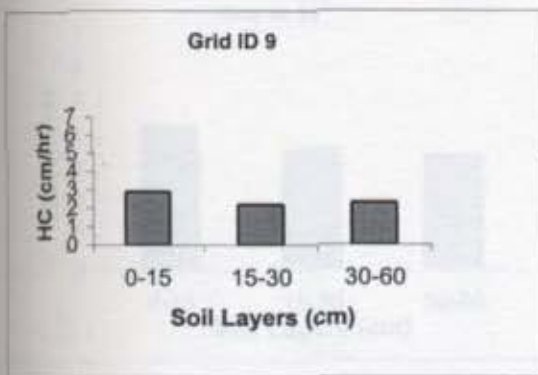
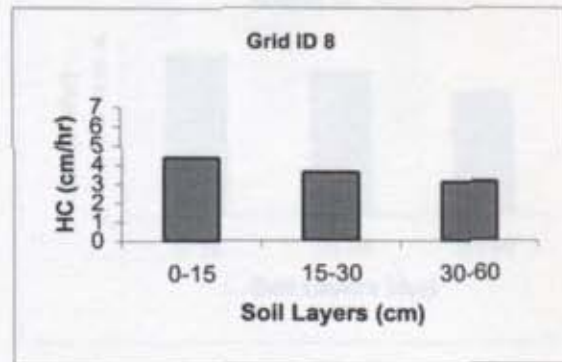
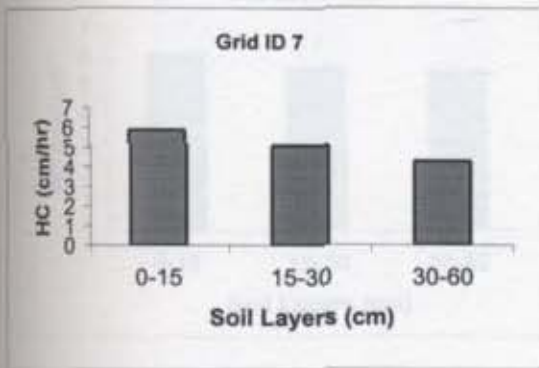


Fig 10 (a): Saturated hydraulic conductivity (cm/hr) of three soil layers (For grid ID 1-6)



**Fig 10(b): Saturated hydraulic conductivity (cm/hr) of three soil layers
(For grid ID 7-12)**

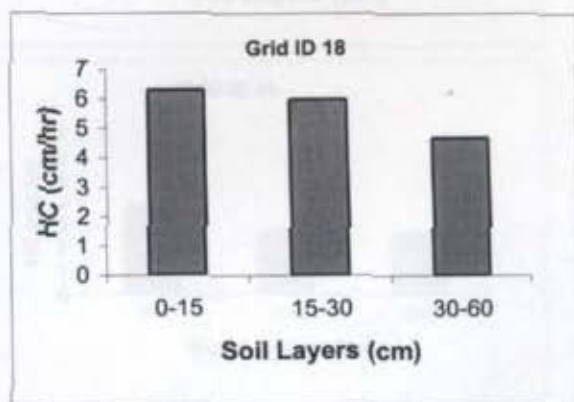
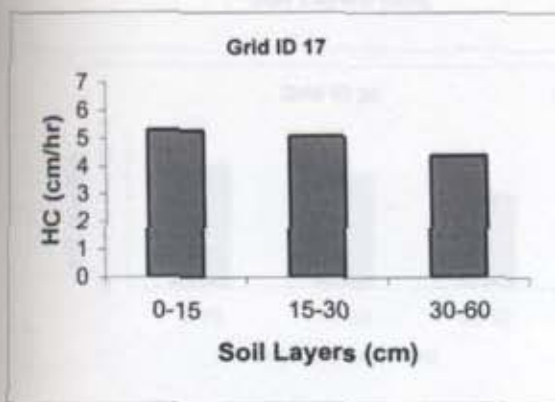
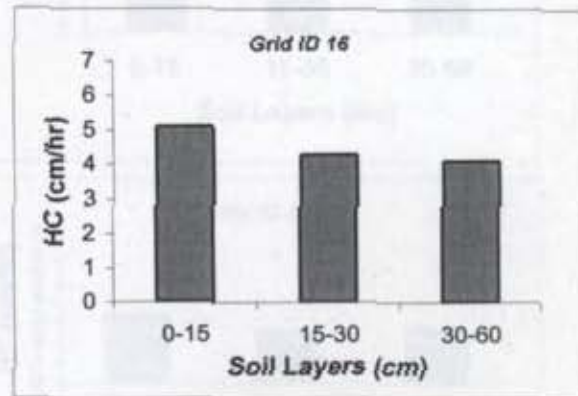
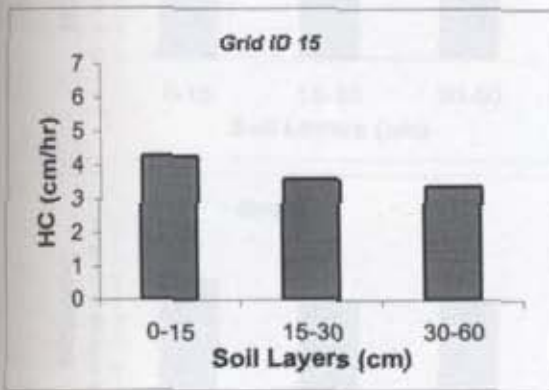
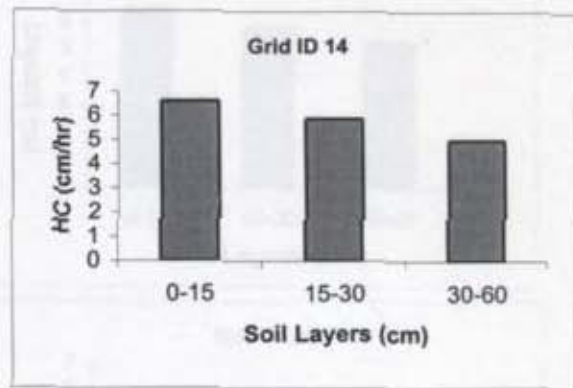
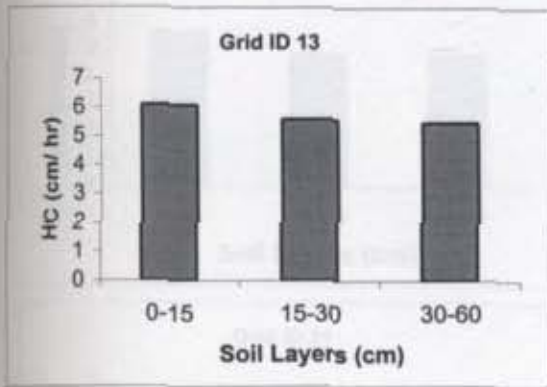


Fig 10 (c): Saturated hydraulic conductivity (cm/hr) of three soil layers (For grid ID 13-18)

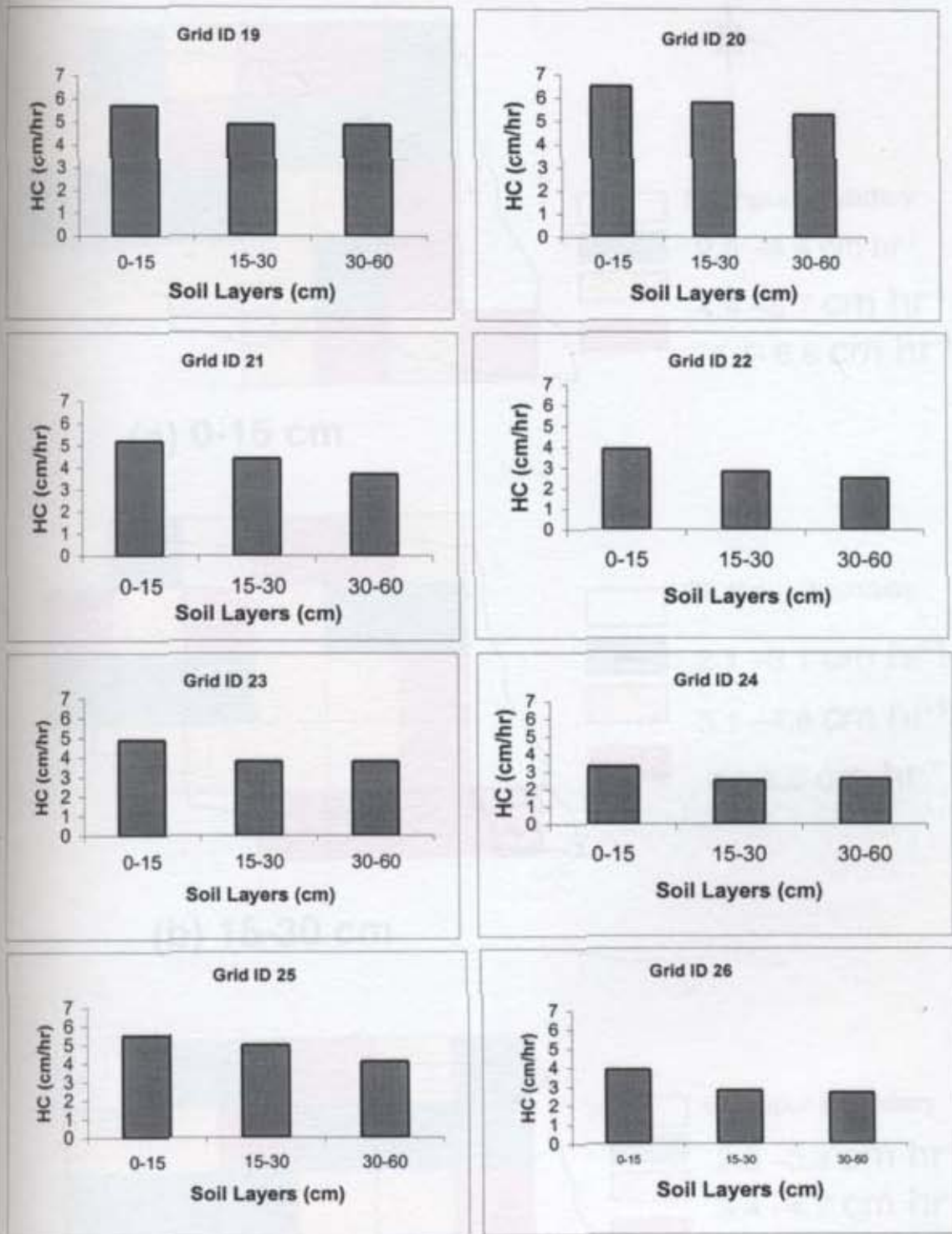
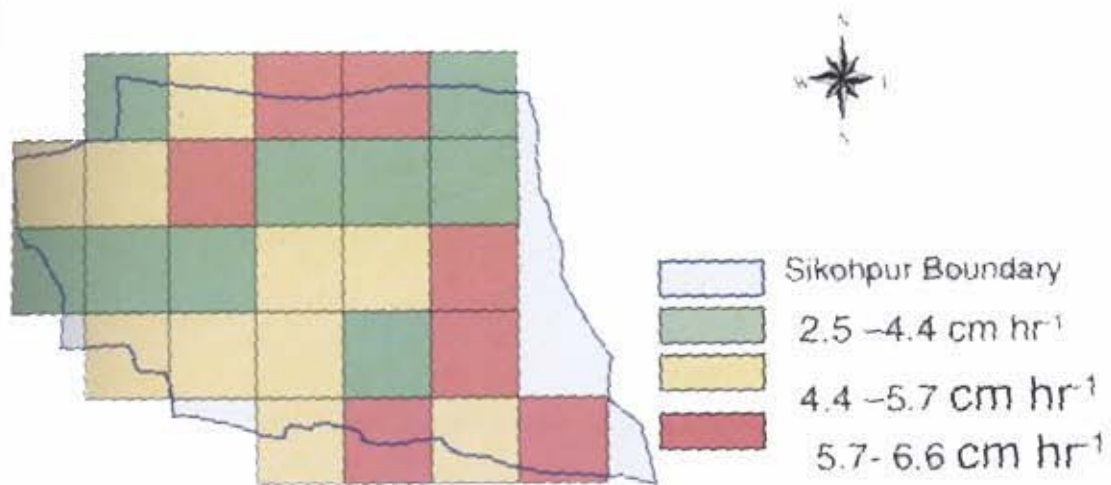
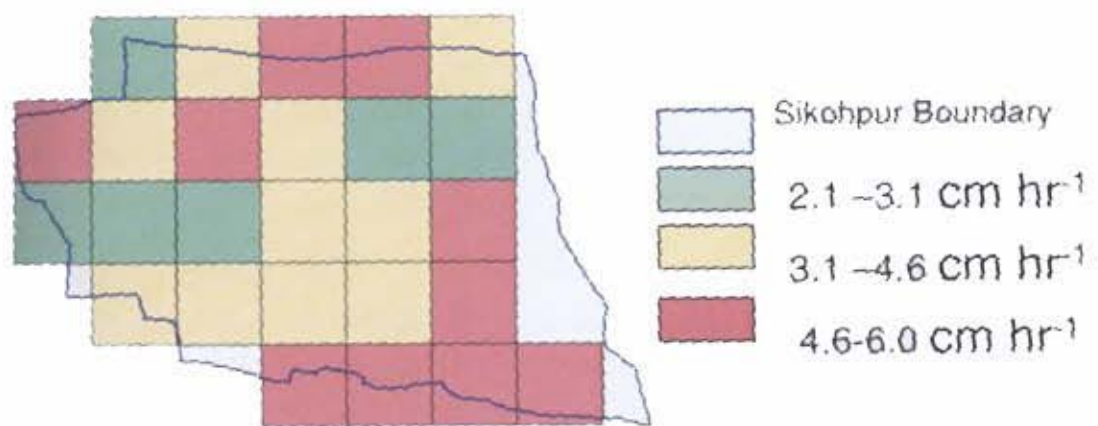


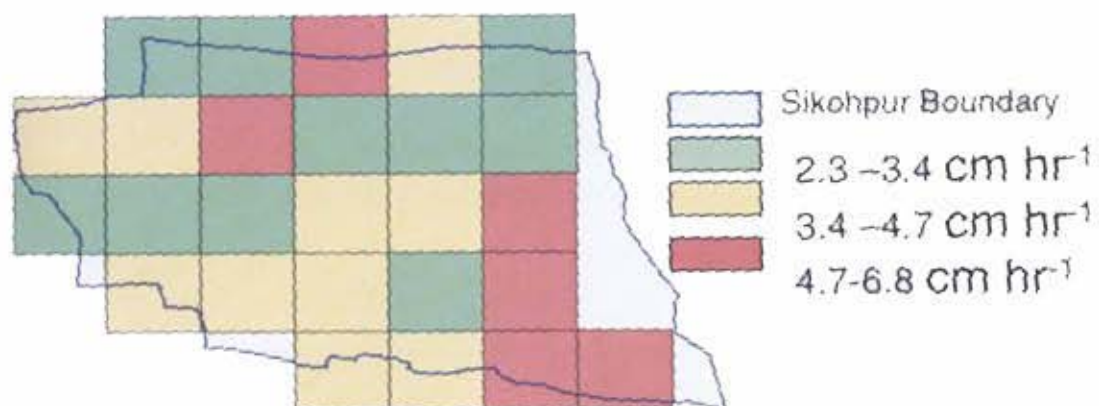
Fig 10 (d): Saturated hydraulic conductivity (cm/hr) of three soil layers (For grid ID 19-26)



(a) 0-15 cm



(b) 15-30 cm



(c) 30-60 cm

Fig 11: Thematic map of saturated hydraulic conductivity (cm/hr) for (a) 0-15 cm layer (b) 15-30 cm layer and (c) 30-60 cm layer

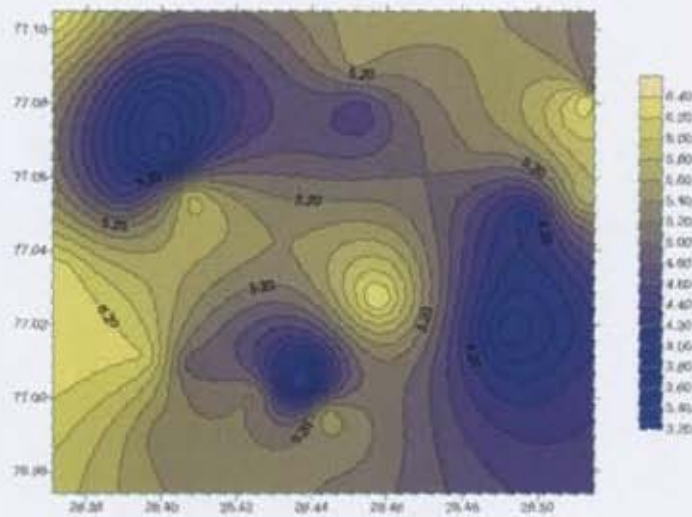
The contour lines of spatial variability map (Fig. 12a, b and c) showed the areas of high HC and low HC on the horizontal surfaces of each layer of three depths : 0-15, 15-30 and 30-60 cm layers. These areas help in identifying the problematic region where HC were high leading all the water to percolate to deeper depths and reducing moisture storage in the soil.

The high values of HC in the entire watershed are due to coarser texture of the soil (sandy loam) where sand percentage is higher (> 80%) (Sandou, 2001). The results are complementary to the BD results. The decrease in HC depthwise followed the same pattern as increase in BD in all the grids. Higher value of HC in surface soil may be due to pulverised ploughed soil which has more number of macropores.

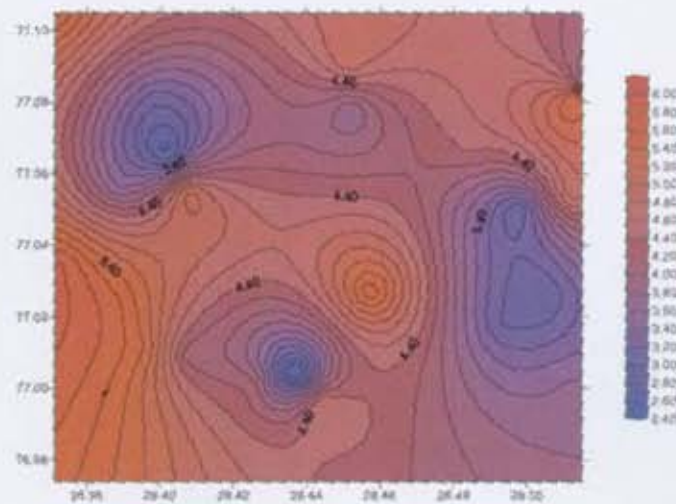
4.1.3 Available Water Capacity (AWC)

The available water capacity (AWC) of soil in different grids of watershed are shown in Table 8. The average AWC in the three depth layers were same having average values as 13.0, 13.4 and 13.7% in the surface, sub-surface and third layer (30-60 cm), respectively. They do not differ significantly. However, in surface layer, AWC varied from 10% to 18%, in subsurface layer it varied from 9 to 19% and in the third layer the variation in AWC was from 9% to 20% with overall average value of 13%. This shows that although there is no significant difference in the AWC between the three depth layers there is enough variability among grid values. This indicate AWC varies more horizontally or spatially than vertically or depthwise. The reason for no variation in depths may be due to the fact that AWC is mainly governed by soil texture and soil texture was uniform in soil profile.

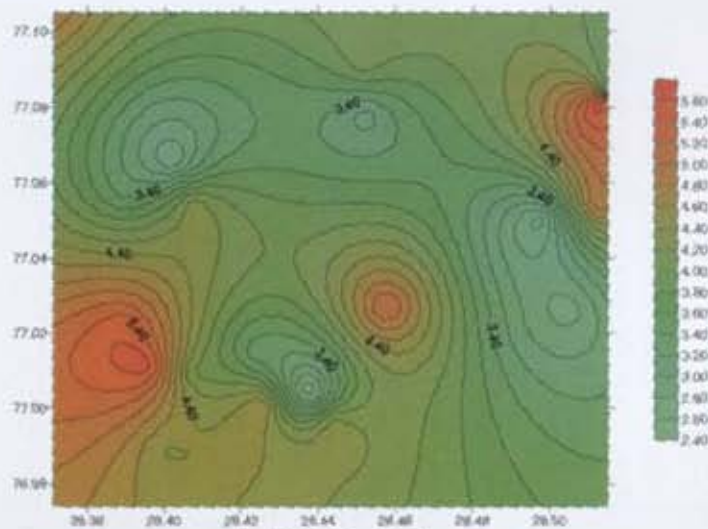
The thematic map and spatial variation in AWC at three depth layers of watershed are shown in Fig. 13 (a, b and c) and Fig. 14 (a, b and c). Thematic map indicated that in surface soil layer, 46% of total area showed AWC value ranging from 10 to 12%, 42% area is under class having AWC from 12 to 15% and rest 12% area has 15 to 18% AWC values. In sub-surface soil layer, AWC values ranging from 9 to 12% occupy 35% of the total area, class of 12 to 15% AWC occupy 50% area and 15 to 19% AWC class occupy 15% area. This indicate that in all the depths maximum area of watershed had AWC in the range 12-15%.



(a) 0-15 cm



(b) 15-30 cm



(c) 30-60 cm

x axis - latitude

Y axis - longitude

Fig 12: Spatial variability of saturated hydraulic conductivity (cm/hr) in watershed

Table 8. Available Water Capacity of 26 grids for the three soil layers

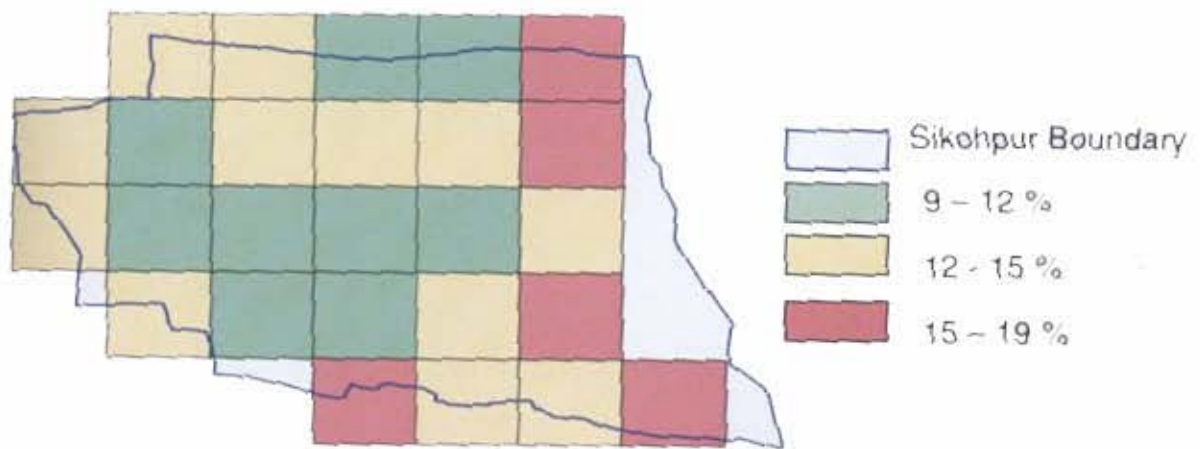
Grid ID	Available water capacity (m ³ /m ³)			
	0-15 cm	15-30 cm	30-60 cm	Average
1	0.10	0.10	0.09	0.10
2	0.11	0.11	0.10	0.11
3	0.11	0.10	0.12	0.11
4	0.14	0.14	0.13	0.14
5	0.14	0.14	0.14	0.14
6	0.10	0.11	0.11	0.11
7	0.12	0.12	0.12	0.12
8	0.15	0.16	0.15	0.15
9	0.18	0.19	0.19	0.19
10	0.12	0.13	0.12	0.12
11	0.14	0.13	0.13	0.13
12	0.10	0.11	0.11	0.11
13	0.14	0.13	0.14	0.14
14	0.16	0.17	0.17	0.17
15	0.13	0.13	0.13	0.13
16	0.10	0.09	0.10	0.10
17	0.18	0.19	0.20	0.19
18	0.12	0.13	0.15	0.13
19	0.14	0.14	0.14	0.14
20	0.15	0.17	0.18	0.17
21	0.12	0.13	0.15	0.13
22	0.12	0.12	0.14	0.13
23	0.11	0.12	0.12	0.12
24	0.13	0.13	0.14	0.13
25	0.14	0.15	0.15	0.15
26	0.14	0.15	0.15	0.15
Average	0.13	0.13	0.14	0.13

C.D. at 5 % level of significance : 0.0140

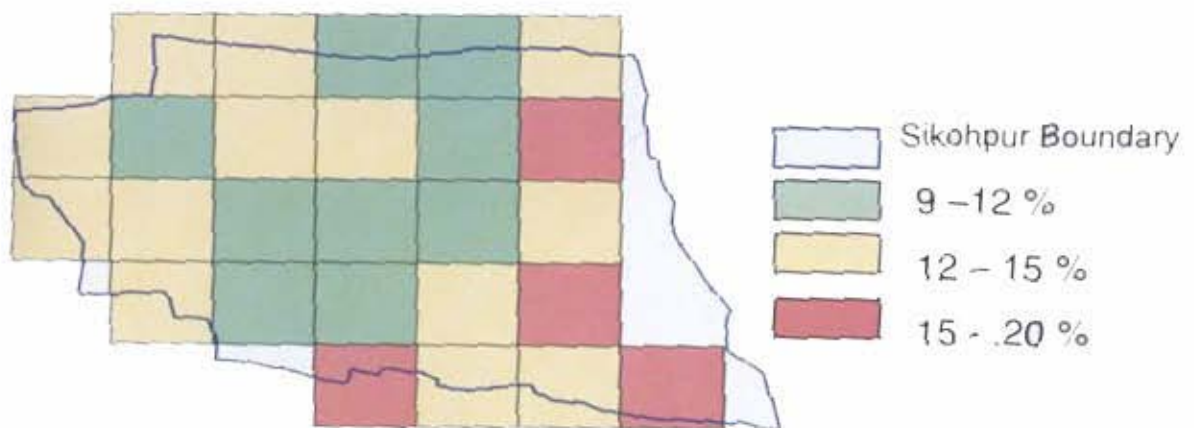
C.D. at 1 % level of significance : 0.0185



(a) 0-15 cm

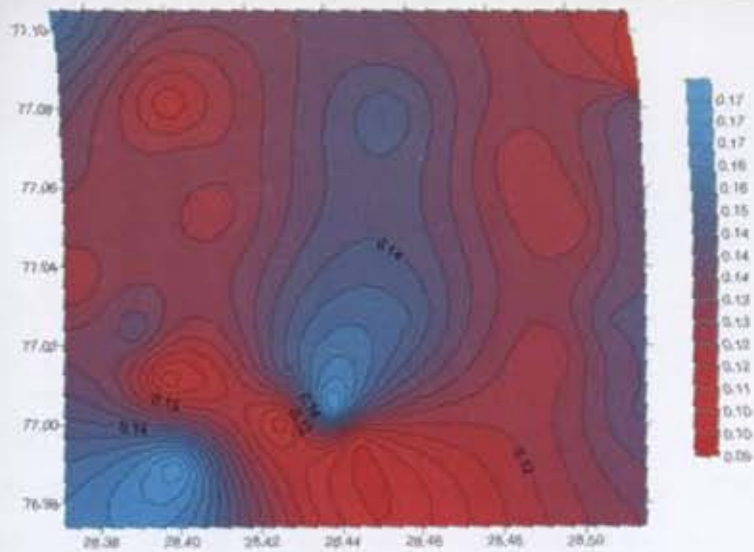


(b) 15-30 cm

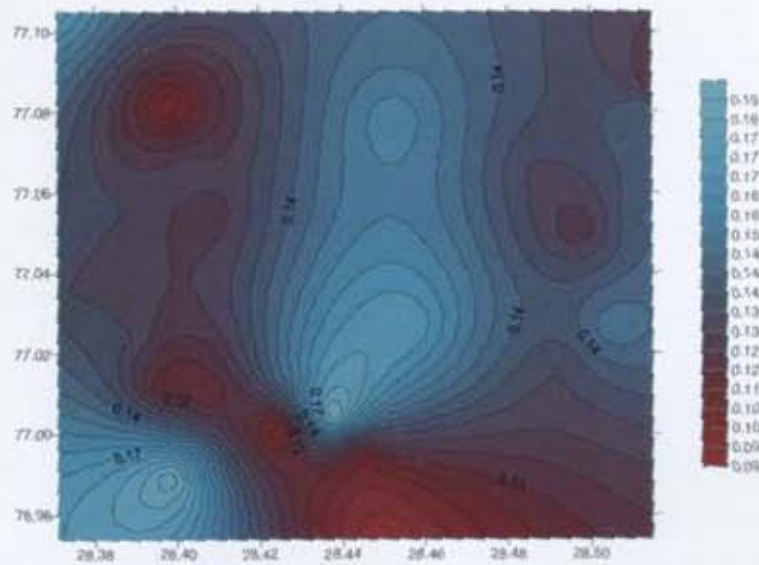


(c) 30-60 cm

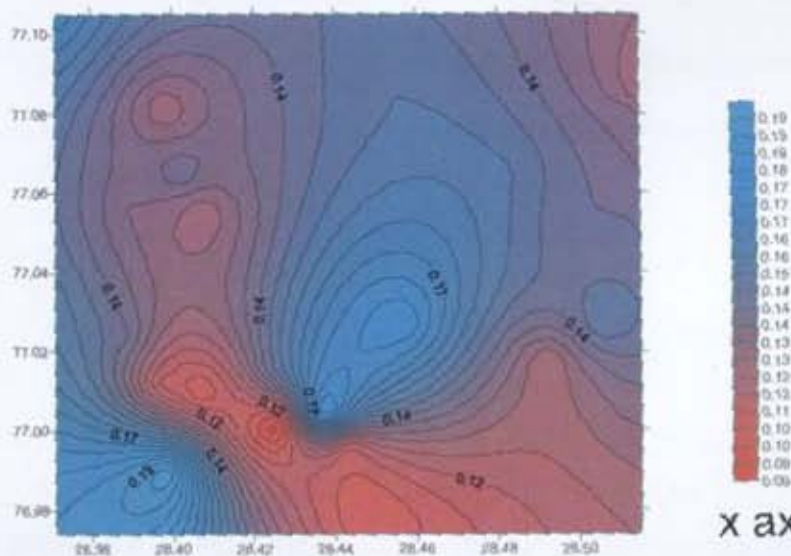
Fig 13: Thematic map of Available water capacity (AWC) for (a) 0-15 cm layer (b) 15-30 cm layer and (c) 30-60 cm layer



(a) 0-15 cm



(b) 15-30 cm



(c) 30-60 cm

x axis - latitude

Y axis - longitude

Fig 14: Spatial variability of Available water capacity (AWC) in watershed

4.2.4 Soil moisture retention

The data on soil moisture retention at different suctions is furnished in Table 9 (a, b and c) and Fig. 15 (a, b, c and d).

Tables 9 (a and b) indicates that for all the grids, the soil moisture was almost equal in all the three depths at 10 kPa. Similar observations were found at other suction values namely 33, 50 and 100 kPa. In all the three depths, the variations in moisture content among different grids was between 16% to 30% at 10 kPa, 14% to 27% at 33 kPa, 12% to 22% at 50 kPa and 8% to 17% at 100 kPa. The average over the grids, the moisture contents in the three depth layers were 22%, 22% and 23% at 10 kPa, 18%, 19% and 20% at 33 kPa, 15%, 16% and 17% at 60 kPa and 12%, 12% and 13% at 100 kPa. This shows that there was no variation in Ψ - θ values for different depths. However, there is sufficient variations among grids for a given depth.

Table 9(c) also indicate that soil moisture content in all the depth, was almost equal at higher suctions (500 and 1500 kPa). The average, over grids, the moisture contents in three depth layers were 9%, 10% and 10% at 500 kPa and 5%, 6% and 6% at 1500 kPa. The trend was similar to that of trend found at lower suction. But statistical analysis shows that there was a significant change in moisture content of soil profile of watershed at higher suction. In all the three depths the variations in moisture content were 7% to 13% at 500 kPa and 4% to 9% at 1500 kPa.

4.2 Assessment of crop growth and yield using crop growth simulation model

Results on simulated growth and yield of different crops are presented cropwise under the following subsections

4.2.1 Simulation of pearl millet yield

Simulation of growth and yield of pearl millet was done using DSSAT 35 software. Actual observations on crop growth variables were collected for the year 2004 and simulation was carried out for the year 2004. The cultivation practices used by the farmers were described in the experimental file (Table 10). The variety of pearl millet grown in this area was BJ-104. Only one irrigation was given at 20 days after sowing (DAS) because it was a rainfed crop and about 290 mm rainfall occurred during the cropping period of that year. The soils file generated using the soil properties

Table 9a. Volumetric water content at 10 kPa and 33 kPa suctions in three depth layers for 26 grids

Grid ID	Volumetric water content (m ³ /m ³)							
	10 kPa				33 kPa			
	0-15	15-30	30-60	Average	0-15	15-30	30-60	Average
1	0.16	0.17	0.17	0.17	0.13	0.15	0.15	0.14
2	0.19	0.19	0.20	0.19	0.17	0.18	0.18	0.18
3	0.17	0.19	0.19	0.18	0.15	0.16	0.17	0.16
4	0.22	0.23	0.23	0.23	0.19	0.20	0.19	0.19
5	0.20	0.21	0.21	0.21	0.18	0.18	0.19	0.18
6	0.16	0.16	0.17	0.16	0.14	0.15	0.15	0.15
7	0.21	0.22	0.22	0.22	0.17	0.17	0.18	0.17
8	0.26	0.27	0.27	0.27	0.21	0.23	0.22	0.22
9	0.29	0.30	0.31	0.30	0.26	0.28	0.28	0.27
10	0.20	0.22	0.21	0.21	0.17	0.18	0.18	0.18
11	0.21	0.21	0.22	0.21	0.18	0.17	0.18	0.18
12	0.18	0.18	0.20	0.19	0.15	0.16	0.17	0.16
13	0.23	0.23	0.24	0.23	0.19	0.19	0.21	0.20
14	0.28	0.30	0.31	0.30	0.23	0.24	0.26	0.24
15	0.21	0.21	0.22	0.21	0.18	0.18	0.19	0.18
16	0.19	0.19	0.20	0.19	0.16	0.15	0.17	0.16
17	0.27	0.28	0.30	0.28	0.23	0.25	0.27	0.25
18	0.21	0.23	0.23	0.22	0.18	0.19	0.22	0.20
19	0.23	0.23	0.24	0.23	0.19	0.19	0.19	0.19
20	0.27	0.28	0.31	0.29	0.22	0.24	0.25	0.24
21	0.18	0.19	0.22	0.20	0.15	0.16	0.19	0.17
22	0.20	0.20	0.21	0.20	0.17	0.17	0.19	0.18
23	0.19	0.21	0.22	0.21	0.16	0.17	0.18	0.17
24	0.23	0.23	0.25	0.24	0.19	0.19	0.21	0.20
25	0.21	0.22	0.24	0.22	0.18	0.19	0.20	0.19
26	0.24	0.26	0.27	0.26	0.19	0.20	0.21	0.20
Average	0.22	0.22	0.23	0.22	0.18	0.19	0.20	0.19
CD at 5%				0.0211				0.0179
CD at 1%				0.0280				0.0238

Table 9b. Volumetric water content at 50 kPa and 100 kPa suctions in three depth layers for 26 grids

Grid ID	Volumetric water content (m ³ /m ³)							
	50 kPa				100 kPa			
	0-15	15-30	30-60	Average	0-15	15-30	30-60	Average
1	0.11	0.12	0.12	0.12	0.08	0.09	0.08	0.08
2	0.15	0.17	0.16	0.16	0.11	0.12	0.11	0.11
3	0.14	0.16	0.15	0.15	0.10	0.11	0.12	0.11
4	0.17	0.18	0.18	0.18	0.12	0.14	0.13	0.13
5	0.15	0.15	0.16	0.15	0.11	0.11	0.11	0.11
6	0.12	0.12	0.13	0.12	0.09	0.09	0.09	0.09
7	0.15	0.15	0.16	0.15	0.11	0.12	0.12	0.12
8	0.17	0.19	0.18	0.18	0.13	0.14	0.14	0.14
9	0.21	0.22	0.23	0.22	0.16	0.18	0.18	0.17
10	0.13	0.13	0.14	0.13	0.11	0.12	0.12	0.12
11	0.15	0.16	0.16	0.16	0.12	0.13	0.14	0.13
12	0.12	0.12	0.13	0.12	0.10	0.11	0.12	0.11
13	0.15	0.16	0.18	0.16	0.11	0.11	0.14	0.12
14	0.19	0.20	0.21	0.20	0.15	0.16	0.17	0.16
15	0.15	0.14	0.15	0.15	0.11	0.12	0.13	0.12
16	0.14	0.15	0.16	0.15	0.11	0.12	0.15	0.13
17	0.19	0.18	0.21	0.19	0.15	0.16	0.19	0.17
18	0.15	0.16	0.18	0.16	0.13	0.13	0.14	0.13
19	0.16	0.16	0.17	0.16	0.14	0.14	0.16	0.15
20	0.19	0.20	0.20	0.20	0.16	0.16	0.17	0.16
21	0.11	0.11	0.14	0.12	0.09	0.09	0.11	0.10
22	0.14	0.15	0.16	0.15	0.11	0.11	0.12	0.11
23	0.13	0.15	0.16	0.15	0.10	0.11	0.12	0.11
24	0.16	0.16	0.17	0.16	0.12	0.12	0.13	0.12
25	0.15	0.16	0.17	0.16	0.13	0.13	0.14	0.13
26	0.16	0.17	0.18	0.17	0.12	0.12	0.14	0.13
Average	0.15	0.16	0.17	0.16	0.12	0.12	0.13	0.13
CD at 5%				0.0211				0.0179
CD at 1%				0.0280				0.0238

Table 9c. Volumetric water content at 500 kPa and 1500 kPa suctions in three depth layers for 26 grids

Grid ID	Volumetric water content (m^3/m^3)							
	500 kPa				1500 kPa			
	0-15	15-30	30-60	Average	0-15	15-30	30-60	Average
1	0.06	0.08	0.07	0.07	0.03	0.05	0.06	0.05
2	0.09	0.10	0.09	0.09	0.06	0.07	0.08	0.07
3	0.08	0.09	0.09	0.09	0.04	0.06	0.05	0.05
4	0.10	0.12	0.10	0.11	0.05	0.06	0.06	0.06
5	0.08	0.09	0.09	0.09	0.04	0.04	0.05	0.04
6	0.07	0.08	0.09	0.08	0.04	0.04	0.04	0.04
7	0.09	0.08	0.09	0.09	0.05	0.05	0.06	0.05
8	0.10	0.11	0.11	0.11	0.06	0.07	0.07	0.07
9	0.11	0.12	0.12	0.12	0.08	0.09	0.09	0.09
10	0.09	0.09	0.10	0.09	0.05	0.05	0.06	0.05
11	0.08	0.08	0.09	0.08	0.04	0.04	0.05	0.04
12	0.08	0.08	0.09	0.08	0.05	0.05	0.06	0.05
13	0.09	0.09	0.12	0.10	0.05	0.06	0.07	0.06
14	0.11	0.13	0.15	0.13	0.07	0.07	0.09	0.08
15	0.09	0.09	0.10	0.09	0.05	0.05	0.06	0.05
16	0.10	0.11	0.13	0.11	0.06	0.06	0.07	0.06
17	0.11	0.12	0.15	0.13	0.05	0.06	0.07	0.06
18	0.09	0.10	0.12	0.10	0.06	0.06	0.07	0.06
19	0.11	0.11	0.12	0.11	0.05	0.05	0.05	0.05
20	0.12	0.12	0.13	0.12	0.07	0.07	0.07	0.07
21	0.06	0.07	0.08	0.07	0.03	0.03	0.04	0.03
22	0.08	0.08	0.09	0.08	0.05	0.05	0.05	0.05
23	0.08	0.08	0.09	0.08	0.05	0.05	0.06	0.05
24	0.09	0.10	0.10	0.10	0.06	0.06	0.07	0.06
25	0.08	0.08	0.10	0.09	0.04	0.04	0.05	0.04
26	0.09	0.09	0.11	0.10	0.05	0.05	0.05	0.05
Average	0.09	0.10	0.10	0.10	0.05	0.06	0.06	0.06
CD at 5%				0.009				0.006
CD at 1%				0.0128				0.009

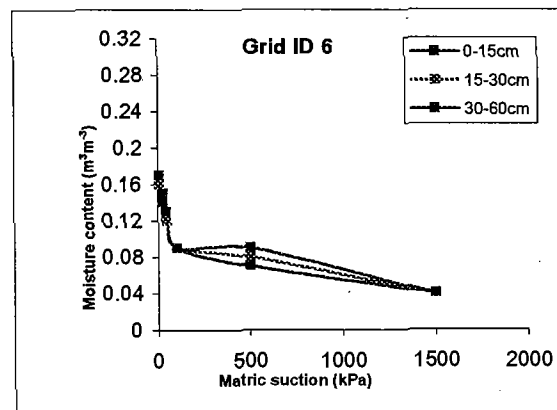
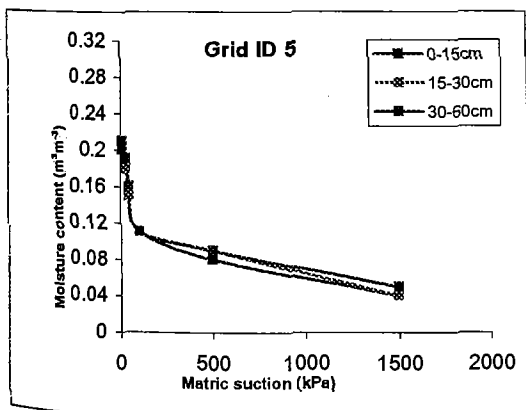
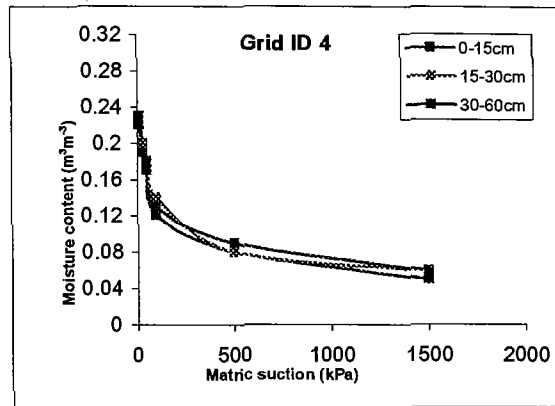
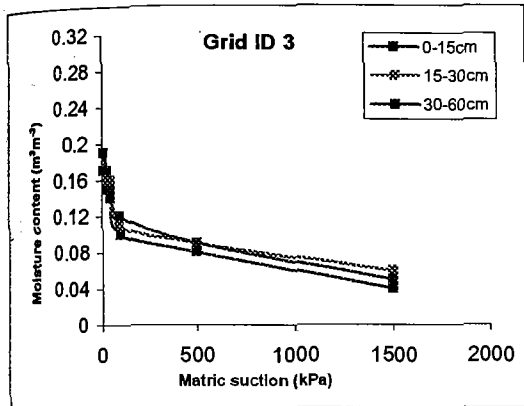
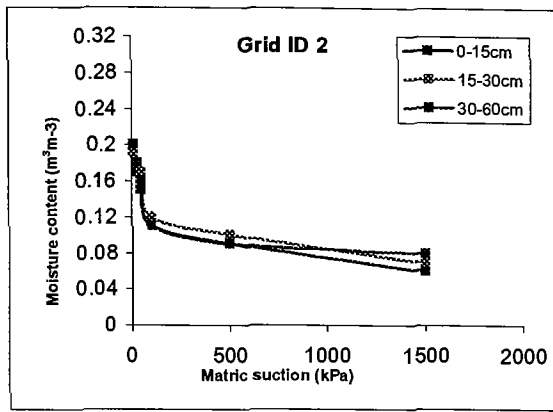
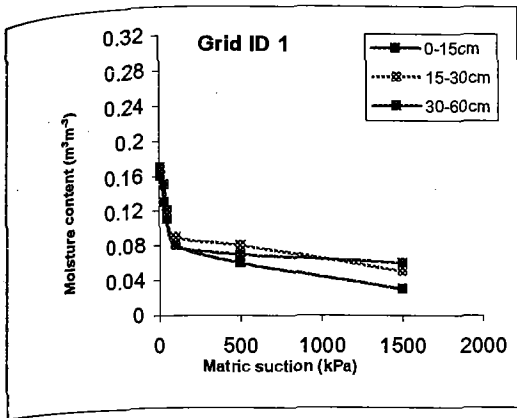


Fig 15(a): Soil moisture characteristic curve of 26 grids (grid ID 1-6)

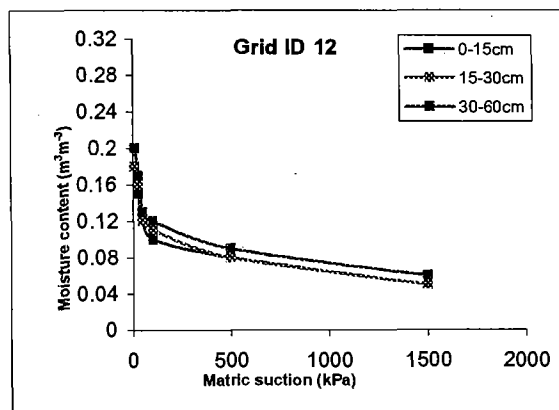
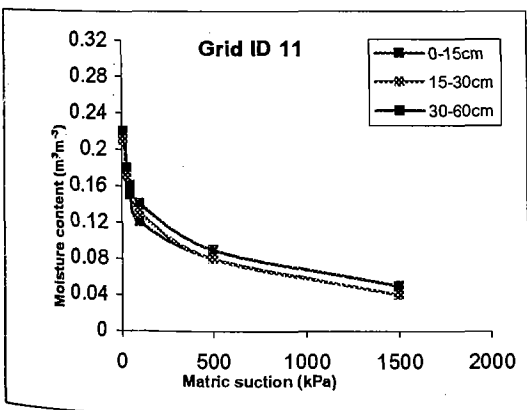
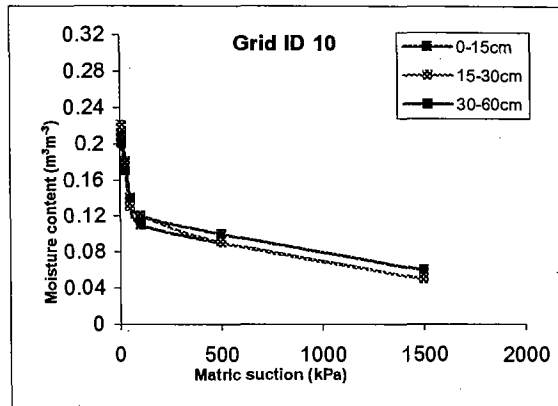
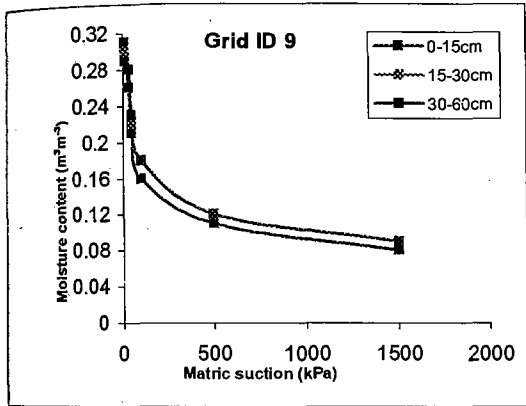
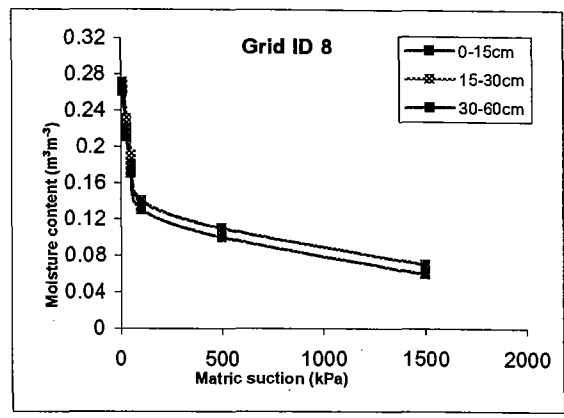
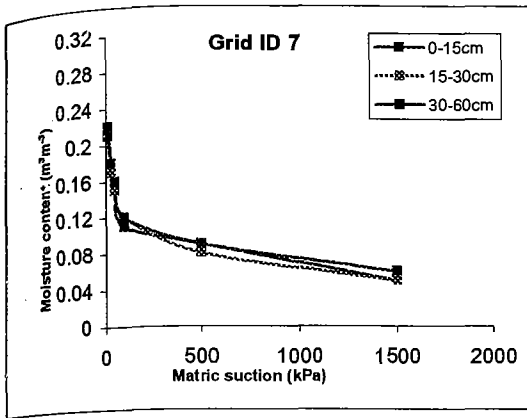


Fig 15(b): Soil moisture characteristic curve of 26 grids (grid ID 7-12)

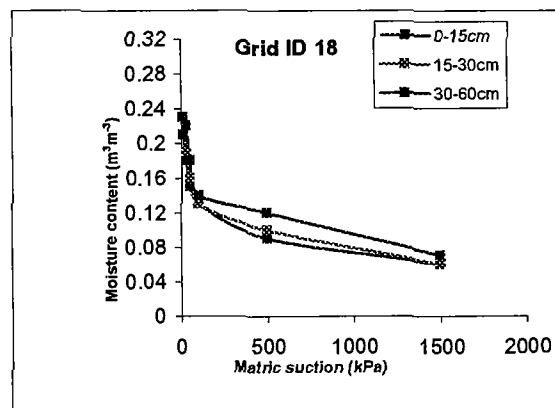
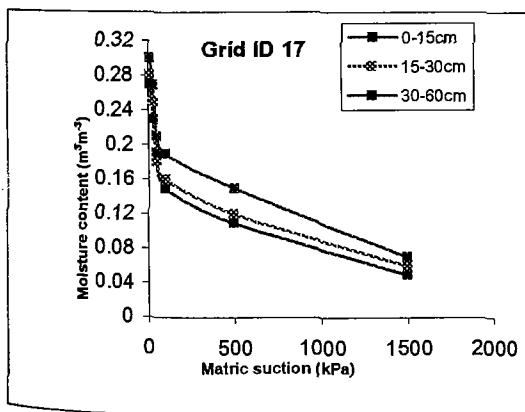
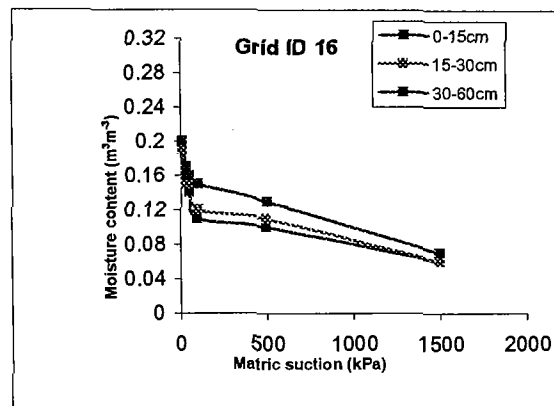
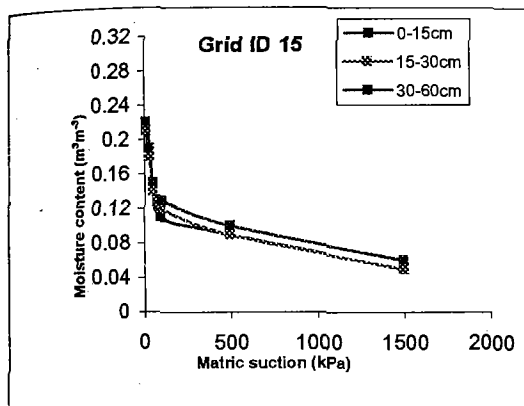
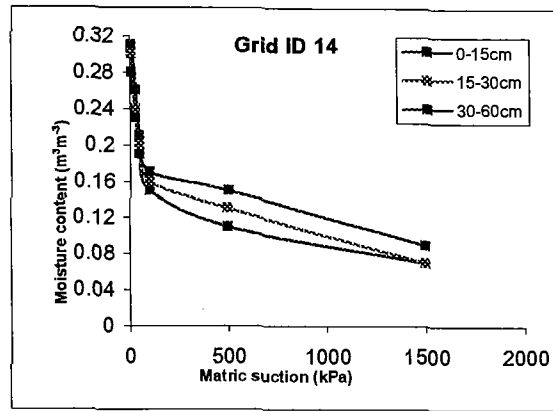
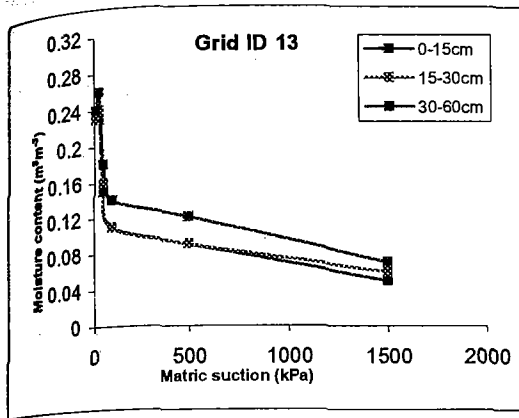


Fig 15(c): Soil moisture characteristic curve of 26 grids (grid ID 13-18)

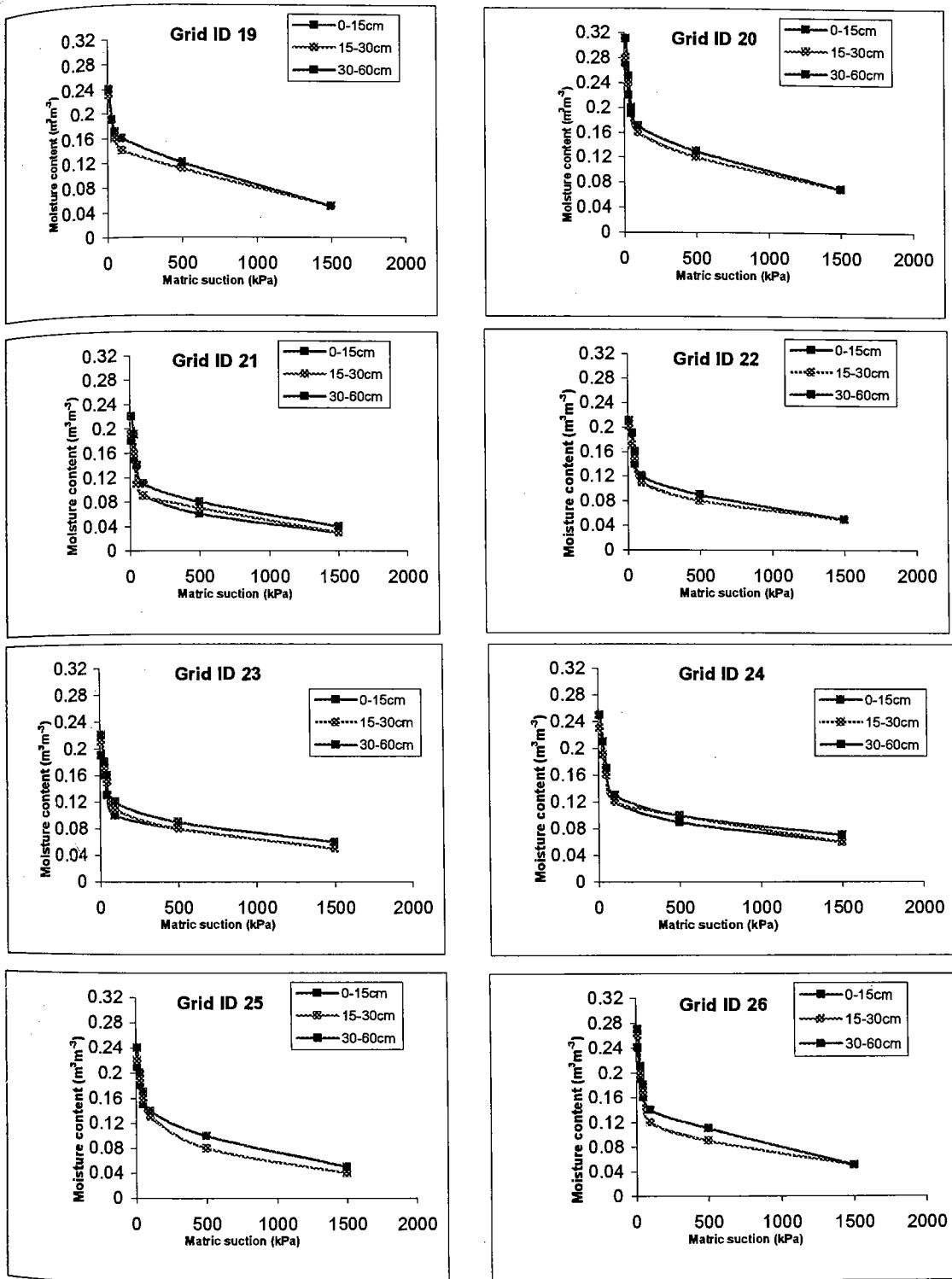


Fig 15(d): Soil moisture characteristic curve of 26 grids (grid ID 19-26)

Table 10. Summary of experiment file for pearl millets

Cultivar	BJ-104
Soil texture	Sandy loam
Soil analysis date	15.07.04
Previous crop	Fallow
Planting date	20.07.04
Emergence date	25.07.04
Plant population at emergence/m ²	8
Planting material	Seed
Row spacing	45 cm
Planting depth	4.0 cm
Seed rate	4 kg/ha
Irrigation	One (20 DAS)
Fertilizer	Urea @ 100 kg N/ha(N)
Harvest date	15.10.04

analysis of each grid was selected as input soil file. The weather data used for this simulation was that of 2004.

The genetic coefficient values used for this simulation were obtained from Gencalc which are shown in Table 11. These values were tuned in such a way that simulated and observed growth values were in agreement during validation of the model.

Table 11. Genetic coefficient used for pearl millet

Genetic coefficient*	Value
P1	140.0
P20	12.0
P2R	130.0
P5	370.0
G1	2.0
G4	0.50
PHINT	43.0

* Genetic coefficient codes are given in Table 5.

When the simulated grain yield was compared with the observed yield of the crop (Table 12) and (Fig. 16), it revealed that the simulated yield was about 6% less than the observed value. The difference in observed and predicted biomass at floral initiation as well as at anthesis stages was about 7%. The simulated final biomass was 5% underestimated as compared to observed biomass (Table 12). The predicted and observed LAI at different development stages are shown in Table 12 and Fig. 16. The observed values of LAI at floral initiation stage anthesis and at harvest were 2.12, 6.06 and 4.17 respectively as compared to simulated value of 1.9, 5.34 and 3.42 at above growth stages (Table 12). The simulated LAI were averagely 10% lower than the observed LAI.

Table 12. LAI, Biomass and Yield of pearl millet at different stages

Stages	LAI		Biomass (kg/ha)		Yield (kg/ha)	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Floral initiation	1.9	2.12	2041	2190		
Anthesis	5.34	6.06	9147	9210		
Harvest	3.42	4.17	14239	15016	1689	1807

Table 13 showed predicted and observed values of main growth and development variables of pearl millet. The values indicated that flowering occurred after 47 DAS in both predicted as well as observed cases. The simulation predicted that nitrogen content of biomass was reduced to 102 kg N/ha at harvest from 117 kg N/ha at anthesis.

The simulated dates of occurrences of phenological stages of crop and accumulation of biomass upto these stages are shown in Table 14. The rate of biomass accumulation was 119 kg/ha/day between end of juvenile and floral initiation and it increased sharply after that. The rate of biomass accumulation was maximum during vegetative growth stage (319 kg/ha/day) i.e. in between floral initiation and end of leaf growth. The accumulation of biomass was 2026 kg/ha, 7028 kg/ha and 4978 kg/ha during end of juvenile to floral initiation, floral initiation to end of leaf growth and end of panicle growth to harvest maturity, respectively.

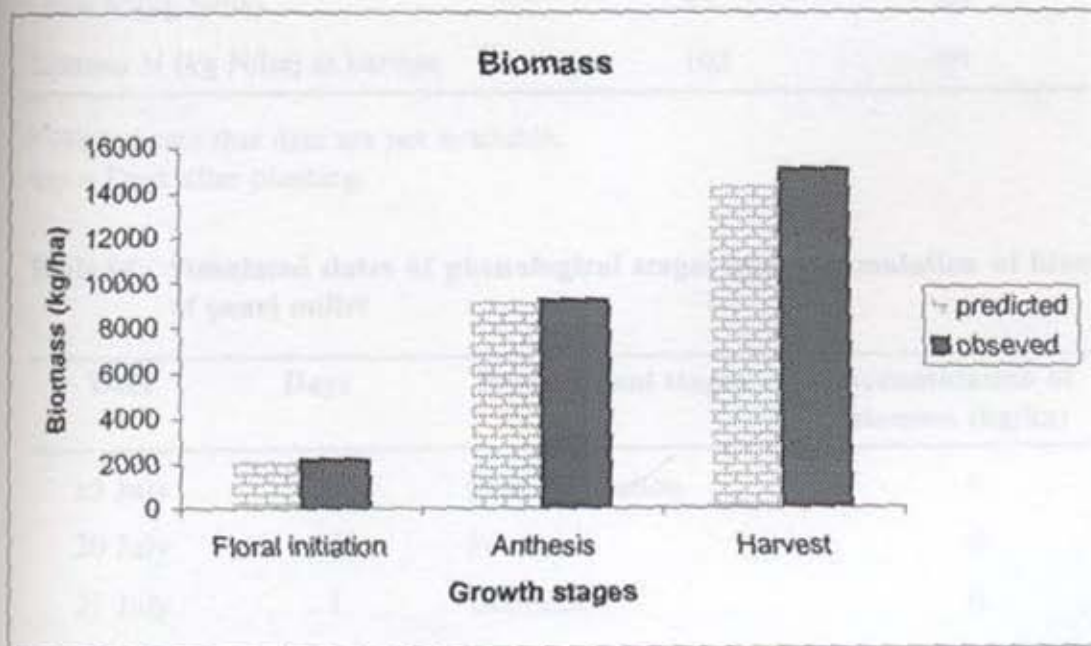
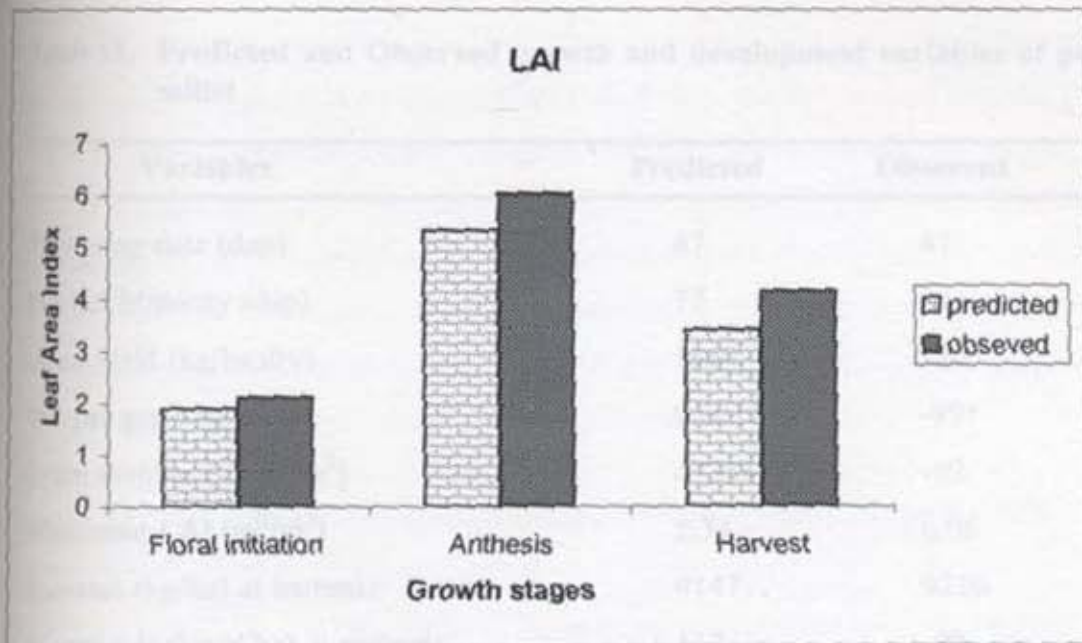


Fig 16: Predicted and Observed LAI and Biomass of Pearl millet

Table 13. Predicted and Observed growth and development variables of pearl millet

Variables	Predicted	Observed
Flowering date (dap)	47	47
Physiol Maturity (dap)	77	84
Grain yield (kg/ha;dry)	1689	1807
Wt. per grain (g; dry)	0.0012	-99*
Grain number (Grain/m ²)	47354	-99
Maximum LAI (m ² /m ²)	5.34	6.06
Biomass (kg/ha) at anthesis	9147	9210
Biomass N (kg N/ha) at anthesis	117	-99
Biomass (kg/ha) at harvest	14259	15016
Grain N (kg N/ha)	5	-99
Biomass N (kg N/ha) at harvest	102	-99

* -99 indicate that data are not available.

dap = Days after planting.

Table 14. Simulated dates of phenological stages and accumulation of biomass of pearl millet

Date	Days	Phenological stages	Accumulation of biomass (kg/ha)
15 July	0	Start Simulation	0
20 July	0	Sowing	0
21 July	1	Germinate	0
24 July	4	Emergence	2
31 July	11	End Juvenile	15
17 August	28	Floral Initiation	2041
8 Sept.	50	End Leaf Growth	9069
10 Sept.	52	End of Anthesis	9147
15 Sept.	57	End Panicle Growth	9281
14 Oct.	86	Harvest Maturity	14259

Table 15 showed the number of days crop has taken to complete various phenological stages. It showed that crop took 7 days to attain end of juvenile phase from emergence, under the weather conditions of 36.4°C average maximum temperature, 27.4°C average minimum temperature and 18.24 MJ/m²/day average solar radiation for this period. It took 17 days from the end of juvenile phase to achieve floral initial stage 22 days from floral initiation to end of leaf growth, 7 days from end of leaf growth to beginning of grain filling stage and 28 days in grain filling phase. The average weather variables during these periods of growth are shown in Table 15.

Table 15. Simulated days between two phenological stages of pearl millet

Development phase	Time duration (days)	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ/m²/day)
Emergence-End Juvenile	7	36.4	27.4	18.24
End Juvenile-Floral Initiation	17	33.2	26.7	18.46
Floral Initiation-End Leaf Growth	22	33.1	25.7	19.92
End Leaf Growth-Beg Grain Filling	7	36.1	26.0	20.97
Grain Filling Phase	28	32.6	22.4	18.25

The model simulation of pearl millet growth and yield shows agreement with the observed values. However, the model simulated somewhat lower values of biomass and LAI at different growth stages. This resulted in about 6% underestimation of yield. In simulation technique at watershed scale, this much variation in simulated values is acceptable. It showed that the model calibration was good and this calibrated model is fit to be used for optimum cropping sequence evaluation and the assessment of long term weather effects on the optimum sequence.

The yield of pearl millet was simulated in each of the 26 grids and using the yield for each grid, an yield map for the watershed was prepared with the help of the

Arc-view GIS software. This map is shown in Figure 17. It showed that crop yield in different grids varied from 1684 to 1732 kg/ha with an average value of 1702 kg/ha. These values were classified into 3 arbitrarily classes of low yield -1684 to 1696 kg/ha., medium yield - 1697 to 1709 kg/ha and high yield - 1710 to 1732 kg/ha, where the low medium and high are relative terms. The yield map for grids showed that if whole watershed is cultivated with pearl millet, the area under low, medium and high classes would be 42%, 30% and 28% of total area of watershed, respectively. This implies that the majority of the area produces low yields of pearl millet and only 28% area is capable of producing higher yield due to variation in soil physical properties.

The spatial variability analysis of the yield for this watershed was carried out using Surfer-6.2 software. Yields were interpolated at 2 kg/ha interval and contours for equal yields were drawn (Fig. 18). This contour map helps in identifying the high yielding and low yielding areas of the watershed for pearl millet. The identified low yield areas should either be improved in soil quality through management practices or an alternative crop may be adopted for this area for enhancing monetary benefit for the farmer.

4.2.2 Simulation of wheat yield

Actual observations on wheat growth variables were collected for the *rabi* season of the year 2004-05. The details of crop cultivation (e.g. sowing date etc.) and management practices used for wheat crop are shown in Table 16. The wheat cultivar sown in the farmer's field was Sonalika. It was planted on 19.11.04 and harvested on 25.03.05. Seed rate used was 100 kg/ha with row spacing 22 cm. Five irrigations were given at 21, 45, 61, 80 and 105 DAS. Crop received about 50 mm of rainfall during the cropping period. Fertilizer in the form of urea @ 125 kg N/ha was applied in 3 split doses : before sowing, 21 DAS and 45 DAS. The weather data used for this simulation was that of 2004-05.

The crop genetic coefficient values used in genotype file of wheat for running the model were 2.0 (PIV), 3.2 (PID), 7.5 (P5), 5.0 (G1), 1.0 (G2), 1.7 (G3) and 60.0 (PHINT) (Table 17). All the coefficients definition is given in Table 5.

The predicted and observed values of LAI, biomass and yield of different phenological stage are shown in Table 18 and Fig. 19. The simulated LAI were somewhat lower than the observed LAI at all the growth stages. It was about 15%, 6% and 13%

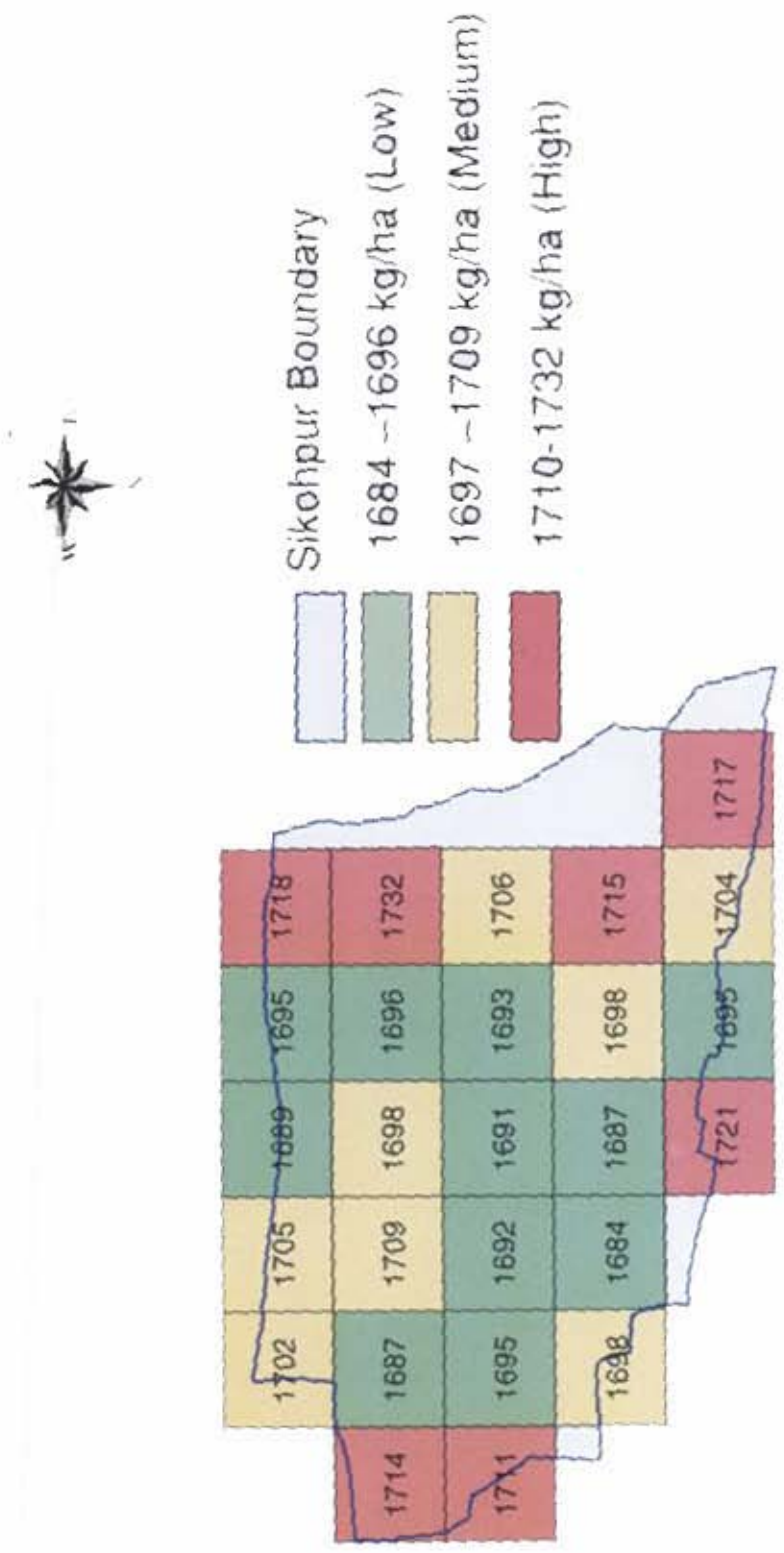


Fig 17: Thematic map of pearl millet yield (kg/ha) for watershed

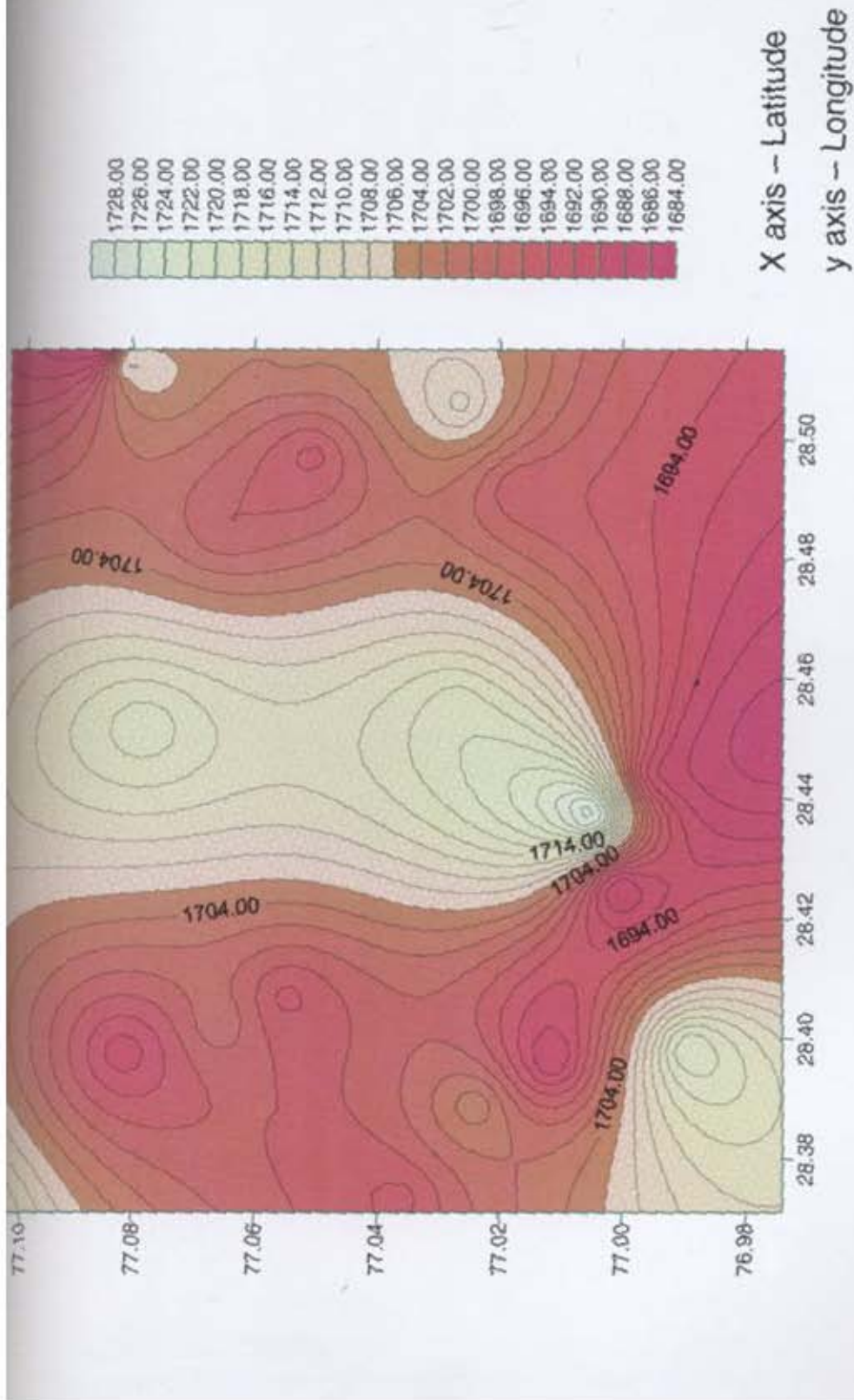


Fig 18: Spatial variability of Pearlmillet yield (kg/ha) in watershed

Table 16. Summary of experiment file for wheat

Cultivar	Sonalika
Soil texture	Sandy loam
Soil analysis date	25.10.04
Previous crop	Pearl millet
Planting date	19.11.04
Emergence date	25.11.04
Plant population at emergence/m ²	40
Planting material	Seed
Row spacing	22 cm
Planting depth	5.0 cm
Seed rate	100 kg/ha
Irrigation	Five, 21, 45, 61, 90 and 105 DAS
Fertilizer	Urea @ 125 kg N/ha
Harvest date	25.03.05

Table 17. Genetic coefficient used for wheat

Genetic coefficient*	Value
P1V	2.0
P1D	3.2
P5	7.5
G1	5.0
G2	1.0
G3	1.7
PHINT	60.0

* Genetic coefficient codes are given in Table 5.

Table 18. LAI, Biomass and Yield of wheat at different stages

Stages	LAI		Biomass (kg/ha)		Yield (kg/ha)	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Tillering	0.81	0.95	422	480		
Flowering	3.87	4.12	2040	2130		
Maturity	1.89	2.17	6688	7040	3622	3780

lower than the measured values at tillering, flowering and maturity stages, respectively. The same trend was seen for biomass prediction. The simulated biomass at tillering, flowering and maturity were about 12%, 7% and 5% lower than the observed biomass at the respective stages. The simulated yield of the crop was found 158 kg/ha less than the observed value (Table 18). The average values of simulated LAI, biomass and grain yield were 11%, 8% and 4% lower than the respective observed value.

All the growth variables were slightly under estimated by the model except flowering date (Table 19) which was same as (79 DAS) observed date of flowering. The simulated value of grain numbers per square meter was 2210 whereas observed value which was about 4% higher than that of simulated value.

Table 19. Predicted and Observed growth and development variables of Wheat

Variables	Predicted	Observed
Flowering date (dap)	79	79
Physiological maturity (dap)	115	118
Grain yield (kg/ha; dry)	3622	3780
Wt. per grain (g; dry)	0.09	0.08
Grain number (Grain/m ²)	2210	2315
Maximum LAI (m ² /m ²)	3.87	4.12
Biomass (kg/ha) at anthesis	2040	2130
Biomass N (kg N/ha) at anthesis	16	-99
Biomass (kg/ha) at harvest	6688	7040
Grain N (kg N/ha)	10	-99
Biomass N (kg N/ha) at harvest	14	-99

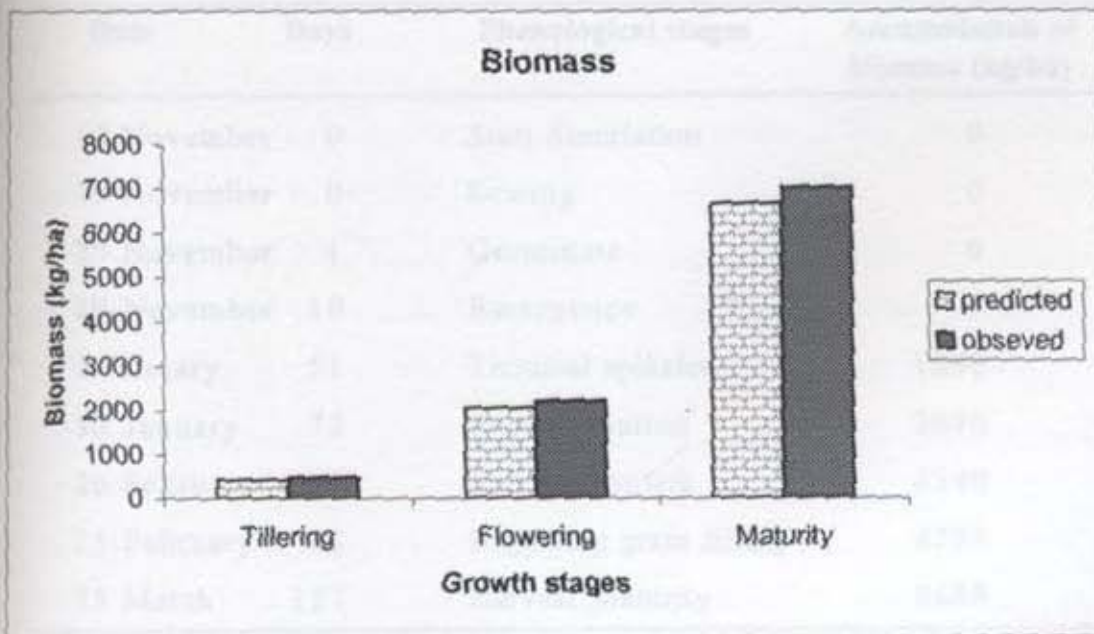
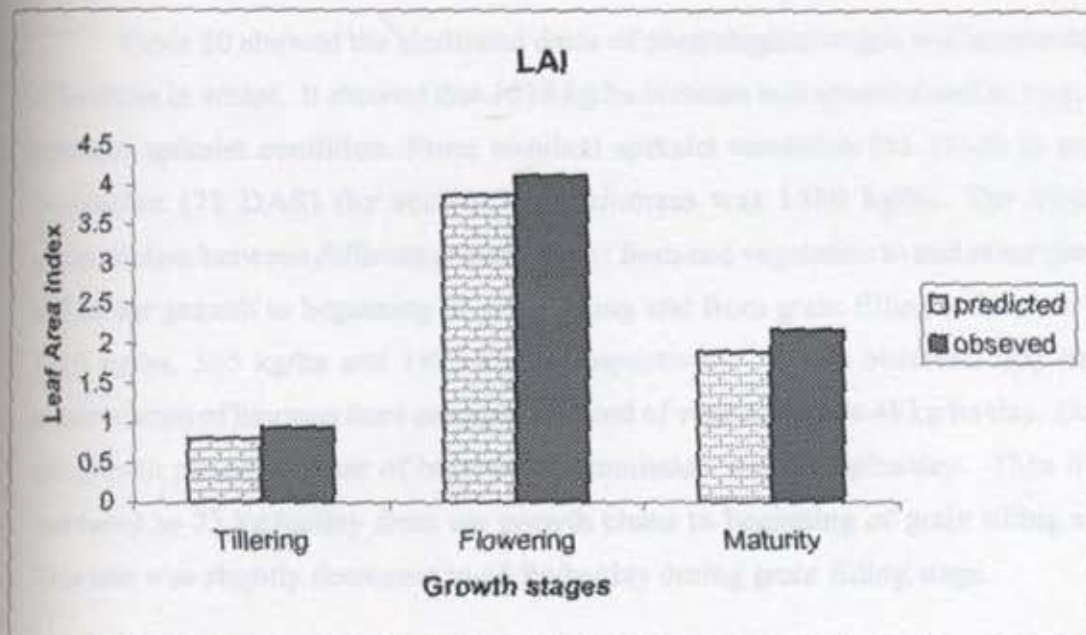


Fig 19: Predicted and Observed LAI and Biomass of Wheat

Table 20 showed the simulated dates of phenological stages and accumulation of biomass in wheat. It showed that 1015 kg/ha biomass was accumulated in crop upto terminal spikelet condition. From terminal spikelet condition (51 DAS) to end of vegetation (72 DAS) the accumulated biomass was 1380 kg/ha. The biomass accumulation between different growth stage : from end vegetation to end of ear growth, end of ear growth to beginning of grain filling and from grain filling to harvest were 1310 kg/ha, 365 kg/ha and 1983 kg/ha, respectively. It was observed that rate of accumulation of biomass from emergence to end of vegetation was 48 kg/ha/day. During ear growth phase, the rate of biomass accumulation was 62 kg/ha/day. Then it was increased to 73 kg/ha/day from ear growth phase to beginning of grain tilling stage. This rate was slightly decreased to 68 kg/ha/day during grain filling stage.

Table 20. Simulated dates of phenological stages and accumulation of biomass in wheat

Date	Days	Phenological stages	Accumulation of biomass (kg/ha)
10 November	0	Start Simulation	0
19 November	0	Sowing	0
20 November	1	Germinate	0
29 November	10	Emergence	5
9 January	51	Terminal spikelet	1650
30 January	72	End vegetation	3030
20 February	93	End ear growth	4340
25 February	98	Beginning grain filling	4705
25 March	127	Harvest Maturity	6688

Results on stimulated days between two successive phenological stages of wheat (Table 21) indicated that crop took 41 days from emergence to terminal spikelet (vegetative stage) under weather variable having average maximum temperature of 22.0°C, average minimum temperature of 8.4°C and average solar radiation of 9.10 MJ/m²/day. Crops completed ear growth phase of its life cycle in 13 days after getting average maximum temperature of 17°C, minimum temperature of 6.8°C and solar

Table 21. Simulated days between two phenological stages of wheat

Development phase	Time duration (days)	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ/m²/day)
Emergence-terminal spikelet	41	22.0	8.4	9.10
End vegetation-beginning ear growth	8	19.7	6.2	11.23
Beginning ear-End ear Growth	13	17.0	6.8	11.29
End Ear Growth-Beg Grain Filling	5	21.4	9.3	14.07
Grain Filling Phase	24	23.5	10.3	17.17

radiation of 11.29 MJ/m²/day. It took 24 days to complete its grain filling phase. During that phase crop experienced average maximum temperature 23.5°C, average minimum temperature 10.4°C and average solar radiation 17.17 MJ/m²/day.

The simulated and observed values of growth and yield showed that model was correctly calibrated and was fit for evaluation of optimum cropping analysis and the assessment of long term weather effects of the optimum sequence.

The yield of the crop was simulated in each of the 26 grids with respective soil properties of each grid and then yield map was prepared with the help of Arc view GIS software which is shown in Fig 20. Figure 20 showed that the wheat yield varied from 3612 kg/ha to 3664 kg/ha in different grids which indicated a variation of about 1.4%. Its average value over all grids was 3635 kg/ha. The watershed is divided into 3 arbitrary classes on the basis of productivity of wheat yield. These classes were low, medium and high in relative terms. The low yield class has the yield range of 3612-3625 kg/ha, medium class has yield range 3626-3642 kg/ha and high yield class has yield production range of 3743-3664 kg/ha. The yield map indicates that 35% area of the watershed comes under low yield, 30% under medium productive area and 35% of the watershed comes under high productive area. The variation in wheat yield under different grids is

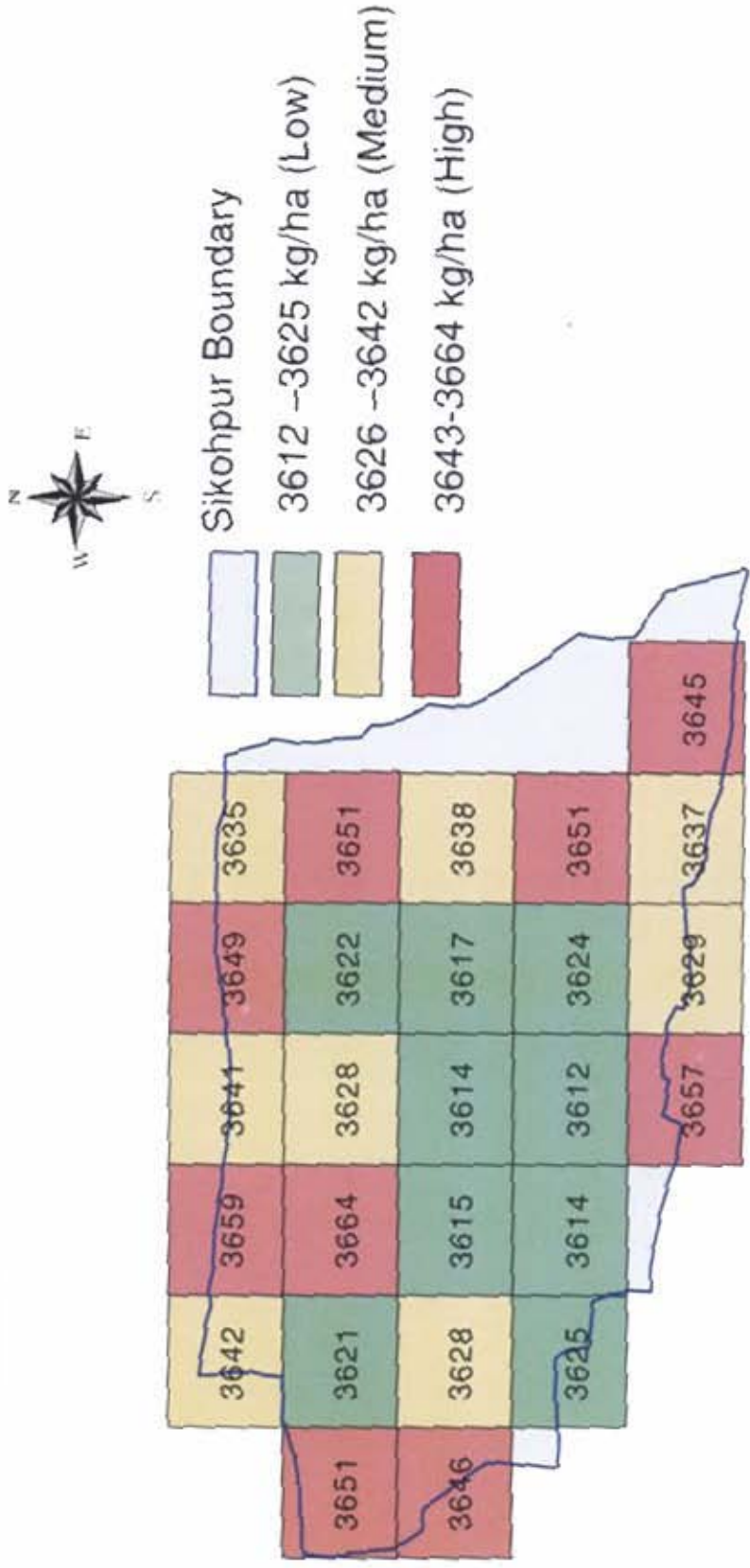


Fig 20: Thematic map of wheat yield (kg/ha) for watershed

about 1.4% and the area under the three classes of yield is almost equal. This indicates that there is not much spatial variation in wheat yield. In this watershed, uniform yields of about 3635 kg/ha are expected over whole watershed cultivated area.

The spatial variability map was prepared for whole watershed with the help of Surfer 6.2 software. Although the yield variation in the watershed is only of the order of 52 kg/ha, within this variation the contour lines at an interval of 5 kg/ha were drawn and shown in Figure 21. This figure indicates the little spatial variability existed in the yield over the cultivated area.

4.2.3 Simulation of chickpea yield

Chickpea crop was not widely grown in the watershed. However, in some localized parts of the watershed, it was cultivated on trial basis.

Simulation of growth and yield of chickpea was carried out with DSSAT 35 software. The crop was grown in the rabi season of year 2004-05. The observations on growth and yield variables of chickpea were collected from farmers field in the same year (2004-05). The experimental details for simulation of chickpea are shown in Table 22.

Table 22. Summary of experiment file for chickpea

Cultivar	G-130
Soil texture	Sandy loam
Soil analysis date	25.10.04
Previous crop	Pearl millet
Planting date	04.11.04
Emergence date	12.11.04
Plant population at emergence/m ²	25
Planting method	Seed
Row spacing	30 cm
Planting depth	8.0 cm
Seed rate	80 kg/ha
Irrigation	Two, 27 and 71 DAS
Fertilizer	Urea @ 50 kg N/ha
Harvest date	19.03.05

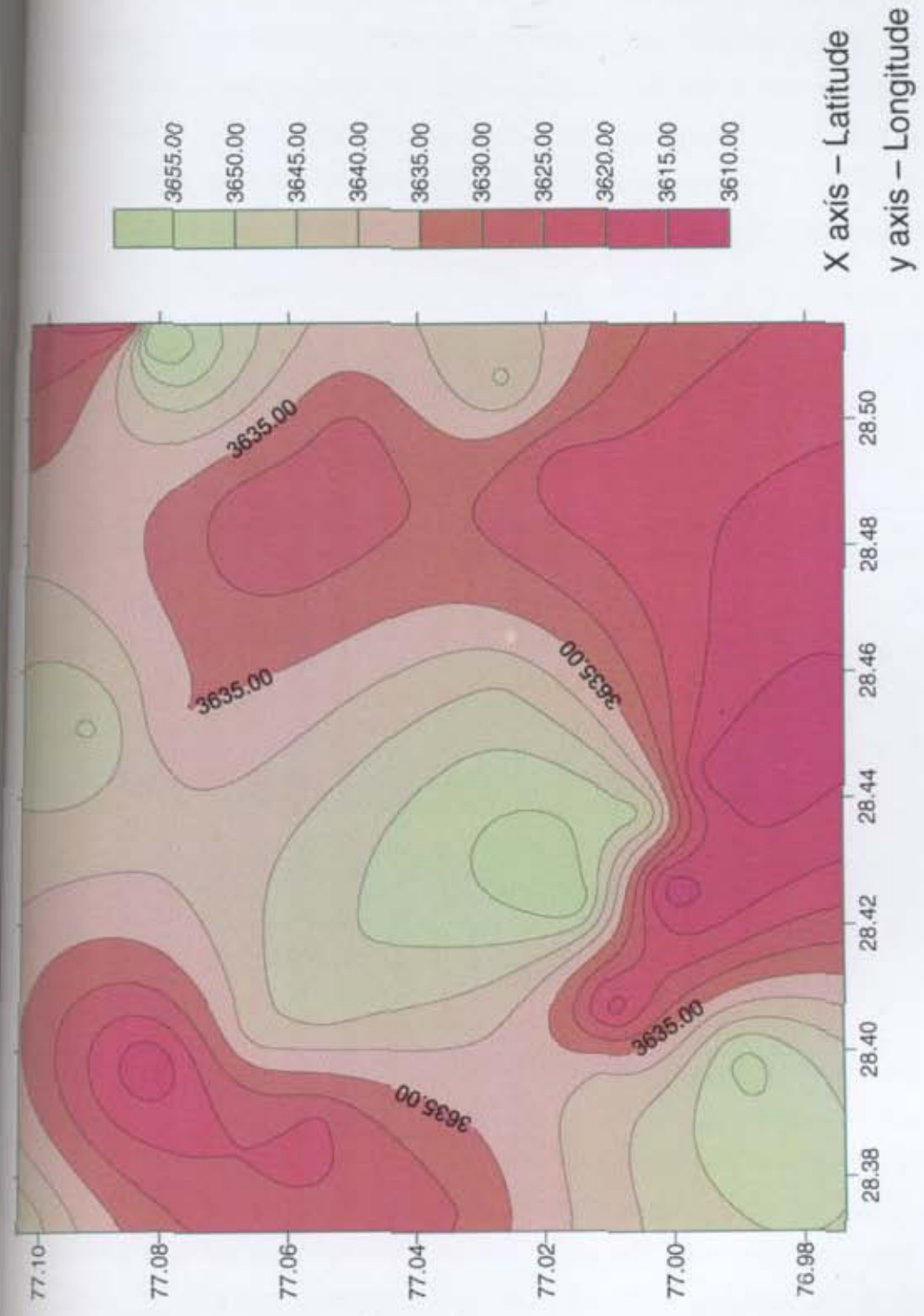


Fig 21: Spatial variability of wheat yield (kg/ha) in watershed

The farmers of the watershed had used G-130 cultivar of chickpea for cultivation. The crop was sown on 04.11.04 and harvested on 19.03.05. Two irrigations were given during its cropping period : first irrigation at 27 DAS and the second at 71 DAS. About 50 mm of rainfall was received by the crop during cropping period. Since it is a leguminous crop, low quantity of fertilizer in the form of urea @ 50 kg N/ha was applied in two split dose first before sowing and second at 27 days after sowing.

The values of different crop genetic coefficients of chickpea which were calculated using Gencalc are shown in Table 23. These values were used in the genotype file of the model for simulation of growth and yield of chickpea.

Table 23. Genetic coefficient used for chickpea

Genetic coefficient*	Value	Genetic coefficient	Value
CSDL	11.00	LFMAX	1.7
PPSEN	0.143	SLAVR	150
EM-FL	37.0	SIZLF	10.0
FL-SH	8.0	XFRT	1.00
FL-SD	15.0	WTPSD	0.181
SD-PM	38.00	SFDUR	29.0
FL-LF	42.00	SDPDV	1.20

* Genetic coefficient codes are given in Table 5.

The comparisons between simulated and observed yields are shown in Table 24 and Fig. 22. which revealed that simulated yield was 7% overestimated as compared to observed yield. The simulated biomass at vegetative, late flowering and at maturity were 5%, 12% and 6% higher than observed values of the biomass, respectively (Table 24). The observed and predicted values of LAI at different growth stages are given in Table 24 and shown in Figure 22. The observed values of LAI at vegetative, late flowering and maturity stages were 0.43, 2.65 and 1.73 respectively as compared to the predicted values of 0.54, 3.07 and 1.96 at the above growth stages. The simulated LAI was averagely 18% higher than observed LAI.

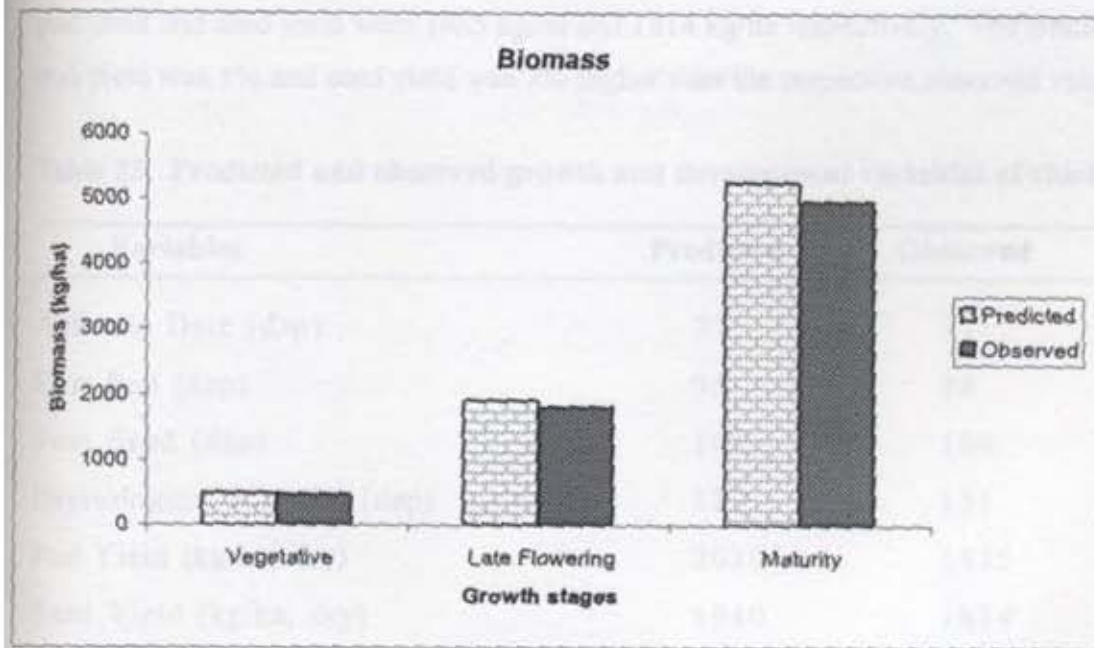
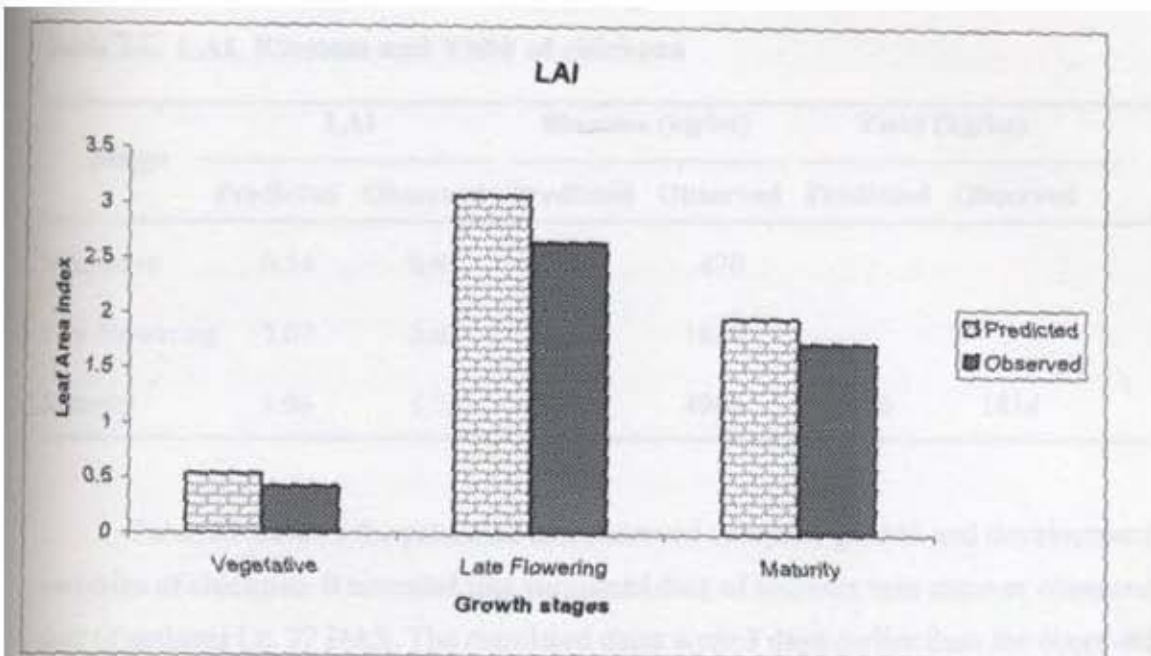


Fig 22: Predicted and Observed LAI and Biomass of Chickpea

Table 24. LAI, Biomass and Yield of chickpea

Stages	LAI		Biomass (kg/ha)		Yield (kg/ha)	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Vegetative	0.54	0.43	494	470		
Late Flowering	3.07	2.65	1918	1826		
Maturity	1.96	1.73	5264	4966	1940	1814

Table 25 showed the predicted and observed values of growth and development variables of chickpea. It revealed that simulated date of anthesis was same as observed date of anthesis i.e. 77 DAS. The simulated dates were 3 days earlier than the observed for both first pod formation stage and first seed formulation stage. The simulated pod yield and seed yield were 2030 kg/ha and 1940 kg/ha respectively whereas the observed pod yield and seed yield were 1935 kg/ha and 1814 kg/ha respectively. The simulated pod yield was 5% and seed yield was 7% higher than the respective observed values.

Table 25. Predicted and observed growth and development variables of chickpea

Variables	Predicted	Observed
Anthesis Date (dap)	77	77
First Pod (dap)	95	98
First Seed (dap)	103	106
Physiological Maturity (dap)	129	131
Pod Yield (kg/ha; dry)	2030	1935
Seed Yield (kg/ha; dry)	1940	1814
Seed Number (Seed/m ²)	190	181
Maximum LAI (m ² /m ²)	3.07	2.65
Biomass (kg/ha) at anthesis	1405	1258
Biomass (kg/ha) at harvest	5264	4966
Final Leaf Number (Main Stem)	32	30

Model predicted simulated dates of phenological stages and accumulated biomass in chickpea are shown in Table 26. This table showed that from emergence to first flowering 2395 kg/ha biomass was accumulated. The biomass accumulation between different growth stages of chickpea were 905 kg/ha, 400 kg/ha, 789 kg/ha and 1035 kg/ha between first flowering to first pod formation, first pod formation to first seed formation, first seed formation to end of pod formation and end of pod formation to physiological maturity. The rate of accumulation of biomass in the crop at different growth stages increased continuously upto physiological maturity condition then it decreased slightly. It was 34%, 47%, 50%, 71% and 73% at first flowering, first pod formation first seed formation, end of pod formation and physiological maturity respectively. After physiological maturity the rate of accumulation was 46% decreased.

Table 26. Simulated dates of phenological stages and accumulation of biomass in chickpea

Date	Days	Phenological stages	Accumulation of biomass (kg/ha)
25 October	0	Start Simulation	0
4 November	0	Sowing	0
9 November	5	Germinate	11
9 November	5	Unfoliate	11
11 November	7	Emergence	15
20 January	77	First flowering	2410
8 February	96	First Pod	3315
16 February	104	First seed	3715
27 February	115	End pod	4504
13 March	129	Physiological maturity	5540
19 March	135	Harvest Maturity	5264

Table 27 showed the simulation days between two phenological stages in chickpea. It indicates that flowering started after 70 days of emergence when the average maximum temperature was 22.7°C, average minimum temperature was 7.9°C and solar radiation was 9.32 MJ/m²/day. First pod formation occurred after 19 days of flowering when weather condition was favourable to crop growth. Seed setting started after 8

Table 27. Simulated days between two phenological stages in chickpea

Development phase	Time duration (days)	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ/m²/day)
Emergence- first flowering	70	22.7	7.9	9.32
First flowering - first pod	19	19.8	6.5	11.58
First pod – first seed	8	20.3	6.9	12.27
First seed –end pod	11	21.8	9.7	14.57
End pod-harvest maturity	20	22.2	10.1	17.83

days of pod formation. During pod formation to beginning of seed setting, the average maximum temperature was 20.3°C, minimum temperature was 6.9°C and solar radiation was 12.27 MJ/m²/day. Results revealed that crop took 20 days to attain harvest maturity stage after end of pod formation. During this phase, crop received 22.2°C of average maximum temperature, 10.1°C of average minimum temperature and 17.83 MJ/m²/day of solar radiation.

The model simulated the chickpea growth and yield were in agreement with the observed values of crop growth and yield. However, the model predicted little higher value of yield which was 5% higher than the observed value. Predicted biomass was averagely 8% overestimated than that of the observed value. These minimal differences showed that the model was well calibrated and is suitable for optimum cropping sequence analysis and the assessment of long term effects of cropping sequence.

The yield of the chickpea was simulated using this model in each of the 26 grids with respective soil files of each grid. The yield map was prepared with GIS software with the 26 simulated yields which is shown in Fig. 23. It showed that the yield of crop varied from 1924 kg/ha to 1997 kg/ha (5% variation) with an average value of 1952 kg/ha. The entire area of watershed was classified into 3 classes on the basis of production capacity of the soil. These classes were designated as low, medium and high and they

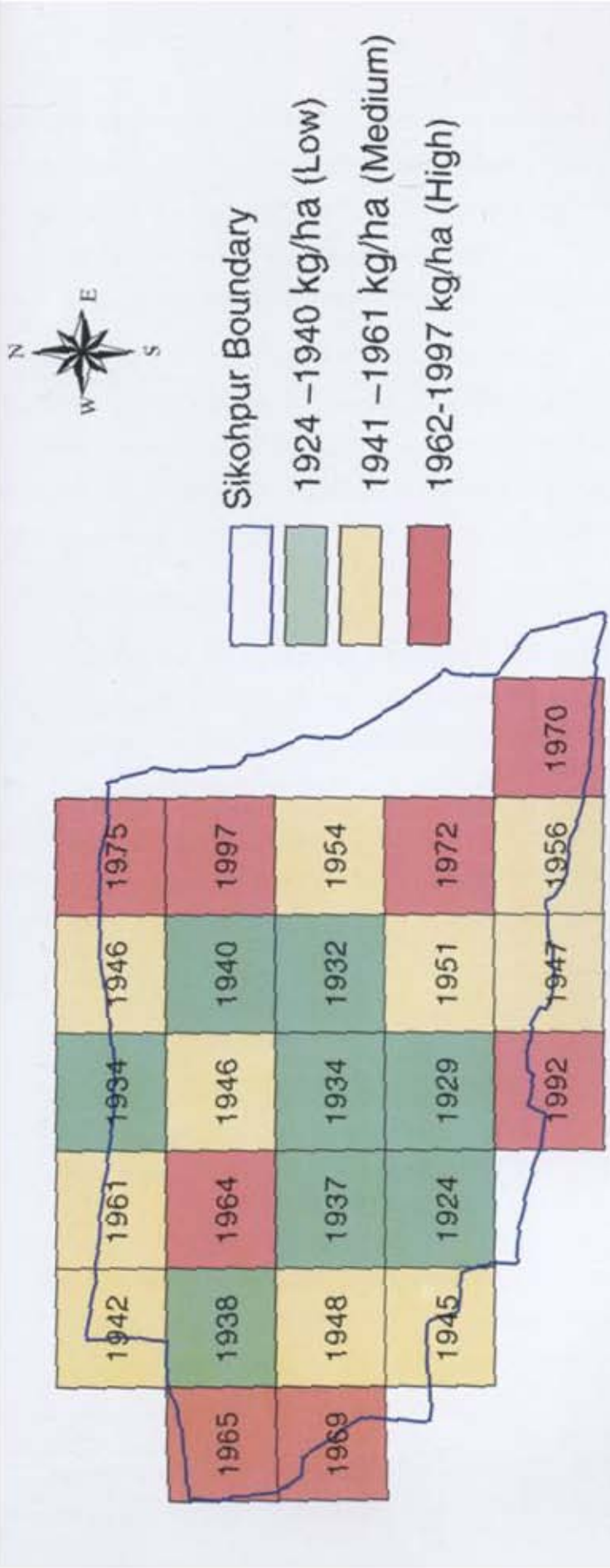


Fig 23: Thematic map of chickpea yield (kg/ha) for watershed

represent low, medium and high productive areas in relative terms. Low productive area has yield range from 1924 to 1940 kg/ha, medium productive area has ranged from 1941 to 1961 kg/ha and high productive area has yield range from 1962 to 1997. Figure also indicated that 30% of the watershed comes under low productive area, 40% comes under medium productive area and rest 30% comes under high productive area.

The spatial variability yield map (Fig. 24) which was prepared using Surfer software with contour interval of 5 kg/ha. This map identifies the low, medium and high productive areas of the watershed. Low productive area thus identified, may be improved through management practices or replaced with some other alternative crop for better use of land resources, so that farmers can get more income from their land.

4.2.4 Proposed new crops

Two new crops were proposed for kharif season for growing in the study area because only one crop i.e. pearl millet was grown in the watershed in the kharif season and its productivity was low in the area. The proposed crops were soybean and sorghum because their agro-climatic requirements perfectly matched with the agro-climatic conditions of this watershed. However, sorghum crop was grown as fodder crop in *rabi* season in some localised patches of the watershed. It was not grown as main crop in *kharif* season.

4.2.4.1 Simulation of soybean yield

Agro-climatic requirements of the crop are shown in the Table 28, which showed that sandy loam texture of the soil is best suited for the crop. It requires 15°C to 30°C of temperature during entire cropping period. Its growth is better in the area of high rainfall 600 to 650 mm. It prefer soil pH value 6.5 to 7.5 (Handbook of Agriculture, 2006).

On the basis of agro-climatic requirements, an experiment file was created in DSSAT 35 which included all the details of the cultivation and management practices of soybean. This is shown in Table 29. The simulation of crop grown and yield was carried out using DSSAT 35 software.

The variety selected for the study was Bragg, a widely grown variety. Its sowing date was given as 15.06.04. The applied seed rate was 44 kg/ha. Row spacing was 50

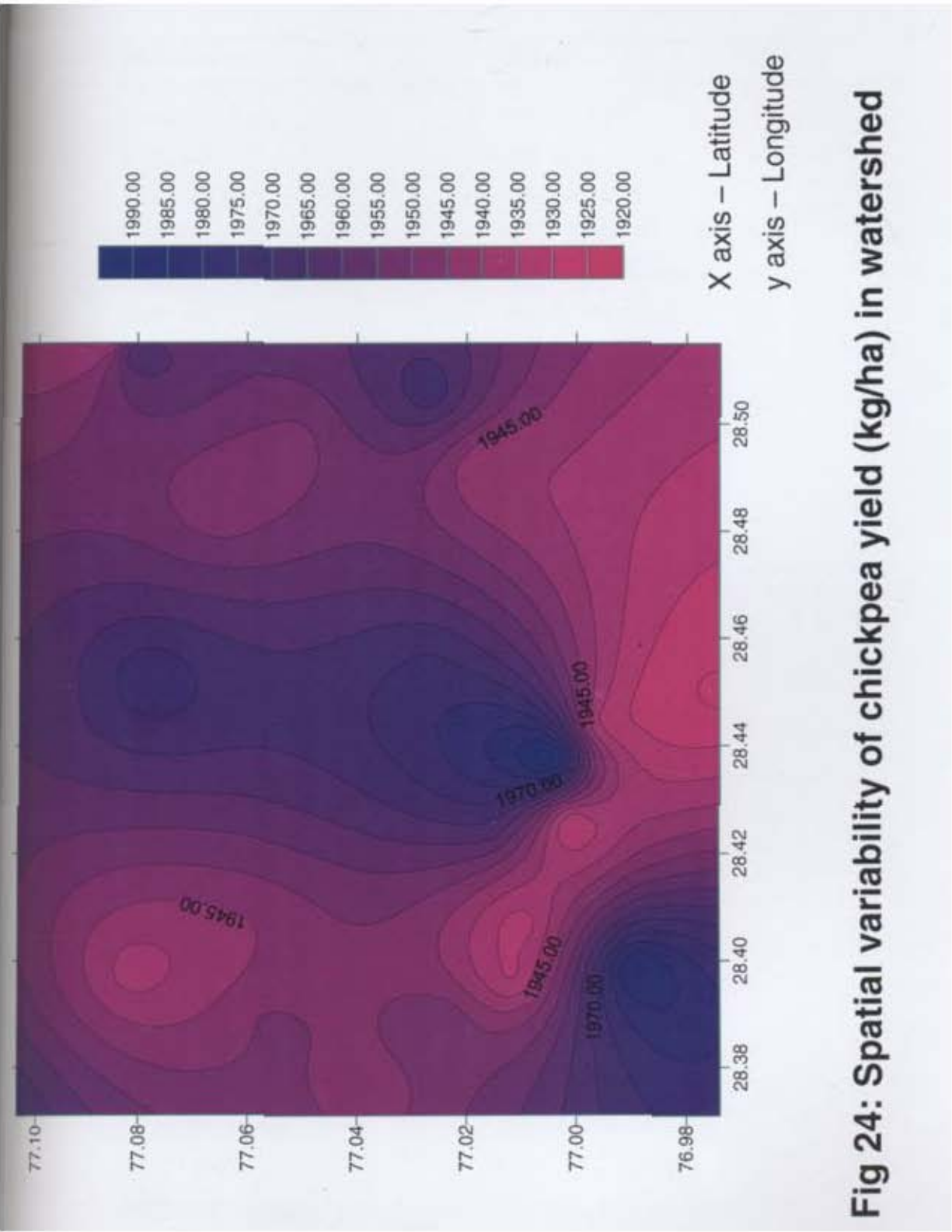


Fig 24: Spatial variability of chickpea yield (kg/ha) in watershed

Table 28. Agroclimatic requirements of soybean

Parameters	Range
Temperature	15 ⁰ C - 30 ⁰ C
Rain fall	600 to 650 mm
Soil texture	Sandy loam
Soil pH	6.5 to 7.5
Sowing time	Onset of monsoon
Spacing	45-60 cm x 2.5 cm
Depth	3-4 cm
Seed rate	20-30 kg /ha
Fertilizer	40-50 kg N/ha
Irrigation	One to two times
Crop duration	100-120 days
Yield	25 to 35 q/ha

(Hand book of Agriculture, 2006)

Table 29. Summary of Experiment file of soybean

Cultivar	Bragg
Soil texture	Sandy loam
Soil analysis date	01.06.04
Previous crop	Fallow
Planting date	15.06.04
Emergence date	20.06.04
Plant population at emergence/m ²	16
Planting material	Seed
Row spacing	50 cm
Planting depth	4.0 cm
Seed Rate	44 kg/ha
Irrigation	One (20 DAS)
Fertilizer	Urea @ 50 kg N/ha
Harvest date	20.10.04

cm. Soybean was a rainfed crop, therefore, only one irrigation at 20 DAS was applied. During cropping period it received about 290 mm rainfall. Due to its leguminous nature, a low rate of fertilizer in the form of urea @ 50 kg N/ha was applied.

The genetic crop coefficients values were calculated using Genecalc with the data collected for the soybean cultivation from nearby areas (IARI, New Delhi and Gurgaon). The crop coefficient values were tuned in such a way that simulated value of yield was in agreement with yield of soybean crop in adjoining areas (25-30 q/ha). These genetic coefficient values are shown in Table 30.

Table 30. Genetic coefficient used for soybean

Genetic coefficient*	Value	Genetic coefficient	Value
CSDL	14.32	LFMAX	1.3
PPSEN	0.241	SLAVR	375
EM-FL	18.0	SIZLF	186
FL-SH	6.5	XFRT	1.00
FL-SD	15.1	WTPSD	0.181
SD-PM	32.3	SFDUR	23.0
FL-LF	18.4	SDPDV	2.20
PODUR	10.0		

* Genetic coefficient codes are given in Table 5.

Table 31 showed predicted growth and development variables of soybean. As this crop is not grown in Shikohpur, no data on observed variables was available. Therefore, comparison between predicted and observed values was not possible but the model predicted values of crop performance are shown in Table 31. The average yield of Bragg cultivar, as reported by farmers of Gurgaon and Delhi was 2700 kg/ha and model simulated the yield of this crop as 2891 kg/ha.

The simulated dates of phenological stages and accumulation of biomass upto these phases are shown in Table 32. It indicates that the accumulated biomass increased continuously up to physiological maturity stage of crop with increase in growing time. It showed that 1485 kg/ha biomass was accumulated upto first flowering stage of the

Table 31. Predicted growth and development variables of soybean

Variables	Predicted
Anthesis Date (dap)	45
First Pod (dap)	65
First Seed (dap)	74
Physiological Maturity (dap)	115
Pod Yield (kg/ha;dry)	3062
Seed Yield (kg/ha;dry)	2891
Maximum LAI (m ² /m ²)	4.86
Biomass (kg/ha) at Anthesis	1485
Biomass (kg/ha) at Harvest	6620

Table 32. Simulated dates of phenological stages and accumulation of biomass in soybean

Date	Days	Phenological stages	Accumulation of biomass (kg/ha)
15 June	0	Start Simulation	0
15 June	0	Sowing	0
20 June	5	Germinate	14
27 June	12	Unfoliate	31
30 July	45	First flowering	1485
19 August	65	First pod	2855
28 August	74	First seed	3465
3 September	80	End Leaf growth	4005
13 September	90	End pod	4870
8 October	115	Physiological maturity	7240
20 October	127	Harvest maturity	6620

crop. During first flowering to first pod formation, first pod formation to first seed formation, first seed formation to end of pod formation and end of pod formation to physiological maturity, the accumulated biomass were 1370 kg/ha, 610 kg./ha, 540 kg/ha, 865 kg/ha and 2370 kg/ha, respectively. The rates of accumulation of biomass during above mentioned growth stages were 68, 68, 90, 86 and 95 kg/ha/day, respectively.

The simulated days between two successive phenological stages of the crops are shown in Table 33. It showed that first flowering started after 33 days of unfoliate stage, when the atmospheric conditions were average maximum temperature - 38.2°C, minimum temperature 28.5°C and solar radiation was 18.04 MJ/m²/day. First pod formation started after 20 days of first flowering. Crop took nine days for first seed setting. The seed setting started when the average maximum temperature was 34.6°C, average minimum temperature was 25.3°C and solar radiation was 19.42 MJ/m²/day. The process of pod formation came to end after sixteen days of first seed setting and after 25 days of end of pod formation, physiological maturity of crops occurred during which crop experienced average maximum temperature of 33.1°C, average minimum temperature 22.1°C and solar radiation of 17.52 MJ/m²/day.

Table 33. Simulated days between two phenological stages in soybean

Development phase	Time duration (days)	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ/m ² /day)
Unfoliate-First flowering	33	38.1	28.5	18.04
First flowering-first pod	20	34.1	26.1	18.75
First pod -first seed	9	34.6	25.3	19.42
First seed – end pod	16	36.1	26.6	22.25
End pod-physiological maturity	25	33.1	22.1	17.52

The yield of the crop was simulated in each of the 26 grids and the yield map for soybean was prepared with the help of Arc view GIS. The map is shown in Fig. 25. It showed that yield of crop varied from 2880 kg/ha to 2924 kg/ha in the entire watershed exhibiting a 2% variation in yield. The average yield was 2898 kg/ha. The watershed was divided into three classes : low, medium and high production area on the basis of production potential for soybean. The low productive area had yield range of 2880-2891 kg/ha. Medium productive area had yield range 2892 to 2906 kg/ha and high productive area had yield range 2907-2924 kg/ha. The map indicated that if whole watershed was cultivated with soybean crops then, 27% of the area produced yield in low class range, 58% area produced yield in medium range of production and 15% of the total area produced yield in high range of production. This shows that about 73% area of the watershed can produce soybean yield in the medium and high class ranges of 2892-2924 kg/ha. This result strongly support the recommendation of soybean introduction to this watershed.

The spatial variability yield map was prepared using Surfer 6.2 version software. The contour lines were interpolated at 2 kg/ha interval. These lines identify the low production area, medium production area and high production area of the watershed (Fig. 26). Based on this map the soybean crop may be introduced to the high and medium production areas, which may provide higher returns to the farmers of this watershed.

4.2.4.2 Simulation of sorghum yield

Table 34 showed the Agro-climatic requirement of sorghum crop. The crop grows better in sandy loam to clayey loam texture of the soil. It requires temperature range from 15°C to 40°C to complete its life cycle. It prefers soil pH 5.5 to 8.5. It is a drought resistant crop, but requires water at critical phase of its life cycle (Handbook of Agriculture, 2006).

Keeping this in view an experiment file was created in DSSAT 35 which included all the details about experimental details and management practices for cultivation of sorghum (Table 35). The simulation of crop growth and yield was carried out using DSSAT 35 software.

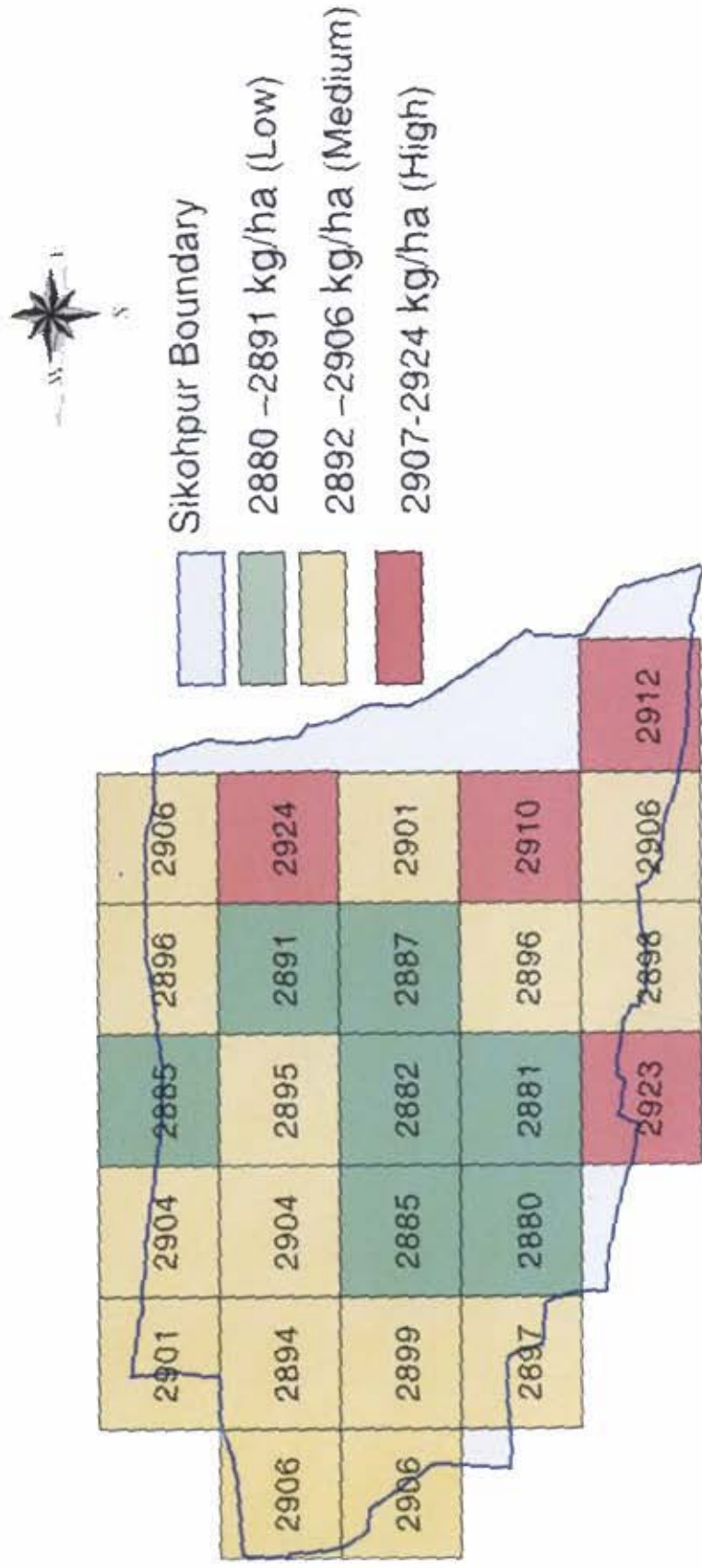


Fig 25: Thematic map of Soybean yield (kg/ha) for watershed

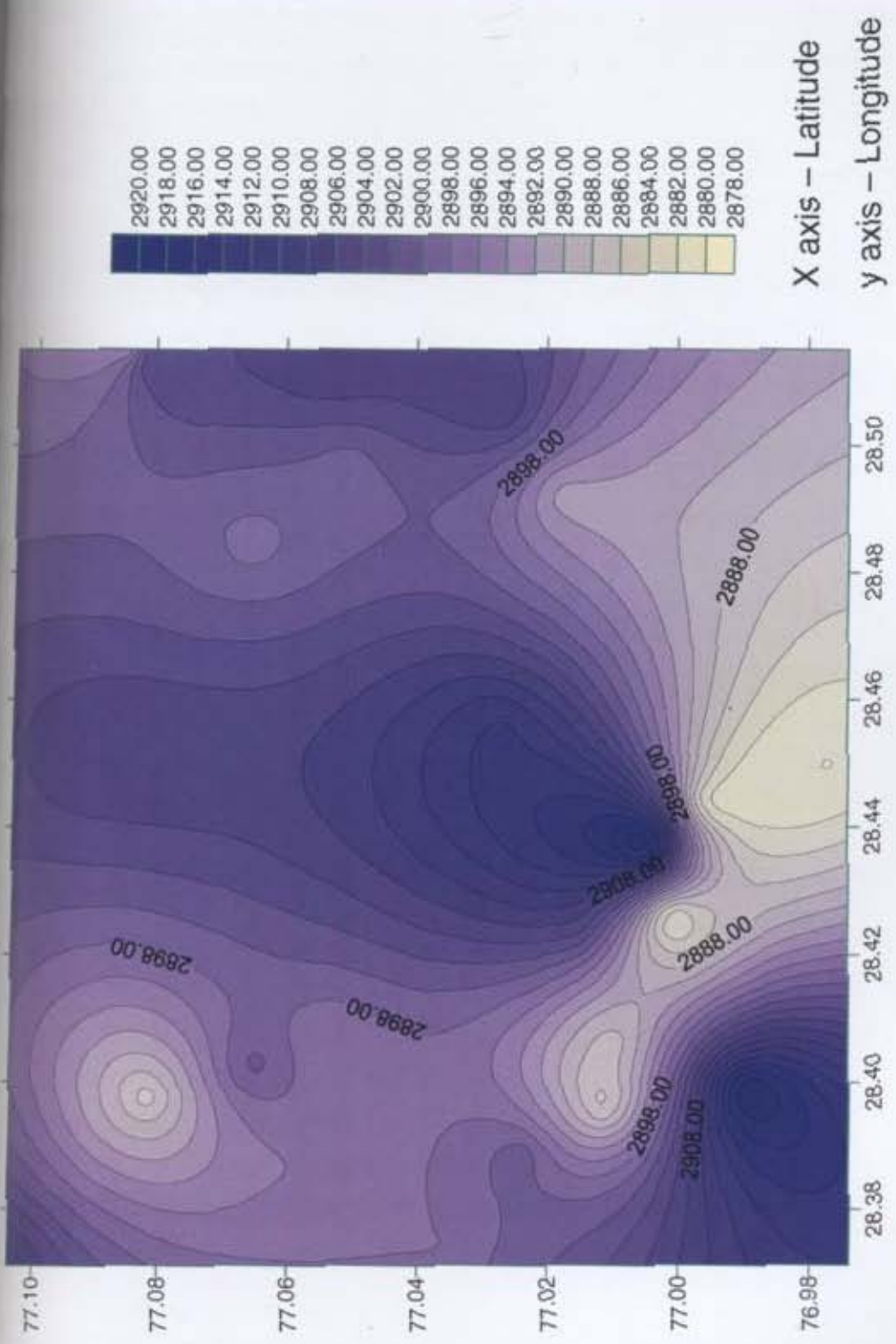


Fig 26: Spatial variability of soybean yield (kg/ha) in watershed

Table 34. Agroclimatic requirements of sorghum

Parameters	Range
Temperature	15 ⁰ C - 40 ⁰ C
Rain fall	400 to 1000 mm
Soil texture	Sandy loam to clayey loam
Soil pH	5.5 to 8.5
Sowing time	onset of monsoon
Spacing	40-45 cm x 15 cm
Depth	3-4 cm
Seed rate	8-12 kg/ha
Fertilizer	60-80 kg /ha
Irrigation	One to two times
Crop duration	100-120 days
Yield	Grain-25 to 35 q/ha

(Handbook of Agriculture, 2006)

Table 35. Summary of Experiment File for sorghum

Cultivar	CSH-18
Soil texture	Sandy loam
Soil analysis date	07.06.2004
Previous crop	Fallow
Planting date	17.06.04
Emergence date	22.06.04
Plant population at emergence/m ²	10
Planting material	Seed
Row spacing	45 cm
Planting depth	4.0 cm
Seed rate	8 kg/ha
Irrigation	One (20 DAS)
Fertilizer	Urea @ 120 kg N/ha
Harvest date	28.09.04

The cultivar selected for the study was CSH-18 which was commonly grown in Rajasthan, Haryana, UP and Delhi. Normal date of sowing was 17.06.04. Seed @ 8 kg/ha was sown with 45 cm of row spacing. It is a drought tolerant rainfed crop. However, one irrigation at 20 DAS was applied. Fertilizer in the form of urea @ 100 kg N/ha was also applied in the experiment.

The genetic coefficient values were calculated using Gencalc using the data collected from the adjoining areas e.g. Delhi (Table 36). The genetic coefficient values were tuned in such a way that simulated yield of the crop was in agreement with the yield data collected for the cultivar.

Table 36. Genetic coefficient used for sorghum

Genetic coefficient*	Value
P 1	410.0
P20	13.60
P2R	40.0
P 5	540.0
G1	3.1
G4	5.60
PHINT	49.0

* Genetic coefficient codes are given in Table 5.

Table 37 showed predicted growth and development variables of sorghum. Due to non-practice of sorghum cultivation in the watershed area, no observed data was available. Farmers from adjoining areas of Gurgaon and Delhi reported that CSH-18 cultivar of sorghum gave the average yield of around 3100 kg/ha. The model predicted the simulated yield of sorghum as 3248 kg/ha.

The accumulated values of biomass with increase in growing periods are presented in Table 38. The table showed that accumulation of biomass was 1980 kg/ha at the end of juvenile phase. Results indicated that 770 kg/ha biomass was accumulated from end of juvenile to floral initiation condition. The biomass accumulation between different growth stages from floral initiation to end of leaf growth, end of leaf growth to

Table 37. Predicted growth and development variables of sorghum

Variables	Predicted
Flowering date (dap)	52
Physiological maturity (dap)	93
Grain yield (kg/ha; dry)	3248
Weight per grain (g; dry)	0.0015
Grain number (Grain/m ²)	52465
Maximum LAI (m ² /m ²)	4.86
Biomass (kg/ha) at anthesis	8965
Biomass N (kg N/ha) at anthesis	112
Biomass (kg/ha) at harvest	13500
Grain N (kg N/ha)	5
Biomass N (kg N/ha) at harvest	97

Table 38. Simulated dates of phenological stages and accumulation of biomass in sorghum

Date	Days	Phenological stages	Accumulation of biomass (kg/ha)
13 June	0	Start Simulation	0
17 June	0	Sowing	0
18 June	1	Germinate	0
22 June	5	Emergence	3
12 July	25	End juvenile	1980
18 August	31	Floral initiation	2750
13 August	57	End leaf growth	6010
22 August	66	End of Anthesis	7230
27 August	71	End panicle growth	8140
28 September	103	Harvest maturity	13500

end of anthesis, end of anthesis to end of panicle growth and from end of panicle growth to harvest maturity were 3260, 1220, 890 and 4360 kg/ha, respectively. The rates of accumulation of biomass during above mentioned four stages were 125, 135, 178 and 136 kg/ha/day, respectively.

The simulated days between two phenological phase of sorghum are given in Table 39. It indicated that crop completed its juvenile stage after 20 days of emergence. During this time it experienced average maximum temperature of 36.2°C, average minimum temperature of 27.9°C and solar radiation of 18.65 MJ/m²/days. After six days of end of juvenile phase - floral initiation was started in the crops. It took 26 days between floral initiation and end of leaf growth, 14 days between end of leaf growth to end of panicle growth and 32 days during grain filling phase. During grain filling phase, crop received average maximum temperature of 33.2°C, average minimum temperature of 21.8°C and average solar radiation of 18.72 MJ/m²/day.

Table 39. Simulated days between two phenological stages of sorghum

Development phase	Time duration (days)	Maximum temperature (°C)	Minimum temperature (°C)	Solar radiation (MJ/m²/day)
Emergence-End Juvenile	20	36.2	27.9	18.65
End Juvenile-Floral Initiation	6	33.7	26.8	18.98
Floral Initiation-End Leaf Growth	26	33.3	25.9	20.14
End Leaf Growth-End of panicle growth	14	35.7	25.3	20.76
Grain Filling Phase	32	33.2	21.8	18.72

The yield of the crop was simulated in each of the 26 grids and the yield map for sorghum was prepared using software Arc view GIS. The thematic map for yield is shown in Fig. 27, which indicated that yield varied from 3236 to 3285 kg/ha with average values of 3255 (kg/ha). The percent variation in yield was 1.5%. All the watershed was

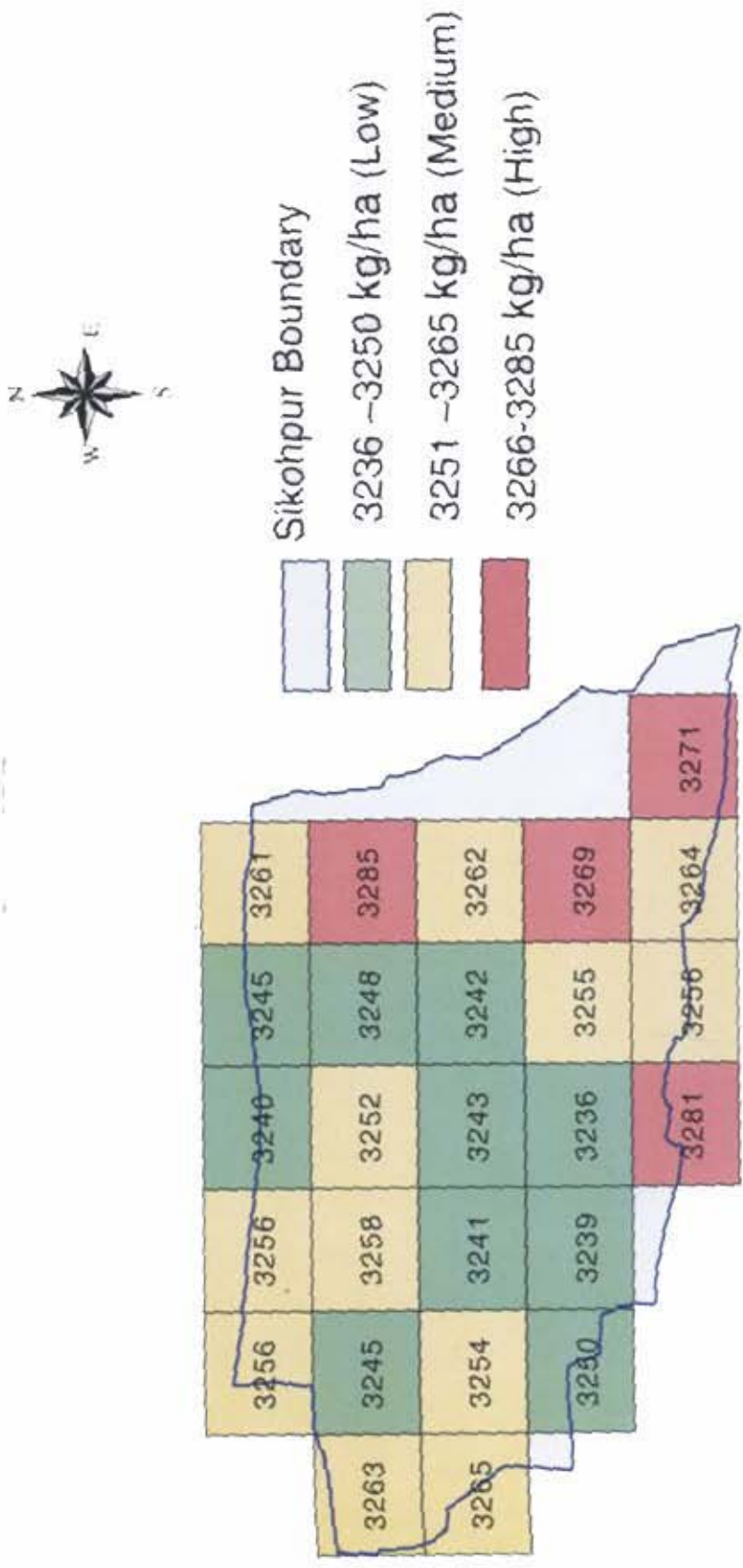


Fig 27: Thematic map of Sorghum yield (kg/ha) for watershed

divided into 3 categories, low, medium and high productive areas on the basis of their production capacity for the crop. The area with low production have yield range 3236-3250 kg/ha, medium production have yield range 3251 to 3265 kg/ha and the area with high production have yield range 3266 to 3285 kg/ha. Thematic map also indicated that 40% of total area of watershed comes under low production, 45% comes under medium production and rest 15% comes under high production area. Since the variation in yield over the watershed is very small (1.5%) and low yield class has mean value 3243 kg/ha which is only 7 kg less than overall average of 3255 kg/ha, the yield production for sorghum is practically uniform over whole watershed. Sitaggany (2001) worked in Shikohpur watershed and also suggested soybean and sorghum crops to be grown in the watershed. His suggestion was based on soil site characteristic, plant available water content and FAO guideline (1983) as modified by Sehgal (1996).

The spatial variability map for yield of crop in the whole watershed was prepared using Surfer software (Fig. 28). Contour lines drawn at an interval of 2 kg/ha identified the low, medium, and high production areas in the variability map. This new crop of sorghum may be introduced to all low, medium and high production areas, of the watershed to improve the resource utilization as well as farmers income from agriculture.

4.2.5 Mustard

Mustard crop was widely grown in the study area as *rabi* crop. It was grown in almost all the grids of the watershed. Its average yield was 15 q/ha.

The management practices used for cultivation of this crop are shown in the Table 40. The cultivar used was Pusa Agrani. Seed rate of 5 kg/ha was used with 30 cm of row spacing for cultivation of the crop. Only one irrigation at pre-flowering stage was given to the crop. Urea @ 100 kg N/ha was applied in two split doses : first before sowing and second at pre flowering stage.

As the DSSAT 35 software does not contain simulation model for mustard, it was not possible to simulate the mustard crop for different grids of the watershed. The other softwares which were available with us and which has model for mustard was INFOCROP. As in this study we have to compare the simulated results of different crops under all the grids, it was essential to use the same simulation package for all the crops. Because each package deals plant growth system in its own different way and

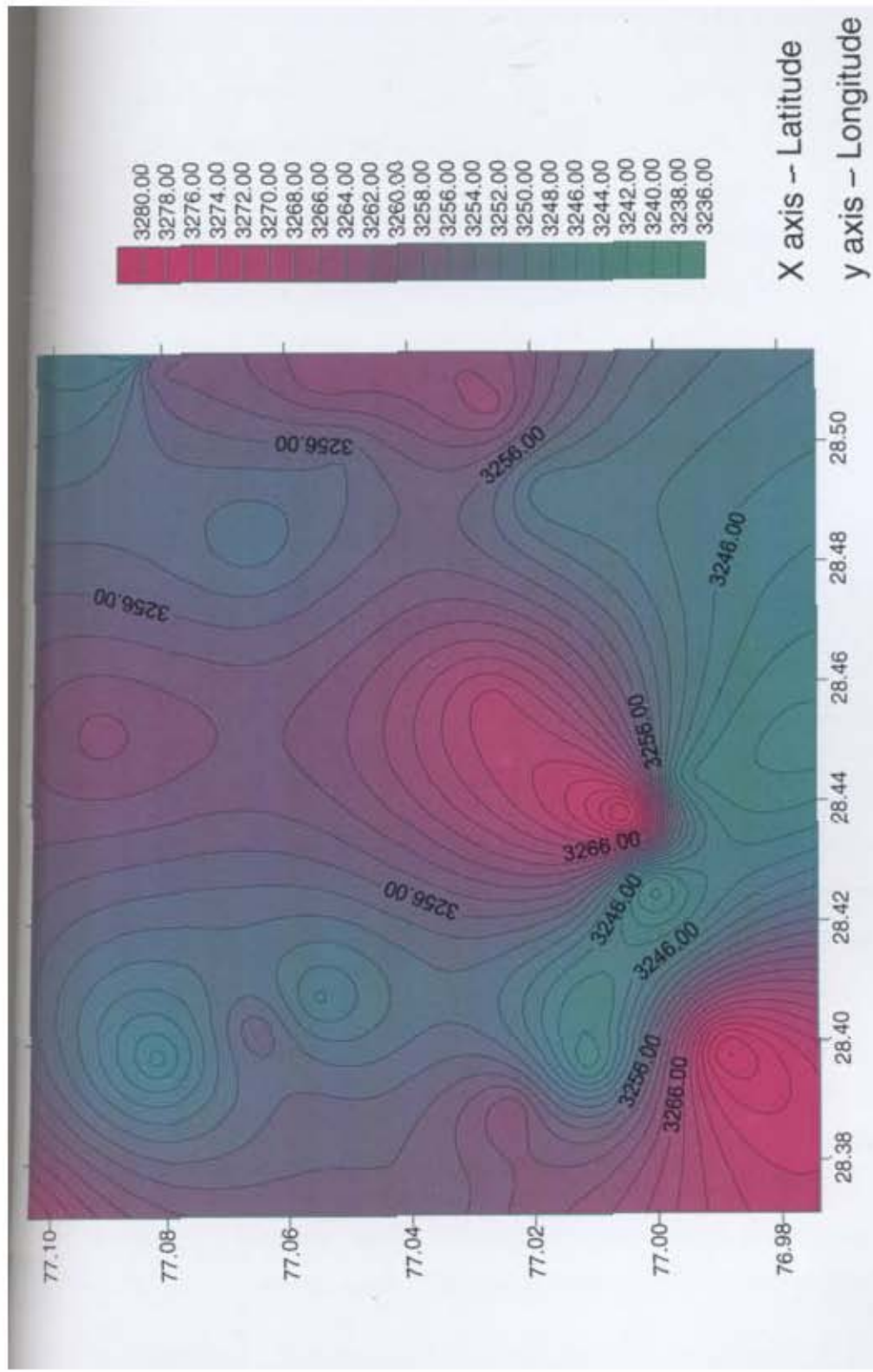


Fig 28: Spatial variability of sorghum yield (kg/ha) in watershed

Table 40. Summary of experimental details of mustard

Cultivar	Pusa Agrani
Soil texture	Sandy loam
Soil analysis date	15.10.04
Previous crop	Pearl millet
Planting date	22.10.04
Emergence date	28.10.04
Plant population at emergence/m ²	35
Plating method	Seed
Row spacing	30 cm
Planting depth	2.5 cm
Planting material	5 kg/ha
Irrigation	One after 30 days
Fertilizer	Urea @ 120 kg N/ha
Harvest date	02.02.05

simulate different processes differently. Therefore, the output yield may contain variations due to model bias if output from two different models for two different crops were compared and then such comparisons would not had been valid. Hence other model for mustard was not used here. All the crops were simulated using DSSAT 35, except mustard for which no simulation was done.

The observed biomass and LAI during entire growth period was given in Figures 29. Fig. 29 indicated that LAI of the crop was increased to 4.5 at 75 DAS then it was decreased gradually to 1.5 at 100 DAS. Fig. 29 also indicate that the biomass was accumulated with higher rate upto physiological maturity of the crop. It was highest (1640 g/m²) at 90 DAS. After physiological maturity stage the biomass was decreased to 1520 g/m² at harvest stage. The total yield obtained after harvesting the crop was 15 q/ha.

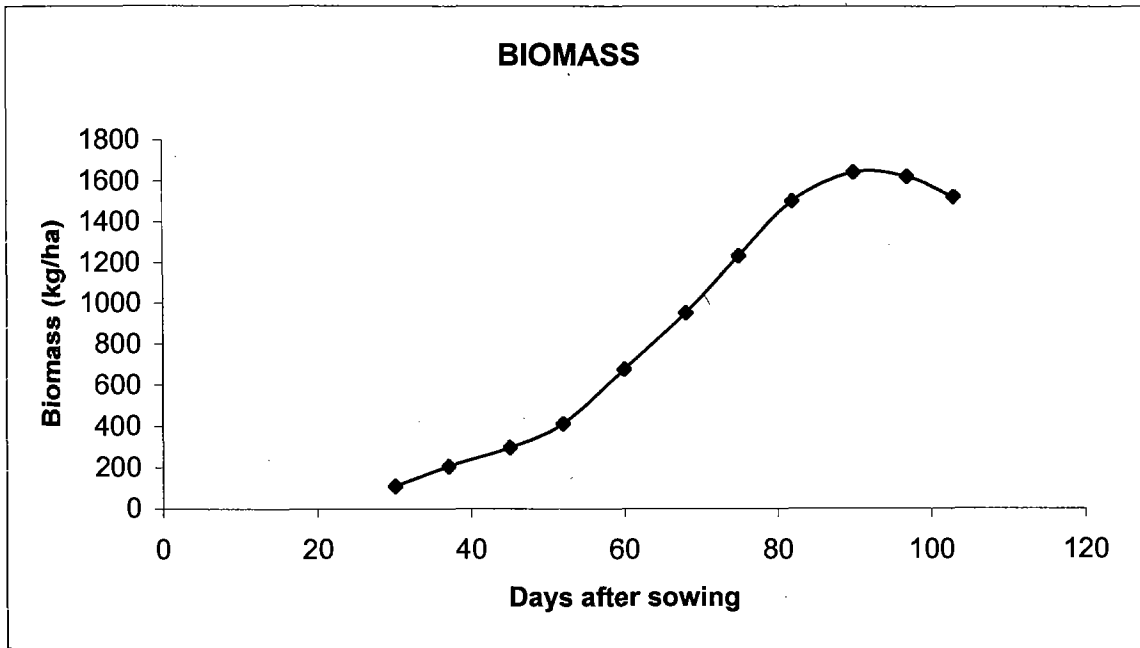
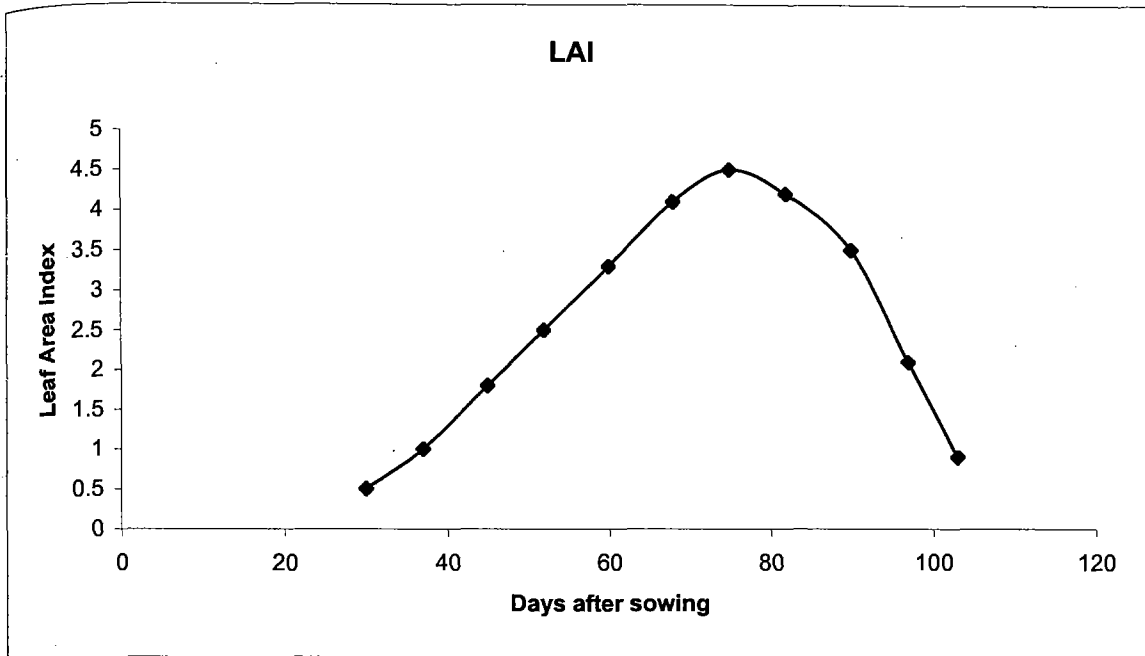


Fig 29- Observed LAI and Biomass of mustard at different growth stages

4.2.6 Economic analysis for selection of optimum cropping sequence

For selecting a best cropping sequence for the Shikhopur watershed, a simple economic analysis for all the six existing and potential crops was made based on the input cost, output price and net profit.

The unit cost of cultivation per hectare for all the six crops namely, pearl millet, soybean, sorghum, wheat, chickpea and mustard are shown in Table 41. It included cost of various field operations during the crop cultivation like cost of ploughing and harrowing, land levelling, seed cost and seed sowing, fertilizer, irrigation, weeding and harvesting along with threshing. The input cost for land operations, crop maintenance and harvest differ for each crop. There are several reasons for this, for example variable soil properties require differential ploughing (number of ploughing) and energy input cost to prepare seed bed according to crop requirement. Water availability varies at different times of year and water table goes deep in summer which requires more energy inputs to draw water for irrigation to meet the differential water requirement of crops, hence increasing cost of irrigation. Seed rates and fertilizer requirements vary for each crop making input seed rate and fertilizer cost different for various crops. The harvest and threshing cost vary depending upon the availability of threshers and manpower at the specific point of time. Thus all these factors are responsible for the variations in input cost of cultivation for each crop.

Table 41. Cost of cultivation for various field operations for six crops

Field operation	Unit cost/ha for different crops (Rs/ha)					
	Pearl millet	Soybean	Sorghum	Wheat	Mustard	Chickpea
Ploughing + harrowing	2000	2500	2000	2500	2500	2500
Land levelling	500	750	500	750	750	750
Seed sowing	500	1250	500	500	500	2000
Fertilizer	600	1250	1250	2000	2000	1250
Irrigation	500	750	500	2500	2000	2000
Weeding	1000	1500	1000	2000	2000	2000
Harvesting	2500	2500	2000	2000	1750	1750
Threshing	750	1250	750	2250	1750	1750
Total	8350	11750	8500	14500	13250	14000

Table 41 indicated that out of three in *kharif* crops namely pearl millet, soybean and sorghum unit cost of cultivation per hectare of soybean was maximum which was Rs. 11750 as compared to Rs. 8500 for sorghum and Rs. 8350 for pearl millet. Among *rabi* crops (wheat, mustard and chickpea) cost of cultivation of wheat crop was maximum (Rs. 14,500) as compared to chickpea (Rs. 14000) and mustard (Rs. 13,250).

The total output prices for the yields are the minimum support prices offered by the Government which a farmer gets his produce. For fodders, the actual price a farmers gets from selling of fodder in "Mandi" are taken. These data were recorded from farmers themselves and are used for the economic analysis.

The total output prices of all the crops, which included price of grain yield and price of fodder yield are shown in Table 42. It showed that total output prices were maximum for soybean (Rs. 28750) among *kharif* crops and for chickpea (Rs. 30,500) among *rabi* crops.

Table 42. Yield and Fodder productions and their selling prices

Input variables	Pearl millet	Soybean	Sorghum	Wheat	Mustard	Chickpea
Grain yield (q/ha)	17	29	33	36	15	20
Fodder yield(q/ha)	100	12	100	40	50	25
Market price of grain (Rs/q)	520	950	520	640	1600	1400
Market price of fodder (Rs/q)	40	100	40	100	10	100
Total output price (Rs/ha)	12840	28750	21160	27040	24500	30500

Table 43 showed the net profit obtained from each crop cultivation per hectare of land. It indicates that net profit/ha of soybean was maximum (Rs. 17,000) as compared to sorghum (Rs. 12,660) and pearl millet (Rs. 4,490) among *kharif* crops, whereas in *rabi* crops, it was maximum for chickpea (Rs. 16,500) as compared to wheat (Rs. 12,540) and mustard (Rs. 11,250). Table 43 also indicated that both pulse crops in *kharif* as well as in *rabi* soybean and chickpea resulted in highest profits as compared to cereals (pearl millet, sorghum and wheat) and oilseed (mustard).

Table 43. Net profit (Rs/ha) for cultivation of major crops

Variables	Pearl millet	Soybean	Sorghum	Wheat	Mustard	Chickpea
Input cost (Rs/ha)	8350	11750	8500	14500	13250	14000
Output price (Rs/ha)	12840	28750	21160	27040	24500	30500
Net profit/ha (Rs/ha)	4490	17000	12660	12540	11250	16500

Farmers of the study area were generally practicing pearl millet wheat fallow or pearl millet-mustard-fallow cropping systems. On the basis of production potential of soil, farmer's requirement and economic analysis of major crops profit for different possible combinations of cropping sequences in one complete crop rotation were worked out and are shown in Table 44.

Table 44. Net profit for different cropping sequences

Cropping Sequence	Profit (Rs/ha/yr)	Rank
Pearlmillet-wheat-fallow	17030	7
Pearlmillet-mustard-fallow	15740	8
Pearlmillet-chickpea-fallow	20990	6
Soybean-wheat-fallow	29540	1
Soybean-mustard-fallow	28250	3
Soybean-chickpea-fallow	33500	*
Sorghum-wheat-fallow	25200	4
Sorghum-mustard-fallow	23910	5
Sorghum-chickpea-fallow	29160	2

* Not recommended.

The highest profit was obtained from soybean-chickpea-fallow sequence leading to the conclusion that soybean-chickpea-fallow is the best combination based on economic considerations. However, the leguminous nature of both the crops in the sequence, may impose some detrimental effects on soil health, the possibility of insect/pest/diseases may increase in the long run (AICDLA, 1982; Shukla *et al.*, 2002). Hence this sequence may not be the best desirable cropping sequence. The second best combinations which are economically profitable are soybean wheat-fallow and sorghum-chickpea-fallow. Both sequences give almost same monetary returns (about Rs. 29000). Agronomists suggest to take one leguminous crop in a cropping sequence in a year which significantly improve the soil physical properties such as hydraulic conductivity, total porosity, aggregate stability and stability index (Shukla *et al.*, 2002; Thakur *et al.*, 1994; Verma & Dixit, 1998). It also increases organic carbon percent and nitrogen percent of soil (Shakaranarayan and Mehta, 1967). As per farmer's requirement, growing of wheat crop for their consumption needs, best combination is soybean-wheat-fallow followed by sorghum-chickpea-fallow sequence. The monetary gains in other combinations of cropping sequences are in order of soybean-mustard-fallow > sorghum-wheat-fallow > sorghum-mustard-fallow > pearl millet-chickpea-fallow > pearl millet-wheat-fallow > pearl millet-mustard-fallow.

The currently practiced sequences are pearl millet wheat-fallow and pearl millet-mustard-fallow which ranked at 7th and 8th out of 9 sequences, according to the economic analysis. As the farmers would prefer maximum benefit out of crop cultivation, the cropping sequence which gave higher economic returns, while taking into considerations of soil health and pest disease issues, the optimum sequences recommended are soybean-wheat-fallow and sorghum-chickpea-fallow followed by soybean-mustard-fallow and sorghum-wheat fallow. The study indicated that if proper protective methods are adopted then two leguminous crops soybean-chickpea may result in highest monetary profits. But our agronomist would agree that this is generally not recommended to have two leguminous crops in a sequence to avoid other problems related with soil quality and pest/insect/disease infestations. Hence based on the application of crop simulation and GIS techniques along with economic concerns, the cropping sequences recommended for Shikohpur watershed are soybean-wheat-fallow and sorghum-chickpea-fallow followed by soybean mustard-fallow and sorghum-wheat-fallow.

4.3 Long term performance evaluation of cropping sequences

To evaluate the long term performance of cropping sequences, simulation of yield for all the existing and potential crops were done for 20 year of weather data starting from 1984 to 2004. The simulated yields of all the crops were converted into equivalent wheat yield based on their selling prices in monetary terms. The unit equivalent wheat yield factor of a crop is obtained by dividing unit selling price of this crop by unit selling price of wheat.

$$\text{Unit equivalent wheat yield factor of a crop} = \frac{\text{selling price of crop}}{\text{selling price of wheat}}$$

The equivalent wheat yield of different crops are shown in Table 45. Table indicated that equivalent wheat yield factor of soybean was 1.48, for sorghum and pearl millet, the value was 0.812, for mustard it was 2.5 and the equivalent wheat yield factor of chickpea was 2.18. It is also observed that as per the production potential of the watershed, total equivalent wheat yield was highest for chickpea followed by soybean and mustard. Lowest wheat yield equivalent was for pearl millet.

Table 45. Equivalent wheat yield of different crops

Crop	Yield (q)	Price of Yield (Rs/q)	Unit Equivalent Wheat Yield Factor	Total Equivalent Wheat Yield (q/ha)
(a)	(b)	(c)	(d)	
Wheat	36	640	1.00	36
Soybean	29	950	1.48	43
Chickpea	20	1400	2.18	44
Mustard	15	1600	2.50	38
Pearl millet	17	520	0.812	14
Sorghum	33	520	0.812	27

$$(d = a \times c)$$

The simulated yield of crop for each year was converted into equivalent wheat yield for all the nine possible cropping sequence combinations. For mustard the average yield of 15 q/ha as reported by farmers was taken for each run of simulation. These simulated wheat equivalent yields were determined for all the nine crop sequences and for all the 20 years of simulation. The crop sequences equivalent wheat yields for 20 years are shown in Table 46. The yield trends over 20 years are shown in Figure 30 for all the nine sequences.

Table 46 showed that for pearl millet-wheat cropping sequence the variation in simulated equivalent wheat yield was 167 kg over 20 years. These variations were 193, 275, 49, 77, 155, 254, 285 and 363 kg in the simulated equivalent wheat yields of sorghum-wheat, soybean-wheat, pearl millet-mustard, sorghum-mustard, soybean-mustard, pearl millet-chickpea, sorghum-chickpea and soybean-chickpea respectively. These variations are due to the impact of weather variability on yields and reflect the performance of crop sequences under different weather conditions.

Although the simulated average equivalent wheat yield of soybean-mustard cropping sequence was more than that of soybean-wheat and sorghum-chickpea cropping sequence (Table 46), the net profit from wheat and chickpea were higher than the mustard and farmers are interested to get maximum benefit from his land, hence soybean-wheat and sorghum-chickpea are more profitable than soybean-mustard sequence. Therefore, they are more preferred sequences.

The long term performance trends of all the nine cropping sequences are depicted in Fig. 30. The cropping sequence yields are presented in terms of equivalent wheat yield in these figures. These variations and trends can be compared with each other. The variations in the equivalent yields reflect the weather variability in 20 years. The trend lines of each cropping sequence indicate the long term production sustainability of the yields. The figures of all sequences exhibit minimum for the years 1987, 2000 and 2002 which were known to be drought years or years of less rainfall. A decline in equivalent yield for 1991 were also observed through the magnitude of this decline is much less as compared to other minima.

Table 46. Simulated equivalent wheat yield of different cropping sequence for 20 years

Year	Simulated equivalent wheat yield (kg/ha)									
	PEAR+WH	SOR+WH	SOY+WH	PEAR+MUS	SOR+MUS	SOY+MUS	PEAR+CHI	SOR+CHI	SOY+CHI	SOY+CHI
1984	4992.28	6239.51	7846.88	5122.28	6369.51	7976.88	5523.00	6770.23	8377.60	8377.60
1985	4937.92	6191.65	7802.08	5097.92	6351.65	7962.08	5481.20	6734.93	8345.36	8345.36
1986	4931.54	6177.96	7785.20	5099.54	6345.96	7953.20	5474.10	6720.52	8327.76	8327.76
1987	4919.42	6168.28	7766.40	5091.42	6340.28	7938.40	5450.72	6699.58	8297.70	8297.70
1988	4980.91	6243.57	7840.96	5110.91	6373.57	7970.96	5546.51	6809.17	8406.56	8406.56
1989	5031.16	6308.44	7922.00	5114.16	6391.44	8005.00	5663.12	6940.40	8553.96	8553.96
1990	5022.66	6307.24	7951.40	5120.66	6405.24	8049.40	5700.14	6984.72	8628.88	8628.88
1991	4993.48	6278.87	7913.68	5108.48	6393.87	8028.68	5589.86	6875.25	8510.06	8510.06
1992	4972.10	6259.12	7918.80	5110.10	6397.12	8056.80	5563.14	6850.16	8509.84	8509.84
1993	5001.72	6296.05	7955.68	5111.72	6406.05	8065.68	5593.10	6887.43	8547.06	8547.06
1994	5046.47	6335.11	8004.00	5121.47	6410.11	8079.00	5633.37	6922.01	8590.90	8590.90
1995	5073.84	6350.30	8015.56	5132.84	6409.30	8074.56	5686.16	6962.62	8627.88	8627.88
1996	5086.52	6361.36	8041.80	5138.52	6413.36	8093.80	5704.92	6979.76	8660.20	8660.20
1997	5072.14	6349.42	7985.84	5140.14	6417.42	8053.84	5689.10	6966.38	8602.80	8602.80
1998	5051.40	6326.24	7945.24	5130.40	6405.24	8024.24	5664.10	6938.94	8557.94	8557.94
1999	5018.46	6294.11	7869.76	5134.46	6410.11	7985.76	5628.92	6904.57	8480.22	8480.22
2000	4988.96	6262.18	7837.88	5127.96	6401.18	7976.88	5567.92	6841.14	8416.84	8416.84
2001	5015.21	6297.36	7889.00	5131.21	6413.36	8005.00	5597.33	6879.48	8471.12	8471.12
2002	4948.92	6225.38	7789.40	5097.92	6374.38	7938.40	5500.82	6777.28	8341.30	8341.30
2003	5018.72	6286.25	7931.56	5124.72	6392.25	8037.56	5632.26	6899.79	8545.10	8545.10
2004	4993.47	6259.38	7900.68	5121.47	6387.38	8028.68	5600.67	6866.58	8507.88	8507.88
Average	5004.63	6277.04	7900.66	5118.49	6390.89	8014.51	5594.78	6867.19	8490.81	8490.81

Where, PEAR - Pearl millet; SOY - Soybean; WH - Wheat; MUS - Mustard; SOR - Sorghum; CHI - Chickpea.

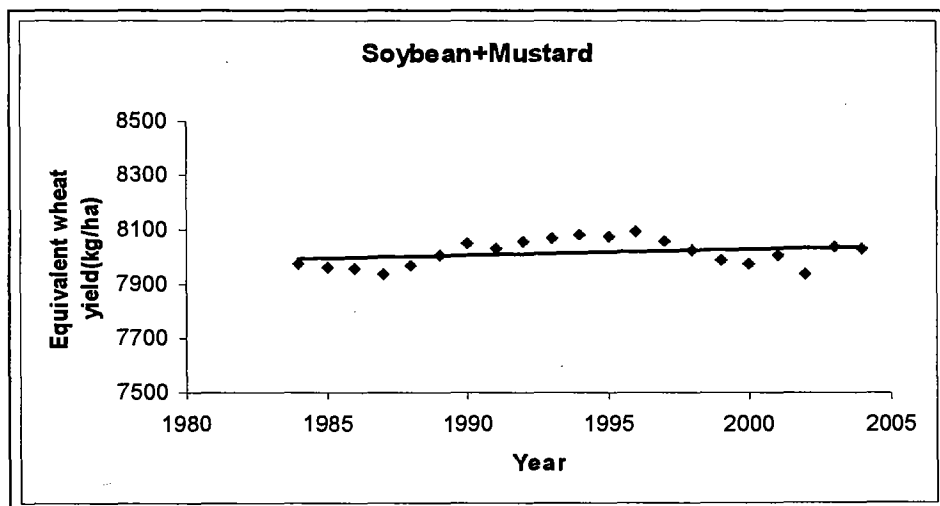
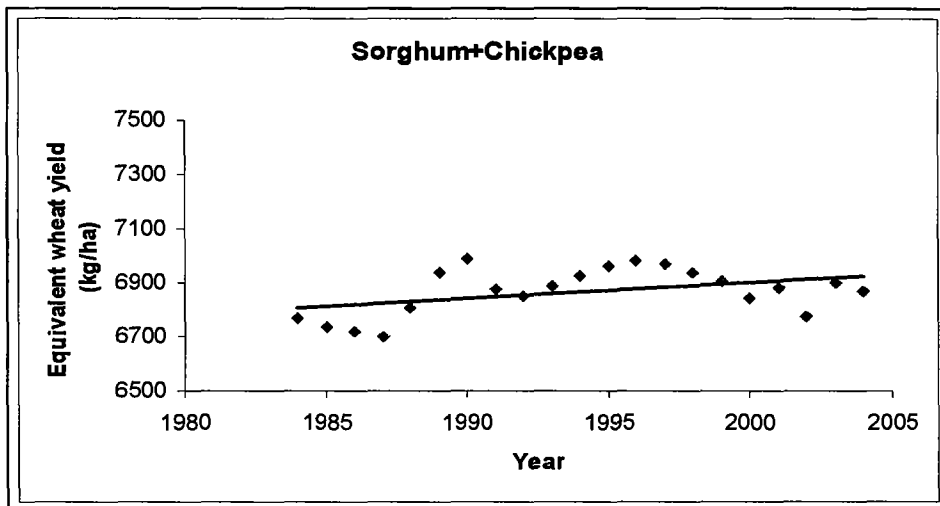
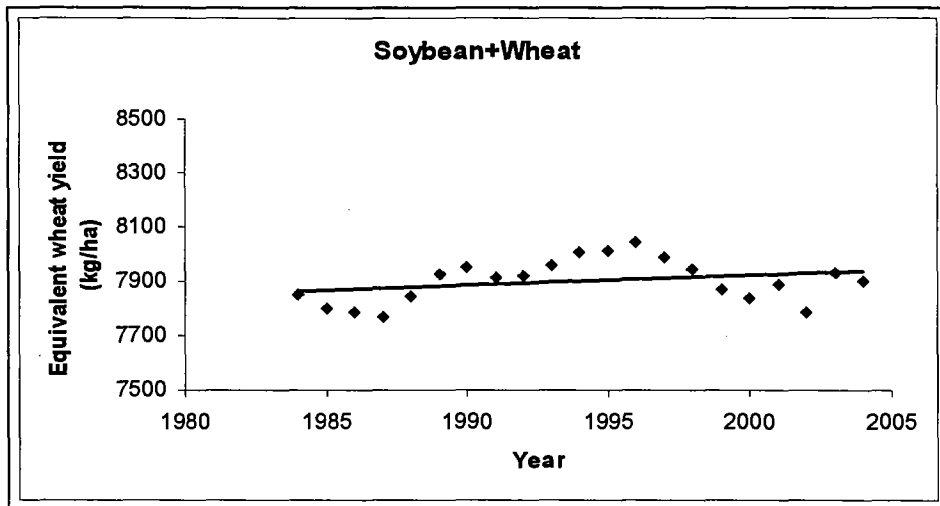


Fig 30- Long term performance of different cropping sequences

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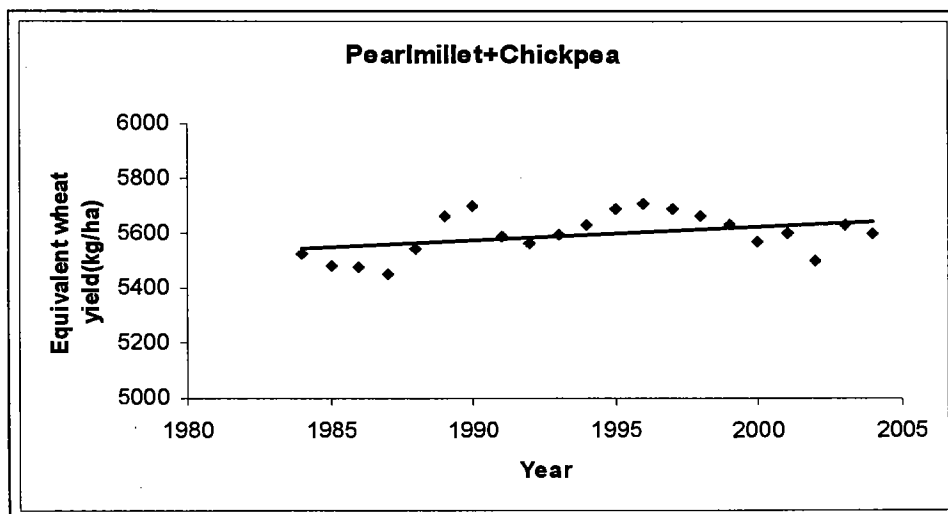
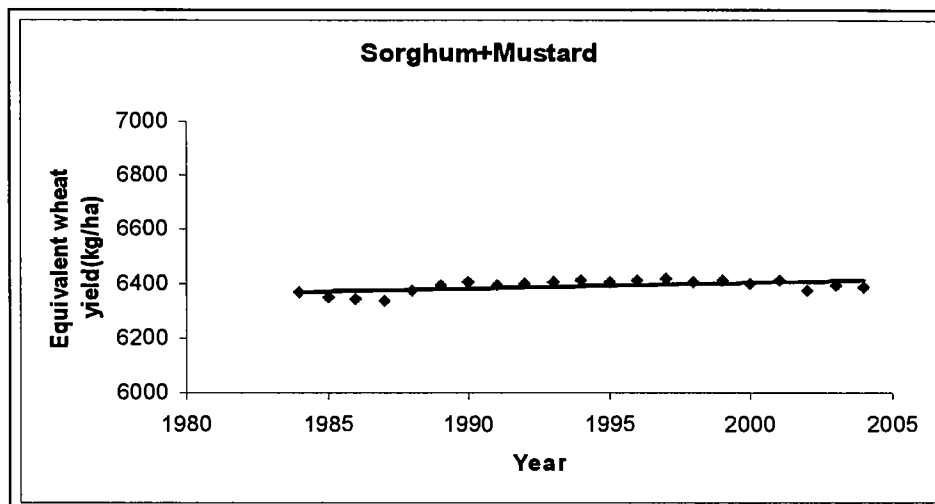
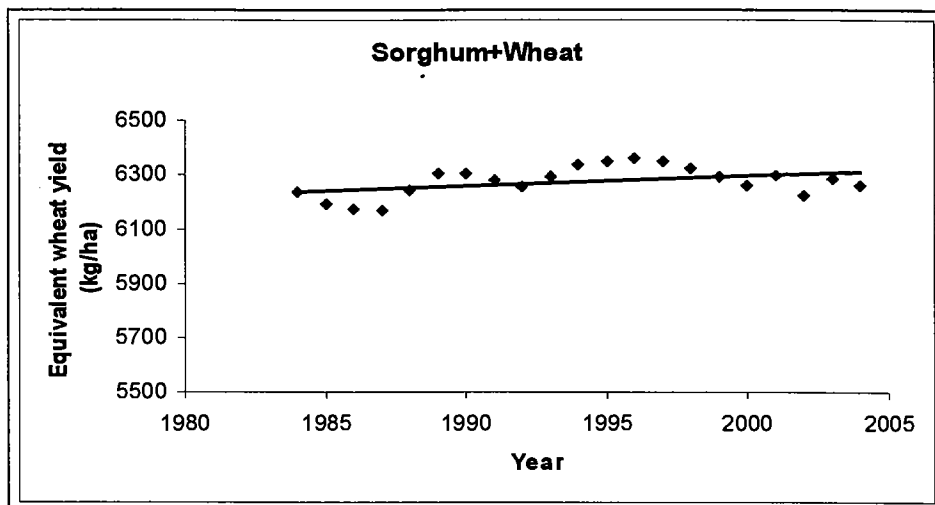


Fig 30.- Long term performance of different cropping sequences

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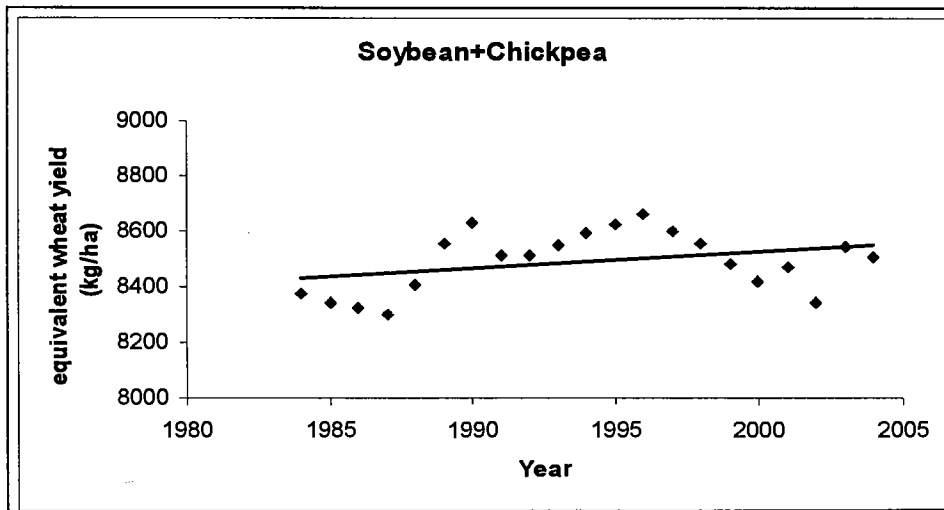
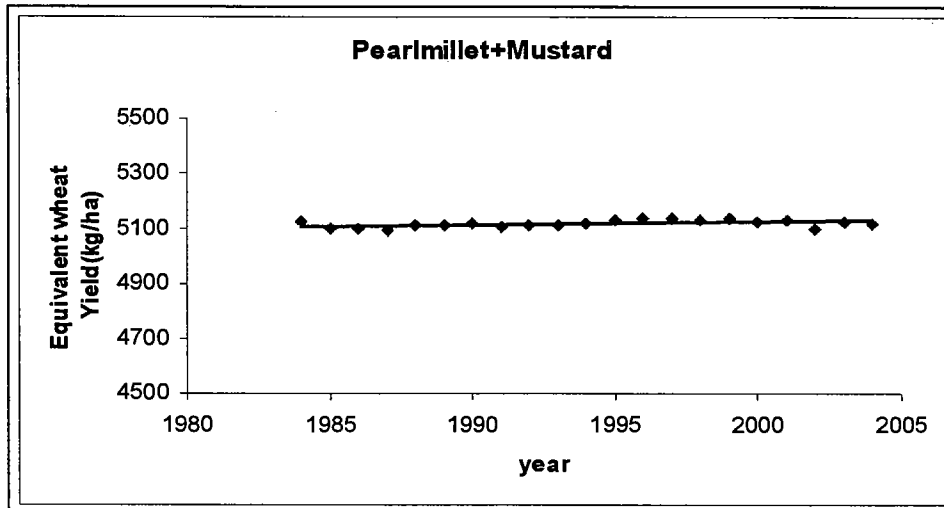
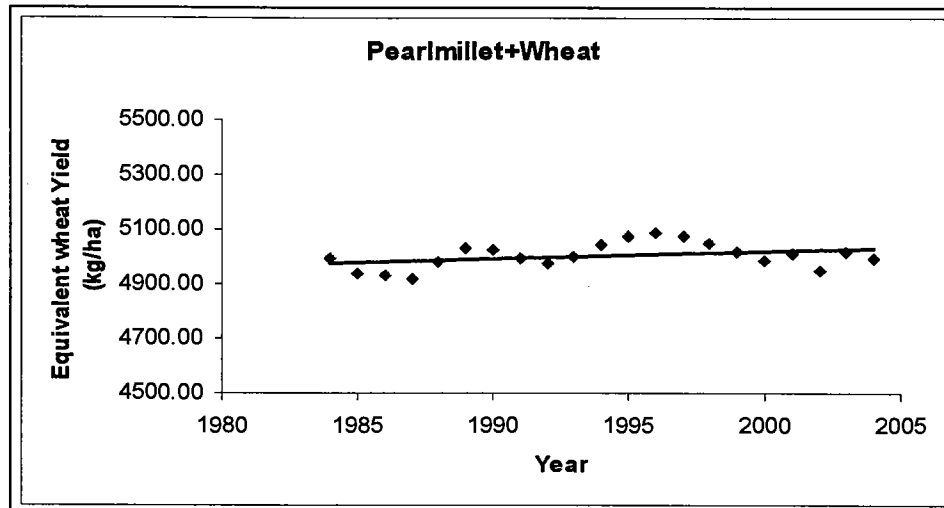


Fig 30.- Long term performance of different cropping sequences

Soybean-wheat and sorghum-chickpea cropping sequence both showed increasing trend of sequence total yield. Though, the variation in yields were 193 kg and 285 kg but the trend was increasing. The third important cropping sequence was soybean-mustard which showed very little fluctuation in equivalent wheat yield but the trend line was almost constant. The fourth important cropping sequence was sorghum - wheat - which also showed slightly increasing trend in yield value during last 20 years.

It was found that all the cropping sequences showed increasing trend of simulated wheat yield equivalent value in the last 20 years. However, there were some variations in the yields during 20 years of simulation but all these variations were below 5% and for watershed scale, this much variation is acceptable. These variations are due to changes in climatic variables like maximum minimum temperature rainfall and solar radiation as reported by (Agrawal *et al.*, 1994; Aggrawal and Kalra, 1944a).

Therefore, it is concluded that soybean-wheat and sorghum-chickpea cropping sequence followed by soybean-mustard and sorghum-wheat cropping sequence are the most optimum cropping sequence in the watershed which can give better results in agro-climatic conditions of watershed.

5. SUMMARY AND CONCLUSIONS

The present investigation was carried out in the Shikohpur watershed, District Gurgaon Haryana to study the "Assessment of optimum cropping sequence of a region based on soil physical properties using crop simulation technique in GIS environment".

The cultivated area (728 ha) of the watershed was divided into twenty six grids of equal sizes (865 m × 865 m). Soil and plant samples were collected from each grid for analysis. Soil physical properties namely moisture content, bulk density (BD), saturated hydraulic conductivity (HC), available water capacity (AWC) and soil moisture retention at six different suctions of 10 kPa, 33 kPa, 50 kPa, 100 kPa, 500 kPa and 1500 kPa were determined for three soil depths 0-15, 15-30 and 30-60 cm in the laboratory for all twenty six grids. Observations on crop growth variables were taken from farmers field of the study area during crop growth period. Meteorological observations were recorded from meteorological observatory of adjoining area which is at IARI, New Delhi.

The variations in soil physical properties of the cultivated area of Shikohpur watershed were quantified using the measured values of the properties in all the twenty six grids. Thematic maps were prepared for bulk density, saturated hydraulic conductivity and available water capacity for all twenty six grids at the three soil depths using Arc View GIS software. These maps indicated the areas of the watershed having undesirable soil properties for a specific crop growth in quantified way for each depth layer separately. The spatial variability analysis of the soil physical properties was carried out using Surfer 6.2 Software. The outcome of this analysis were contour maps for BD, HC and AWC at the three soil depth layers. Contour lines at small intervals were drawn using interpolation method. These maps helped in identifying the areas of soil physical constraints to a specific crop growth.

Simulation of crop growth and yield was carried out using Decision Support System, DSSAT V35 for all the existing and proposed potential crops. The models were calibrated for the existing crops namely pearl millet, wheat and chickpea using farmers field data and for potential crops namely soybean and sorghum using data from adjoining areas. Results obtained from simulation technique on crop growth and yields

were analysed economically. Based on input cost and output prices net profit for cultivation of each crop was determined. Optimum cropping sequences were determined on the basis of highest profitability along with soil health, pest/disease considerations for the watershed. Long term performance evaluation of these cropping sequences were carried out with the twenty years of historic for sustainability of yields.

Results obtained from soil analysis showed that bulk density (BD) of surface layer (0-15 cm) was lower than the soil beneath (> 15 cm). It increased significantly depth wise for each grid. Average value of BD for all the grids changed significantly from 1.59 Mg/m³ in surface soil to 1.60 Mg/m³ in lower depth (30-60 cm). There was a significant variation in soil BD among twenty six grids at all the soil layers. It ranged from 1.44 Mg/m³ to 1.61 Mg/m³ in surface layer, from 1.52 Mg/m³ to 1.66 Mg/m³ in subsurface layer and from 1.56 to 1.66 Mg/m³ in the lower layer at 30-60 cm. Thematic maps of BD of the watershed reflected that BD of 85% area of watershed ranged from 1.49 to 1.61 Mg/m³ in surface layer of soil. In subsurface layer about 90% of the area has BD ranging from 1.53 to 1.66 Mg/m³ and in the lower layer 85% of the area showed BD range 1.53 to 1.66 Mg/m³.

The hydraulic conductivity (HC) was found higher in the surface layer and it decreased significantly with depth in all the grids. The average HC over twenty six grids decreased from 5 cm/hr in surface layer to 4.27 cm/hr in the sub-surface layer showing a significant reduction of 14.3%. There was no significant difference found in HC in between second and third layers. However, 20% reduction in HC was observed in third layer compared to surface layer. The overall average HC of watershed was 4.42 cm/hr indicated that the soils are well drained. A variation of 4.1 cm/hr in HC was found in surface soil of all the twenty six grids which ranged from 2.5 to 6.6 cm/hr. The range of HC in sub-surface soil was 2.1 to 6.0 cm/hr and in the lower layer was 2.3 to 6.8 cm/hr. The high values of HC in the watershed were due to coarse texture of the soil, where sand percentage is higher (>80%). The results were complimentary to the BD results. The decrease in HC depthwise followed the same pattern as increase in BD in all the grids.

The average values of available water capacity (AWC) in the three depth layers were nearly same which were 13.0, 13.4 and 13.7% in the surface, sub-surface and

lower layers, respectively. However, in the surface layer, AWC varied from 10% to 18%, in sub-surface layer, it varied from 9 to 19% and in the third layer the variation was from 9% to 20% among twenty six grids. It indicated that AWC varies more horizontally or spatially than vertically or depth wise. Results revealed that in all the depths, maximum area of watershed had AWC in the range of 12-15%.

The contour maps obtained from spatial variability analysis showed the region of high and lows value of BD, HC and AWC. These regions help in identifying the unsuitable areas for crop growth of the watershed due to soil physical constraints which required some attention to ameliorate these constraints in improving the soil quality for the benefit of farmers.

Results on soil moisture content at different suctions showed that for all the grids, the soil moisture was almost equal in all the three depths at 10 kPa, 33 kPa, 50 kPa and 100 kPa. But at higher suctions of 500 kPa and 1500 kPa, it was found that, there was a significant change in moisture contents of the three soil depths of watershed. The spatial variability in moisture - suction characteristics existed among grids for each depths.

Crop growth and yield was simulated using DSSAT V35. Simulations of growth and yield for five crops perlmillet, wheat, chickpea, soybean and sorghum, were done for all the twenty six grids. Soil files for all the twenty six grids were prepared separately using soil properties of each grid which were same for all the crops for a specific grid. For each crops separate Genotype file and Experiment files were created. For a single year of run same weather file of 2004-05 was applicable for all the grids as well as for all the crops.

Simulated growth and yield of perlmeillet were in agreement with the observed value. The simulated yield was about 6% less than the observed value. The differences in observed and predicted biomass at floral intiation and harvest were 7% and 5%. The predicted values of LAI at floral initiation, anthesis and at harvest were 1.9, 5.34 and 3.42 as compared to observed value of 2.12, 6.06 and 4.17, respectively. The yield of the crop in different grids varried from 1684 to 1732 kg/ha. The average crop yield was 1702 kg/ha. Out of total area of watershed 42% area was low yield producing area having yields ranging from 1684 to 1696 kg/ha, 30% were medium

producing are having yield range of 1697 to 1709 kg/ha and 28% of the area were found to be high producing area having yield range 1710 to 1732 kg/ha.

Simulation of growth and yield of wheat crop showed that simulated LAI was about 15%, 6% and 13% lower than the measured values at tillering, flowering and maturity stage, respectively. The simulated biomass was 12% 7% and 5% lower than the observed biomass at the above mentioned growth stages, respectively. The simulated yield was about 4% less than the observed value. A spatial variation of 52 kg/ha of wheat yield was found in the twenty six grids. The areas under low, medium and high yield production were 35%, 30% and 35%, respectively, which indicated that the area under the three classes of yield were almost equal and there was not much spatial variation in wheat yield in this watershed. Uniform yields were expected over whole watershed cultivated area.

For chickpea, the simulated biomass at vegetative, late flowering as well as at maturity were 5%, 12% 6% higher than observed values, respectively, of the biomass. The simulated values of LAI were 0.54, 3.07 and 1.96 at the above mentioned growth stages, respectively, in comparison to observed values of 0.43, 2.65 and 1.73. The simulated pod yield was 5% and seed yield was found 7% higher than the respective observed values. The yield variation in crop yield among the twenty six grids of the watershed was from 1924 kg/ha to 1997 kg/ha (4%). Out of the total cultivated part of watershed 70% came under medium to high yield production area (1941-1997 kg/ha).

Two new crops, soybean and sorghum were proposed in the watershed for *kharif* season because farmers were growing only one food grain crop i.e. pearl millet. These crops were introduced because site soil characteristic and agroclimatic conditions were perfectly matching with the agro-climatic requirement of these proposed crops.

Simulation for growth and yield of soybean and sorghum were done for all the twenty six grids of the watershed. It was found that biomass accumulation increased continuously with increase in growing time upto physiological maturity conditions in both the crops. The percent variation of yield within twenty six grids were 2% in soybean and 1.5% in sorghum, which reflected very little spatial variability in yields of both the crops in whole watershed. This indicated that both the crops can be

introduced to all the grids of this watershed resulting in higher returns to the farmer of this watershed.

Another important crop mustard was widely grown in the whole area of the watershed. Farmers reported that the average yield of the was 15 q/ha. The DSSAT 35 Software does not contain mustard model and other model for mustard was not used to avoid model bias. Therefore, no simulation for mustard was done and the average yield of 15 q/ha was undertaken for further analysis.

The model simulations of all the crops were in agreement with the observed values. The deviations in simulated growth and yield variables from observed values were within 10% which were accepted at watershed scale. Hence, the model calibrations were fit to be used for optimum cropping sequence evaluation and the assessment of long term effects of the optimum sequence.

The spatial variability maps for all the crops identified the low and high yield producing areas of the watershed for each crop. This helped in selecting areas which needed a change of cropping sequence.

For selection of optimum cropping sequence of the study area, a simple economic analysis for all the six crops was made based on the difference in total output price and total input cost. It was observed that the cost of cultivation was highest for soybean (Rs. 11,750) as compared to sorghum (Rs. 8500) and pearl millet (Rs. 8350) in *kharif* crops. Among *rabi* crops, it was maximum for wheat (Rs. 14500) compared to chick pea (Rs. 14000) and mustard (Rs. 13250). The output prices were highest for soybean (Rs. 28750) in *kharif* crops and chickpea (Rs 30500) in *rabi* crop. The net profit/ha was found maximum for soybean (Rs. 17000) as compared to sorghum (Rs. 12660) and pearl millet (Rs. 4490) among *kharif* crops, whereas in *rabi* crops, it was found maximum for chickpea (Rs. 16500) as compared to wheat (Rs. 12540) and mustard (Rs. 11250).

Out of the nine possible cropping sequences for the watershed, soybean chickpea cropping sequence showed highest return but due to leguminous nature of both the crops, this cropping sequences is not advisable. Among the other eight cropping sequences soybean-wheat-fallow and sorghum-chickpea-fallow cropping sequences were most profitable and gave better returns (around Rs 29000) than other

cropping sequence. The monetary gains in other combinations of cropping sequence were in order of soybean-mustard-fallow > sorghum-wheat-fallow > sorghum-mustard-fallow > pearl millet-chickpea-fallow > pearl millet-wheat-fallow > pearl millet-mustard-fallow. Based on the application of crop simulation and GIS techniques along with economic concerns the cropping sequences recommended for Shikohpur watershed were soybean-wheat fallow and sorghum-chickpea-fallow followed by soybean-mustard fallow and sorghum-wheat-fallow.

The long term performance of all the cropping sequences were evaluated using simulation for 20 year weather data from 1984 to 2004. The simulated yield of all the six crops were converted into equivalent wheat yield for direct comparisons. The simulated equivalent wheat yield for all the nine cropping sequences were determined for 20 years and were plotted for each sequence to evaluate their long term performance under weather variability. Although the weather variability was reflected in the yield variations of the sequences, the trend lines for 20 years yields show an increasing trend for all the cropping sequences. This implies that the proposed cropping sequences will show the sustainability of yields on long term basis.

Based on all the results obtained during investigations it can be concluded that:

1. Significant variations were found in the values of bulk density (BD) in different depths of soil profile. Average value of BD for all the grids changed significantly from 1.54 Mg/m^3 in surface soil to 1.60 Mg/m^3 in lower depth (30-60 cm). On profile average basis the soil BD in the entire watershed ranged from 1.50 Mg/m^3 to 1.64 Mg/m^3 .
2. The saturated hydraulic conductivity (HC) was highest in the surface layer and it decreased significantly with depth among all the grids. The average HC over grids decreased from 5 cm/hr in surface layer (0-15 cm) to 3.89 cm/hr in the lower (30-60 cm) layer showing a significant reduction of about 20%. The overall average HC of watershed was 4.42 cm/hr indicating that the soils are well drained.
3. There is no significant difference in the available water capacity (AWC) between the three depth layers (0-15, 15-30 & 30-60 cm), but there is enough variability among grid values, which indicate AWC varies more horizontally or spatially than vertically or depthwise.

4. There was no variation of soil moisture content values for different depths at lower suctions (upto 100 kPa) but there were significant variations found in their values at higher suctions (500 and 1500 kPa) at different depths. Significant variations in these values were found among grids for a given depth.
5. Majority of the area (72%) of watershed produced low to medium yields of pearl millet and only 28% area of watershed is capable of producing high yields.
6. There is not much spatial variation in wheat yield was found in this watershed. The yield variation among different grids was about 1.5% and uniform wheat yields of about 3635 kg/ha may be expected over whole watershed cultivated area.
7. The spatial variation of around 4% was found in the yield of chickpea among all the grids. 70% of total area of watershed is capable of producing medium to high yield (range 1941-1947 kg/ha).
8. Soybean and sorghum may prove to be good alternative to pearl millet. They are best fitted in the agro-climatic conditions and soil characteristics of the Shikohpur watershed.
9. Soybean-wheat-fallow and sorghum-chickpea-fallow cropping sequences are the recommended optimum sequences for the Shikohpur watershed followed by soybean-mustard-fallow and sorghum-wheat-fallow cropping sequence based on variations in soil physical properties and economic analysis.
10. The long term performance of recommended optimum cropping sequences show an increasing trend of cropping system yield over 20 years weather, indicating the sustainability of cropping sequence yields over long periods.

Future Thrust

More research is needed to develop interfaces to integrate crop simulation models and GIS Software to analyse the spatial variability in crop yields due to variable soil properties and different management scenarios. The recommended cropping sequences based on simulated results need to be validated experimentally in the watershed by conducting demonstration trials and showing that these proposed cropping sequences perform better and providing higher economic returns to the farmers.

ABSTRACT

Identification of suitable crops for specific regions will help in suggesting optimum cropping sequences for increased food production and in land use planning for maximum utilisation of soil resources. For the farmers, as crop cultivation is their livelihood it will help them to get maximum profit from increased food production. The crop simulation technique in combination with GIS technique when used for the Shikohpur watershed, resulted in comparison of various cropping sequences and evaluation of optimum cropping sequence for long term performance. The soil properties namely moisture content, bulk density (BD), hydraulic conductivity (HC) and available moisture capacity (AWC) were mapped, on grid basis, for the watershed using Arc view GIS. It was found that the average value of BD of soil of Shikohpur watershed significantly varied from 1.54 Mg/m² to 1.60 Mg/m³ between surface layer (0-15 cm) and lower layer (30-60 cm). A significant variation of 20% was found in the HC of surface layer and lower layer, and for available water capacity, no difference were observed at different depths. Spatially, all the properties varied significantly. Yields of all the existing crops pearl millet, wheat and chickpea were simulated for each grid by considering soil physical properties of that grid as input soil file to simulation models in DSSAT35 and yield maps were prepared. Two new potential crops, soybean and sorghum, were introduced in the watershed based on their agroclimatic requirements. Yields of these crops were also simulated for each grid and their yield maps were prepared. Simulation methods identified the low and high yield producing areas of the watershed for all the crops. The percentage area of the watershed, which produced medium to high yield of crops were 58% for pearl millet, 65% for wheat, 70% for chickpea, 60% for sorghum and 73% for soybean. The spatial variation in yields were 2.8%, 1.4%, 5%, 1.5% and 2% for pearl millet, wheat, chickpea, sorghum and soybean, respectively. Various combinations of kharif and rabi crops were evaluated and compared based on their economic profitability. The best options among all possible cropping sequences were identified as soybean-wheat-fallow and sorghum-chickpea-fallow and their long term performances in the watershed were evaluated. It was found that the performances of recommended cropping sequences showed an increasing trend under variable conditions of 20 years of historic weather data. This further strengthen the suitability of the recommended cropping sequences for sustainable production in this watershed.

भौगोलिक सूचना तंत्र पर्यावरण में फसल अनुरूपण तकनीक का प्रयोग करते हुए मृदा के भौतिक गुणों पर आधारित किसी क्षेत्र के लिए अनुकूलतम फसल क्रमण का मूल्यांकन

सार

किसी विशेष क्षेत्र के लिए उपयुक्त फसलों की पहचान से, मृदा संसाधनों के अधिकतम उपयोग के लिए भू-उपयोग नियोजन में और बढ़े हुए खाद्यान्न उत्पादन के लिए अनुकूलतम फसल क्रमण निर्धारण में बहुत सहायता मिलेगी। चूंकि किसानों के लिए अपने जीवन निर्वाह के लिए खेती करना जरूरी है इसलिए, इस तकनीक से उन्हें, बढ़े हुए खाद्यान्न उत्पादन से अधिकतम लाभ प्राप्त करते में बहुत सहायता मिलेगी शिकोहपुर जलसंभर क्षेत्र में जब भौगोलिक सूचना तंत्र तकनीक के साथ फसल अनुरूपण तकनीक का इस्तेमाल किया गया तो इससे दीर्घावधि निष्पादन के लिए अनुकूलतम फसल क्रमण का मूल्यांकन और विभिन्न फसल क्रमणों की तुलना में बेहतर परिणाम प्राप्त हुए। जलसंभर के लिए आर्क व्यू भौगोलिक सूचना तंत्र का प्रयोग करते हुए ग्रिड आधार पर, मृदा के गुणों नामतः नमी अंश, विपुल घनत्व (BD), हाइड्रोलिक संवहनता (HC) और उपलब्ध नमी क्षमता का मानचित्रण किया गया। इससे यह पाया गया कि शिकोहपुर जलसंभर क्षेत्र की मिट्टियों के विपुल घनत्व (BD) के औसत मान में, सतही पर्त (0.15 से.मी.) और निम्न पर्त (30-60 से.मी.) के बीच 1.54 मि.ग्रा./वर्ग मी. से 1.60 मि.ग्रा./वर्ग मी. का उल्लेखनीय अन्तर था। सतही पर्त और निम्न पर्त की हाइड्रोलिक संवहनता (HC) में 20% का उल्लेखनीय जल क्षमता के लिए विभिन्न गहराइयों पर कोई अन्तर पर्यवेक्षित नहीं किया गया। विशेष रूप से सभी गुणों में मॉडलों के लिए इनपुट सॉयल फाइल के रूप में उस ग्रिड की मिट्टी के भौतिक गुणों को ध्यान में रखते हुए प्रत्येक ग्रिड के लिए, वर्तमान फसलों, बाजरा गेहूं और चने की उपज का अनुरूपण किया गया और उपज मानचित्र तैयार किए गए। जल संभर क्षेत्रों में उनकी सस्य-जलवायु संबंधी आवश्यकताओं के आधार पर दो नई आशाजनक फसलों, सोयाबीन और ज्वार की खेती शुरू की गई।

प्रत्येक ग्रिड के लिए इन फसलों की पैदावार भी अनुरूपित की गई और उनके उपज मानचित्र तैयार किए गए। सभी फसलों के लिए, जलसंभर क्षेत्रों की पहचान अनुरूपण पद्धति के द्वारा की गई। जलसंभर क्षेत्र की फसलों की पैदावार का मध्यम से उच्च प्रतिशत था, बाजरे के लिए 58%, गेहूं के लिए 65%, चने के लिए 70% ज्वार के लिए 60% और सोयाबीन के लिए 73%। बाजरे, गेहूं, चना, ज्वार और सोयाबीन की उपज में, क्रमशः 2.8%, 1.4%, 5%, 1.5% और 2% का विशेष अन्तर था। खरीफ और रबी की फसलों के विभिन्न संयोजनों का, उनकी आर्थिक लाभदायकता के आधार पर, मूल्यांकन और तुलना की गई। सभी संभावित फसल क्रमणों में सर्वोत्तम विकल्प के रूप में सोयाबीन-गेहूं-परती और ज्वार-चना-परती फसल क्रम की पहचान की गई और जल-संभर क्षेत्र में उनके दीर्घावधि निष्पादन का मूल्यांकन किया गया। इससे यह परिणाम प्राप्त हुआ कि, अनुशासित फसल क्रमणों के निष्पादन से, ऐतिहासिक मौसम डाटा के 20 वर्षों को विभिन्न दशाओं के तहत वृद्धि की ओर रुझान प्रदर्शित हुआ।

इस तथ्य के आधार पर, इस जल संभर क्षेत्र में टिकाऊ उत्पादन के लिए अनुशासित फसल क्रमणों की उपयुक्तता और अधिक बढ़ जाती है।

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APPENDIX I

Simulated yields of major crops in 26 grids of the watershed

Grid ID No.	Pearl Millet	Wheat	Chickpea	Soybean	Sorghum
1	1687	3612	1929	2881	3236
2	1693	3617	1932	2887	3242
3	1692	3615	1937	2885	3241
4	1709	3664	1964	2904	3258
5	1705	3659	1961	2904	3256
6	1689	3641	1934	2885	3240
7	1695	3649	1946	2896	3245
8	1718	3635	1975	2906	3261
9	1732	3651	1997	2924	3285
10	1696	3622	1940	2891	3248
11	1698	3628	1946	2895	3252
12	1691	3614	1934	2882	3243
13	1706	3638	1954	2901	3262
14	1715	3651	1972	2910	3269
15	1698	3624	1951	2896	3255
16	1684	3614	1924	2880	3239
17	1721	3657	1992	2923	3281
18	1695	3629	1947	2898	3256
19	1704	3637	1956	2906	3264
20	1717	3645	1970	2912	3271
21	1698	3625	1945	2897	3250
22	1695	3628	1948	2899	3254
23	1687	3621	1938	2894	3245
24	1702	3642	1942	2901	3256
25	1714	3651	1965	2906	3263
26	1711	3646	1969	2906	3265
Average	1702.00	3635.19	1952.02	2898.31	3255.27

APPENDIX II

Simulated yield of different crops for 20 years

Year	Pearl millet	Sorghum	Soybean	Chickpea	Wheat
1984	1690	3226	2856	1904	3620
1985	1660	3204	2846	1896	3590
1986	1662	3197	2840	1892	3582
1987	1652	3190	2830	1885	3578
1988	1676	3231	2852	1920	3620
1989	1680	3253	2875	1972	3667
1990	1688	3270	2905	1986	3652
1991	1673	3256	2891	1941	3635
1992	1675	3260	2910	1928	3612
1993	1677	3271	2916	1941	3640
1994	1689	3276	2925	1955	3675
1995	1703	3275	2922	1974	3691
1996	1710	3280	2935	1980	3698
1997	1712	3285	2908	1972	3682
1998	1700	3270	2888	1965	3671
1999	1705	3276	2862	1947	3634
2000	1697	3265	2856	1922	3611
2001	1701	3280	2875	1934	3634
2002	1660	3232	2830	1905	3601
2003	1693	3254	2897	1953	3644
2004	1689	3248	2891	1940	3622
Average	1685	3252	2881	1939	3636

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