Drought Climatology of Indo-Gangetic Region of India Using Remote Sensing and Crop Growth Simulation Models

N. SUBASH

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DECLARATION

I hereby declare that the thesis entitled, **"Drought Climatology of Indo-Gangetic Region of India Using Remote Sensing and Crop Growth Simulation Models"** is an authentic record of research work carried out by me under the supervision and guidance of Dr. H.S. Ram Mohan, Department of Atmospheric Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the award of the Ph.D. degree in the Faculty of Marine Sciences and no part thereof has been presented for the award of any other degree in any University / Institute.

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N. SUBASH

CERTIFICATE

This is to certify that this thesis titled, **“Drought Climatology of Indo-Gangetic Region of India Using Remote Sensing and Crop Growth Simulation Models”** is an authentic record of the research work carried out by Mr. N. Subash, under my supervision and guidance at the Department of Atmospheric Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Ph.D. degree of Cochin University of Science and Technology under the Faculty of Marine Sciences and no part thereof has been presented for the award of any degree in any university.

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Dr. H.S. Ram Mohan
Supervising Guide
Professor, Department of Atmospheric Sciences
& Director, School of Marine Sciences

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CHAPTER 1

Introduction

1.1 Introduction

India is endowed with a rich and vast diversity of natural resources, particularly soil, water, weather, agro-biodiversity and ecological regimes. India is a largely agrarian society with nearly 64 per cent of the population dependent on agriculture, although the share of agriculture in the gross domestic product has been continuously declining over the last 50 years. Crop production takes place in almost all land class types, namely, dry, semi dry, moist, sub humid and humid. Agriculture will continue to be important in India's economy in the years to come as it feeds a large and growing population, employs a large labour force, and provides raw material to agro-based industries.

The Indian subcontinent is predominantly characterized by a tropical monsoon climate, where climatic regimes are governed mainly by the differences in rainfall both in quantity and distribution. The Indo-Gangetic Region (IGR) extends over four countries – India, Pakistan, Nepal and Bangladesh. The IGR of India occupies nearly 20% of the total geographical area of the country and encompasses five States: West Bengal, Bihar, Uttar Pradesh, Haryana and Punjab. The IGR has come into existence as a result of continuous deposition of alluvium from the hills and mountains from both sides of the Plains, i.e. the Himalayas in the north and the ranges of the Deccan Plateau in the south. It is one of the most fertile agricultural regions of the country and is also a densely populated region. Rice-wheat is the major cropping system in the IGR. With the advent of the "Green Revolution", these two crops have come to occupy a significant area in the region, which is the "food bowl" or "food basket" of India. . Rainfed rice predominates in the abundant rainfall zones of the eastern part where there is scope for growing rice under ponded water conditions during the rainy season, while irrigated rice is grown in the western part. Wheat assumes greater prominence in the western part, where it is normally grown with irrigation in winter, in rotation with rice. The IGR accounts for 53 per cent of total area under rice and wheat crops. About two-thirds increase in output of rice and wheat in the country during the last two decades has come from this region which reveals its importance in the country's food security. During the same period, along with the spread of green revolution technology, rice-wheat crop rotation has emerged as the dominant crop sequence in the IGR.

In IGR, the climate and weather are dominated by the largest seasonal mode of precipitation in the world, due to the summer monsoon circulation. Over and above this seasonal mode, the precipitation variability has predominant interannual and intra-seasonal components, giving rise to extremes in seasonal anomalies resulting in large-scale droughts and floods, and also short-period precipitation extremes in the form of heavy rainstorms or prolonged breaks on a synoptic scale. Further, the IGR climate is also marked by cold waves during winter and heat waves during the pre-monsoon season. Indeed, it is these extremes that have the most visible impact on human activities and therefore, receive greater attention by all sections of the society.

There are four major reasons for droughts in these areas – delay in the onset of monsoon/failure of monsoon, variability of monsoon rainfall, long breaks in monsoon and spatial variation in the persistence of monsoon rains. Even though there has been a significant increase in the application of water-conserving technologies and in water storage facilities, a recurrence of multiyear droughts result in greater impacts on agriculture today because of the rapid expansion and urbanization of the region's population during the past several decades and the associated increased pressure on water and other natural resources. Droughts are abnormal recurring climatic events, occurring when there is a prolonged absence or deficiency or poor distribution of precipitation from the normal pattern.

To assess the drought, drought indices are normally used. Drought indices are normally continuous functions of rainfall and/or temperature, river discharge or other measurable variable. Rainfall data are widely used to calculate drought indices, because long term rainfall records are often available. Rainfall data alone may not reflect the spectrum of drought related conditions, but they can serve as a pragmatic solution in data-poor regions. Hydrometeorological data based indices include Palmer Drought Severity Index (PDSI), Bhalme-Mooley Drought Index (BDMI), Crop Moisture Index (CMI), Agro-Hydro Potential (AHP), Standardized Precipitation Index (SPI), Surface Water Supply Index (SWSI), Reclamation Drought Index (RDI), Deciles etc.

According to a study by Nain *et al*. (2005), agriculture drought monitoring with crop simulation model has edge over other conventional and popular drought monitoring approach such as SPI. Crop growth and yield are determined by a number of factors such as genetic characters of crop cultivar, physical and chemical soil characteristics, weather, management practices such as date of sowing/planting, amount and time of irrigation and fertilizer application and biotic stresses. However, generally for a given area, year-to-year yield variability has been mostly modeled through weather as a predictor using either empirical or crop growth simulation approach.

With the advent of space technology, continuous availability of multi-spectral sensors on satellites, remote sensing data provide timely, accurate, synoptic and objective estimation/monitoring of crop growing conditions. Remote sensing data have certain advantage over meteorological observations for yield modeling, such as dense observational coverage, direct viewing of the crop and ability to capture effect of non-meteorological factors. A comparison of three technologies viz, meteorological indices, crop growth simulation models, remote sensing data can provide effective drought assessment tool.

1.2. Definition of the research problem

The IPCC (2001) in its Third Assessment Report (TAR) reported that under climate change the chances of occurrence of extreme droughts would increase in the Indian Subcontinent. In India, the climate and weather are dominated by the largest seasonal mode of precipitation in the world, due to the summer monsoon circulation. Over and above this seasonal mode, the precipitation variability has predominant inter-annual and intra-seasonal components, giving rise to extremes in seasonal anomalies resulting in large-scale droughts and floods, and also short-period precipitation extremes in the form of heavy rainstorms or prolonged breaks on a synoptic scale. Indeed, rainfall during a typical monsoon season is by no means uniformly distributed in time on a regional/local scale, but is marked by a few active spells separated by weak monsoon or break periods of little or no rain. Thus, the daily distribution of rainfall at the local level has important consequences in terms of the occurrence of extremes. Further, the Indian climate is also marked by cold waves during winter in the north, and heat waves during the pre-monsoon season over most parts of the country. Tropical cyclones, affecting the coastal regions through heavy rainfall, high wind speeds and storm surges, often leave behind widespread destruction and loss of life, and constitute a major natural disaster associated with climatic extremes. Indeed, it is these extremes that have the most visible impact on human activities and therefore, receive greater attention by all sections of the society. There are four major reasons for droughts in India-delay in the onset of monsoon/ failure of monsoon, variability of monsoon rainfall, long break in monsoon and areal difference in the persistence of monsoon. Almost a quarter of India’s land area is prone to drought. Areas that receive up to 60 centimeters of rainfall annually are the most drought prone. The drought is almost directly linked to the areal variation in the monsoon, the effect of which lasts for much longer than the actual span of the monsoon. The most affected community is the marginal farmers, as mostly they are dependent on rainfed agriculture.

Historical records indicate that drought occurs in any form of severity in one or other places in the Indo-Gangetic Region of India in every year, which is the food bowl of India. A recurrence of these multiyear droughts today would result in substantially greater and more varies impacts because of the rapid expansion and urbanization of the region's population during the past several decades and the associated increased pressure on water and other natural resources, every though there has been a significant increase in water storage facilities and the application of water-conserving technologies. At present, several drought indices, simulation models and modern tools such as remote sensing are available to assess the drought climatology and several studies were conducted in India without integrating of these.

1.3. Research Objectives

In this study, the three different approaches for characterizing the agricultural drought conditions are compared in order to develop a rational integrated agricultural drought assessment index with respect to rice and wheat over the study region. This study also provides the historical drought patterns and frequency over the region using different approaches and also the usefulness of integrated approach to agricultural drought forecasting in terms of rice-wheat well in advance.

1.4. General agro-climatology of IGR

The IGR primarily comprises five States: West Bengal, Bihar (undivided), Uttar Pradesh (undivided), Haryana and Punjab (Fig 1.1). There are three more Indian districts – in Rajasthan and Himachal Pradesh State - that primarily fall within the IGR but outside of the five States are not considered here. Since most of the long-term data sets are available for undivided Bihar and Uttar Pradesh, here we have considered Bihar and Jharkhand as Bihar and Uttar Pradesh and Uttaranchal as Uttar Pradesh. IGR is a great crescent of alluvial soils that stretches from the delta of the Indus in the west to the Ganga-Brahmaputra delta in the east. The sediment has been deposited in rifts with the varying depth, at places reaching 4500 m.

The general slope of the ground is from west to east i.e., 200 meters above mean sea level in the west to near sea level in the east. Annual rainfall varies from 300 mm to 1600 mm increasing towards east at the rate of roughly 0.6 mm/km. Five types of moisture regimes exist in the IGR viz., arid, semi-arid, dry sub-humid, moist sub-humid and humid. Developed from huge amount of silt brought by rivers emerging from the mighty Himalayas, namely, the Indus and its tributaries, Ganga, Yamuna, Ghagra and Kosi, this region is endowed with natural resourced viz., deep productive soils, plentiful surface as well as groundwater and climate which is favorable for double and triple cropping. The Indo-Gangetic Region is bound on the north by the abruptly rising Himalayas, which feed its numerous rivers and are the source of the fertile alluvium deposited across the region by the two river systems. The southern edge of the plain is marked by the Vindhya- and Satpura Range, and the Chota Nagpur Plateau. On the west rises the Iranian Plateau, with only the floodplain bluffs, changes in river channels and other related features of river erosion forming natural features. Two narrow terrain belts, collectively known as the Terai, constitute the northern boundary of the Indo-Gangetic Region. In the area where the foothills of the Himalayas encounter the plain, small hills known locally as ghar (meaning house in Hindi) have been formed by coarse sands and pebbles deposited by mountain streams. Groundwater from these areas flow on the surface where the plains begin, converting large areas along the rivers into swamps. The southern boundary of the plain begins along the edge of the Great Indian Desert in the state of Rajasthan, before continuing east along the base of the hills of the Central Highlands to the Bay of Bengal. The hills vary in elevation from 300 to 1200 meters and lie on a general east-west axis. The major cropping systems are rice-wheat, rice-mustard-rice, cotton-wheat, pearl millet-wheat, rice-sugarcane and maize-wheat. The crops are rice, wheat, maize, cotton, sugarcane and pearl millet. These crops are grown in large areas of IGP in rabi and kharif seasons.

The climate of the Indo-Gangetic Region is dominated by the Asian summer monsoon. The cool, dry winter is followed by a warming trend with daytime temperatures reaching as high as 45°C in June or July. The temperature rise is broken by the onset of the monsoon rains, when the daytime maximum temperature will immediately drop 5°C or more with the first rains. Summer temperatures are generally higher in the northwest part of the IGR, corresponding to later onset of the rainy season. In most of the IGR, winter temperatures is very low allowing production of wheat, potatoes and other cool season crops where irrigation is possible. Annual precipitation varies from 400 mm in western IGR to 1600 mm in eastern India.

Within the IGR, Indo-Gangetic Plain (IGP) is homogenous in topography, in the west the elevation of the IGP is 150-300 m whereas in the east it is generally less than 50 m. The Planning Commission, Government of India (1979) divided the country into 15 broad agro-climatic zones based on physiography and climate. Four of these broad agro-climatic zones fall in this IGR.

They are

1. Lower Gangetic Region – ACR III (West Bengal)
2. Middle Gangetic Region – ACR IV (Bihar and Eastern Uttar Pradesh)
3. Upper Gangetic Region – ACR V (Western Uttar Pradesh)
4. Trans-Gangetic Region – ACR VI (Haryana, Punjab, Rajasthan)

The general agro-climatic characteristics (Ghosh, 1991; Basu and Guha, 1996; Narang and Virmani, 2001) of these four regions are summarized as follows,

Lower Gangetic Region: This zone experiences a sub-humid to humid and sub-tropical climate. It receives 1200-1600 mm annual rainfall. The soils are perfectly suited for rice cultivation and rice constitutes the main staple food of the people. Rice is grown primarily as a rainy season crop under long-duration flooded conditions. It also constitutes the marshy saline bog lands where hardly any farming is possible. This region consists of the following zones;

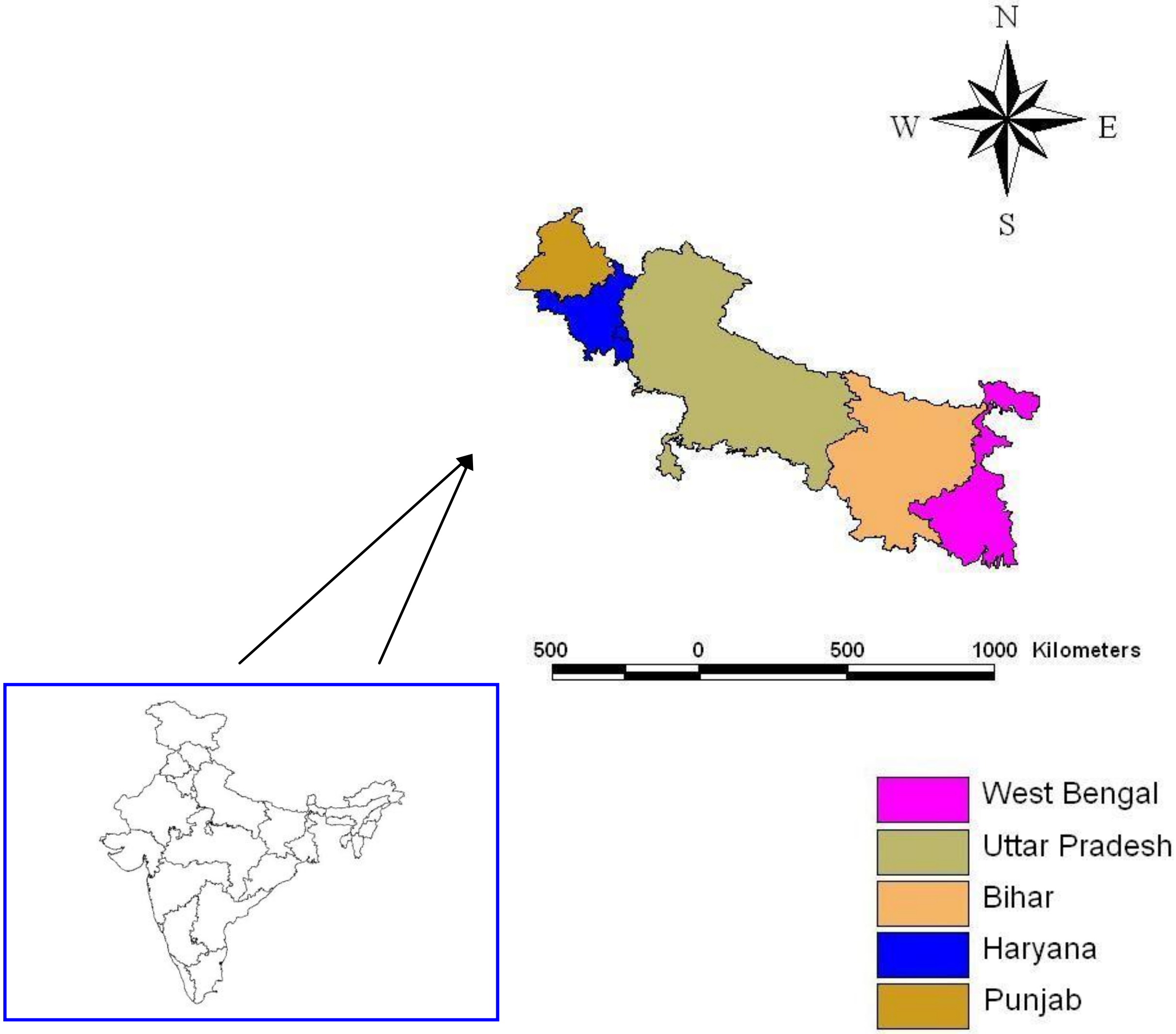

Fig.1.1: Location of the study area and its administrative boundary.
(Inset map represents India map)

<u>ACZ D1—Old and New Alluvial Zone</u>: This Zone lying on the east of the Ganges River constitutes the traditional rice-growing zone of this region. This zone experiences a sub-humid to humid and sub-tropical climate. Rice is grown primarily as a rainy season crop under long-duration flooded conditions. The soils are ideally suited for rice cultivation and rice constitutes the main staple food of the people. Wheat is a recent entrant into West Bengal. Prior to the era of HYVs, hardly any wheat was cultivated in West Bengal. But since the advent of HYVs in the late 1960s, because of their short duration and photoperiod-insensitive nature, a sizeable area in West Bengal is now sown to wheat, particularly this zone, which enjoys comparatively cool winters. This makes wheat cultivation a successful economic proposition.

ACZ D2—Laterite and Red Soil Zone: This zone constitutes the major rice growing component of West Bengal and lies on the western side of the Ganges River. It accounts for the maximum area of rice in the State. Very little area has come to be occupied by wheat; perhaps because of (i) low soil water holding capacity and little opportunity for irrigation, and (ii) a comparatively higher temperature regime (warmer winters with no or very little chilling period).

ACZ D3—Coastal Saline Soil Zone: Being coastal saline zone, it has hardly any sizeable cultivated area. In fact, it constitutes the marshy saline bog lands of West Bengal where hardly any farming is possible.

Middle Gangetic Region: It has an annual rainfall of 1000-1200 mm, of which 85-90 % received during the monsoon months of June-September and this zone experiences a sub-humid, sub-tropical climate. Eastern Uttar Pradesh is considered as naturally the most-suited rice-growing area in the IGR and rice is also the primary staple food of the people living here. The soils of south Bihar zones are well drained and water availability is high and is comparatively free from recurring floods except on the eastern flank where floods occur once in every 2-4 years. This region consists of the following zones;

ACZ C1—Eastern Plain Zone: This zone lies between the Saryu and Ganges Rivers in the Central IGR. It has an annual rainfall of 1000–1200 mm, of which 85–90% is received during the monsoon months of June-September/October and is also endowed with good soils. This zone constitutes a major traditional rice-growing area of the IGR. The density of rice area is quite high and extent of rice cultivation well spread, except in the southwest.

ACZ C2—North-Eastern Plain Zone: This zone lies north of the River Saryu and between the Rivers Gandak and Ghaghra. The area enjoys a subhumid, sub-tropical climate. The monsoon season lasts from June–September. The annual rainfall of 1000–1200 mm or more and low flood intensity accounts for rice cultivation on an extensive scale in this zone. In fact, Eastern Uttar Pradesh, with copious rainfall and heavy to medium heavy textured soils, is considered as naturally the most-suited rice-growing area in the IGR. Therefore, the intensity of rice cultivation is very high in this region and rice is also the primary staple food of the people living here.

ACZ C3—South Bihar Alluvial Plain Zone: This zone lies to the south of the Ganges River with the Sone River forming its major tributary on the southern flank. It is comparatively free from recurring floods except on the eastern flank where floods occur once in every 2–4 years. The soils of this zone are well drained and water availability is high. Rice cultivation is concentrated along the Sone and Ganges Rivers; with the intensity decreasing in flood-prone areas.

ACZ C4—North-West Alluvial Plain Zone: This zone lies on the east of the River Gandak and north of the Ganges River, at an elevation of 50–100 m (msl). It has an annual rainfall of about 1200 mm but it is most frequently flooded. Deep water paddy in the flood-prone areas and upland rainfed paddy at upper elevations, besides transplanted paddy are major rice-based cropping features of this zone. High frequency of floods (once every year or every 2 years) makes growing of most other crops a risky proposition and the predominance of paddy in this region is, therefore, inevitable.

ACZ C5—North-East Alluvial Plain Zone: This zone constitutes, along with the North-West Alluvial Plain Zone, the second most severely affected flood-prone area of the state after the North-West Alluvial Plain Zone ACZ C4. This is inundated almost regularly every year by high floods of the Kosi and Ganges Rivers and their Himalayan tributaries. Accordingly, even though agro-climatically suitable for rice production, the intensity of rice area here is comparatively low.

Sizeable area of wheat is cultivated in the Middle-Gangetic Plains Region, as well. But this is largely concentrated in eastern Uttar Pradesh. The density of wheat cultivation tends to thin out from the west to the east of the region. The state of Bihar, though showing sizeable area under wheat, has a comparatively thinner spread of area in the north-eastern and southern flanks. Agro-climatically, the Bihar IGR region has mild winters and, therefore, has a rather shorter wheat-growing span. In fact, the growing season of wheat tends to be shorter by almost 30–35 days as compared with that of the Trans-Gangetic/ Western Uttar Pradesh regions. The abrupt rise of temperatures in spring which often causes terminal heat stress, further curtails the growing period. This enforced maturity results in imperfectly developed or incompletely filled grains. In spite of these handicaps, because wheat has a stable performance (though at lower yield levels) and as it fits very well in the 2-crops-a-year rice-based system, it is cultivated extensively in the entire Middle-Gangetic Plains Region. Of course, the area intensity fluctuates in response to the water availability resource and the time of planting available.

Upper Gangetic Region: It has an annual rainfall of 800-1200 mm. It possesses an extensitive network of irrigation facilities and soils are deep alluvial, medium to heavy textured but are easily ploughable. The favourable climate and soil and the availability of ample irrigation facilities make growing of rice a natural choice for the area. This region consists of the following zones;

ACZ B1—Western Plain Zone: This zone constitutes the western-most districts of Uttar Pradesh, the most fertile zone of the state. It constitutes the sugarcane belt of Uttar Pradesh. Agro-climatically, it is well endowed with a congenial climate, possesses an extensive network of irrigation and abundant underground water reserve (due to high recharge from the Yamuna and Ganges Rivers and their tributaries coming from the Himalayas). In spite of all these favorable factors, it has, however, very minimal area of rice and that too confined mostly to district Saharanpur. This area has a large number of sugar factories, both in the organized and unorganized (farmer-owned unrefined sugar manufacturing units) sectors. Further, as sugarcane is the most popular crop, there is little scope for rice which competes with sugarcane for labor, capital and intensive field care.

ACZ B2—Mid-Western Plain Zone and 'Bhabar and Tarai Zone': This area constitutes the sub-humid zone. It has an annual rainfall of 1000–1200 mm and also enjoys ample irrigation resources. The underground water-table is shallow and can be easily exploited. Soils too are comparatively heavy permitting successful cultivation of rice. Rice constitutes a major crop of the area, only next to wheat.

ACZ B3—Central Plain Zone: It has an annual rainfall of 800–1200 mm and is liberally sourced by the Ganges and Yamuna Rivers and their tributaries. Soils are deep alluvial, medium to medium heavy textured but are easily ploughable. The favorable climate and soil, and the availability of ample irrigation facilities make growing of rice a natural choice for the area. This zone has a sizeable area of rice though its scatter is generally more widespread.

ACZ B4—South-Western Semi-Arid Zone: This zone constitutes relatively the driest parts of Uttar Pradesh. The area has mostly a rainfed farming type of environment and, therefore, accounts for a minimal area of rice.

This region, besides receiving ample winter rains (80–100 mm), also enjoys abundant irrigation water availability. It has deep, well-drained alluvial fertile soils. The region has a well-developed infrastructure; like rail, roads, transport, communications, electricity, a vast network of canal and tubewell-based irrigation systems, and an easy access to markets. Fertilizers and other inputs, a fairly high level of agro-technology and credit are readily available. In Western Uttar Pradesh, and in *Tarai* regions the main competition to wheat comes from sugarcane, while in the dry zone, low water requiring crops like canola and mustard, winter legumes such as chickpea, mixed crops, etc. are cultivated during *rabi*.

Trans-Gangetic Region: Agroclimatologically, this zone falls in the low rainfall zone of 400-800 mm. But this zone has the unique advantage of enjoying the highest irrigation intensity in the country, with more than 94 % of net area sown being irrigated through a network of perennial canals and tubewells. Groundwater reserves are being fully exploited with the result that this area is showing a sharp decline in groundwater-table, averaging 20 cm per annum (Narang and Gill, 1994). This region consists of the following zones;

ACZ A1—Central Plain Zone: Agro-climatologically, this zone falls in the low rainfall zone of 400–800 mm. But this zone has the unique advantage of enjoying the highest irrigation intensity in the country, with more than 94% of net area sown being irrigated through a network of perennial canals and nearly 0.8 million tubewells. Groundwater reserves are being fully exploited with the result that this area is showing a sharp decline in groundwater-table, averaging 20 cm per annum (Narang and Gill 1994). Overall congenial growing conditions (bright sunshine duration of 13–14 hrs or more) during most of the active growth period of rice and a continuous replenishment of irrigation water. The farmers grow rice on light sandy loam/loam textured soils found on more than half of this zone. It requires 1500 mm of irrigation water applied over 100–110 day active crop growing phase besides the 330 mm average normal effective rain received during the growing season (Narang and Gulati 1992). The water application consists of scheduling 20–25 cm water at land preparatory tillage, puddling and transplanting. Water is then kept ponded for about two weeks. It is followed subsequently by fresh irrigations applied 1–2 days after the surface water has seeped in and the soil surface develops hair-size cracks. This process is repeated 20–30 times during the life-cycle of the crop. Irrigation is discontinued about 2–3 weeks prior to harvest. In fact, the “Green Revolution” which originated at Ludhiana, has spread rapidly engulfing the whole Central Plain Zone endowed with good canal and tubewell, fresh water resource.

ACZ A2—Western Plain Zone: In this zone rice competes with cotton, which is another major cash crop of the area. Tubewell water use is moderate, as the underground water is mostly brackish; and, therefore, soils at places are saline and alkali with an impeded drainage. Cotton and other oilseeds/pulse grains can no longer be grown. Farmers are shifting to rice cultivation. This shift in cropping pattern is causing considerable concern for the sustainability of cotton production in the area.

ACZ A3—Sub-Montane Undulating Zone and Undulating Plain Zone: There is a sizeable area of rice in this undulating plain zone of the sub-montane tract, soils get enriched with good sedimentation of silt and clay during the rainy season. Availability of canal and tubewell irrigation supplemented by rain makes large-scale growing of rice quite feasible and rice area has virtually spread to occupy all of the plain land available in the Undulating Plain Zone.

ACZ A4—Eastern Zone: This zone includes the very fertile eastern districts of Haryana. This are is famous for *Basmati* rice production. The area, being generally short of groundwater resources (due to poor and marginal quality water) is generally dependent on canal water and rainfall for sustaining rice. Therefore, rice is normally planted with the onset of the monsoon; this comparatively late planting makes this area suitable for growing of *Basmati* rice, which requires a steadily falling temperature regime with comparatively cool nights, and high relative humidity during the reproductive and grain development phase. These environmental conditions are considered to improve the quality of *Basmati* rice in terms of its aroma, cooking quality, less breakage of slender-long grains during milling and polishing.

ACZ A5—Western Zone: This zone constitutes the south-western arid parts of Haryana state interspersed with desert-like soils, sand dunes, scarce water availability, highly brackish (poor quality) waters and limited canal irrigation resource. Thus, rice area in this zone is nominal as rice growing is limited to certain pockets only, where, besides canal water, some supplemental tubewell irrigation water is also available

Wheat cultivation is widespread in this agroclimatic region, because it receives good winter rains (100–110 mm) and is well endowed with a very comprehensive irrigation system of tubewells and canals. Besides, this region enjoys long bright sunshine-hour duration (10–12 hrs/day) and low temperatures appropriate for vernalization and good seed-set in wheat. Fertilizer and herbicide use is widespread; mechanization (tractorized land preparation, harvesting, threshing and transportation of produce) is extensive; and basic infrastructure of rail, road, transport, communications, electricity supply, etc., are adequate. The farmers of the region too are very progressive, entrepreneur-minded, receptive to the adoption of new innovative technologies and adept in managerial skills. Since the introduction of high-yielding varieties (HYVs) of wheat from the late 1960s and rice from early 1970s, the farmers of the region have maintained an uninterrupted lead of ever increasing yields of wheat and rice in India.

According to Mandal *et al*. (1999), this region is divided into 18 agro-ecological sub-zones. This agro-ecological zone map is based on the superimposition of three basic maps viz., soil-physiography, bioclimate and length of growing period (Fig. 1.2). The detailed agro-ecological characteristics of each of sub-division are narrated in Table 1.1.

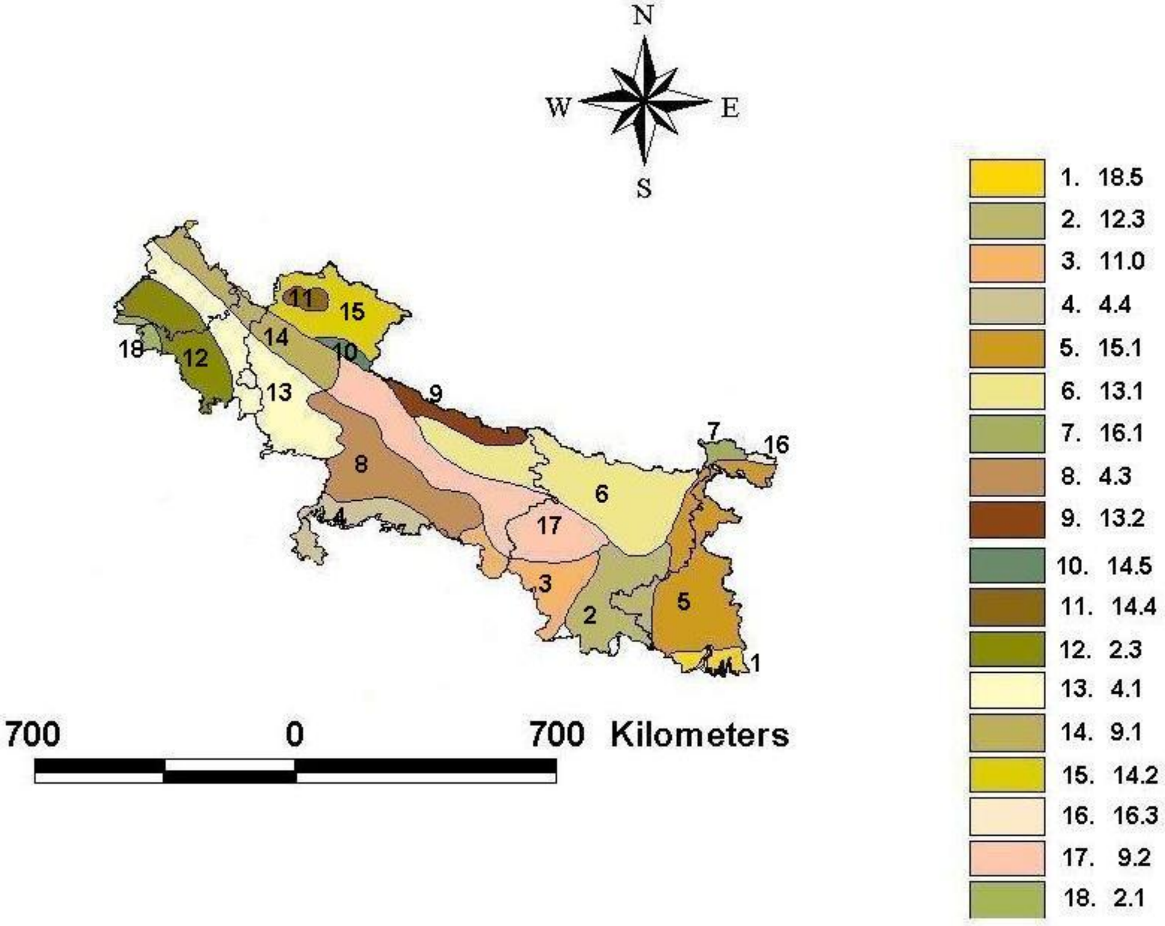

Fig.1.2: Agro-ecological sub-region map of IGR

Sl. No	Agro-Ecological region	Agro-ecological sub-region and Length of Growing Period (LGP)		Representative stations	Latitude (^{0}N) Longitude (^{0}E) Altitude (m)
1	Western Plain, hot arid eco-region M9E1	2.3	South-Western Punjab Plain, hot typic-arid ESR with deep, loamy desert soils, low AWC and LGP 60-90 days (M9Et2)	Hisar	29.10,75.44, 215
2	Northern Plain N8D2	4.1	North Punjab Plain, hot semi-arid ESR with deep loamy alluvium-derived soils, medium AWC and LGP 90-120 days (N8Dd3)	Ludhiana	30.56,75.52, 247
		4.3	Ganga Yamuna Doab, Rohilkhand and Avadh plain, hot moist semi-arid ESR with deep, loamy alluvium-derived soils, medium to high AWC and LGP 120-150 days (N8Dm4)	Allahabad Kanpur	25.27,81.44, 98 26.26,80.22, 126
		4.4	Madhya Bharat Plateau, hot, moist semi-arid ESR with deep loamy and clayey mixed Red and Black soils, medium to high AWC and LGP 120-150 days (N6Dm4)	Jhansi	25.27, 78.35, 251
3	Northern Plain, hot subhumid (dry) N8C3	9.1	Punjab and Rohilkhand Plains, hot dry/moist subhumid transitional ESR with deep, loamy to clayey alluvium-derived soils, medium AWC and LGP 120-150 days (N8(Cm)Cd4)	Karnal	29.28, 77.44, 239
		9.2	Rohilkhand, Avadh and south Bihar Plains, hot dry sub humid ESR with deep loamy alluvium-derived soils, medium to high AWC and LGP 150-180 days (N8Cd5)	Lucknow Faizabad	26.52, 80.56, 111 26.47, 82.08, 133
4	Transitional AER	11.0	Moderately to gently sloping Chattisgarh/Mahanadi Basin, hot moist/dry subhumid transitional ESR with deep loamy to clayey red and yellow soils, medium AWC and LGP 150-180 days (J3Cd/Cm5)	Hazaribagh	23.59,85.22, 611
5	Eastern Plateau and Eastern Ghats, hot subhumid J23C3(4)	12.3	Chhotanagpur plateau and Garjat Hills, hot, dry-subhumid ESR with moderately deep to deep loamy to clayey red and lateritic soils, medium AWC and LGP of 150-180 days (J2Cd5)	Dhanbad	23.47, 86.30, 156
6	Eastern Plain, hot subhumid (moist) O8C4	13.1	North Bihar and Avadh Plains, hot dry to moist subhumid transitional EST with deep, loamy alluvium-derived soils, low to medium AWC and LGP 180-210 days (O8Cd/Cm6)	Pusa Purnea Gorakhpur	25.39, 84.40, 52 25.46, 87.28, 38 26.45, 83.25, 78
		13.2	Foothills of Himalayas, warm to hot moist subhumid ESR with deep loamy to clayey Tarai soils, high AWC and LGP 180-210 days (B10Cm6)	Bahraich	27.34,81.36, 124
7	Western Himalayas, warm subhumid	14.2	Kumaun Himalayas, warm moist to dry subhumid transitional ESR with medium to deep loamy to clayey	Tehri Garhwal	30.52,78.02, 1600

Table 1.1: Agro-ecological sub-regions of Indo-Gangetic States (Contd….)

	A15C(BA)4(5)		Brown Forest and Podzolic soils, medium AWC and LGP 150-210 days (A15Cd/Cm6)		
		14.4	Kumaun Himalayas, warm humid to per humid transitional ESR with shallow to medium deep loamy red and yellow soils, low AWC and LGP 270-300 days (A3BA9)	Not Considered	
		14.5	Foothills of Kumaun Himalayas (Subdued), warm moist subhumid ESR with medium to deep, loamy Tarai soils, medium AWC and LGP 270-300 days (A10A9)	Not Considered	
8	Assam and Bengal Plain, hot subhumid to humid Q8C(BA)5	15.1	Bengal basin and north Bihar Plain, hot moist subhumid ESR with deep loamy to clayey alluvium-derived soils, medium to high AWC and LGP 210-240 days (O8Cm7)	Asansol Krishnanagar Dumka	23.42, 87.01, 150 23.24, 88.31, 015 24.12, 87.15, 149
9	Eastern Himalayas, warm perhumid C11A5	16.1	Foot-hills of Eastern Himalayas, warm to hot perhumid ESR with shallow to medium, loamy-skeletal to loamy Tarai soils, low to medium AWC and LGP 270-300 days (C10A9)	Not Considered	
		16.2	Darjeeling, warm perhumid ESR with shallow to medium deep loamy brown and red hill soils, low to medium AWC and LGP 300 days (C11A10)	Not Considered	
10	Eastern Coastal Plain, hot subhumid to semi-arid S7CD2-5	18.5	Gangetic Delta, hot moist subhumid to humid ESR with deep, loamy to clayey Coastal and Deltaic alluvium-derived soils, medium AWC and LGP 240-270 days (S7Cm7)	Not Considered	

Table 1.1: Agro-ecological sub-regions of Indo-Gangetic States

CHAPTER 2

Literature Survey, Data and Methodology

2.1. Literature Survey

Rice and wheat are the most important food crops for human kind. Both these food crops are grown in about 27 per cent of the total available land, under different climatic, soil and ecological situations. Rice and wheat require certain range of temperature and water requirement for optimum growth. Chaudhary and Ghildyal (1969) observed that 26.5 °C – 37.5 °C was the optimum temperature range for germination, whereas temperature beyond 41 °C was lethal. Alternating high or low temperatures were considered by them to be less harmful than continuous low or high temperatures: high temperatures were lethal, the low temperatures delayed germination. Temperature influences growth rate, duration and productivity. Generally, growth rate increased linearly in the temperature range of 22-31 °C and higher temperatures adversely affected rice growth and productivity (Yoshida, 1981). A rice crop requires about 2000-4000 degree days which corresponds to 80-160 days when grown at a mean temperature of 25 °C. According to Srinivasulu and Rao (1974), the cold tolerant varieties gave optimum germination even at 10 °C and hence, they suggested germination at 10 °C as a useful screening technique for identifying varieties suitable for growing in cooler regions.

Since the water requirement of rice is higher than that of any other crop of a similar duration, assured and timely supply of irrigation water has a great influence on the yield of the crop. In the life cycle of rice plant, there are certain critical stages when water requirement is high. The water requirement is high during the initial seedling period covering about 10 days. Tillering to flowering is the most critical stage when rice crop should not be subjected to any moisture stress. Enough water from panicle initiation stage to flowering (heading) should be ensured. Flooding is not necessary if weeds can be controlled economically through chemical means or by manual weeding before the plants become vegetatively strong. Application of small quantities of water at short intervals to keep the soil saturated is more effective and economical than flooding at long intervals. Until the transplanted seedlings are well established, water should be allowed to stand in the field at a depth of two to five centimetres. Thereafter about five centimetres of water may be maintained up to the dough stage of the crop, Water should be drained out from the field 7 to 15 days before harvest depending on the soil type to encourage quick and uniform maturity of grain.

Wheat crop has wide adaptability. It can be grown not only in the tropical and sub-tropical zones but also in the temperate zone and the cold tracts of the far north, beyond even the 60^0 N latitude. Wheat can tolerate severe cold and snow and resume growth with the setting in of warm weather in spring. The best wheat are produced in areas favored with cool, moist weather during the major portion of the growing period followed by dry, warm weather to enable the grain to ripen properly. The optimum temperature range for ideal germination of wheat seed is 20 to 25^0C. During the heading and flowering stages, excessively high or low temperatures and drought are harmful to wheat. Wheat plant requires about 14-15^0C optimum average temperature at the time of ripening. The temperature conditions at the time of grain filling and development are very crucial fro yield. Temperatures above 25^0 C during this period tend to depress grain weight. When temperatures are high, too much energy is lost through the process of transpiration by the plants and the reduced residual energy results in poorer grain formation and lower yields.

Adequate soil moisture is required for normal development of the wheat plant at all the stages of growth. The crown root initiation stage and heading stage are critical stages when plant suffers most due to moisture stress. In case of dwarf high yielding varieties, a pre-sowing irrigation should be given and crop sown when the field becomes fit for operation. Studies on moisture availability periods during the crop season as well as the rainfall pattern and its trends of that region harmonize the drought climatology. Hence, the literature survey section is divided into different sub-sections viz., moisture availability index study, standardized precipitation index and monsoon rainfall index study, crop growth simulation modeling and drought assessment and remote sensing application and drought assessment.

2.1.1. Moisture Availability Index Studies

Rainfall variability is the major factor influencing the agricultural productivity and sustainability in the tropics (Virmani, 1994). According to De Datta (1981) for better growth of rice, a low water level should be maintained in the early stages of the crop. During the early vegetative growth phase, a shallow water depth improves tillering; adequate water level should be maintained during reproductive growth because rice consumes a large quantity of water during this phase. During the ripening phase, rice needs little water, and the fields are usually drained 10 days before harvest to facilitate mechanical harvest.

The knowledge of expected weekly rainfall at different probability levels would be useful for better crop planning and management. Several researchers have attempted to describe the probability of occurrence of rainfall amounts at different periods starting from daily to annual scale (Chow, 1951; Chow, 1953; Yevjevich, 1972; Popov, 1980). Several investigators suggested crop planning and management strategies based on occurrence of rainfall at different probability levels for different periods depending on crop as well as phenological stages (Singh, 1978; Virmani *et al*., 1982; Rao, 1982; Verma and Sarma, 1988; Mishra, 1995; Mishra *et al*., 1999). Gamma probability distribution has been found to be a good fit for weekly rainfall data of the country and has been used by several researchers for estimation of expected rainfall at different probability levels pertaining to different agro-climatic regions (Mooley, 1973; Biswas *et al.,* 1989; Chattopadhyay and Ganesan, 1995; Goel and Singh, 1999; Subash and Das, 2004).

Several researchers have attempted to classify rice growing areas based on mean rainfall, rainfall probability and potential evapotranspiration (Hargreaves, 1971; Biswas, 1982; Sarkar and Biswas, 1986; and Abrol and Gadgil, 1999). Based on long term normal rainfall and potential evapotranspiration, the water availability period was classified into moist (PET>R>PET/2) and humid (R>PET) by Singh *et al*., (1996). The integrated method suggested by Abrol and Gadgil (1999) involves estimation of rainfall at different probability levels and potential evapotranspiration to get a clear understanding of water availability, water demand of the area and also in getting the appropriate effect of distribution of adequate amount of rainfall at different probability levels. The Moisture Availability Index (MAI) is the ratio of weekly-expected rainfall at desired probability level and the potential evapotranspiration of that week.

2.1.2. Different types of droughts and its assessment

2.1.2.1. Different types of droughts

Drought is the most complex and least understood of all natural hazards, affecting more people than any other hazard. Drought affects virtually all climatic regions (Wilhite, 2000a) and more than one half of the earth is susceptible to drought each year (Kogan, 1997). According to Hewitt (1997) drought ranks first among natural disasters in number of persons directly affected. The impacts of drought depend largely on societal vulnerability at the time when drought occurs. This temporary feature caused by the global climatic variations viz., ENSO, Global warming, change in Global General Circulation (GGC) pattern etc, occurs in all parts of the World with different time scales, frequencies and probabilities. Drought may begin at any time, attain many degrees of severity and last indefinitely. Drought is a “creeping phenomenon” (Gillette, 1950), making its onset and retrieval difficult to determine and it is a temporary recurring natural disaster, which originates from the lack of precipitation and impacts severe economic losses and several damage to living organisms. The effects of drought accumulate slowly over a considerable period of time and sometimes it discontinued suddenly. There is no precise and universally accepted definition of drought. The quantification of impacts of drought on agriculture is a very difficult task. Ultimately drought affects economic and social sectors, and due to this several drought definitions have been developed by a variety of disciplines for some or other purposes.

Drought is a sinister hazard of nature. Although it has scores of definitions, it originates from a deficiency of precipitation over an extended period of time, usually a season or more. This deficiency results in a water shortage for some activity, group, or environmental sector. Drought should be considered relative to some long-term average condition of balance between precipitation and evapotranspiration (i.e., evaporation + transpiration) in a particular area, a condition often perceived as “normal”. It is also related to the timing (i.e., principal rainy season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness (i.e., rainfall intensity, number of rainfall events) of the rains. Other climatic factors such as high temperature, high wind, and low relative humidity are often associated with it in many regions of the world and can significantly aggregate its severity.

Drought should not be viewed as merely a physical phenomenon or natural event. Its impacts on society result from the interplay between a natural event (less precipitation than expected resulting from natural climatic variability) and the demand people place on water supply. Human beings often worsen the impact of drought. Recent droughts in both developing and developed countries and the resulting economic and environmental impacts and personal hardships have underscored the vulnerability of all societies to this "natural" hazard.

Drought is a complex physical and social process of widespread significance. It is not usually a statewide phenomena, with differing conditions in the state often making drought a regional issue. Despite all of the problems that droughts have caused, drought has proven to be difficult to define and there is no universally accepted definition because:

- drought, unlike floods, is not a distinct event;
- drought is often the result of many complex factors such that drought often has no well-defined start nor end; and
- the impacts of drought vary by affected sector, thus often making definitions of drought specific to particular affected groups.

According to Wilhite and Glantz (1985), drought has been grouped into four broad categories viz., meteorological, agricultural, hydrological and socio-economic. The American Meteorological Society (1997) also groups drought definitions and types into four above categories, Meteorological drought: Usually expressions of precipitation's departure from normal over some period of time. Meteorological drought is often defined by a period of substantially diminished precipitation duration and/or intensity. The commonly used definition of meteorological drought is an interval of time, generally on the order of months or years, during which the actual moisture supply at a given place consistently falls below the climatically appropriate moisture supply. Meteorological drought is usually defined by the measure of the departure of precipitation from the normal and the duration of the dry period. The area of concern must be taken into consideration with this definition. Atmospheric conditions that cause the deficiencies of moisture vary greatly from region to region. Some definitions identify droughts based on the number of days an area goes with precipitation that is lower than a specified level.

Hydrological drought: Usually expressions in surface and subsurface water supplies. It reflects effects and impacts of droughts. It is measured as streamflow, snowpack, and as lake, reservoir and groundwater levels. There is usually a delay between lack of rain or snow and less measurable water in streams, lakes and reservoirs. Therefore, hydrological measurements tend to lag other drought indicators. Extended periods of lacking precipitation cause these water supplies to drop below normal. This drought is no different than the others in regard to the fact it is caused by a lack of moisture, but is different than the others in one significant way. Hydrological droughts are usually not occurring at the same time as the others, instead lags behind. This drought deals more with effects the lack of moisture has on the hydrological system as a whole. It takes longer periods of time for the lack of moisture to show up in places such as the ground water, reservoir, and lake levels. When the flow in these places is affected significantly enough, this can have economic effects on the area on things such as hydroelectric power plants and recreational areas. Though the climate/weather is the main contributor to hydrological drought, things such as changes in landscape, land use, and construction of dams also have significant impacts on the drought. Such changes may not have a great effect on the immediate region; it is a sure thing that it will impact the region downstream from the moisture. This is also true with meteorological drought. The frequency and severity of hydrological drought is often defined on a watershed or river basin scale.

Although all droughts originate with a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system. Hydrological droughts are usually out of phase with or lag the occurrence of meteorological and agricultural droughts. It takes longer for precipitation deficiencies to show up in components of the hydrological system such as soil moisture, streamflow, and ground water and reservoir levels. As a result, these impacts are out of phase with impacts in other economic sectors. For example, a precipitation deficiency may result in a rapid depletion of soil moisture that is almost immediately discernible to agriculturalists, but the impact of this deficiency on reservoir levels may not affect hydroelectric power production or recreational uses for many months. Also, water in hydrologic storage systems (e.g., reservoirs, rivers) is often used for multiple and competing purposes (e.g., flood control, irrigation, recreation, navigation, hydropower, wildlife habitat), further complicating the sequence and quantification of impacts. Competition for water in these storage systems escalates during drought and conflicts between water users increase significantly.

Agricultural drought: Agricultural drought occurs when there is inadequate soil moisture to meet the needs of a particular crop at a particular time. It usually occurs after or during meteorological drought, but before hydrological drought and can also affect livestock and other dry-land agricultural operations. Generally refer to situations in which the moisture in the soil is no longer sufficient to meet the needs of the crops growing in the area. Focus is placed on precipitation shortages, reduced ground water/reservoir levels, differences between actual and potential evapotranspiration, and so on. When soil moisture is lacking, this may hinder crops potential development, leading to low plant numbers and eventually lower final yield. The water demand of a crop depends on weather conditions (such as temperature, relative humidity), its biological make-up, what stage of growth the crop is in, and the physical/chemical make-up of the soil. If soil moisture is high enough to allow for proper early development, later lacking moisture may not deplete final yield if the moisture can be replaced as the growing season goes on (irrigation, or sufficient rainfall meets those needs).

A good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of crop development, from emergence to maturity. Deficient topsoil moisture at planting may hinder germination, leading to low plant populations per hectare and a reduction of final yield. However, if topsoil moisture is sufficient for early growth requirements, deficiencies in subsoil moisture at this early stage may not affect final yield if subsoil moisture is replenished as the growing season progresses or if rainfall meets plant water needs. Time and space processes of supply and demand are the two basic processes that should be considered for inclusion in an objective definition of drought, its assessment and severity. If demand for water and other shared natural resources is increasing societal vulnerability to water supply interruptions caused by drought, then future droughts can be expected to produce greater impacts, with or without any increase in the frequency and intensity of meteorological drought.

Socio-economic drought: Definitions associating droughts with supply of and demand for an economic good. Socioeconomic drought occurs when physical water shortages start to affect the health, well-being, and quality of life of the people, or when the drought starts to affect the supply and demand of an economic product. Socioeconomic definitions of drought associate the supply and demand of some economic good with elements of meteorological, hydrological, and agricultural drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts. The supply of many economic goods, such as water, forage, food grains, fish, and hydroelectric power, depends on weather. Because of the natural variability of climate, water supply is ample in some years but unable to meet human and environmental needs in other years. Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply.

Drought impacts are commonly referred to as direct or indirect. Reduced crop, rangeland, and forest productivity; increased fire hazard; reduced water levels; increased livestock and wildlife mortality rates; and damage to wildlife and fish habitat are a few examples of direct impacts. The consequences of these impacts illustrate indirect impacts.

For example, a reduction in crop, rangeland, and forest productivity may result in reduced income for farmers and agribusiness, increased prices for food and timber, unemployment, reduced tax revenues because of reduced expenditures, increased crime, foreclosures on bank loans to farmers and businesses, migration, and disaster relief programs. Direct or primary impacts are usually biophysical. Conceptually speaking, the more removed the impact from the cause, the more complex the link to the cause. In fact, the web of impacts becomes so diffuse that it is very difficult to come up with financial estimates of damages. The impacts of drought can be categorized as economic, environmental, or social.

Not all impacts of drought are negative. Some agricultural producers outside the drought area or with surpluses benefit from higher prices, as do businesses that provide water-related services or alternatives to water-dependent services. Many economic impacts occur in agriculture and related sectors, including forestry and fisheries, because of the reliance of these sectors on surface and subsurface water supplies. In addition to obvious losses in yields in crop and livestock production, drought is associated with increases in insect infestations, plant disease, and wind erosion. Droughts also bring increased problems with insects and diseases to forests and reduce growth. The incidence of forest and range fires increases substantially during extended droughts, which in turn places both human and wildlife populations at higher levels of risk.

Income loss is another indicator used in assessing the impacts of drought because so many sectors are affected. Reduced income for farmers has a ripple effect. Retailers and others who provide goods and services to farmers face reduced business. This leads to unemployment, increased credit risk for financial institutions, capital shortfalls, and loss of tax revenue for local, state, and federal government. Less discretionary income affects the recreation and tourism industries. Prices for food, energy, and other products increase as supplies are reduced. In some cases, local shortages of certain goods result in the need to import these goods from outside the stricken region. Reduced water supply impairs the navigability of rivers and results in increased transportation costs because products must be transported by rail or truck. Hydropower production may also be curtailed significantly.

2.1.2.2. Conceptual and operational definitions of drought

Conceptual definitions, formulated in general terms, help people understand the concept of drought. For example: Drought is a protracted period of deficient precipitation resulting in extensive damage to crops, resulting in loss of yield. Conceptual definitions may also be important in establishing drought policy. For example, Australian drought policy incorporates an understanding of normal climate variability into its definition of drought. The country provides financial assistance to farmers only under “exceptional drought circumstances,” when drought conditions are beyond those that could be considered part of normal risk management. Declarations of exceptional drought are based on science-driven assessments. Previously, when drought was less well defined from a policy standpoint and less well understood by farmers, some farmers in the semiarid Australian climate claimed drought assistance every few years.

Operational definitions help people identify the beginning, end, and degree of severity of a drought. To determine the beginning of drought, operational definitions specify the degree of departure from the average of precipitation or some other climatic variable over some time period. This is usually done by comparing the current situation to the historical average, often based on a 30-year period of record. The threshold identified as the beginning of a drought (e.g., 75% of average precipitation over a specified time period) is usually established somewhat arbitrarily, rather than on the basis of its precise relationship to specific impacts.

An operational definition for agriculture might compare daily precipitation values to evapotranspiration rates to determine the rate of soil moisture depletion, and then express these relationships in terms of drought effects on plant behavior (i.e., growth and yield) at various stages of crop development. A definition such as this one could be used in an operational assessment of drought severity and impacts by tracking meteorological variables, soil moisture, and crop conditions during the growing season, continually reevaluating the potential impact of these conditions on final yield. Operational definitions can also be used to analyze drought frequency, severity, and duration for a given historical period. Such definitions, however, require weather data on hourly, daily, monthly, or other time scales and, possibly, impact data (e.g., crop yield), depending on the nature of the definition being applied. Developing climatology of drought for a region provides a greater understanding of its characteristics and the probability of recurrence at various levels of severity. Information of this type is extremely beneficial in the development of response and mitigation strategies and preparedness plans. In order to improve the agricultural production by alleviating the drought conditions, it is a pre-requisite to identify the causes of drought. The main cause of drought is lack of rainfall at one stage of crop growth or the other. For understanding this, a climatological analysis of drought, especially its frequency, duration, intensity and time of occurrence are very important. This provides a deep insight into the causes and effects of drought on different farmers in different ecosystems.

2.1.2.3. Sequence of Drought Impacts

The sequence of impacts associated with meteorological, agricultural, and hydrological drought further emphasizes their differences. When drought begins, the agricultural sector is usually the first to be affected because of its heavy dependence on stored soil water. Soil water can be rapidly depleted during extended dry periods. If precipitation deficiencies continue, then people dependent on other sources of water will begin to feel the effects of the shortage (Fig.2.1). Those who rely on surface water (i.e., reservoirs and lakes) and subsurface water (i.e., ground water), for example, are usually the last to be affected. A short-term drought that persists for 3 to 6 months may have little impact on these sectors, depending on the characteristics of the hydrologic system and water use requirements.

When precipitation returns to normal and meteorological drought conditions have abated, the sequence is repeated for the recovery of surface and subsurface water supplies. Soil water reserves are replenished first, followed by streamflow, reservoirs and lakes, and ground water. Drought impacts may diminish rapidly in the agricultural sector because of its reliance on soil water, but linger for months or even years in other sectors dependent on stored surface or subsurface supplies. Ground water users, often the last to be affected by drought during its onset, may be last to experience a return to normal water levels. The length of the recovery period is a function of the intensity of the drought, its duration, and the quantity of precipitation received as the episode terminates.

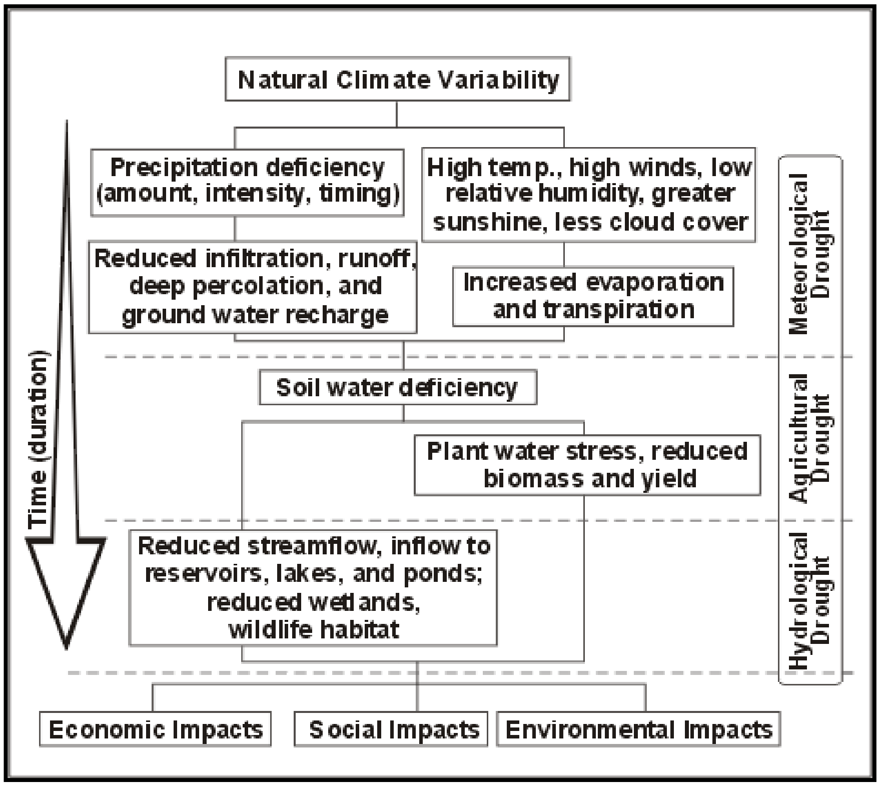

Fig. 2.1: Natural climate variability and different types of drought and its impacts (*adopted from www.drought.unl.edu*)

2.1.2.4. Drought Assessment

Every year one or other part of the country experiences droughts of varying intensity during different time scales. The success of drought preparedness and mitigation depends, to a large extent, upon timely information on drought onset, progress, extent and its end. These types of information can be obtained through drought indices which provide decision makers with information on drought severity and can be used to elicit drought contingency plans. Many drought indices such as the Palmer Drought Severity Index (Palmer, 1965), the decile index (Gibbs and Maher, 1967), the China-Z index (CZI)(Wu *et al*., 2001), the Surface Water Supply Index (Shafer and Dezman, 1982), Bhalme-Mooley Index (Bhalme and Mooley, 1979) are widely used (Table 2.1) while the Standardized Precipitation Index (SPI)(McKee *et al*., 1993) has achieved world popularity. Most of these indices are normally continuous functions of rainfall and/or temperature. SPI can be computed for different time scales, can provide early warning of drought and also help to assess drought severity, and is less complex than the PDSI.

2.1.3. Standardized Precipitation Index and Monsoon Rainfall Index Studies

McKee *et al*. (1993) developed the Standardized Precipitation Index (SPI) that can identify drought or wet events at a given temporal scale for any station that has historic rainfall data. SPI is nothing but the number of standard deviations that the observed cumulative rainfall at a given time scale would deviate from the long-term mean. The SPI compares drought of different regions better than the Palmer indices do (Guttman, 1998). However, the SPI is based on knowledge of the climatology of the study region, and one assumption of the SPI is that all locations have the same frequency of severe and extreme drought (Hayes *et al*., 1999). The precipitation record is fit with a probability density function (Pearson Type III) and subsequently transformed using an inverse normal (Gaussian) function (Guttman, 1998). This insures that the mean SPI value for any given location (and duration) is zero and the variance is one.

Index and its developer	Input data	Time scale	Brief description
Palmer Drought Severity Index (PDSI) – Palmer (1965)	*P, T*	Weekly, biweekly, monthly	Based on moisture inflow, outflow and storage
Crop Moisture Index – Palmer (1968)	*P,T,ET,L, RO*	Weekly	A PDSI derivative, which reflects moisture supply in the short term across major crop producing regions
Standardized Precipitation Index (SPI) – McKee *et al*. (1993)	*P*	Multiple of months	An index based on the probability of precipitation for any time scale
Surface Water Supply Index (SWSI) – Shafer and Dezman (1982); Garen (1993)	*P, sn, RO, reservoir storage*	Monthly	Probability based, similar to the SPI, but is also considers the snow pack, runoff, and reservoir storage
Reclamation Drought Index (RDI) – Bureau of Reclamation (USA)	*P*	Monthly	River basin scale. Since the index is unique to each river basin, interbasin comparison is not possible
Bhalme-Mooley Index (BMI) – Bhalme and Mooley (1979)	*P*	Monthly	The BMI models the percentage departure of P from the long-term averages using an algorithm similar to that of the PDSI
Deciles – First promoted by the Australian drought authorities who currently use it.	*P*	Monthly	The decile method groups monthly precipitation occurrences into deciles. By definition 'much lower than' normal precipitation.
National Rainfall Index (NRI) – Gommes and Petrassi (1994)	*P*	Monthly	The NRI patterns abnormalities of precipitation on a continental scale
Percentage of Normal (PN)	*P*	Monthly, weekly or any time scale	PN is obtained by dividing P with a normal value. It is a simple calculation well suited to the needs of TV weather people and general audiences.

(P- Precipitation; T- Temperature; ET- Evapotranspiration; L – Soil moisture RO – Runoff; sn – snowpack)

Table 2.1: Different drought indices, input data required and its time scale

Ntale and Gan (2003) modified the SPI in two ways for East Africa. First, instead of fitting a gamma distribution to the ‘smoothed’ precipitation data, they used an unbiased P3 plotting-position formula suggested by Nguyen *et al*. (1989) to reduce the possible effects of outliers. Second, they derived the final index value by transforming the non-exceedance probabilities into standard P3 variates using the regional flood-index method instead of a Gaussian normal distribution, which would introduce distortion in the distribution tails for skewed precipitation data. They found that the modified SPI produced results that are more representative for East Aftrica’s drought conditions than the Original SPI of McKee *et al*. (1993). Also, a number of studies evaluated the performance of SPI over different countries (e.g. Wu *et al*. (2001) – in China, Ansari (2003) and Morid *et al*. (2006)– in Iran, etc). But only limited studies were conducted in India using SPI. Patel *et al*. (2007) used monthly time series of rainfall data (1981-2003) from 160 stations to derive SPI, particularly at 3-month time scales. This 3-month SPI was interpolated to depict spatial patterns of meteorological drought and its severity during typical drought and wet years. Correlation analysis was also done to evaluate usefulness of SPI to quantify effects of drought on food grain productivity. Further, time series of SPI were exploited to assess the drought risk in Gujarat. Oza *et al*. (2002) evaluated the use of Standardized Precipitation Index for drought assessment in the region of North-west India. Generally, meteorological drought in India is defined when rainfall in a month or a season is less than 75 % of its long-term mean, if the rainfall is 50-74 % of the mean, a moderate drought event is assumed to occur, and when rainfall is less than 50 % of its mean a severe drought occurs (Smakhtin and Hughes, 2004). Keeping this in mind, this study was done with the objectives of; (1) to analyze the effectiveness and dependability of SPI and MRI during June to September monsoon months in detecting characteristics of drought with respect to rice during kharif season and wheat during rabi season (2) to find any trends in monsoon rainfall, frequency occurrence of drought classification of SPI and MRI over IGR during 100 years period to analyze the drought risk in these IGR States and (3) to evaluate the usefulness of SPI and MRI to forecast rice and wheat productivity over IGR States.

2.1.3. Rainfall and temperature variability and its trends over India

The effects of climate change on various environmental variables have been widely observed in many-regions around the world on different scales (IPCC, 2001). Several studies by Chen *et al*.(1992), Chaudhary(1994), Izrael *et al*.(1997), Mirza and Dixit (1997), Rankova (1998) and Ren *et al*.(2000) have been carried out to analyse the trends in long term precipitation and temperature, its inter-annual, seasonal and decadal variability at local, regional, national and continental scales in Asia. The Inter Governmental Panel on Climate Change (IPCC) has projected that globally averaged temperature could rise by 1.4 – 5.8^{O}C over the next 100 years, while it is projected to increase between 1.0 to 1.4^{O}C and 2.23 to 2.87^{O}C by 2020 and 2050, respectively in South Asia (IPCC, 2001). Thapaliyal and Kulshrestha(1991), Rao and Kumar(1992), Rupakumar *et al*.(1992), Srivastava *et al*.(1992) and Parthasarathy *et al*.(1993,1994) studied trends of annual and seasonal rainfall at various locations and at different scales. Most of these studies reported that Indian summer monsoon has shown remarkable stability in spite of some decadal variations as well as large inter-annual variability. The long-term series of Indian Summer Monsoon Rainfall (ISMR) has no discernible trends, but decadal departures are found above and below the long term average alternatively for 3 consecutive decades (Kothyari and Singh, 1996). There is an increase in occurrence of extreme rainfall events over northwest India in recent decades (Singh and Sontakke, 2002). An analysis of the long-term trends in individual monthly mean rainfall over India for the period 1870-2003 from linear fits produces negative slopes (average 0.09 mm/year) for June, July and September, and a significant positive slope of similar value for August (Patra *et al*., 2005). The long-term changes of ISMR have been examined by employing Mann-Kendall rank test, while the short-term climatic variations have been investigated by applying Cramer's t-test employing 11 year running means. The most striking features are the epochs of above- and below-normal rainfall. The periods 1880–95 and 1930–63 are characterized by above-normal rainfall with very low frequency of droughts. The periods 1895–1930 and 1963–90 are characterized by below-normal rainfall with very high frequency of droughts. Srivastava *et al*. (1992) found that there is no trend in all-India rainfall during the monsoon season as well as in annual rainfall. However, they found a decreasing trend in rainfall over some hilly areas of northeast India. Similarly, Kripalani and Kulkarni (1996) reported that there is no trend depicting a longer-term climatic change for southwest monsoon and annual rainfall over India. In another study (Srivastava *et al*., 1992), a few sub-divisions showed increasing trends in annual rainfall, whereas a few showed decreasing trends. Trends and periodicities in the annual rainfall of 31 meteorological sub-divisions of India during the period 1901 - 1960 using Mann – Kendall rank method, low pass filter and power spectrum analysis indicated a positive trend over central India and the adjoining parts of the peninsula and a negative trend in some parts of eastern India (Parthasarathy and Dhar, 1974). There were no long-term trends or periodicities in pre-monsoon season rainfall over Gangetic West Bengal during the period 1901 – 1992. However, short-term fluctuations were present and a negative tendency from 1915 onwards until the early 1970s and further rise in the 1970s could be observed (Sadhukhan *et al*., 2000). Results revealed that while there are year-to-year fluctuations of seasonal summer rainfall (June to September) over India, the Mann – Kendall rank statistic suggests no significant long-term trends (Kripalani and Kulkarni, 2001). Sinha Ray and Srivastava (2000) have found that there is a significant decreasing trend in the occurrence of cyclonic storms over Indian seas for the period 1981 – 1997. They also investigated eleven-year running total frequency of heavy rainfall days for different rainguage stations and each station was subjected to Mann-Kendall rank statistic fest at 95% level of confidence. There was an increasing trend in the frequency of heavy rainfall over Mumbai during the southwest monsoon and on an annual basis.

Several countries in the tropical Asia region have reported increasing surface temperature trends in recent decades (Rupakumar *et al*., 1994; IPCC, 2001). An analysis of seasonal and annual surface air temperatures (Pant & Kumar, 1997) has shown a significant warming trend of 0.57 ^{o}C per hundred years over India. The warming is found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in any major part of the country except for a significant negative trend over Northwest India. Also, data analyzed in terms of daytime and night-time temperatures indicate that the warming was predominantly due to an increase in the maximum temperatures, while the minimum temperatures remained practically constant during the past century. Another study covering the period 1901-87, found that the countrywide mean maximum temperature has risen by 0.6 ^{o} C, and the mean minimum temperature has decreased by 0.1 ^{o}C (Rupakumar *et al*., 1994). The seasonal/annual mean temperatures during 1901- 2000 are based on data from 31 stations, while the annual mean maximum and minimum temperature during 1901-1990 are based on data from 121 stations. Spatially, a significant warming trend has been observed along the west coast, in central India, the interior peninsula and over north-east India, while cooling trend has been observed in north-west India and a pocket in southern India. Singh and Sontakke (2002) reported that in the Indo-Gangetic Plains (IGP) of India, the annual surface air temperature had a rising trend (0.53 ° C/100-yr, significant at 1% level) during 1875–1958 and decreasing trend (–0.93 ° C/100-yr, significant at 5% level) during 1958–1997. The post-1958 period cooling of the IGP seems to be due to expansion and intensification of agricultural activities and spreading of irrigation network in the region. In a study on decadal trends, the two recent decades (1971-80 & 1981-1990) have registered higher warming rates than the earlier decades (Srivastava *et al*., 1992).

2.1.5. Crop Growth Simulation Models and drought assessment

Dynamic crop growth simulation started in the early 1960s, with its successful application to well-defined growth processes such as canopy photosynthesis. Since then, the rapid development of computing power has led to development of models on many aspects of crop growth. Crop growth models are useful tools to quantify the environmental limits to crop production. Their application minimizes the requirement for costly and lengthy experimentation (Loomis *et al*., 1979). Crop growth simulation models can be used to analyze the effect of various climatic factors on crop growth and yield considering the interactions with edaphic, biotic and agronomic factors. Such an analysis is normally not possible with conventional experimental limitations because of confounding factors. The International project on 'Simulation and Systems Analysis in Rice Production (SARP)' is an endeavor to introduce systems modeling in Asian research Institutes. The SARP project was carried out by the Wageningen Agricultural University's Department of Theoretical Production Ecology (TPE) and Institute for Agro-Biological Research (AB-DLO), in collaboration with the International Rice Research Institute (IRRI) of Philippines and several national agricultural research centers (ARC) and Universities in Southeast Asia. The goal of SARP (1984-1995) was to build research capacity in systems analysis and crop simulation in Asian national SARCs and to demonstrate that systems modeling is sufficiently mature to be applied to the solution of practical research problems.

A set of models (Table 2.2) was developed under this project (Mutsaers and Wang, 1999);

Sl No	Model Name	Application
1	ORYZA-1	A model for potential rice growth under non-limiting water and N conditions, for studies on potential production, agroecological zonation, climate change and varietal characteristics.
2	Modifications of ORYZA-1	To simulate water-limited production of lowland rainfed rice and damage by bacterial blight and rice borers.
3	ORYZA-0	A simplified mode, designed for N management studies. Combined with an optimization procedure, it generates optimum N rates and timing
4	ROTAT-RW	A prototype model to simulate rice-wheat rotations, which can be adapted to other crops in rotation with rice.

Table 2.2: Different Crop growth models developed under SARP Project and its application

The most successful application has been in nitrogen management of irrigated rice. In India and China, model based recommendations were generated for rates and timing of N application. These were experimentally verified and in several cases gave up to 15 % higher yield than current recommendations at the same or a lower application rate (Berge *et al*., 1997). Good prediction was obtained of potential rice yield under different temperature and radiation regimes, and this was used to classify zones for potential rice production (Kropff *et al*., 1994) and in climate change studies (Matthews *et al*., 1995). The upper limits of rice yield were also explored and the importance was established of source capacity (canopy duration, carbohydrate translocation from stems to grain) and sink strength (duration of grain filling, floret density) as determinants of maximum yield potential (Aggarwal *et al*., 1997; Kropff *et al*., 1994; Penning de Vries, 1991).

In addition to these international collaborative efforts, there have been some indigenous efforts as well. A wheat crop model was developed based on radiation capture principles and thermal reflectance in 1982 at the Indian Agricultural Research Institute (IARI) in collaboration with the Space Applications Centre, Ahmedabad (Ajai *et al*., 1984). This dynamic model was basically developed for forecasting wheat yields on a regional basis, using remote sensing signatures as input. This model was further developed as WTGROWS to understand the dynamics of interactions between weather elements, soil factors, variety, water, and N management (Aggarwal *et al*., 1994). Another dynamic model for mustard BRASSICA- was developed at IARI with indigenous efforts. It is capable of predicting phenology, growth and yield for Brassica crops in different agro-environments (Rao, 1992). Besides the limited efforts on developing models, there has been considerable work in India on calibrating and validating the existing models for various crops. ORYZA series of models have been extensively calibrated and validated for all major rice growing agro-environments of India under the SARP Project (Kropff *et al*., 1996).

Many crop simulation models are now available to users: these ranges from multispecies models to suites of models with shared characteristics (Jones *et al*., 1995). Several studies have been carried out to develop an integrated assessment of climate variability as well as climate change on regional and global supplies and demand (Rosenweig and Parry, 1994; Adams *et al*, 1995; Alexandrov and Hoogenboom, 2000a). The crop models integrate the effects of different factors on productivity, and supplement results of field trials. These dynamic models have been used for determining the production potential of a location, for matching agro-technology with the farmers' resources, analyzing yield gaps, forecasting of yields and assessing the impact of climatic variability and climate change on agriculture (Teng and Penning de Vries, 1992; Penning de Vries, 1993; Kropff *et al*., 1996, Ten Berge *et al*., 1997; Tsuji *et al*., 1998; Aggarwal, 2003; Matthews and Stephens, 2002; Pathak *et al*., 2003; Alexandrov and Hoogenboom, 2000a & b). Some of the important crop models and their applications are listed in Table 2.3.

The Decision Support System for Agrotechnology Transfer (DSSAT; Tsuji *et al*., 1994) is a comprehensive decision support system for assessing agricultural management options. IBSNAT, the International Benchmark Sites Network for Agrotechnology Transfer, was a network consisting of University of Hawaii and many global collaborators. Together they created a network of national, regional, and international agricultural research for the transfer of agrotechnology among global partners in both developed and lesser developed countries. Since 1994, the International Consortium for Agricultural Systems Application (ICASA) network oversees the continued development of systems tools, including DSSAT. It has been widely used in both developed and developing countries (Algozin *et al*., 1988; Jagtap *et al*., 1993; Lal *et al*., 1993; Singh *et al*., 1993; Thornton and Wilkens, 1998).

Porter *et al*. (1993) compared three wheat simulation models (AFRCWHEAT, CERES-Wheat and SWHEAT) under non-limiting nitrogen and water availability conditions using two cultivars and found that best prediction for all growth parameters was given not always by the same model. Chipanshi *et al*. (1997) simulated wheat yields at three locations in Saskatchewan (Swift Current, Saskatoon and Melfort) using the CERES-Wheat model. The simulations were made using climatic data of selected years from the start of the growing season upto the prediction date; data for the remainder of the season were taken from 1960-1990 climate records. Predictions using this method were found to agree well with the measured data, suggesting that simulations made using a combination of historical climate records and current weather data as inputs provide good indications of yield.

In India, several studies have demonstrated the utility of different crop models. These have focused on determining potential yields of cultivars of different crops in various agro-climatic regions (Aggarwal *et al*., 1996; Pathak *et al*., 2003), determining optimal plant types for higher yield potential (Aggarwal *et al*., 1997), optimizing

Crop Growth Model	Application	Reference
CROPGRO-Soybean - DSSAT	To develop yield-evapotranspiration relationship and to assess the influence of soil water-storage capacity on yield	Alagarswamy *et al.* (2000)
CERES-Rice - DSSAT	Potential yield during kharif season over Kerala	Rao and Subash (1996)
CERES-Wheat CERES-Barley CERES-Maize	To predict the impact of climate change and CO_2 concentrations ($2xCO_2$ scenario) on Wheat, Barley and Maize and their water use in Spain	Guerena *et al*. (2001)
CERES-Wheat	Effects of changes in minimum and maximum temperature on wheat yields in the central US – Off-line approach	Rosenzweig and Tubiello(1996)
ALMANAC and CERES-Maize	Comparison of these two models for nine US locations and found that both models appeared reasonable at most sites for applications involving management decisions requiring reasonable long-term mean grain yields and reasonable variations around the mean.	Kiniry *et al*. (1997)
CERES-Wheat	Early prediction of spring wheat yields in Saskatchewan from current and historical weather data	Chipanshi *et al*. (1997)
CERES-Rice and CERES-Wheat	Used to quantify the phenology, yield, and yield components of cultivar response and also to predict, extrapolate and generalize the long-term performance of these crops grown in sequence for three rice-wheat sites in Bangladesh.	Timsina *et al*. (1998)
CERES-Maize and WOFOST	Compared the performance of these models in simulating the water balance and crop of maize	Ines *et al*. (2001)
SHOOTGRO	As a potential winter wheat management tool in the Czeck Republic	Zalud *et al*. (2003)
EPICphase and CROPWAT	Evaluated the performance of these models on their ability to simulate maize grain yield reduction caused by water stress under semiarid conditions.	Cavero *et al*. (2000)
AFRCWHEAT, CERES-Wheat, SWHEAT	Simulation of growth parameters	Porter *et al*.(1993)
AGNPS	Cropland management and pollution	Hession *et al*. (1989)
PLANTGRO	Forest production planning	Pawitan (1996)
SWAT	Watershed hydrology, water quality	Srinivasan and Arnold (1994)
WEPP	Watershed erosion	Savabi *et al*. (1997)
CROPSYS	Cropping systems and rotations	Donatelli *et al*. (1997)
LINTUL	Agroecological zoning	Van Keulen and Stol (1995)
WOFOST	Crop production potential, land use planning	Van Laanen *et al*. (1992)

Table 2.3: Some important crop growth and other related models and their application

agronomic management (Berge *et al*, 1997), developing pest management strategies (Chander *et al*, 2002 a &b), impact assessment of climatic change (Aggarwal and Sinha, 1993; Aggarwal and Mall, 2002; Aggarwal, 2003).

Rao and Subash (1996) conducted a field experiment at Pilicode (12^0 12^1 N, $75^0 10^1$ E), Kerala to assess the potential yield of rice for five cropping seasons using different dates of transplanting. Popular varieties Jaya (120-125 d), Jyothi(110-125 d) and Triveni (95-105 d) were used. It was found that the simulated grain yield through the CERES-Rice model was in good agreement with the observed yield during 1993 kharif while simulated grain yield was higher than that of the observed during 1994 kharif on all transplanting dates. Heavy rains during 1994 kharif brought floods. Incidence of gall midge and rice bug was also high at the time, leading to a high percentage of grain chaffing. Hundal and Prabhjyot Kaur (1999) used CERES-Rice model to evaluate various agronomic practices in rice production under Punjab conditions.

Aggarwal *et al*. (2004) developed a generic simulation model "InfoCrop", involves processes of crop growth and development, soil water, nitrogen and carbon and crop-pest interactions. InfoCrop is a Decision Support system (DSS) that has been developed by Indian Agricultural Research Institute of Indian Council of Agricultural Research, New Delhi with the goal of developing models for major annual crops. The models in this DSS have similar structure, and are designed to simulate the effects of weather, soils, agronomic management including planting, nitrogen, residues and irrigation and major pests on crop growth and yield.

2.1.6. Remote Sensing Application for Drought Assessment

Remote sensing is the science and art of obtaining information about an object through the analysis of data acquired by a device that is not in contact with the object. Accurate and real-time drought assessment on regional, national and international scales is becoming increasingly important in both developing and developed countries. In particular, crop monitoring, drought assessment and yield estimation may play a fundamental role in supporting policy formulation and decision-making in agriculture. Traditional methods of drought assessment and monitoring rely on rainfall as well as temperature data. Non-availability of spatially distributed network of meteorological observatories and inaccuracies in measurement may result in errors in detecting the drought, especially agricultural drought. The new scientific technologies of remote sensing, satellite imaging, geographical information systems (GIS) and geographical positioning system (GPS) can be put to effective use in forecasting and monitoring drought. GIS/RS if incorporated in drought mitigation and research process exhibits two principal advantages. First, the technology allows long-term time-series studies and storage of the information, which may prove invaluable in future situations. Secondly, GIS/RS improves information accessibility. Remote sensing platforms can provide large amounts of data quickly and inexpensively, relative to other means of collection, and GIS can bring together vast amounts of information from a wide variety of sources and make the information quickly visible and applicable in emergency situations (Verstappeen, 1995). Satellite-sensor data can also be used to detect the onset of drought, its duration and magnitude (Thiruvengadachari and Gapalkrishna, 1993).

Crop yields can be predicted 5 to 13 weeks prior to harvests using remote sensing techniques (Ungani and Kogen, 1998). Vegetative conditions over the world are reported occasionally by NOAA National Environmental Satellite Data and Information System (NESDIS) using the Advanced Very High Resolution Radiometer (AVHRR) data (Kogan, 2000). A recent successor to AVHRR is the Moderate-Resolution Imaging Spectrometer (MODIS), an advanced narrowband-width sensor, from which composited reflectance data are made available at no cost every 8 days by NASA and USGS, through the Earth Resources Observation Systems (EROS) data center (Justice and Townshend, 2002a). Raw images are available on a daily basis, but their use involves considerable extra processing. Time series of MODIS imagery provide near real-time, continuous and relatively high resolution data, on which the assessment of drought development and severity in regions with scarce and inaccurate on-the-ground meteorological observations (like southwest Asia) could be based. At present, there is no efficient system in the region to analyze and deliver drought-related information to the stakeholders on the ground. Only the Indian National Remote Sensing Centre (NRSC) has undertaken drought assessment and reporting since 1986, using Indian satellite sensors and AVHRR (Thiruvengadachari *et al*. 1987; Kumar and Panu 1997; Johnson *et al*. 1993). The Indian IRS-1C/D wide field sensor (WiFS) could be a strong tool for regional drought assessment with its spatial resolution of 188 m and weekly repeat coverage. Other new sensors which could contribute towards drought monitoring are the Vegetation wide-field sensor on SPOT satellites, and the MERIS sensor on Envisat, although neither is available as simply in near-real time as MODIS. The Normalized Difference Vegetation Index (NDVI) is the most commonly used vegetation index (Jensen, 1996). Among the various vegetation indices that are now available, NDVI is an universally acceptable index for operational drought assessment because of its simplicity in calculation, easy to interpret and its ability to partially compensate for the effects of atmosphere, illumination geometry etc. NDVI is a function of green leaf area and biomass. However, NDVI a) uses only two bands and is not very sensitive to influences of soil background reflectance at low vegetation cover, and b) has a lagged response to drought (Reed, 1993; Rundquist and Harrington, 2000; Wang *et al*. 2001) because of a lagged vegetation response to developing rainfall deficits due to residual moisture stored in the soil. Previous studies have shown that NDVI lags behind antecedent precipitation by up to 3 months (Justice *et al*., 1986; Farrar *et al*., 1994; Wang, 2000; Wang *et al*., 2001). The lag time is dependent on whether the region is purely rainfed, fully irrigated, or partially irrigated (Farrar *et al*., 1994; Wang, 2000). The greater the dependence on rainfall, the shorter the lag time. NDVI itself does not reflect drought or non drought conditions. But the severity of a drought (or the extent of wetness, on the other end of the spectrum) may be defined as NDVI deviation from its long-term mean. This deviation is calculated as the difference between the NDVI for the current time step and a long-term mean NDVI for that month. When the deviation of NDVI is negative, it indicates the below-normal vegetation condition/health and, therefore, suggests a prevailing drought situation. The greater the negative departure, the greater the magnitude of a drought. In general, the departure from the long-term mean NDVI is effectively more than just a drought indicator, as it would reflect the conditions of healthy vegetation in normal and wet months/years. This indicator is widely used in drought studies (Johnson *et al*., 1993). Its limitations are that the deviation from the mean does not take into account the standard deviation, and hence can be misinterpreted when the variability in vegetation conditions in a region is very high in any one given year.

NDVI is derived as under;

$$NDVI = (NIR - Red)/(NIR + Red)$$

where Near Infra Red and Red are the reflected radiations in these two spectral bands.

Water, clouds and snow have higher reflectance in the visible region and consequently NDVI assumes negative values for these features. Bare soil and rocks exhibit similar reflectance in both visible and near IR regions and the index values are near zero. The NDVI values for vegetation generally range from 0.1 to 0.6, the higher index values being associated with greater green leaf area and biomass. In general, growth and decay of crop canopy represents similarities in the temporal vegetation index profile during the crop growth. The peak of this profile corresponds to peak vegetation cover of the crop. Interpretation of vegetation index profile can be used to derive information on the crop stage. Further vegetation index level at peak vegetative stage or the time integration of vegetation index profile is related with accumulated biomass in the crop or crop condition or crop yields. Lowering of vegetation index values reflects moisture stress in vegetation, resulting from prolonged rainfall deficiency. Such a decrease in vegetation index could also be caused by other stresses such as pest/disease attack, nutrient deficiency or geochemical effects. The seasonal vegetation index profile is thus reflective of vegetation dynamics and condition. Comparison of vegetation index profile of the reporting year and a previous normal agricultural year provides assessment of drought impact in the scale of previous agricultural scenario.

Satellite data processed into NDVI can be used to indicate deficiencies in rainfall and portray meteorological and/or agricultural drought patterns both timely and spatially, thus serving as an indicator of regional drought patterns. NDVI is a measure or estimate of the amount of radiation being absorbed by plants. The amount of radiation absorbed is directly related to evapotranspiration, since the plant must cool primarily by evaporating water. The evapotranspiration is constrained by the amount of water in the soil and for relatively low rainfall amounts; the amount of water in the soil is constrained by rainfall. Hence NDVI correlates with rainfall (Rowland *et al*., 1996). Drought will continue to occur, but the application of NDVI as a tool for decision making will allow better integration and more timely planning of methods to promote food security.

2.2. Data and Methodology

2.2.1. Temporal and spatial variability of Moisture Availability Index

One to three representative rain gauge sites – depending on the size of the region - from each agro-ecological sub-region were considered for the analysis. The location of study sites are shown in Fig.2.2. The long-term (at least 25 years) weekly rainfall and temperature (maximum and minimum) data were collected for these stations from India Meteorological Department, Govt. of India, Pune. In most parts of this region, rice-wheat is the predominant cropping system and rice is the important kharif crop.

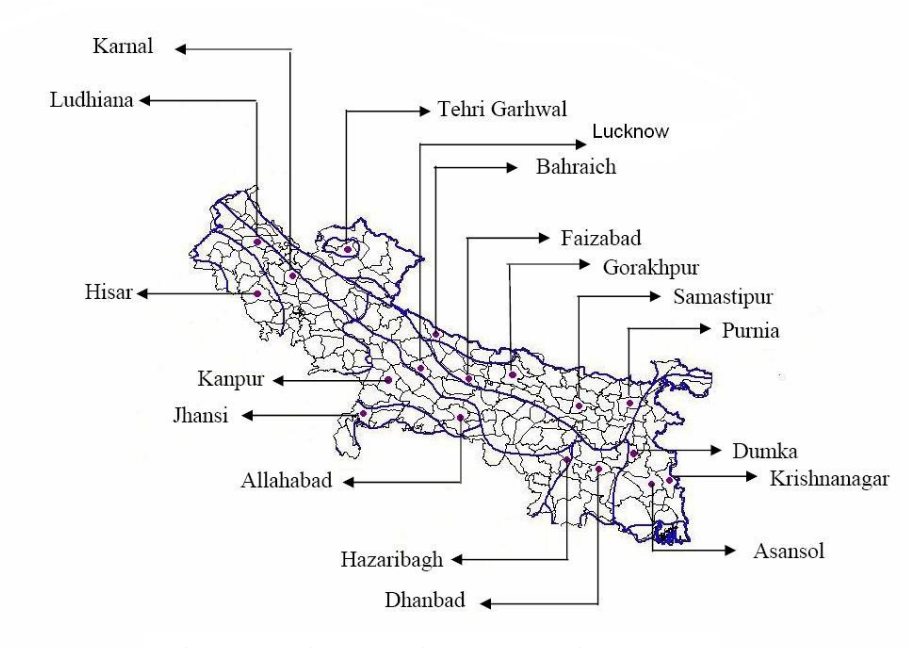

Fig.2.2: The locations of study area

Generally, the field preparation for kharif rice starts from the month of May and crop harvesting begins normally during September-October depending on the rice varieties. Hence, the rainfall data from the 18th Standard Meteorological Week (SMW) (April 30 – May 6) to the 44th SMW (October 28 – November 4) were considered for all the analyses in this study.

Methodology

Incomplete Gamma Distribution Model

A random variable 'x' is said to have a gamma probability distribution with parameters α and β if its probability density function is given by:

$$f(x) = \frac{1}{\Gamma \alpha \, \beta^{\alpha}} x^{\alpha - 1} e^{-\frac{x}{\beta}} \qquad 0 < x < \propto \qquad (1)$$

= 0 otherwise.

In this distribution, α and β are known as shape and scale parameters, respectively, and Γ α is the gamma function. Maximum likelihood estimation technique was employed for obtaining the estimates of α and β. Chi-square test was employed for testing the goodness of fit. Chi-square test statistic is defined as:

$$\chi^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{\beta^2 \alpha} , \qquad (2)$$

which is distributed as χ^2 with (n-1) degrees of freedom.

The distribution function of gamma probability model is defined as:

$$P(X \le x) = F(\alpha, \beta, x) = \int_0^x f(x)dx = \frac{1}{\Gamma \alpha \beta^{\alpha}} \int_0^x x^{\alpha - 1} e^{-\frac{x}{\beta}} dx \qquad (3)$$

The expected rainfall at 50, 60, 70, 80 and 90 per cent probability levels for 18th SMW to 44th SMW was estimated using equation 3.

Moisture Availability Index (MAI)

Hargreaves (1971) proposed a method based on monthly probabilistic rainfall at 75 % for classification of moisture availability period. Several researchers (Biswas, 1982, Sarkar and Biswas, 1986; Abrol and Gadgil, 1999) modified the above methodology depending upon the crop as well as the purpose. The methodology suggested by Abrol and Gadgil (1999) is used in this study to find out moisture availability periods within the crop season. The Moisture Availability Index (MAI) is the ratio of weekly-expected rainfall at desired probability level and the potential evapotranspiration of that week. The Potential evapotranspiration was estimated based on modified FAO Penman-Monteith method

(Allen *et al*., 1994). Weekly MAI at different probability levels starting from 50 % to 90 % were estimated and the weeks were classified with respect to rice as,

Dry: $\mathrm{MAI}_{(\textit{at desired probability level})} < 0.50$

Moist: $\mathrm{MAI}_{(\textit{at desired probability level})}$ between 0.5 and 1

Humid: $\mathrm{MAI}_{(\textit{at desired probability level})} > 1$

The desired probability level can be chosen by the planners at different risk levels. Based on MAI during crop season, different crop planning and management strategies are also suggested in this study.

2.2.2. Rainfall and temperature trend studies

The monthly rainfall data series during 1906-2005 of 5 States available from the website of Indian Institute of Tropical Meteorology (www.tropmet.ac.in) was used in this study. They have considered 94 rain gauge stations well distributed over the region for preparing this data series, one from each of the districts which is the small administrative area and area-weighted mean monthly rainfall of all the meteorological sub-divisions as well as for the whole country by assigning the district area as the weight for each representative rain gauge station. The area, production and productivity of kharif rice over IGP states from 1974-75 to 2005-06 was taken from the Directorate of Rice, Ministry of Agriculture, Govt. of India and is available on-line at http://www.dacnet.nic.in. The area, production and productivity of wheat over IGP states from 1966-07 to 2005-06 was taken from the Directorate of Wheat Development, Ministry of Agriculture, Govt. of India and is available on-line at http://www.dacnet.in/dwd/.

Rainfall Characteristics and Trend Analysis

According to the World Meteorological Organization (WMO), the normal precipitation at a given station at any scale can be assumed as the mean of the precipitation over a 30-year period (WMO, 1989). Using this criterion the data series under study have been subdivided into three periods 1906-1935, 1936-1965 and 1966-2005. The averages of monthly, seasonal and annual rainfall and their standard deviation were calculated for each period, in order to find out the rainfall variation during different normal periods. The coefficient of variation for monthly, seasonal and annual rainfall for each normal period was calculated to know whether there is any trend in the variability of rainfall during the study period. Based on climatic features of the months, India Meteorological Department has defined four seasons, viz. winter (January and February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–December). The percent contribution of monthly and seasonal rainfall to annual rainfall was also calculated for each normal period as well as for the entire data set to know the whether there is any change or shift of rainfall pattern. The analysis was done for each of the five States as well as for the IGR. The monthly rainfall for the IGR was calculated by averaging the rainfall data of the five States. The Mann-Kendall nonparametric test, as described by Sneyers (1990), was applied to the monthly and monsoonal normal periods 1906-1935, 1936-1965, 1966-2005 and for the entire period 1906-2005, in order to detect trends. The Mann-Kendal test has been used by several researchers to detect trends in hydrological time series data (Brunetti *et al*., 2000a.b, Serrano *et al*., 1999). The slopes of the trends were calculated by fitting the data series into method of least – square linear fitting.

Mann-Kendall Test: Mann-Kendall test basically involves the ranks obtained by each data in the data series. The n time series values (X1, X2, X3, ….., Xn) are replaced by their relative ranks (R1, R2, R3,….., Rn) (starting at 1 for the lowest up to n). (Kundzewicz and Robson, 2000; Chiew and Sirivardena, 2005).

The test statistic S is:

$$S = \sum_{i=1}^{n-1} \left[\sum_{j=i+1}^{n} \mathrm{sgn}(R_j - R_i) \right]$$

$$\text{where} \quad \begin{aligned} \mathrm{sgn}(x) &= 1 \ \text{ for } \ x > 0 \\ \mathrm{sgn}(x) &= 0 \ \text{ for } \ x = 0 \\ \mathrm{sgn}(x) &= -1 \ \text{ for } \ x < 0 \end{aligned}$$

If the null hypothesis Ho (ie, there is no trend in the data set) is true, then S is approximately normally distributed with:

$\mu = 0$

$\sigma = n (n - 1) (2n + 5) / 18$

The z-statistic is therefore (critical test statistic values for various significance levels can be obtained from normal probability tables):

$z = | S | / \sigma^{0.5}$

A positive value of S indicates that there is an increasing trend and vice versa.

Temperature trends over the region

Based on their distinct climatic and geographical settings, the country is delineated into seven homogeneous regions, viz., Western Himalaya (WH), Northwest

(NW), North Central (NC), Northeast (NE), West Coast (WC), East Coast (EC) and Interior Peninsula (IP). The Indian Institute of Tropical Meteorology used the following procedure to categorize the monthly homogenous temperature series, used over a network of 121 stations, are the same as those used by Pant and Rupa Kumar (1997) for the period 1901-1990, which were originally sourced from the monthly weather records of the India Meteorological Department (IMD). The data have then been updated for the period 1991-2003 from the Indian Daily Weather Reports (IDWRs) published by the IMD. In order to project a more realistic temperature climatology onto the limited data used, climatological normals of monthly mean maximum and minimum temperatures for the period 1951-80 for 388 well-spread stations have been taken from IMD. To prepare spatially well representative means of temperatures for the above-mentioned homogeneous regions, the following procedure has been adopted. The available station temperature data have been converted to monthly anomaly time series for the period 1901-2003, with reference to the respective station normal values. The station-wise monthly temperature anomaly time series are first objectively interpolated onto a 0.5°x 0.5° grid for the entire period of 1901-2003. Then, the climatological normals (1951-80) of temperature at 388 stations have been interpolated onto the same grid, resulting in high-resolution grid point temperature climatology for the country. The gridded monthly anomaly values are then added to the gridded climatology based on 388 stations, finally producing a long-term gridded data set of actual temperatures for India for the period 1901-2003. All-India and regional monthly temperature series are computed by simple averages of the constituent grid point data of the respective regions. The regions have been delineated based on their distinct climatic and geographical settings (Kothawale and

Rupakumar, 2005). Indo-Gangetic region consists of three homogenous temperature regions Northwest (NW), North Central (NC) and Northeast (NE). The monthly, seasonal and annual trends were analyzed using Mann-Kendall test as per the procedure explained in the rainfall section.

2.2.3. Standardized Precipitation Index

The SPI was developed by McKee *et al*. (1993, 1995) and defined as the number of standard deviations that the observed cumulative rainfall at a given time scale would deviate from the long-term mean. The Colorado Climate Center, the Western Regional Climate Center and the National Drought Mitigation Center use the SPI to monitor drought in the USA (Edwards and McKee, 1997). The concept that a deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture, snowpack, and streamflow led to develop the Standardized Precipitation Index (SPI) (McKee *et al*., 1993). The SPI was designed to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee *et al*. (1993) originally calculated the SPI for 3–, 6–, 12–, 24–, and 48–month time scales. The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. McKee *et al*. (1993) also defined the criteria for a drought event for any of the time scales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought’s “magnitude”.

Calculation

Thom (1966) found the gamma distribution to fit climatological precipitation time series data. The calculation of Gamma function is explained earlier. Since the gamma distribution is undefined for x = 0 and q = P(x=0)>0 where P(x=0) is the probability of zero precipitation, the cumulative probability becomes,

$$H(x)=q + (1 - q)G(x)$$

If *m* is the number of zeros in a precipitation time series and *n* is the total number of years considered, *q* can be estimated by *m/n*. The cumulative probability, H(x), is then transformed into the standard normal distribution to obtain SPI. This transformation is very tedious, cumbersome and not practical for computing the SPI for large numbers of data points for all the stations for each month of the study period. The Z or SPI value is more easily obtained using an approximation provided by Abramowitz and Stegun (1972) that converts cumulative probability to the standard normal random variable Z.

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) \qquad \text{for } 0 < H(x) \leq 0.5$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) \qquad \text{for } 0.5 < H(x) < 1.0$$

where,

$$t = \sqrt{\ln\left[\frac{1}{(H(x))^2}\right]} \qquad \text{for } 0 < H(x) \leq 0.5$$

$$t = \sqrt{\ln\left[\frac{1}{(1 - H(x))^2}\right]} \qquad \text{for } 0.5 < H(x) < 1.0$$

and

$c_0 = 2.515517$
$c_1 = 0.802853$
$c_2 = 0.010328$
$d_1 = 1.432788$
$d_2 = 0.189269$
$d_3 = 0.001308$

2.2.4. Monthly Monsoon Rainfall Index

The monthly rainfall during monsoon season was indexed by taking the monthly rainfall in terms of percentage deviation from its mean. The rainfall index for any month is expressed as

$$MRI_i = \frac{(R_i - R) * 100}{R}$$

Where MRI_i is the monthly Rainfall Index for the ith year, R_i is the monthly rainfall for the ith year and R is the mean monthly rainfall.

The SPI drought classification suggested by Hayes *et al*. (1996) and MRI classification by the India Meteorological Department were used (Tables 2.4a & 2.4b).

(a) SPI drought classification

SPI	Drought category
2.00 and above	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 and less	Extremely dry

(b) MRI Classification

MRI	Drought category
20 % of more	Excess
-19 to 19 %	Normal
-20 to -59 %	Deficient
-60 to -99 %	Scanty
- 100 %	No rain

Table 2.4a and b: Classification scale for SPI and MRI values

2.2.5. Kharif Rice Productivity Index (KRPI) and Wheat Productivity Index (WPI)

The production of rice-wheat depends on non-meteorological parameters such as type of seeds used, crop area, availability of irrigation facilities, fertilizers, pesticides and also on the government incentives to the farming sector during the year as well as the previous year and meteorological parameters such as rainfall, temperature, relative humidity and solar energy. The total non-meteorological parameters i. e., the total technological inputs to the farming sector have been growing steadily and are difficult to quantify. Therefore, to know the pattern of trends and to quantify the growth rate of total technological inputs to the agricultural sector the actual productivity was fitted into an exponential curve as well linear curve.

The exponential curve suggested by Neter *et al*. (1982) was used in this study. The Technological Productivity,

$$TP_i=ab_i$$

where a and b are constants to be determined empirically and i = 1,2,3, …… representing 1974-75 to 2005-06 for rice and 1966-67 to 2005-06 for wheat. To normalize the productivity data, the following indices were used.

The KRPI and WPI were taken as the percentage of the technological trend productivity (exponential or linear) to the actual productivity. The normalized KRPI for the i^{th} year is

$$KRPI_i = \frac{(P_i - TP_i)100}{TP_i}$$

$$WPI_i = \frac{(P_i - TP_i)100}{TP_i}$$

Where *KRPIi and WPIi* are the kharif rice productivity index and wheat productivity indices for the i^{th} year, P_i is the actual productivity for the i^{th} year and TP_i is the technological trend productivity for the i^{th} year.

2.2.6. Crop Growth Simulation Models

In this study, DSSATv4.0 is used to simulate crop growth for rice and wheat. DSSAT v4.0 has been developed through collaboration between scientists at the University of Florida, the University of Georgia, University of Guelph, University of Hawaii, the International Center for Soil Fertility and Agricultural Development, Iowa State University and other scientists associated with the International Consortium for Agricultural Systems Applications (ICASA).

The following is a brief summary of DSSAT v4.0

DSSAT v4.0 is MS Windows-based DSS. All crop models were combined into the Cropping System Model (CSM), which is based on a modular modeling approach. CSM uses one set of code for simulating soil water, nitrogen and carbon dynamics, while crop growth and development are simulated with the CERES, CROPGRO, CROPSIM and SUBSTOR modules. The CENTURY-based soil carbon and nitrogen model for improved performance in low input agricultural systems and for simulation carbon sequestration was added as a separate soil module to CSM.

DSSAT v4 includes:

- More than 18 different crops simulated with CSM, including maize, wheat, rice, barley, sorghum, millet, soybean, peanut, dry bean, chickpea, cowpea, faba bean, velvet bean, potato, tomato, bell pepper, cabbage, bahia and brachiaria and bare fallow.
- The DSSAT v3.5 legacy models, including cassava, sunflower, sugarcane, taro, tanier, and pineapple.
- Identical soil modules for the simulation of the soil water, nitrogen and carbon balances.
- The CENTURY-based soil carbon and nitrogen module.
- The Crop Management Data tool XBuild for entering and editing of experimental data.
- The Soil Data tool SBuild for entering and editing of soil data.
- Weather Data Manager WeatherMan for entering, analyzing and generating weather and climate data.
- The Experimental Data tool ATCreate for entering and editing detailed growth, development and yield data as well as soil water, nitrogen, and carbon measurements.
- The Graphics program GBuild for graphical display of simulated and experimental data.

Five districts, viz., Ludhiana, Hisar, Kanpur, Faizabad and Samastipur were selected to study the drought assessment through crop growth models. The crop simulation model was run on the average input data set for these stations for historical weather data set. The yield output of crop simulation model was used to characterize the agricultural drought. The gamma distribution has been fitted with rice and wheat simulated yield using process of maximum likelihood estimation of the gamma distribution, to characterize the normal, good and drought year for the wheat productivity in these districts. The details are described in Chapter 8.

2.2.7. Remote Sensing Applications

About MODIS Data and NDVI

The MODIS Vegetation Index products are designed to provide consistent, spatial and temporal measures of global vegetation conditions that can be used to monitor photosynthetic activity. Vegetation indices represent ‘integrative’ measurements of vegetation biophysical properties (greenness) useful in the characterization of ecosystem variability and health in time and space. The MODIS (Terra and Aqua) Vegetation Index products are designed to provide key, long-term time series measurements that have their heritage in the NOAA-AVHRR data record and which serve as a bridge to the future NPOESS platform. Vegetation Indices are easily derived from ground-, air-, and spaceborne sensors, resulting in a wealth of information regarding their utility and limitations. An important advantage of vegetation indices is their simplicity and robustness as the vegetation index computation is derived similarly for every pixel. As a result, vegetation indices are widely used in various operational applications, including famine early warning systems, land cover classification, epidemiology, drought detection, land degradation, deforestation, and change detection and monitoring. Vegetation indices are also important parameters to various kinds of local, regional, and global scale models, serving as intermediaries in the assessment of various biophysical parameters, such as green cover, biomass, LAI, and fraction of absorbed photosynthetically active radiation (fAPAR). Two MODIS vegetation indices, the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI), are produced globally over land every 16-days. Whereas the NDVI is chlorophyll sensitive, the EVI is responsive to canopy structural variations and is ‘optimized' for improved sensitivity in high biomass regions and improved vegetation monitoring through a de-coupling of the canopy background signal and a reduction in residual atmosphere influences. The two vegetation indices complement each other in global vegetation studies. Satellite observations of vegetation greenness have been used as a means to characterize amount, rate, direction, location, timing, drivers and consequences of changes in ecosystem structure and function at various spatio-temporal scales.

Seasonal and inter-annual vegetation dynamics and phenological patterns at the ecosystem level (e.g., timing and rate of green-up and senescence of vegetation classes, and amplitude and duration of growing season) constitute one of the key driving variables for modeling and monitoring of terrestrial ecosystems. In response to natural and/or anthropogenic effects, the scientific community is increasingly interested in deriving information about and tracking changes in ecosystems from remotely sensed data, in order to better understand the natural and human-induced processes of changes in land cover (LC) and land use (LU) over time and space, their implications for biogeochemical cycles, and ways of interventions through management, planning, and policy to ensure sustainability of ecosystem goods and services. Moderate Resolution Imaging Spectroradiometer (MODIS) as an instrument on board NASA's Terra and Aqua platforms for remote sensing of the atmosphere, oceans and land surfaces provides vegetation indices more precisely.

About the MODIS data set – *(MOD13A3" = Level 3 product)*

Data Source: ***Land Processes Distributed Active Archive Center (LPDAAC) maintained by U.S. Geological Survey (USGS), NASA at Earth Resources Observation and Science Center (EROS)***

The MODIS instrument operates on both the Terra and Aqua spacecraft. It has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands and it acquires data at three spatial resolutions: 250-m, 500-m, and 1,000-m.

Bands 1 and 2 are natively 250m resolution. Bands 3 through 7 are natively 500m resolution. The remaining bands are 1 km resolution. Bands 1 through 7 contain the visible, NIR, and SWIR (Short Wave Infra-red) which are of greatest importance for monitoring vegetation dynamics. It is on these bands that our efforts have focused. There are a variety of different data levels that any satellite data goes through. Level 0 data is straight from the instrument, raw radiance values. This form is not friendly to most image processing systems and requires custom code to transform it into something more end user friendly. This product is not made available to the general public. Level 1 products are the lowest level of product available to the end user. These products are in 5 minutes chunks of sensor acquisition and are still in swath format. Swath format is not a projection it is the view as the sensor “sees” the Earth. Though this product is available to the end user special tools are still required to manipulate these data into a map projection and to correct for the MODIS “bow-tie” effect. The bow tie is a phenomena associated with sweeping instruments where the instantaneous field of view increases as the sensor sweeps away from nadir. As the instrument looks further out to the side it “sees” a larger area on the ground. A consequence of this is that subsequent scans will have overlapping observations on the outer edges of a swath. This needs to be accounted for when putting the data into a map projection. The next step in the processing chain is Level 2. For MODIS Level 2 products are corrected for atmospheric contamination (aerosols, and geo angles). Level 2 products are not archived; they are immediately mapped into the Sinusoidal projection and gridded into 10-degree units called tiles. These files are daily level 2 gridded (L2G) surface reflectance and associated products in a format, which is easily read by image processing software and manipulated by an end user.

Level 3 and 4 products are end-user value added products nearly all of which were derived from composites of some kind. For purposes of data reduction and removal (or minimization) of bad data it is useful to take the best observations over a series of days and produce one output. This process is called compositing and has been done for years with a variety of different satellite data products. For the MODIS instrument the repeat cycle of nadir overpasses is 16 days. This means that every 16 days the instrument will be traveling on nearly the exact same path. For this reason standard composite periods for MODIS are multiples of 8 days, exactly the mid-point of the repeat cycle. Thus we see time steps in composited products of 8, 16 and 32 days of data. MODIS data may be available at different collection, or version, processing levels. Data for version 4 and above have been validated and approved for scientific research.

There are several composite MODIS vegetation products. Sixteen-day composites are available at 250 m, 500 m, 1 km, and 0.05 degree resolutions. There are also monthly composites with 1 km, and 0.05 degree resolutions. Each file contains bands of data for both the traditional Normalized Difference Vegetation Index (NDVI) and new Enhanced Vegetation Index (EVI). There are also bands of data for quality control in each file. The data type is 16 bit signed integer, which has a theoretical range of values from -32,768 to +32,768. The documented data range is from -2000 to +10000 with a fill value of -3000. If you wish to convert these numbers to the traditional data range, cell values should be divided by 10,000. These data must then be stored with a float data type of IEEE 4 byte real. The Vegetation Index products have a label prefix of MOD13 for the Terra sensor and MYD13 for the Aqua sensor. On the ordering web page the product name indicates the sensor, composite period, spatial resolution, and data version number.

Data Processing

MODIS data granules for the years 2000 to 2006 of 12 months for the study area were collected and imported from HDF format into image format and further re projected using Geographic projection with the aid of Erdas Imagine 8.7 software. All the contiguous data sets were integrated through Mosaicking processes in order to get the single file for entire study area for each month of the year.

The image containing additional area other than present study has been eliminated using Image subset option with reference to the boundary of study area. To obtain optimal classification accuracy, the NDVI data were filtered to correct pixels containing low quality or erroneous values: pixels containing water were removed from the image stack using majority filtering algorithm. The MODIS NDVI values equal to or below zero were assumed to be typically caused by water bodies / snow, and thus, excluded from the data sets. Finally statistical parameters such as Mean, Median, Mode, Maximum, Minimum, Range and Standard deviation has been computed for all the five states with the help of Zonal statistics module available in Arc GIS 9.1 software. The software was also used to produce thematic maps for each months showing NDVI status.

CHAPTER 3

Temporal and Spatial Variability of Moisture Availability and Rice Productivity

3.1 Introduction

Timely availability of sufficient quantity of good quality water is one of the critical constraints in enhancing rice production. Rainfall is the major source of water for rainfed agriculture. Even though the Indo-Gangetic Region (IGR) receives fairly sufficient rainfall (annual mean -1099.1 mm), its erratic distribution pattern- temporal as well as spatial - affects the rice growth and thereby production in one or other part of the region. With the advent of the "Green Revolution", rice and wheat crops have come to occupy a significant area in the Indo-Gangetic Region of India. The comparatively short-duration (100-120 days of rice after transplanting) of new varieties of paddy have offered a unique opportunity for extension of area (Narang and Virmani, 2001). Since 50% of the rice-cultivated area is rainfed, any aberrations of rainfall pattern such as delay of monsoon, breaks in the monsoon activity, prolonged dry spells during the crop season and at times even continuous flooding affect the production. It is estimated that the rice demand for India will be 100 and 140 million tons in the year 2010 and 2025, respectively (Mishra, 2004). Intermittent droughts during vegetative and milky stages, flood during early stages, stagnation of water for long duration, unbalanced/improper usage of fertilizers and delay of sowing/transplanting are major reasons for large spatial variation of rice productivity in this region. The eastern part of the region is bestowed with abundant natural resources and called as "High Potential, Low Productivity" region (CPWF, 2003). Since moisture availability during the crop growing season provides a comprehensive depiction of the region, the following sections sketch the moisture availability during the kharif crop season.

3.2. Location of study sites and normal weekly rainfall

The mean annual rainfall varies from 552.0 mm with a standard deviation of 284.9 mm at Karnal (9.1 sub-region) to 1589.6 mm at Dhanbad (12.3 sub-region) with a standard deviation of 460.3 mm (Table 3.1). The coefficient of variation (CV) of annual rainfall ranges from 80.8 per cent at Hisar (2.3 sub-region) to 21.9 per cent at Asansol (15.1 sub-region). The eastern part of the IGR receives more rainfall compared to the western part. Table 3.2 shows the mean weekly rainfall, standard deviation and coefficient of variation of rainfall for the 18 selected stations of IGR. Hisar (2.3 sub-region) of the western plain region receives rainfall >70 % of PET from 24th week (June 11-17) to 37th week, with maximum rainfall of 50.8 mm in the 28th week. The CV is almost always above 100 per cent and in only two weeks (29th and 31st weeks) was below 100 per cent.

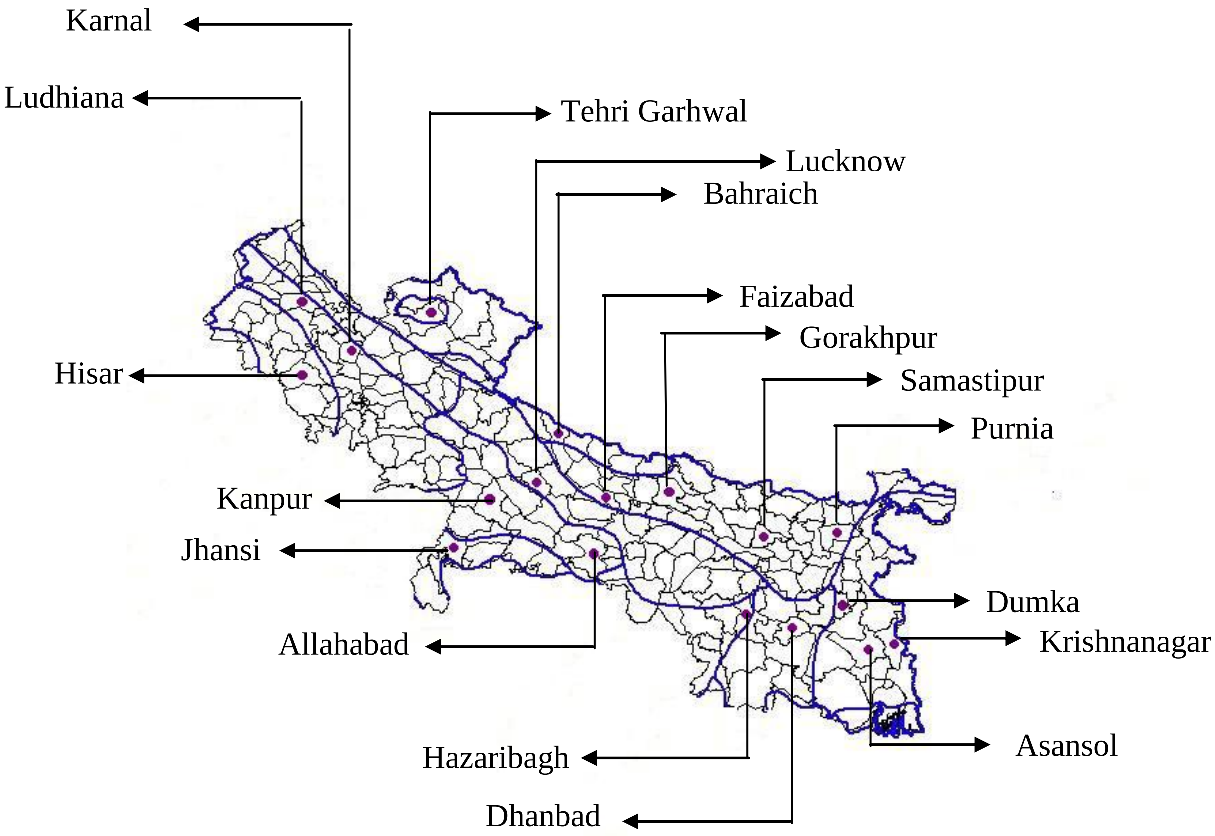

Fig 3.1: Location of selected sites over Indo-Gangetic Region *(blue lines represent agro-climatic sub-regions of the study area)*

Sl No	District/Site	Mean annual rainfall (mm)	Standard deviation (mm)	Coefficient of variation (per cent)
1	Hisar	905.6	731.9	80.8
2	Ludhiana	766.1	265.8	34.7
3	Allahabad	964.3	265.1	27.5
4	Kanpur	883.9	309.9	35.1
5	Jhansi	880.1	213.6	24.3
6	Karnal	**552.0**	284.9	51.6
7	Lucknow	1005.3	441.6	43.9
8	Faizabad	1158.6	337.5	29.1
9	Hazaribagh	1252.3	302.6	24.2
10	Dhanbad	**1589.6**	460.3	29.0
11	Samastipur	1222.4	328.4	26.9
12	Purnea	1538.0	426.1	27.7
13	Gorakhpur	1228.4	373.2	30.4
14	Bahraich	1266.8	354.8	28.0
15	Tehri Garhwal	1280.4	284.6	22.2
16	Asansol	1435.2	314.8	21.9
17	Krishnanagar	1226.1	472.1	38.5
18	Dumka	1399.7	449.7	32.1

Table 3.1: Mean annual rainfall (mm), standard deviation and coefficient of variation (%) of selected stations of IGR

Ludhiana (4.1 sub-region) of the northern plain hot semi arid zone receives rainfall >70 % of PET from 26th (June 25-July 1) to 36th week, with maximum rainfall of 61.8 mm received during the 28th week followed by 32nd week (54.2 mm). The CV reached is 100 per cent only during 29th and 33rd weeks. Allahabad (4.3 sub-region) and Jhansi (4.4 sub-region) of the same agro-ecological region receive rainfall > 70 % of PET from 26th week (June 25-July 1) to 38th week (Sept 17-23), with maximum rainfall of 77.1 mm and 92.4 mm (Fig.3.2), respectively in the 37th and 32nd week . The CV is below 100 per cent from 28th to 36th week and from 27th to 33rd week, respectively for Allahabad and Jhansi.

Std Weeks	Hisar			Ludhiana			Allahabad		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
18	14.7	24.0	162.7	6.0	15.5	258.7	1.2	2.6	224.8
19	16.6	32.6	196.5	6.3	11.7	186.2	2.1	6.5	312.3
20	20.2	31.6	156.5	4.4	8.8	202.5	5.4	13.7	256.4
21	17.7	25.8	145.5	4.7	11.2	240.2	3.1	9.5	300.6
22	20.6	35.2	170.8	3.9	10.4	267.9	2.9	7.4	258.4
23	22.7	37.5	164.8	9.6	18.7	195.4	14.8	32.8	222.0
24	31.8	40.4	126.8	10.9	13.2	120.4	16.8	37.1	221.2
25	37.6	53.6	142.8	16.1	23.0	143.0	29.8	32.8	110.0
26	42.8	51.1	119.4	27.3	28.6	104.5	51.0	40.5	79.3
27	44.5	46.6	104.8	50.4	62.7	124.5	41.1	54.1	131.6
28	50.8	52.6	103.5	61.8	76.2	123.4	71.5	55.1	77.0
29	45.6	44.2	97.0	40.0	37.5	93.9	54.8	49.7	90.8
30	43.2	47.2	109.3	48.1	48.9	101.5	60.7	46.1	75.9
31	40.0	37.7	94.1	49.3	50.8	103.0	60.8	59.8	98.4
32	37.9	42.9	113.1	54.2	54.7	101.0	69.4	63.7	91.8
33	35.0	42.5	121.5	32.5	29.7	91.6	53.7	47.2	87.8
34	34.1	35.2	103.3	32.6	39.5	121.2	76.5	94.5	123.6
35	34.3	39.2	114.1	42.0	52.3	124.6	70.6	66.8	94.6
36	32.4	50.7	156.6	43.8	98.5	225.0	55.5	51.2	92.2
37	34.5	43.2	125.1	22.9	33.8	147.7	77.1	111.1	144.1
38	18.8	28.5	151.8	11.2	21.2	190.2	30.0	44.8	149.1
39	30.0	62.3	207.9	22.0	91.4	414.9	12.8	17.4	136.7
40	11.9	22.3	187.5	1.7	4.4	261.9	17.0	27.4	161.3
41	11.1	33.9	305.5	2.1	6.3	304.1	8.6	21.7	250.9
42	8.6	23.7	275.9	5.4	21.3	393.9	7.0	20.5	293.9
43	6.9	16.6	239.5	0.1	0.5	500.3	0.4	1.9	478.9
44	16.8	23.0	136.6	22.6	30.0	133.0	1.2	4.6	384.5

Std Weeks	Kanpur			Jhansi			Karnal		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
18	1.7	4.6	271.9	1.4	4.0	282.3	5.7	14.2	250.5
19	2.8	9.5	335.6	2.2	6.8	313.1	3.4	5.3	155.6
20	3.4	8.3	243.2	2.5	6.2	250.4	1.2	2.5	206.6
21	4.0	7.2	177.1	3.7	7.9	215.6	4.6	10.0	216.3
22	5.6	14.2	252.3	2.0	5.1	249.4	3.2	6.7	209.1
23	8.9	20.7	231.2	11.9	19.1	160.6	6.6	16.6	251.3
24	5.3	11.5	215.9	12.6	27.4	216.8	5.3	9.0	170.4
25	26.6	35.9	134.7	29.6	37.2	125.8	26.5	44.9	169.0
26	37.3	44.5	119.3	44.5	63.1	141.9	20.1	26.8	133.3
27	43.8	55.5	126.8	54.3	42.8	78.7	45.6	79.1	173.4
28	68.4	55.3	80.9	62.3	47.1	75.7	57.9	60.5	104.4
29	66.5	64.0	96.2	59.3	56.5	95.3	24.0	29.9	124.5
30	53.7	54.3	101.1	63.8	60.9	95.4	39.3	44.2	112.6
31	54.9	48.9	89.0	69.2	59.6	86.2	39.8	51.2	128.5
32	61.7	58.9	95.5	92.4	83.8	90.7	42.6	44.9	105.6
33	57.5	62.8	109.4	52.4	45.2	86.2	37.3	54.2	145.4
34	51.7	47.9	92.6	54.0	70.0	129.7	36.3	47.4	130.4
35	44.3	60.0	135.4	52.3	58.1	111.0	24.7	36.4	147.2
36	56.1	59.8	106.5	44.6	64.6	144.9	19.2	34.7	180.3
37	60.4	74.7	123.7	52.9	67.5	127.4	14.3	30.6	213.4
38	28.7	43.4	151.1	29.0	49.8	171.6	8.1	21.8	270.4
39	23.1	51.8	223.8	11.2	18.9	167.8	9.0	35.1	391.2
40	16.0	30.1	187.9	13.6	25.3	186.0	2.4	7.8	323.7
41	18.6	57.9	311.0	9.0	32.0	356.6	0.1	0.4	469.0
42	7.8	22.5	289.5	3.4	11.3	329.9	1.0	3.5	346.4
43	0.6	3.7	583.8	0.2	0.9	434.0	0.0	0.0	-
44	15.5	30.3	195.0	0.5	2.0	368.0	2.6	11.7	452.1

Table 3.2: Mean, standard deviation (SD) and coefficient of variation (CV) of standard meteorological weeks rainfall over 18 selected stations of IGR (Contd…)

Std Weeks	Lucknow			Faizabad			Hazaribagh		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
18	1.7	6.0	346.9	1.2	4.0	346.4	6.4	12.5	196.9
19	2.3	3.7	158.2	1.3	2.6	207.8	12.6	15.5	123.0
20	5.5	9.1	166.6	8.6	12.9	149.8	11.8	17.2	145.8
21	5.3	18.1	342.5	10.9	21.1	194.0	14.4	19.5	135.7
22	6.4	13.8	216.4	5.8	10.3	177.8	9.5	17.4	183.8
23	17.5	34.8	198.6	15.6	20.0	128.2	32.3	45.7	141.5
24	14.3	21.1	147.3	24.5	28.7	116.8	44.7	59.5	133.0
25	31.4	45.9	146.3	47.3	73.5	155.5	38.4	32.8	85.5
26	58.1	67.2	115.5	40.3	39.7	98.7	91.3	89.5	98.0
27	42.5	51.0	120.1	51.0	57.7	113.2	62.8	59.6	94.8
28	73.3	59.5	81.2	78.9	77.9	98.7	71.9	50.6	70.4
29	61.0	65.7	107.8	107.6	75.9	70.5	89.3	67.5	75.6
30	65.0	62.7	96.3	55.4	44.1	79.5	70.8	58.2	82.1
31	54.5	51.3	94.1	124.7	158.7	127.2	96.8	77.7	80.3
32	65.9	61.3	93.0	99.2	78.7	79.3	72.3	63.2	87.4
33	56.1	58.8	104.8	83.1	91.2	109.7	50.9	36.8	72.4
34	44.2	41.2	93.1	39.3	30.8	78.4	56.2	52.3	93.1
35	70.8	110.0	155.5	47.5	76.8	161.5	43.6	37.2	85.4
36	64.9	86.4	133.2	52.9	56.0	105.9	66.8	94.8	141.9
37	76.9	117.5	152.8	82.3	95.0	115.4	73.2	74.5	101.8
38	35.4	58.6	165.3	45.8	102.3	223.3	43.3	55.2	127.4
39	25.1	48.8	194.7	25.1	26.5	105.6	48.5	51.0	105.1
40	17.0	26.6	156.4	39.0	43.5	111.6	20.8	33.1	159.2
41	14.5	55.9	385.9	2.1	5.2	253.4	16.5	34.5	208.7
42	9.1	24.8	273.6	19.3	43.5	225.5	7.3	12.5	170.7
43	0.0	0.1	317.4	0.6	1.9	346.4	5.6	13.7	246.2
44	4.6	18.9	412.7	0.5	1.1	234.3	2.4	5.2	221.9

Std Weeks	Dhanbad			Samastipur			Purnea		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
18	14.3	22.0	153.9	10.1	15.3	151.7	18.9	19.4	102.6
19	13.4	21.2	158.5	10.9	17.6	161.1	23.7	26.1	110.2
20	21.9	23.9	109.2	14.1	27.0	191.5	32.1	30.5	95.0
21	12.6	19.7	156.5	19.7	26.0	132.1	25.7	24.8	96.5
22	15.3	20.1	131.5	14.2	19.0	134.3	49.5	75.8	153.2
23	40.0	48.5	121.2	21.1	31.3	148.4	65.2	103.6	158.9
24	49.5	42.1	85.1	29.2	34.8	119.2	53.8	60.8	112.9
25	71.5	57.6	80.5	58.0	66.4	114.6	52.3	38.7	74.0
26	89.7	70.9	79.1	60.7	71.5	117.9	73.6	68.6	93.3
27	97.9	78.4	80.1	68.7	69.0	100.3	88.7	77.8	87.7
28	68.1	36.6	53.7	81.3	75.1	92.3	97.3	73.0	75.1
29	88.0	78.0	88.7	74.6	69.6	93.2	94.5	58.6	62.0
30	97.4	65.4	67.2	68.5	61.6	89.9	64.8	45.9	70.8
31	82.1	68.0	82.8	71.8	66.7	92.8	92.7	82.9	89.5
32	79.9	57.9	72.4	66.1	72.1	109.0	51.6	40.2	77.9
33	74.4	44.2	59.4	70.7	69.9	98.9	61.2	69.2	113.0
34	58.3	58.0	99.5	76.4	83.9	109.8	76.6	78.6	102.6
35	82.7	76.4	92.4	50.1	46.4	92.6	53.3	62.3	116.9
36	73.5	63.9	87.0	62.3	68.9	110.6	68.4	69.5	101.6
37	83.9	54.9	65.5	68.0	73.3	107.8	95.7	83.7	87.4
38	59.3	78.5	132.4	43.9	56.9	129.8	33.4	45.3	135.4
39	90.1	86.9	96.4	42.1	55.9	132.9	92.1	90.9	98.8
40	58.8	74.3	126.4	43.1	80.0	185.9	48.5	78.4	161.7
41	35.7	58.8	164.7	14.1	24.6	174.0	20.5	39.4	192.4
42	16.0	38.5	240.0	9.8	29.7	303.2	19.2	45.7	238.4
43	6.7	14.2	213.3	5.5	25.2	459.6	2.0	9.3	457.8
44	4.0	9.7	242.6	3.2	9.9	309.2	4.3	8.7	203.7

Table 3.2: Mean, standard deviation (SD) and coefficient of variation (CV) of standard meteorological weeks rainfall over 18 selected stations of IGR (Contd…)

Std Weeks	Gorakhpur			Bahraich			Tehri Garhwal		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
18	5.3	11.8	224.7	5.1	11.0	215.2	16.8	22.6	135.0
19	7.2	11.8	163.8	7.1	10.4	147.0	20.0	25.0	124.6
20	14.9	28.8	193.6	10.6	15.8	148.3	16.6	23.4	141.3
21	5.4	11.5	213.2	9.9	19.4	196.7	15.9	15.0	94.3
22	17.8	34.7	194.7	17.1	38.3	224.3	15.4	19.6	127.9
23	50.4	106.3	211.0	13.0	18.6	143.2	27.7	44.8	161.5
24	31.3	45.1	144.1	46.1	83.0	180.0	23.2	29.5	127.5
25	37.8	48.0	127.0	45.6	46.5	101.9	25.3	24.9	98.8
26	65.5	48.1	73.5	56.5	51.8	91.7	33.7	24.8	73.5
27	58.1	51.2	88.1	68.8	85.1	123.6	46.2	52.6	114.0
28	96.9	87.4	90.2	104.6	81.7	78.1	61.6	49.2	79.9
29	70.5	62.8	89.1	90.6	92.9	102.5	67.6	49.7	73.5
30	61.0	57.3	93.9	75.7	68.4	90.3	61.9	57.9	93.5
31	65.6	40.8	62.2	63.1	51.0	80.8	75.0	51.3	68.4
32	72.9	63.2	86.7	62.8	46.1	73.4	48.5	37.6	77.5
33	89.2	92.8	104.0	76.7	72.7	94.8	63.9	49.3	77.2
34	92.0	79.8	86.7	76.0	102.4	134.7	57.1	43.4	76.0
35	58.1	83.6	144.0	62.9	69.0	109.7	37.5	38.3	102.1
36	80.2	72.6	90.6	81.2	129.5	159.4	50.9	62.3	122.3
37	68.0	59.5	87.5	87.0	118.3	136.1	37.5	33.7	90.0
38	38.2	52.7	137.9	42.4	64.9	153.0	25.8	39.8	154.0
39	32.7	35.7	109.1	36.7	72.2	196.6	24.3	46.3	190.7
40	30.7	43.2	140.8	31.5	62.6	198.4	5.3	12.7	240.2
41	6.0	14.9	249.2	14.5	33.1	228.3	13.2	40.3	305.6
42	15.3	39.9	260.9	9.3	24.7	265.2	21.3	70.8	332.9
43	0.0	0.1	509.9	0.5	2.0	381.3	2.8	8.7	318.0
44	1.2	4.3	359.0	2.4	6.9	285.9	55.9	72.9	130.4

Std Weeks	Asansol			Krishnanagar			Dumka		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
18	21.7	26.8	123.3	22.4	27.7	124.1	18.9	30.6	161.9
19	15.0	19.8	132.5	26.9	39.1	145.5	15.9	25.8	162.0
20	23.9	24.8	103.7	18.6	28.6	154.0	15.2	17.2	113.2
21	29.1	32.3	111.1	35.6	39.2	110.0	23.7	30.1	126.8
22	19.7	24.5	124.3	34.0	40.8	120.0	21.3	23.3	109.4
23	58.7	55.3	94.2	55.9	70.5	126.2	44.1	44.3	100.5
24	35.5	35.4	99.8	28.6	24.7	86.3	47.7	51.0	106.8
25	60.1	55.5	92.3	47.0	43.3	92.2	55.7	54.5	97.9
26	76.6	73.0	95.3	62.3	41.6	66.7	58.4	61.3	105.1
27	76.8	64.4	83.9	58.4	58.2	99.6	75.0	57.8	77.1
28	58.1	46.9	80.6	95.3	78.7	82.6	81.2	75.2	92.6
29	69.8	54.8	78.6	64.4	47.8	74.2	76.8	64.5	84.0
30	71.7	60.9	84.9	73.1	64.2	87.9	80.8	55.0	68.1
31	66.1	57.9	87.7	50.8	42.0	82.7	56.8	49.9	87.8
32	59.2	48.4	81.8	39.4	30.3	77.0	77.8	56.4	72.5
33	65.8	50.9	77.3	71.0	70.1	98.7	75.2	49.2	65.4
34	48.7	56.3	115.6	38.0	45.6	120.0	57.6	42.1	73.1
35	77.3	64.2	83.1	62.3	59.9	96.2	68.0	67.7	99.5
36	68.3	58.0	84.9	46.9	76.9	164.0	57.7	48.8	84.6
37	70.1	40.2	57.3	34.6	36.8	106.1	61.8	40.9	66.3
38	35.3	29.9	84.8	25.6	24.1	93.9	48.3	49.4	102.2
39	86.8	136.2	157.0	40.5	59.2	146.2	79.6	94.2	118.3
40	44.1	45.4	103.0	20.9	27.5	131.6	62.1	75.9	122.3
41	25.3	33.4	132.2	27.2	72.6	267.0	25.5	29.4	115.4
42	22.7	50.6	223.0	9.5	20.0	211.1	15.5	28.7	184.7
43	8.6	22.8	264.7	13.8	32.1	232.5	5.6	12.6	223.3
44	7.6	18.6	246.2	4.7	11.5	246.2	4.9	10.9	224.3

Table 3.2: Mean, standard deviation (SD) and coefficient of variation (CV) of standard meteorological weeks rainfall over 18 selected stations of IGR

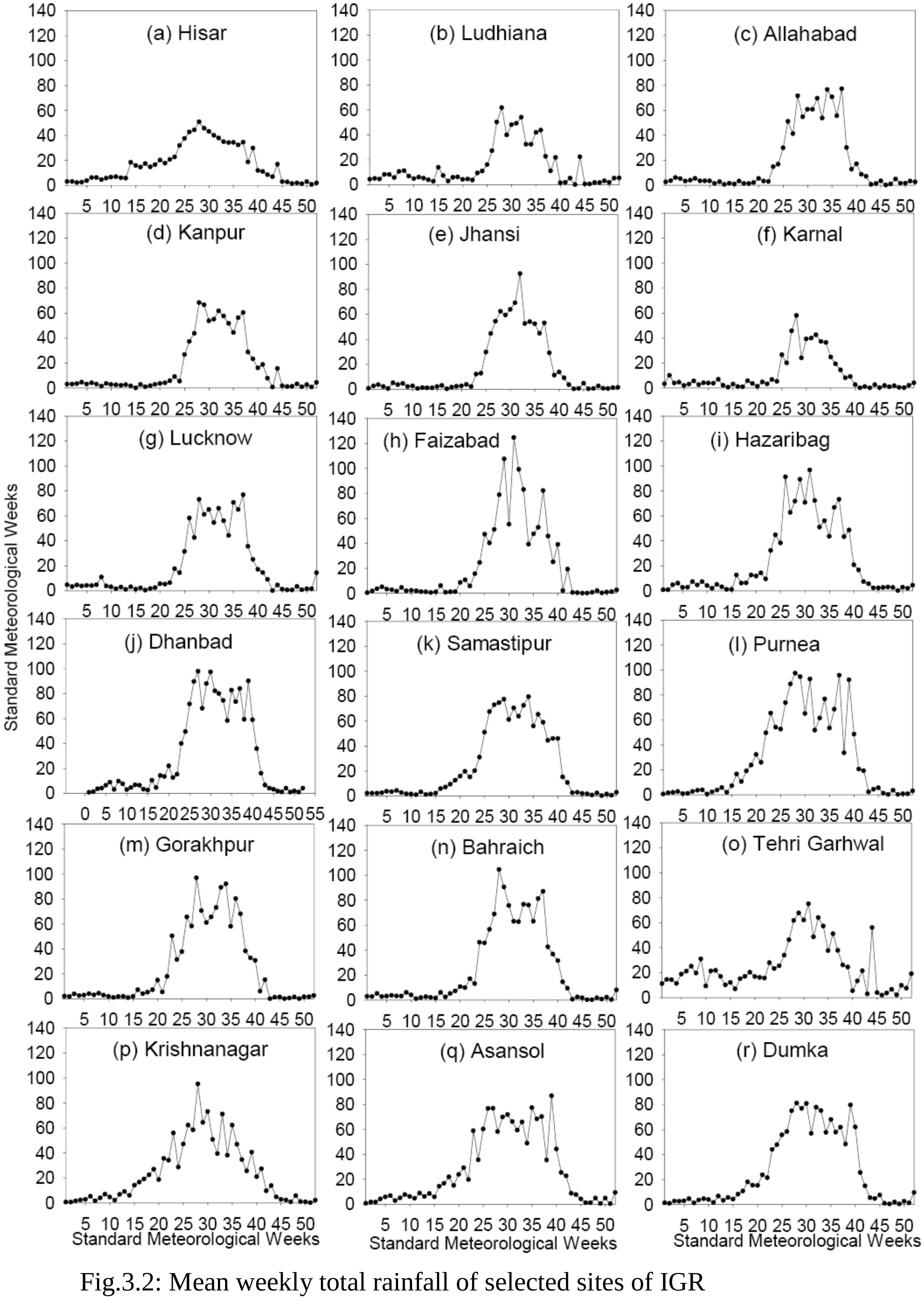

Fig.3.2: Mean weekly total rainfall of selected sites of IGR

The distribution pattern indicates that Allahabad receives higher rainfall (more than 50 mm) from 28th to 37th week while Jhansi receives it from 27th to 32nd week only. But Kanpur of the same sub-region (4.3 sub-region) receives rainfall > 70 % of PET from 25th week (June 18-24) to 38th week (Sept 17-23), with a maximum rainfall of 68.4 mm received during 28th week followed by 66.5 mm during 29th week. The CV dips below 100 per cent from 28th week onwards, but not more than 2 continuous weeks having lower CV are experienced.

In the case of Lucknow and Faizabad of 9.2 sub-region, the CV for almost all the weeks is above 100 per cent with maximum rainfall received during the 37th week and 31st week, respectively. Rainfall>70 % PET is observed from 25th week onwards and continues up to 39th week for both the stations. The weekly rainfall distribution indicates that Faizabad receives more rainfall than Lucknow.

Karnal (sub-region 9.1) of the Northern plain hot sub-humid agro-ecological region receives rainfall of more than 70 % PET from 27th week up to 34th week. Maximum rainfall of 57.9 mm is received during the 28th week and the CV never dips below 100 per cent. Hazaribagh (sub-region 10.0) of Jharkhand State receives a maximum rainfall of 96.8 mm during the 31st week followed by 91.3 mm during the 26th week. The CV is also below 100 per cent from 25th week to 35th week. A maximum rainfall of 97.9 mm is received during the 27th week followed by 97.4 mm during the 30th week at Dhanbad (sub region 12.3). This station receives fairly good rainfall during almost all the weeks of May.

Samastipur and Purnea (sub-region 13.1) receive maximum rainfall of 81.3 mm and 97.3 mm, respectively in the 28th week (July 9-15). The mean rainfall is more than 70 % of PET from 24th week onwards at Samastipur but the higher values of CV indicate the higher risk factor. From 28th week onwards the CV decreases and remained below 100 per cent up to 36th week. In case of Purnea, there are four weeks (29th, 31st, 37th and 39th) having more than 90 mm rainfall. Even though Purnea is prone to floods during these periods, the high value of CV indicates the high year-to-year variability. Hence the farmers of this region can grow their nursery during the last week of May or the first week of June, so that they can transplant their seedlings during the last week of June or the first week of July to utilize maximum rainfall.

The rainfall period lies between 23rd week (June 4-10) to 40th week (Oct 1-7) for Gorakhpur (sub-region 13.1) with a maximum rainfall (90.6 mm) in the 28th week. For Bahraich (sub-region 13.2) the weekly mean data indicate that the rainfall period lies between 24th week (June 11-17) to 40th week with a maximum rainfall of 104.6 mm received during 28th week followed by 90.6 mm during 29th week. The Tehri Garhwal (sub-region 14.2) of the Western Himalayas receives rainfall > 70 % of PET from 23rd week onwards up to 39th week. Maximum rainfall of 75 mm is received during 31st week followed by 67.6 mm during 29th week. The CV goes below 100 per cent from 28th week onwards and continues so up to 34th week.

Asansol receives a maximum rainfall of 86.8 mm during the 39th week (Sept 24-30), but higher value of standard deviation and CV indicate the higher year-to-year variability. Analysis also shows that from 23rd week (June 4-10) onwards rainfall is greater than 70 % of PET and continues up to 41st week (Oct 8-14). But Krishnanagar and Dumka of the same region receive rainfall greater than 70 % of PET from the 21st week onwards up to 41st week. This indicates that this region gets fairly good rainfall during the retreating monsoon period also, even though with higher variability.

The weekly distribution pattern shows that the eastern of IGR receives higher rainfall as well as more pre-monsoon rains and this helps the farmers of this region to start their field preparation in advance.

3.3. Rainfall Analysis

3.3.1. Rainfall probability analysis

Gamma distribution is fitted to non-zero standard meteorological weekly rainfall data of all the stations. The parameters of the gamma probability distribution have been estimated using maximum likelihood method. On the basis of chi-square test, at 95% significance level, gamma probability distribution is found to fit well to all the weekly data sets. Figure 3.3 shows the expected rainfall of selected sites at different probability levels for Standard meteorological weeks (SMWs) from 18th (April 30-May 6) to 44th (Oct 29 – Nov 4) together with mean PET.

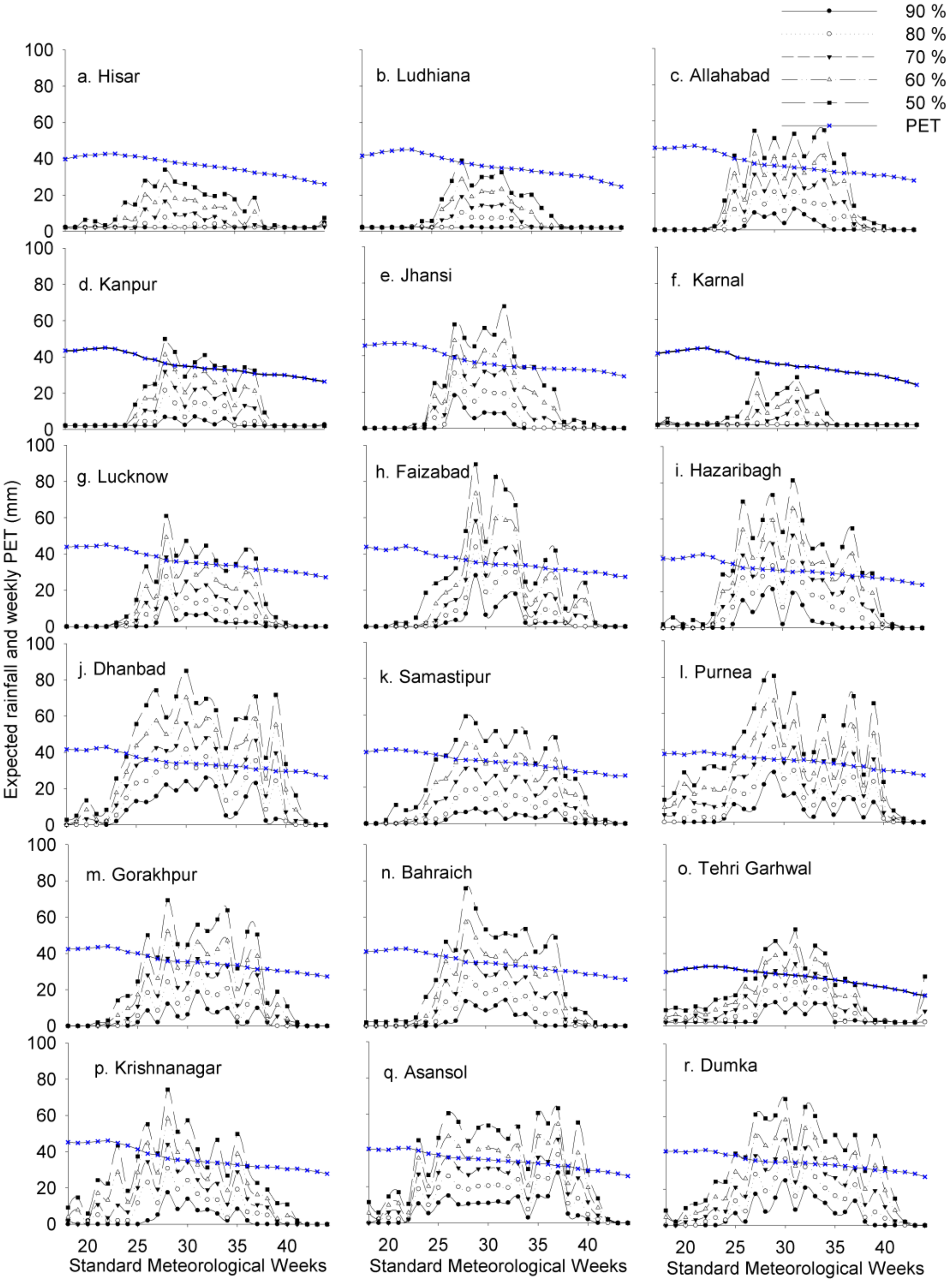

Fig 3.3: Expected weekly rainfall at different probability levels and mean PET for selected stations of IGR

The minimum expected weekly rainfall for starting field preparation depends mainly on the soil characteristics and evaporative demand of that place. But generally at least 20 mm weekly rainfall is required to begin field preparation. The detailed rainfall probability characteristics of each site are summarized below.

At Hisar, only a few weeks ie., 26th, 28th and 31st SMWs experience above 10 mm at 70 % probability level while a maximum of 16.6 mm is expected during 28th week. This indicates that the dependence on rainfall for farming operations is not appropriate. Ludhiana (from 28th to 33rd week) receives more than 10 mm rainfall continuously though this is also not sufficient to start field preparation. A continuous rainfall period is expected between 26th week (June 25-July 1) to 35th week (Aug 27- Sept 2), except 31st and 27th weeks, with a peak rainfall of 30.7 mm during the 28th and 30th weeks followed by 30.5 mm during the 32nd week (Aug 6-12) at Allahabad. But Kanpur of the same sub-region can expect rainfall from 28th week onwards and up to 32nd week. This indicates that the rainfall period is lower for Kanpur compared to Allahabad.

At Jhansi, the rainfall period begins from 27th week (July 2-8) and continues up to 33rd week (Aug 13-19). Thus only 7 weeks are available with an expected rainfall > 20 mm. However, a peak rainfall of 39.6 mm is expected during the 27th week followed by 32.2 mm during the 32nd week. In the case of Karnal, no week is expected to get rainfall > 20 mm. It is noticed that for Lucknow, the rainfall period lies between 28th week (July 9-15) to 32nd week (Aug 6-12), except 29th week and there is probability of getting a maximum rainfall of 38.3 mm during the 28th week followed by 24.9 mm during the 30th week (July 23-29). But in the case of Faizabad, the rainfall period lies between 28th week (July 9-15) to 33rd week (Aug 13-19) with probability of getting a maximum rainfall of 58.4 mm during the 29th week followed by 41.3 mm during the 33rd week (Aug 13-19). Even though these two sites are situated in the same agro-ecological region, there is a lot of variation of expected rainfall at different probability levels.

It is expected that rainfall of more than 20 mm is received from 26th week (June 25- July 1) to 34th week (Aug 20-26) at Hazaribagh. Peak rainfall of 51.1 mm is expected during the 31st week (July 30-Aug 5) and 46.5 mm during the 29th week (July 16-22). But in the case of Dhanbad, the rainfall period starts from 24th week (June 11-17) and continues up to 41st week (Oct 8-14). This indicates that Dhanbad can expect 18 continuous rainfall weeks with an expected rainfall > 20 mm. However, a peak rainfall of 56.2 mm is expected during the 30th week (July 23-29) followed by 48.1 mm during the 32nd week (Aug 6-12).

The analysis shows that the rainfall period of Samastipur lies between 27th week (July 2-8) to 37th week (Sept 10-16), except 32nd, 35th and 36th weeks. During this period, at least 20 mm rainfall per week at 70 % probability level is expected. Peak rainfall of 30.5 mm is expected during the 28th week followed by 29.8 mm during the 29th week at 70 % probability level. But in case of Purnea, the rainfall period lies between 25th (June 18-24) to 37th week (Sept 10-16), except 33rd week. A peak minimum rainfall of 54.1 mm is expected at 70 % probability level during the 29th week followed by 48.1 mm during the 28th week. Even at 90 % probability level, during the 28th and 29th weeks (July

9-15 & 16-22) there is an expected rainfall of at least 20 mm. The rainfall pattern indicates that there are two rainfall maxima within the monsoon season and this shows that there will be a small break within the monsoon activity after occurrence of heavy showers during the initial phase of the monsoon.

It is observed that rainfall period lies between 28th week (July 9-15) to 34th week (Aug 20-26) at Gorakhpur and there is a chance of getting a maximum rainfall of 37.3 mm during the 28th week followed by 37.2 mm during the 31st week (July 30-Aug 5). But in the case of Bahraich, the rainfall period begins from 26th week and continues up to 34th week (Aug 20-26); peak rainfall of 41.1 mm is expected during the 28th week (July 9-15) followed by 34.6 mm during the 29th week. In the case of Tehri Garhwal, the rainfall period begins from 28th week and continues up to 34th week with maximum rainfall of 34.3 mm expected during the 31st week and 30.5 mm during 29th week. For Asansol, at least 20 mm rainfall is expected from 25th week (June 18-24) up to 39th week (Sept 24-30) excepting 34th and 38th weeks. Peak rainfall of 46.2 mm is expected during the 37th week (Sept 10-16) followed by 36.4 mm during the 26th week (June 25- July 1). But in the case of Krishnanagar, the rainfall period begins from 25th week and continues up to 35th week only (Aug 27-Sept 2); peak rainfall of 44 mm is expected during the 28th week (July 9-15). It is found that an expected rainfall of more than 20 mm is received from 27th week (July 2-15) to 37th week (Sept 10-16) at Dumka. Peak rainfall of 47.3 mm is expected during the 30th week (July 23-29) followed by 42.7 mm during the 32nd week.

3.3.2. Moisture Availability Index

Based on expected rainfall at different probability levels, weekly moisture availability indices were computed for all the 18 sites. The crop planning can be done considering chances of failure or success of an endeavor. It is evident that the action taken by the planner will depend heavily on his choice of the risk level. The Moisture Availability Index (MAI) never reaches > 0.5 in any of the weeks for Hisar and Ludhiana. At Allahabad, the MAI is high (>0.5) at 70 % probability level and it is between 28th week and 35th week (Fig. 3.4). This indicates the crop is always in moist situation for 7 weeks and in the remaining weeks under stress conditions. In the case of Jhansi, MAI attains maximum (> 1.0) during 27th week with the onset of monsoon and then remains less than 1.0 during other weeks. This indicates that at 70 % probability level, the rice crop will be under moist situation during 28th week to 33rd week. At Kanpur, it is noticed that at 70 % probability level, MAI is high (>0.5) from 29th week up to 34th week. However, the MAI never reaches 1.0 in any of the weeks. This indicates the crop will be always in moist situation for 6 weeks and in the remaining weeks the crop will be under stress condition. It is noticed that for Karnal, the MAI is never above 0.5 and attains maximum value of 0.44 during 32nd week. As far as Lucknow is concerned, there is only one week (28th week) with MAI more than 1.0; from 29th week onwards MAI is greater than 0.5 and continues so up to 33rd week. This indicates the crop will have adequate moisture only for 7 weeks and in the remaining weeks will be under stress condition. However, for Faizabad of the same sub-region shows higher MAI from 29th week to 33rd week, except 30th week.

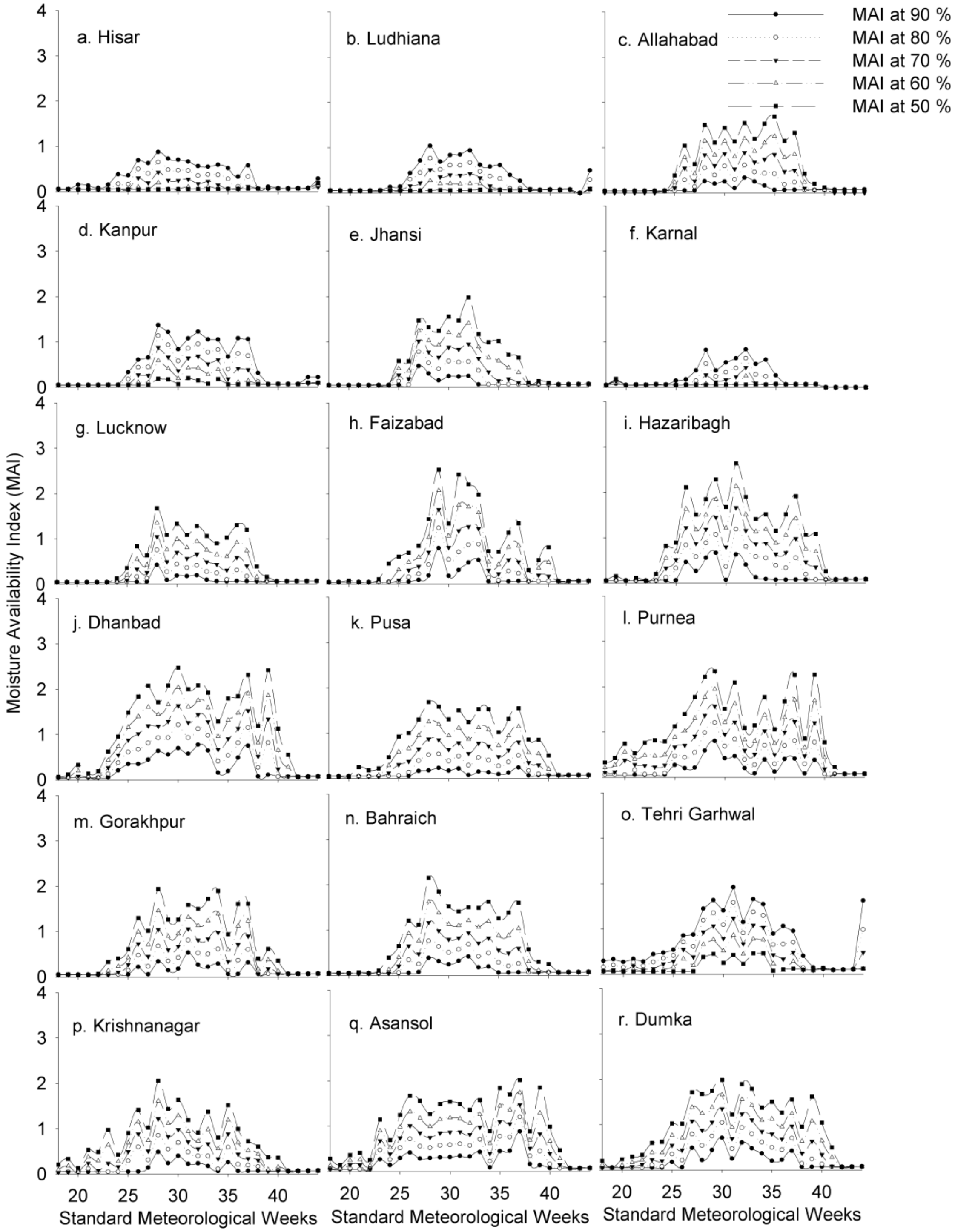

Fig 3.4: Expected weekly MAI at different probability levels for selected stations of IGR

From the analysis it is noticed that for Hazaribagh, the MAI is more than 0.5 from 25th week and up to 37th week. But the value of MAI becomes higher than 1.0 during 26th to 32nd week, except 27th and 30th weeks. For Dhanbad, it is noticed that at 70 % probability level, MAI is > 0.5 from 24th week and continues so up to 39th week. However, the MAI is higher from 26th week to 33rd week. This indicates the crop will be under humid situation for almost 2 months. In the case of Samastipur, MAI starts increasing from 24th week and becomes more than 0.5 from 27th week and to 37th week. But it is never more than 1 during this period. This indicates that at 70 % probability level, the rice crop will be always under moist situation. But for the case of Purnea, MAI is more (>0.5) from 25th week to 39th week continuously. However, for Gorakhpur, the MAI is more than 0.5 from 26th week to 37th week. Even though, these are located in the same sub-region, moist period will be longer for Purnea followed by Gorakhpur. But for Bahraich, the MAI is more from 26th to 37th week, but MAI > 1.0 only during 28th week. This indicates that the rice crop will be under moisture stress from 38th week onwards at 70 % probability level.

In the case of Tehri Garhwal, it is noticed that at 70 % probability level, MAI > 0.5 from 26th week to 34th week and becomes >1.0 in four weeks (29th, 31st, 33rd and 34th week). This indicates that the rice crop will get 9 moist weeks. For Asansol, it is noticed that at 70 % probability level, MAI is more (>0.5) from 25th weeks and continues so up to 39th week except 34th week, but MAI will be higher than 1 during 34th to 36th week, which normally coincides with the milky stage of the crop. But for Krishnanagar, the MAI is more from 25th to 35th week, and at Dumka, MAI is more than 0.5 during 27th to

37th week. Hence, moist period is lengthier for Asansol followed by Krishnanagar and Dumka (Fig. 3.5).

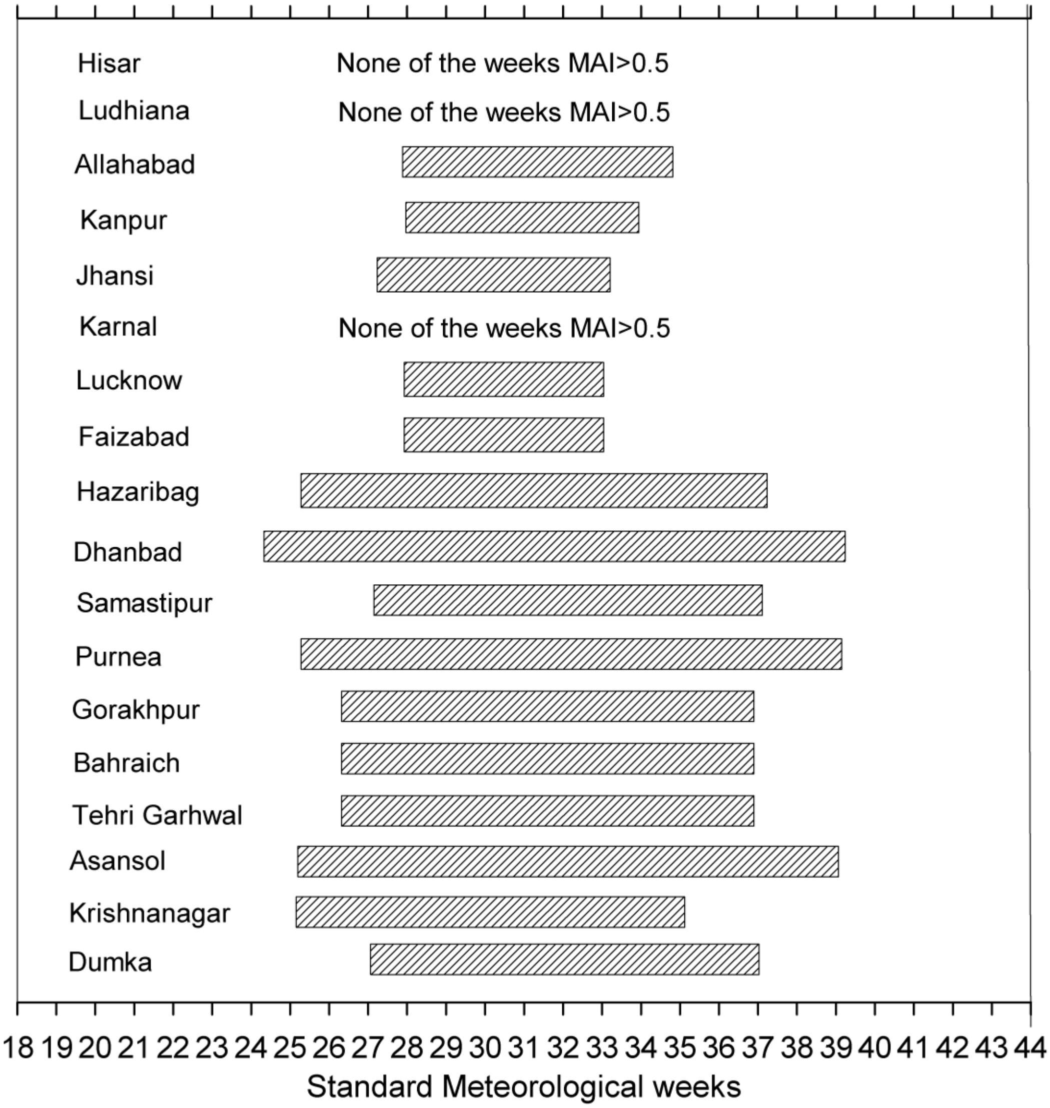

Fig 3.5: Variation of MAI (> 0.50) at 70 % probability across selected stations of IGR

3.4. Spatial variation of rice productivity and Crop planning and Management strategies

The spatial variation of rice productivity at the district level during the triennium ending 2000-01 indicated that a wide spatial variation in rice productivity (Fig. 3.6). This spatial variation is mainly due to water availability during the crop period. There are 37 districts with high rice productivity (> 2500 kg/ha), 52 districts with medium productivity (2000-2500 kg/ha), 38 districts with medium-low productivity (1500-2000 kg/ha), 51 districts with low productivity (1000-1500 kg/ha) and 13 districts with very low productivity (< 1000 kg/ha). The low productivity is a result of bio-physical factors like low irrigation, undulating physiography and extreme climatic events like floods and

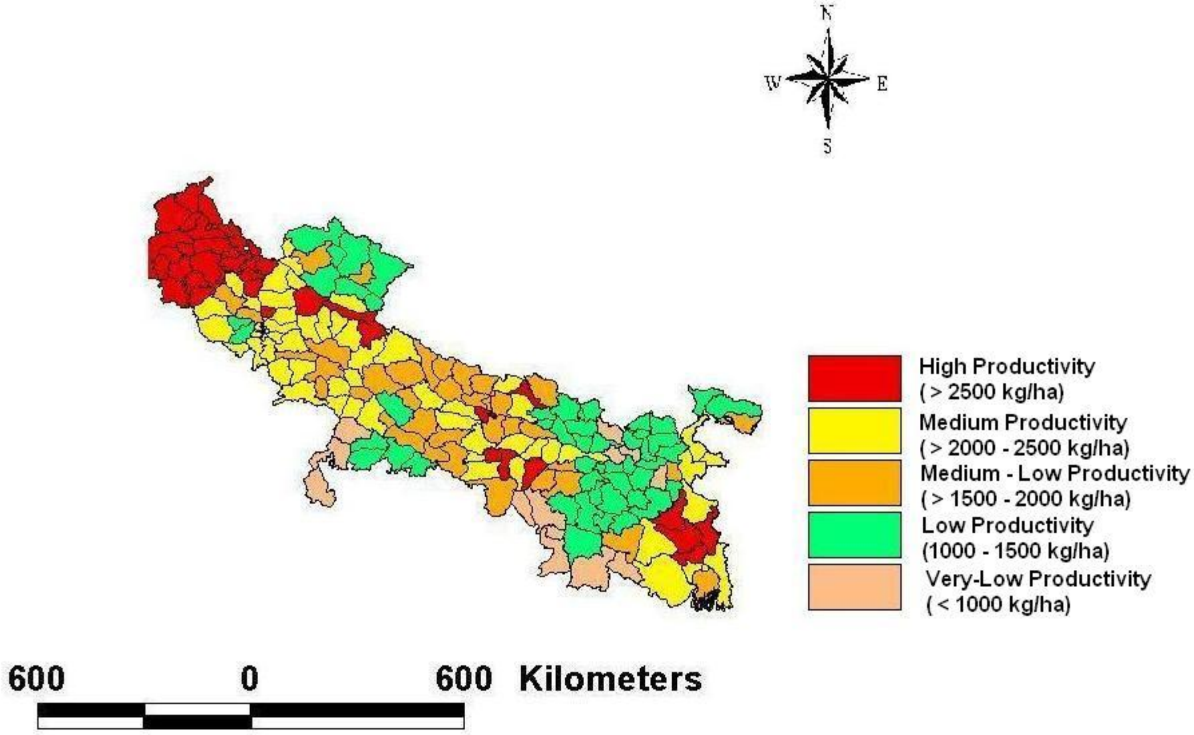

Fig 3.6: Spatial variation of rice productivity over IGR during the triennium ending 2000-01

droughts on one side and poor socio-economic status of rice farmers leading to poor crop management.

Since the farmers' of this region normally used local traditional varieties and followed traditional management and cultural practices rather than scientific and climatologically driven management practices. To achieve maximum productivity, they have to use high/medium/low duration varieties as well as adopt scientific way of crop management and cultural practices. The appropriate crop management strategies for important sub-regions (refer Chapter 1, Table 1.1 and Fig. 1.2) are given below,

Sub-regions 15.1: It is evident that the initial wet period starts from 22nd week and hence this period is suitable for transplanted rice from the first week of June. Medium (110-130 days) to long duration (140-150 days) varieties can be grown as this region has relatively long rainy period and seasonal surplus water availability(Fig. 3.7). For long duration varieties, water stress will affect only after 39th week, by which time the crop will be near maturity. Ensuring right time of nursery raising and transplantation is most important in transplanted rice. Field bunding will help to conserve rain water. However for Krishnanagar and Dumka districts, it is better to plant short (90-100 days) and medium (110-125 days) duration varieties as water stress condition will start from 36th and 38th week, respectively. Long duration varieties will face water stress during milky and dough stages (grain development) and will thereby have reduced yield.

Sub-regions 13.1 and 13.2: Generally in these sub-regions, moist period starts from 27th week up to 37th week (70days) and dry conditions prevail from 38th week onwards. This is good for medium duration varieties to be grown without water stress till maturity.

Long duration varieties can be taken as transplanted rice in low land (water stagnation during crop period) region where there is stagnant run off water. Timely planting is important as some areas face inundation from runoff water. In midlands and uplands (no water stagnation - except for limited periods, the land doesn't hold moisture in the rooting zone in excess of that held at field capacity), long duration varieties will suffer water stress during reproductive stages under rainfed condition. Purnea has a relatively longer rainy period (25-39th week) and well-distributed moist and humid periods; long duration rice varieties can be grown without water stress in this region as timely transplanting is possible as indicated by rainfall distribution.

Sub-regions 11 and 12.3: These regions have relatively larger rainfall duration. However, humid period dominates from 25-34th weeks. Direct seeded upland rice is the major crop in this region, which is suited to the rainfall distribution and topography. Dry spell comes only towards the dough stage and ripening stage by which time the damage to crops is minimum. Medium duration varieties are ideal for this region. Introduction of direct-seeded and transplanted aerobic rice varieties in this region can increase productivity. In Dumka, though the region has prolonged rainfall, two dry spells come in 25th and 37th weeks. First dry spell may affect the tillering in early transplanted rice where as second dry spell can affect grain filling in case of medium and long duration varieties. However, residual moisture in the soil can save the situation. In uplands, in case of delayed sowing, short duration (90-100 days) varieties may be preferred for this region. In case of delayed sowing, pre monsoon tillage will help to conserve moisture and check weeds. Closer spacing is ideal for delayed sown conditions.

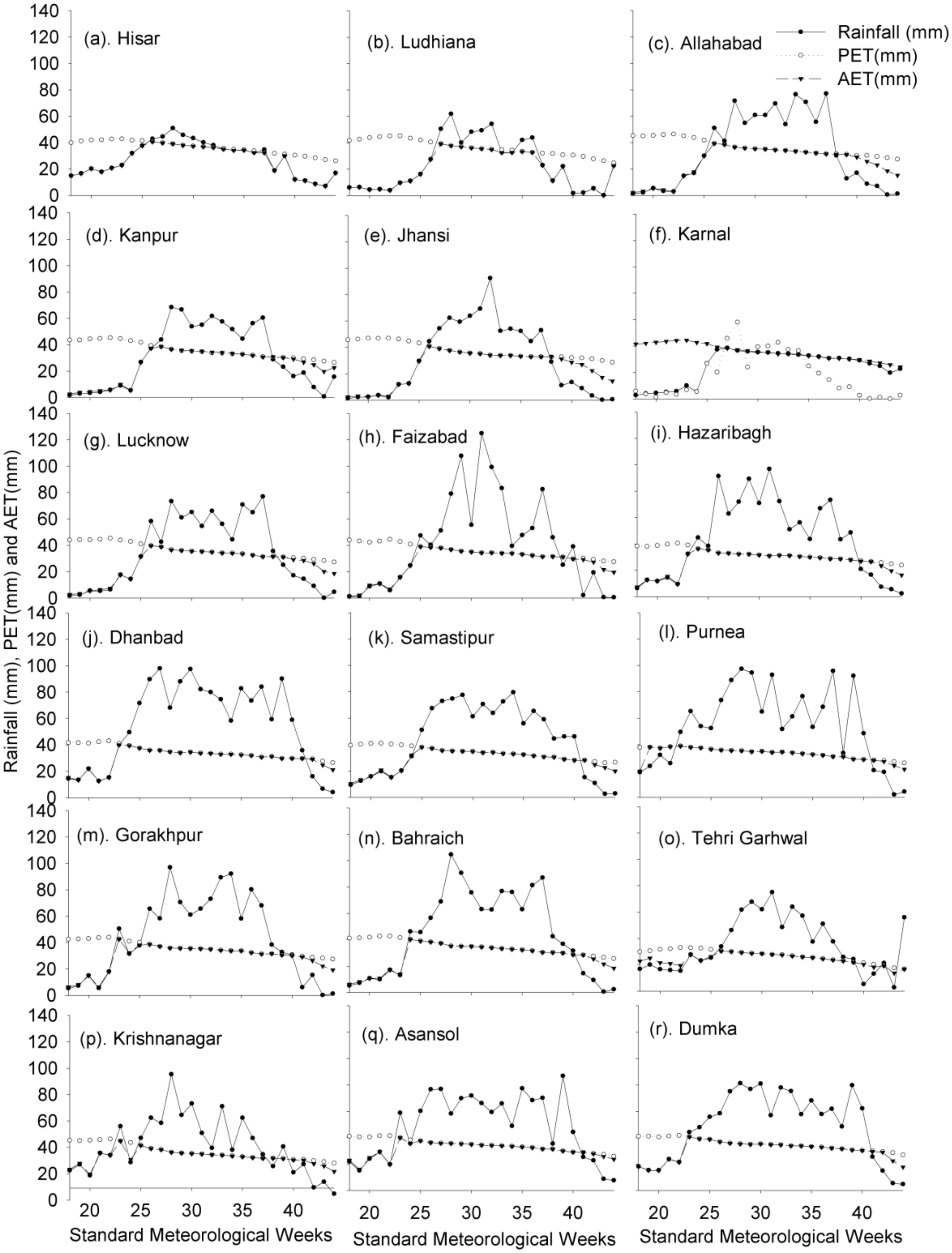

Fig 3.7: Weekly water balance components for selected stations of IGR

Sub-regions 4.3, 4.4 and 9.2: These sub-regions have relatively shorter monsoon season while the variability in distribution of rainfall is more. Early drought during seedling stage is a possibility. Summer ploughing can help conserve soil moisture in this region. Only short duration varieties can be taken up in these areas, which are purely rainfed. Long and medium duration varieties may suffer water stress from flowering period. Also this region has suitability for medium duration varieties. However, dry spells during panicle initiation is a cause of concern. In situ water harvesting and runoff collection measures are important to protect the crop with lifesaving irrigation.

Sub-region 2.3, 4.1 and 9.1: Due to erratic and scanty rainfall, high water deficit lead to frequent crop failures as coincides with grain formation/filling stage and crop sterility. Since moisture availability is a constraint, supplementary irrigation is essential for raising short duration rice varieties.

The rainfall analysis indicates that the western part of the region has more probability of water stress period (dry: MAI<0.5) during the critical phenophases of the crop. To meet the crop water requirements and mitigate the water deficits during the critical growth periods, supplemental irrigation is strongly recommended. In addition to the specific management strategies mentioned above, adoption of run-off rainwater management conservation measures suited to small and marginal farmers, wherever possible during long dry spells, is recommended to increase the rice productivity of the region. Since most of the farmers in the eastern region are poor, the adoption of non-monetary inputs like timely sowing, application of balanced dose of fertilizers, timely irrigation and timely harvesting of crops may also increase the productivity. Since along with rainfall, soil characteristics and physiography of the place also influence the productivity of rice of a place, better results can be achieved by super-imposing the soil and physiography maps of the region with moisture availability map of the region. Supplemental irrigation during the critical growth periods is valuable for increasing production and gives the maximum economic benefits to resource poor, marginal to small land holding farmers for better livelihoods.

CHAPTER 4

Evaluation of Standardized Precipitation Index and Monsoon Rainfall Index for Drought Climatology with respect to rice and wheat

4.1. Introduction

Water availability in the rainfed region is entirely dependent on the monsoon rain. Since monsoonal rainfall is erratic, farmers of rainfed regions have to follow the important management factors viz., optimize rice transplanting to maximize rain water availability during rice season, capture and utilize residual soil moisture for wheat, and complete wheat grain filling before the onset of high temperatures. Farmers with irrigation facilities may not have to wait for the monsoon rain and thus can transplant rice earlier, to make full use of high solar radiation early in the season. Timely planting of wheat is essential to take advantage of early season low temperatures. Timely adoption of all these management practices directly or indirectly involves monsoon rainfall. Historical records indicate that drought occurs every year in any form of severity in one or more States in the IGR. Rainfed rice predominates in the abundant rainfall zones of the eastern part where there is scope for growing rice under ponded water conditions during the rainy season, while irrigated rice is grown in the western part. Wheat assumes greater prominence in the western part, where it is normally grown with irrigation in winter, in rotation with rice. In some areas in the eastern part of the region (West Bengal), where water is not a limiting factor, especially in the West Bengal rice-rice rotation is followed.

There are four major reasons for droughts in these areas – delay in the onset of monsoon/failure of monsoon, variability of monsoon rainfall, long breaks in monsoon and spatial variation in the persistence of monsoon rains. Even though there has been a significant increase in the application of water-conserving technologies and in water storage facilities, a recurrence of multiyear droughts would result in greater impacts on agriculture today because of the rapid expansion and urbanization of the region's population during the past several decades and the associated increased pressure on water and other natural resources. The success or failure of the rice (kharif) -wheat (rabi) (rice-wheat system) in any year is always viewed with the greatest anxiety as they are closely linked with the behaviour of the southwest monsoon rains received during June to September. Since rice and wheat are the staple food in this part of the region, any drought would directly affect the food security of the region.

Frequency and intensity of meteorological droughts over IGR with reference to rice crop during kharif season and wheat crop during rabi season have been assessed using Standardized Precipitation Index (SPI) and Monsoon Rainfall Index (MRI). As the monthly distribution of rainfall is more crucial than the cumulative seasonal rainfall on rice-wheat productivity an attempt is made here to assess the effectiveness of monthly SPI and MRI from June to September on rice-wheat productivity over five major rice-wheat growing States of India. An attempt is also made to test the use of monthly SPI and MRI for early kharif rice productivity-rabi wheat productivity forecast for these States.

4.2. Productivity trends

4.2.1. Rice

The State-wise productivity of kharif rice from 1974 to 2005 is depicted in Fig. 4.1(a-f). The rice crop continues to show an overall steady increase in productivity in all the States. The percentage increase in triennium productivity ending 1976 to 2005 was 119 per cent for IGR. But higher percentage of increase (140 per cent) in triennium productivity was noticed in West Bengal followed by Uttar Pradesh (127 per cent). However, a very low value of 26 per cent increase in triennium productivity was observed in Bihar. Kharif rice productivity under five productivity groups in IGR States during different triennia ending 1976, 1983, 1991, 1999 and 2005 are shown in Fig. 4.2.

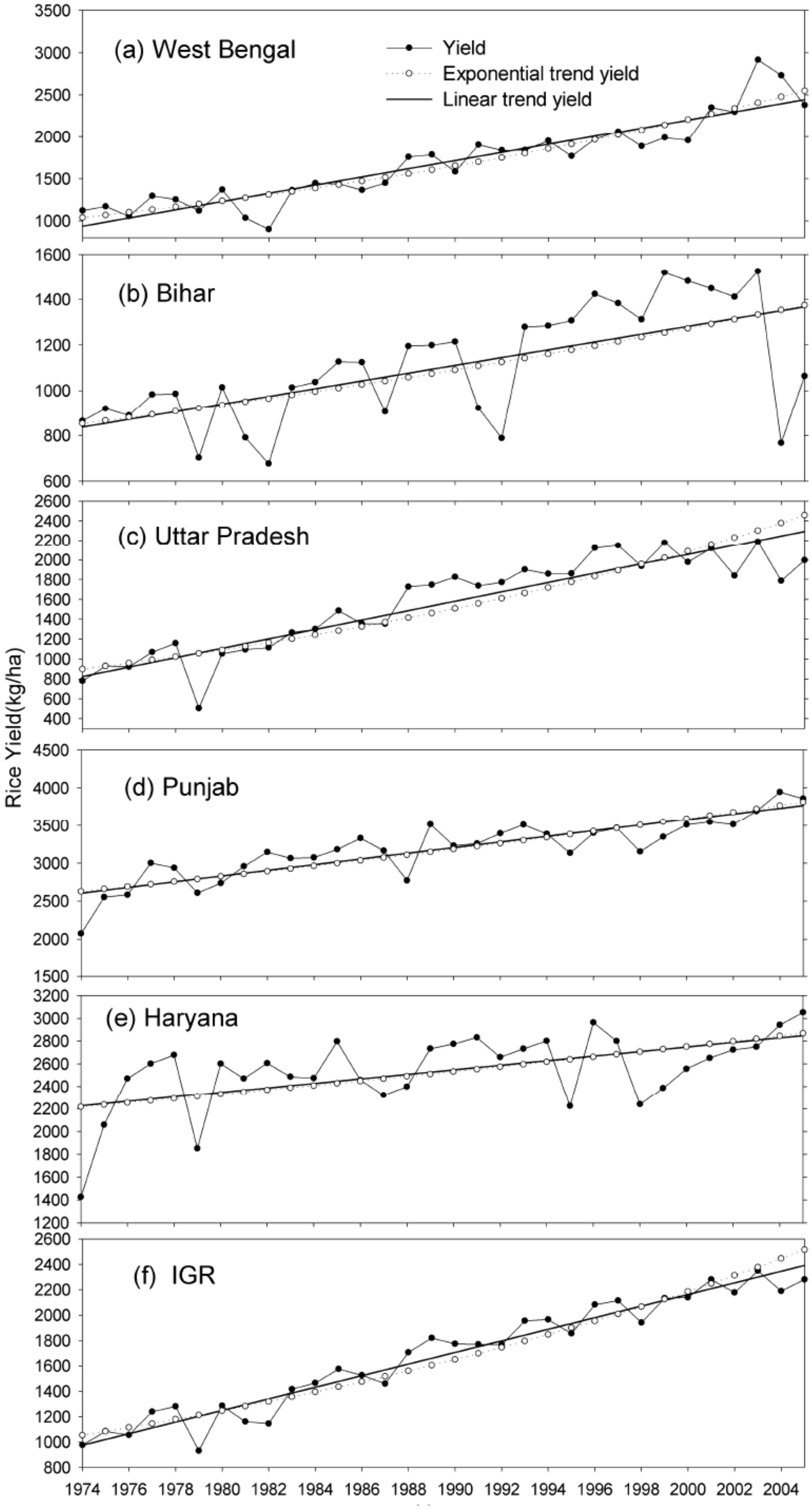

Fig. 4.1: Rice yield variability (a-f) during 1974-2005 and its exponential and linear trends over IGR

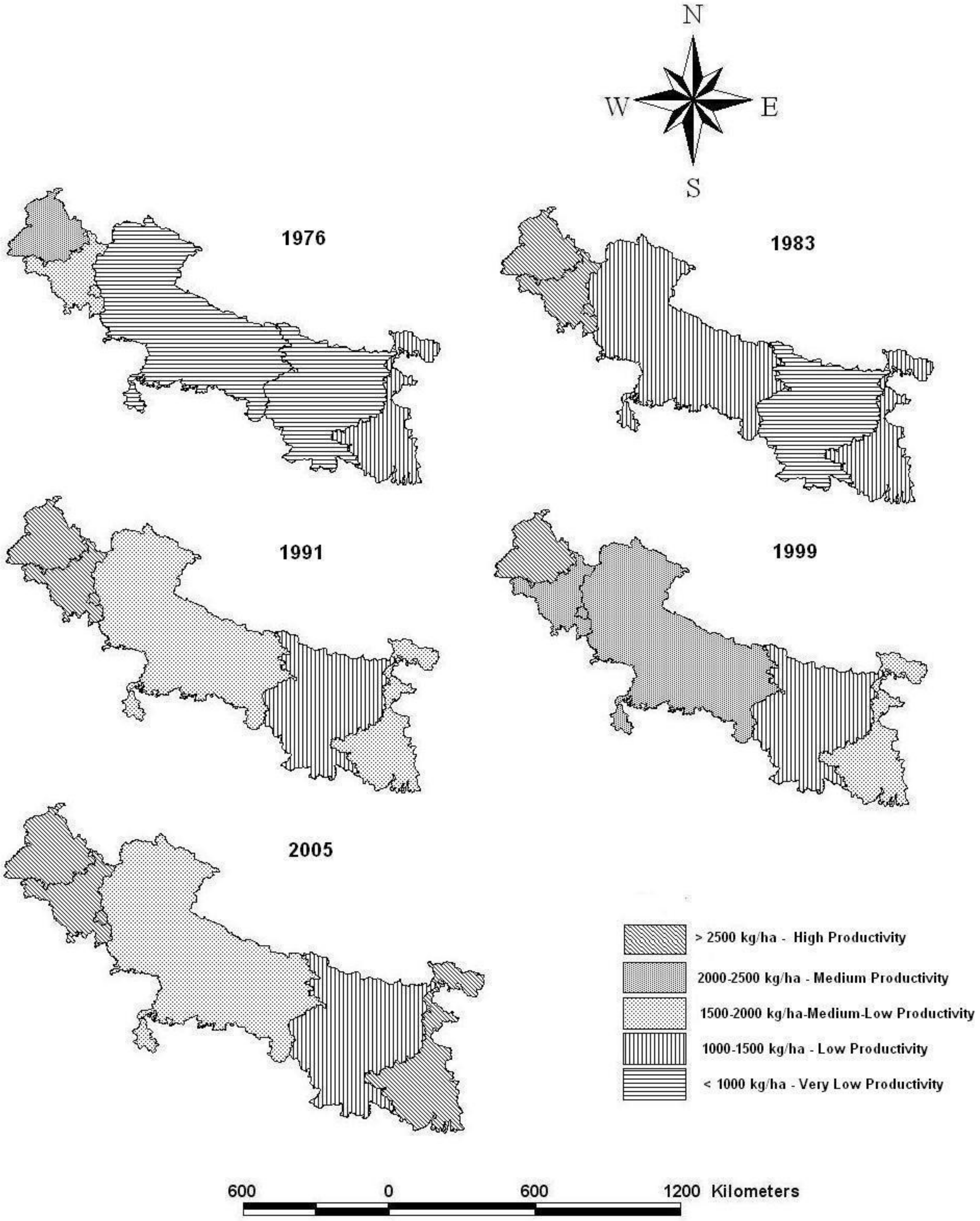

Fig. 4.2: Kharif rice productivity under five productivity groups in IGR States during different triennia ending periods

It is clear that none of the States fall under the category of high productivity group (> 2500 kg/ha) during the triennium ending 1976, while 3 States viz., Punjab, Haryana and West Bengal fall under this category during the triennium ending 2005. Similarly, none of the States fall under the category of very low productivity (< 1000 kg/ha) during the triennium ending 2005 in IGR. This clearly shows the spreading of “Green Revolution” to the entire IGR, even though at different rates.

The kharif rice productivity values were fitted into exponential as well as linear curve and found that R^2 value is more for linear fit for the IGR. The linear and exponential kharif rice technological trend equations and its regression statistics are shown in Table 4.1.

States	Linear Technological Rice Productivity	Exponential Technological Rice Productivity
Rice		
West Bengal	TRP_{ti}= 887.34+(49.05*ti) R=0.92 * , SEE=193.60	TRP_{ti} = 1006.93(1.02944)^{ti} R=0.93 * , SEE=0.049
Bihar	TRP_{ti}= 823.10+(17.45*ti) R=0.65 * , SEE=195.75	TRP_{ti} = 839.46(1.01552)^{ti} R=0.61 * , SEE=0.082
Uttar Pradesh	TRP_{ti}= 819.31+(45.25*ti) R=0.91 * , SEE=195.60	TRP_{ti} = 868.96(1.0330)^{ti} R=0.86 * , SEE=0.079
Punjab	TRP_{ti}= 2578.19+(36.91*ti) R=0.86 * , SEE=205.51	TRP_{ti} = 2594.18(1.01209)^{ti} R=0.84 * , SEE=0.032
Haryana	TRP_{ti}= 2232.00+(19.08*ti) R=0.54 * , SEE=283.43	TRP_{ti} = 2197.86(1.008347)^{ti} R=0.52 * , SEE=0.056
IGR	TRP_{ti}= 945.31+(44.76*ti) R=0.97 * , SEE=106.29	TRP_{ti} = 1023.29(1.02849)^{ti} R=0.95 * , SEE=0..905

ti = 1,2,3, ……….. for the period from 1974-75 to 2005-06
* *Significant at 0.001 level*

Table 4.1: Linear and exponential technological trend equations for rice productivity and its regression statistics for different IGR States and IGR

All the IGR States, except West Bengal show higher R^2 value for linear fitting of rice productivity compared to exponential fitting. From the table, it can be stated that the kharif rice productivity over IG region has grown at the rate of 45 kg/ha/year during study period. However, West Bengal shows a higher growth of 49.1 kg/ha/year followed by Uttar Pradesh (45.3 kg/ha/year). It is also noticed that least growth of 17 kg/ha/year was achieved by Bihar followed by Haryana (19.1 kg/ha/year).

4.2.2. Wheat

The State-wise productivity of wheat from 1966-67 to 2005-06 is depicted in Fig. 4.3(a-f). The IGR States contribute 65.3 % area and 74.2 % production to India's total area and production of wheat. The wheat crop also continues to show an overall steady increase in productivity in all the States. The wheat productivity in IGR States during different triennia ending periods 1968, 1976, 1983, 1991, 1999 and 2005 are shown in Fig. 4.4.

The percentage increase in triennium productivity ending 1968 to 2005 was 117.6 per cent for IGR. However, it has been noticed that there was slight (5.1 per cent) decreasing of wheat productivity from triennium ending 1999 to 2005. But higher percentage of increase (141 per cent) in triennium productivity was noticed by Haryana followed by Uttar Pradesh (132.6 per cent). However, 70.9 per cent increase in triennium productivity was observed in West Bengal, which is not known as a traditional wheat growing area. From the graph, it is clear that the productivity gap among the IGR States has been increasing from the triennium ending 1968 to 2005.

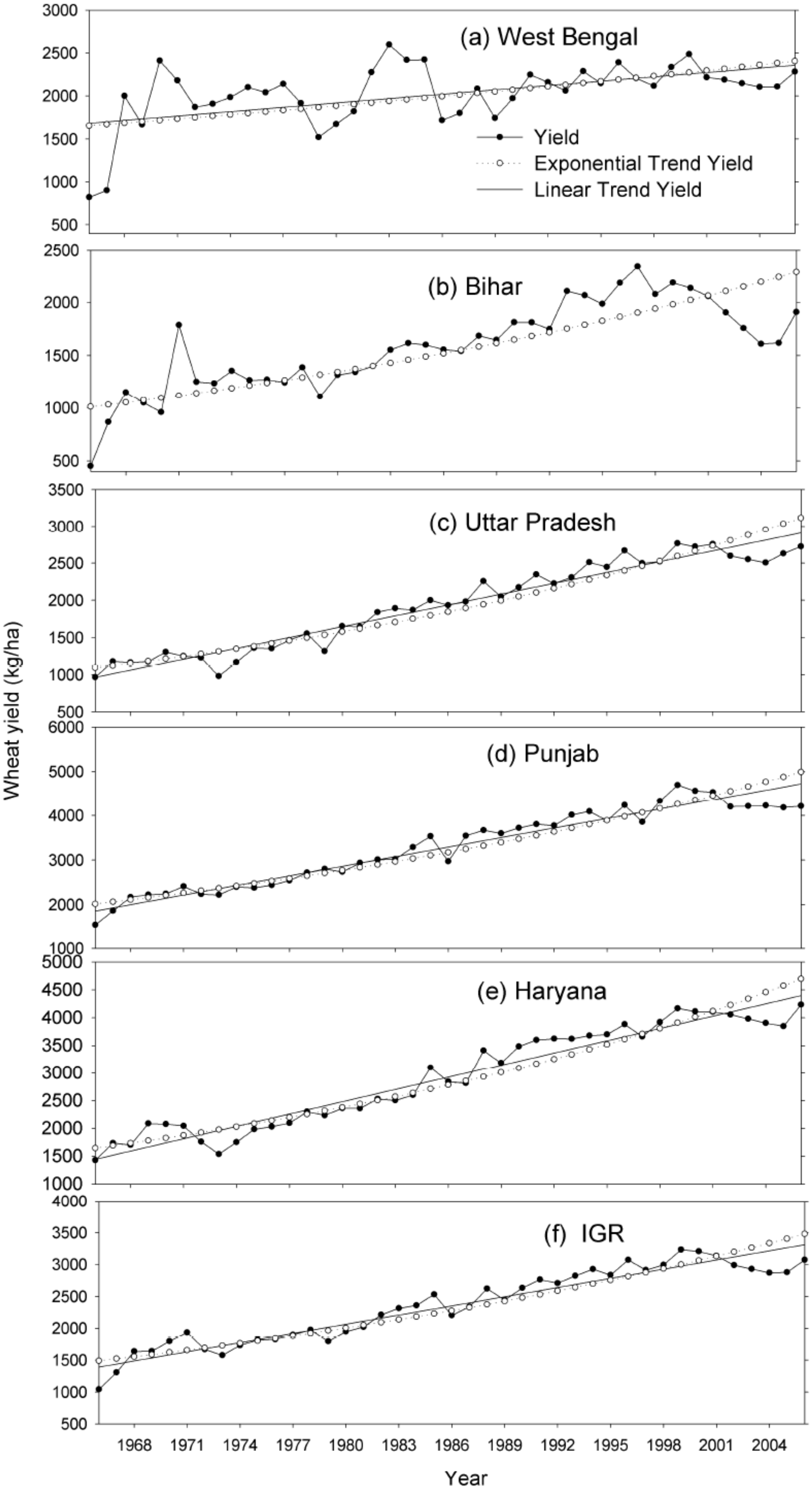

Fig. 4.3: Wheat yield variability (a-f) from 1966-67 to 2006-07 and its exponential and linear trends over IGR

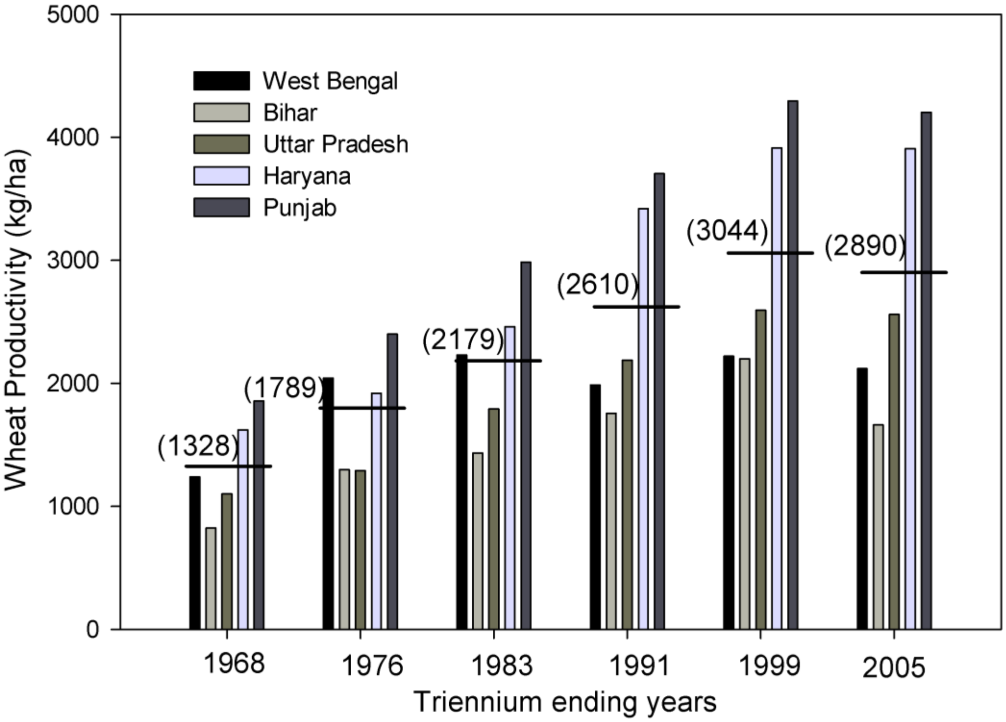

Fig. 4.4: Wheat productivity in IGR States during different triennium ending periods *(the figures in parenthesis indicates IGR average)*

During the triennium ending 1968, in all the States, except Bihar, the wheat productivity was very close to average productivity of IGR, but during the triennium ending 2005, the productivity values of Punjab and Haryana were very much higher than average of IGR. Similarly, the productivity of West Bengal, Bihar and Uttar Pradesh was far below the average productivity of IGR.

The wheat productivity values were fitted into exponential as well as linear curve (Fig. 4.3(a-f)) and found that R^2 value is more for linear fit for the IGR as well as for all the States. The linear and exponential wheat technological trend equations and its regression statistics are shown in Table 4.2. From the Table, it is attributed that the wheat productivity over IGR has grown at the rate of 46.7 kg/ha/year during study period. However, Haryana shows a higher growth of 72.6 kg/ha/year followed by Punjab (69.9 kg/ha/year). It is also noticed that least growth of 15.1 kg/ha/year was achieved by West Bengal followed by Bihar (28.5 kg/ha/year).

States	Linear Technological Wheat Productivity	Exponential Technological Wheat Productivity
West Bengal	$TWP_{ti}= 1719.05+(15.06*ti)$ $R=0.50^{*}$, SEE=317.41	$TWP_{ti} = 1636.82(1.00942)^{ti}$ $R=0.50^{*}$, SEE=0.087
Bihar	$TWP_{ti}= 985.57+(28.45*ti)$ $R=0.82^{*}$, SEE=237.72	$TWP_{ti} = 988.55(1.02063)^{ti}$ $R=0.79^{*}$, SEE=0.084
Uttar Pradesh	$TWP_{ti}= 940.34+(47.49*ti)$ $R=0.97^{*}$, SEE=143.87	$TWP_{ti} = 1061.70(1.0266)^{ti}$ $R=0.96^{*}$, SEE=0.042
Punjab	$TWP_{ti}= 1821.45+(69.94*ti)$ $R=0.97^{*}$, SEE=224.20	$TWP_{ti} = 1967.89(1.02294)^{ti}$ $R=0.96^{*}$, SEE=0.037
Haryana	$TWP_{ti}= 1399.93+(72.62*ti)$ $R=0.97^{*}$, SEE=227.52	$TWP_{ti} = 1599.56(1.0266)^{ti}$ $R=0.96^{*}$, SEE=0.0411
IGR	$TWP_{ti}= 1373.27+(46.71*ti)$ $R=0.96^{*}$, SEE=175.13	$TWP_{ti} = 1455.46(1.021457)^{ti}$ $R=0.94^{*}$, SEE=0.043

ti = 1,2,3, ……….. for the period from 1966-67 to 2005-06

[*] *Significant at 0.001 level*

Table 4.2: Linear and exponential technological trend equations for wheat productivity and its regression statistics for different IGR States and IGR

4.3. Gamma distribution for monthly Rainfall probability

Gamma distribution was found to be a good fit to the monthly monsoon rainfall data of all the IGR States as well as for the mean IGR. Table 4.3 shows the monthly expected rainfall at different probability levels for all the States and IGR. It is clear from the table that during June, IGR is expected to get a rainfall of 231.9 mm and it is 215.9 mm during July at 60 % probability level. For Punjab and Haryana, more than 100 mm rainfall is expected only during July and August. Uttar Pradesh is expected to receive

66.5 mm rainfall during June. It is obvious from the table that IGR is expected to get considerable amount of rainfall during July and August at 60 % probability level.

Months	Rainfall (mm) at different probability levels						
	70	60	50	40	30	20	10
West Bengal							
June	282.9	294.3	303.8	312.2	319.6	326.2	333.1
July	377.4	387.7	396.2	403.5	410.2	415.9	422.3
August	315.1	325.2	333.6	340.9	347.2	353.0	358.3
September	250.7	261.1	269.9	277.4	284.2	290.5	296.1
Bihar							
June	125.2	136.4	146.0	154.6	162.4	169.8	176.5
July	252.7	262.4	270.5	277.3	283.5	289.2	294.9
August	243.0	251.6	258.7	264.6	270.3	275.0	279.7
September	160.3	169.9	177.9	185.0	191.5	197.4	203.8
Uttar Pradesh							
June	57.9	66.5	74.3	81.6	88.3	94.6	101.2
July	192.9	206.3	217.7	227.8	237.0	245.4	253.2
August	200.1	210.6	219.4	227.0	233.9	240.4	246.1
September	111.3	123.8	134.8	144.8	154.0	162.6	171.0
Punjab							
June	24.3	30.3	36.0	41.5	46.8	52.0	57.0
July	120.5	132.3	142.6	152.0	160.5	168.4	175.8
August	108.5	120.3	130.5	139.7	148.1	156.0	163.5
September	33.9	47.7	62.4	77.8	93.7	109.6	125.4
Haryana							
June	27.4	33.1	38.5	43.6	48.5	53.1	57.6
July	98.8	111.8	123.3	133.8	143.6	152.7	161.6
August	97.5	109.5	120.1	129.7	138.6	146.9	154.8
September	33.7	46.1	59.2	72.5	86.1	99.6	112.9
IGR							
June	111.5	117.4	122.4	126.8	130.9	134.3	137.7
July	224.9	231.9	237.7	242.6	246.9	251.4	255.9
August	210.5	215.9	221.0	224.9	228.8	232.7	236.5
September	135.3	142.3	148.0	153.0	157.5	161.9	166.2

Table 4.3: Monthly expected rainfall (mm) during monsoon months over IGR States and its mean at different probability levels

4.4. Standardized Precipitation Index (SPI) and Monsoon Rainfall Index (MRI)

4.4.1. Frequency of SPI and MRI

The histograms of the drought frequency classes of the SPI during June to September for IGR States are shown in Fig. 4.5. It has been found that about 14 per cent of the years, the SPI class falls under the dry category during June for West Bengal.

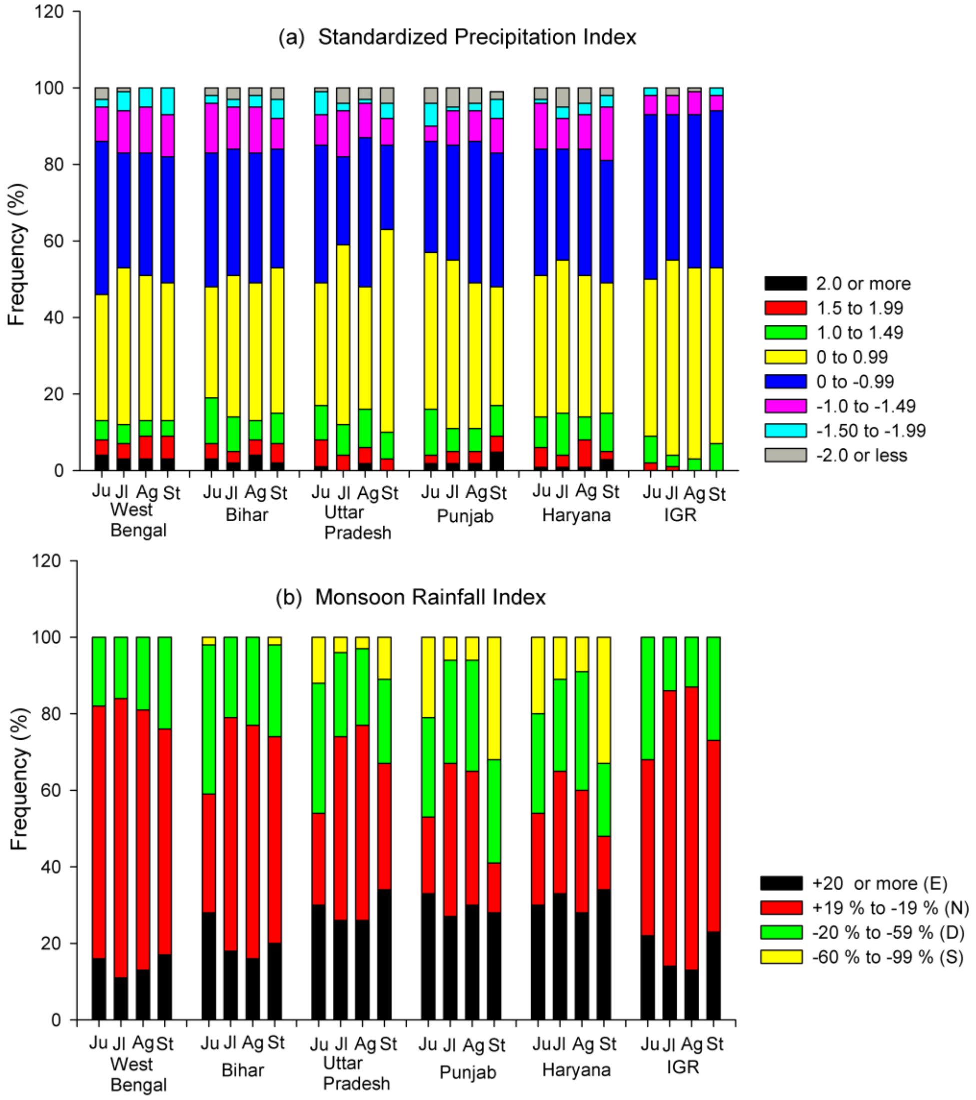

Fig. 4.5: Histograms of the drought frequency classes of the (a) SPI and (b) MRI during June to September for IGR States

However, 17 per cent of the years SPI reach below -1 during July and August and 18 per cent during September. But for Bihar, 17 per cent of the years the value of SPI reaches dry category during June and August and 18 per cent during September.

In the case of MRI, it is noticed that none of the months during the study period fell under the category of scanty rainfall for the IGR. The same pattern has been noticed for West Bengal also. But for Bihar, the MRI during June reaches the category of scanty rainfall for two years (1927 & 1972). About 21 and 20 per cent of the years, the June MRI reached below -60 % for Punjab and Haryana, respectively. Similarly, 32 and 33 per cent of the years the September MRI attained below -60 % for these States.

4.4.2. Influence of monthly SPI on KRPI & WPI

The influence of June to September SPI on KRPI and WPI over IGR States is shown in Figs. 4.6 and 4.7, respectively. The State-wise inferences are as follows:

- West Bengal : Out of 32 years under study, nine years (1979, 1981, 1982, 1986, 1995, 1998, 1999, 2000 & 2005) fell under deficit rice productivity (KPRP< -5). During these deficit years, except 1995, SPI value of one of the monsoon months was negative and clustering of more points in the 1st and 3rd quadrant during June highlight the importance of June SPI to KPRI. But in the case of wheat, 12 years fell under deficit wheat productivity and during all these years SPI values of one of the monsoon months were negative.
- Uttar Pradesh: Eight years (1979, 1981, 1982, 1987, 1991, 1992, 2004 & 2005) fell under deficit productivity (KPRP< -5). During these deficit years SPI value of at

least one of the monsoon months were < -1 and June and September SPI contributed more to KPRI. The SPI values during August (r: 0.38) showed significant relation with wheat productivity.

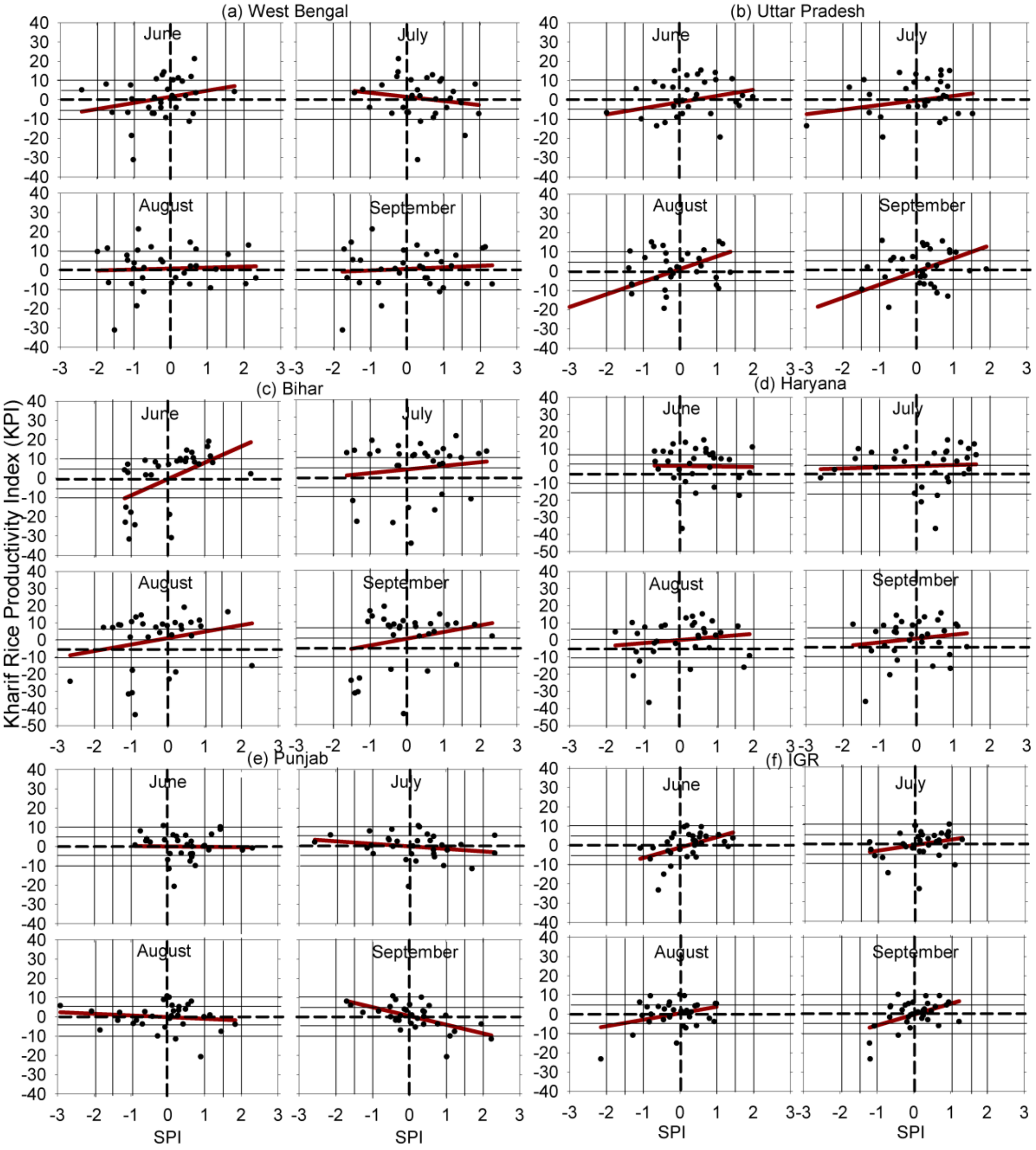

Fig. 4.6: Standardized Precipitation Index (SPI) Vs Kharif Rice Productivity Index (KPI) from June to September during 1974 to 2005 over IGR States

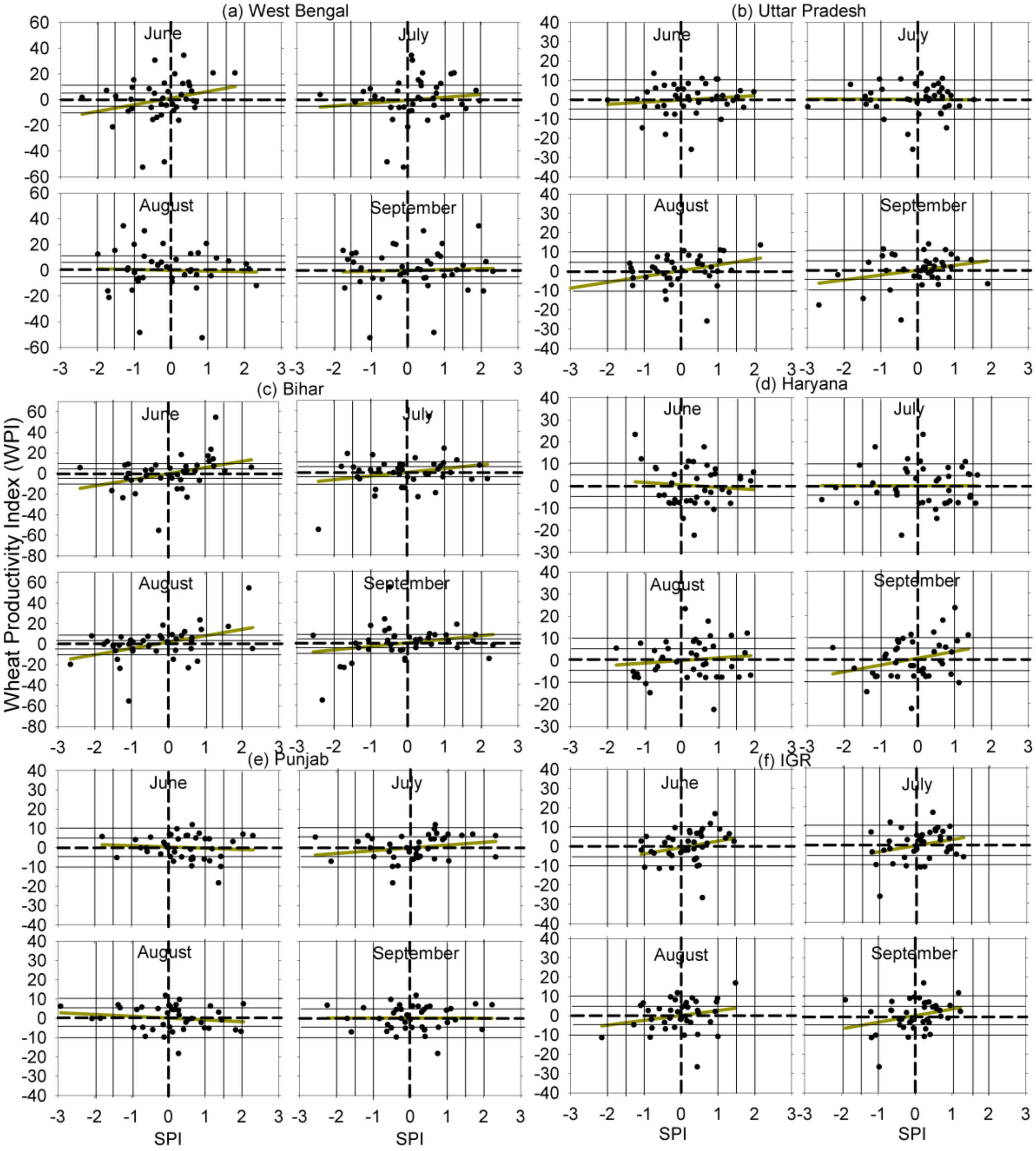

Fig. 4.7: Standardized Precipitation Index (SPI) Vs Wheat Productivity Index (WPI) from June to September during 1966-67 to 2005-06 over IGR States

- Bihar: Nine years (1974, 1979, 1980, 1981, 1982, 1987, 2002, 2004 & 2005) fell under deficit productivity (KPRI< -5). During these deficit years, except 1995, SPI value of one of the monsoon months was negative; June, July and August SPI contribute more to KPRI. However, SPI values during June (r=0.36) and August (r = 0.41) have more influence on wheat productivity.
- Haryana: Six years (1974, 1975, 1995, 1998, 1999 & 2000) fell under deficit productivity (KPRP< -5). It is noticed from the graph that the regression lines are almost parallel and around 80 % of the points clustered in 1st and 4th quadrant implying that even during occurrence of negative monthly SPI values the KRPI reached above technological trend and availability of other irrigation sources may be the reason for higher productivity. This also indicated that high rainfall during September helps the timely sowing of the wheat crop in this region.
- Punjab: Six years (1974, 1979, 1988, 1995, 1998, 1999) fell under deficit productivity (KPRP< -5). It is noticed from the graph that the regression lines during June, July and August are almost parallel and close to x-axis. Since 99.3 % rice area was under irrigation during 2005-06, effect of dry spells during the monsoon season did not affect the productivity. More points clustered in the 1st quarter suggested that positive SPI values during July and August may influence the WPI.

4.4.3. Influence of monthly MRI on KRPI and WPI

The correlation coefficients of monthly MRI on KRPI and WPI are shown in Table 4.4. As far as IGR is concerned, June MRI and KRPI have highly significant correlation at 1 % level while September MRI and KRPI have significant correlation at 5 % level.

IGR States	Correlation coefficients during			
	June	July	August	Sept.
Between MRI and KRPI				
West Bengal	0.26	0.17	0.04	0.07
Bihar	0.39*	0.17	0.10	0.34*
Uttar Pradesh	0.19	0.16	0.04	0.34*
Punjab	0.02	0.15	0.16	0.58**
Haryana	0.02	0.12	0.10	0.09
IGR	0.46**	0.30	0.26	0.38*
Between MRI and WPI				
West Bengal	0.25	0.12	0.04	0.05
Bihar	0.36*	0.24	0.42	0.25
Uttar Pradesh	0.13	0.01	0.38	0.29
Punjab	0.09	0.23	0.16	0.00
Haryana	0.09	0.00	0.12	0.29
IGR	0.27	0.27	0.22	0.29

** Significant at 5 % level*
*** Significant at 1 % level*

Table 4.4: The correlation coefficients of monthly MRI on KRPI and WPI

There is significant (5 % level) correlation between June and September MRI and KRPI for Bihar. However, the influence of September rainfall on KRPI for Uttar Pradesh and Punjab is high. The relation between KRPI and rainfall index during June-September for Bihar is depicted in Fig. 4.8. During the eight deficit productivity years (except 2004), June rainfall index falls under the deficient drought class indicating that June rainfall is crucial for timely sowing of rice in this region. But during July, only four years received deficient rainfall. During the year 1982, July to September received deficient rainfall and the productivity index reached 31 %.

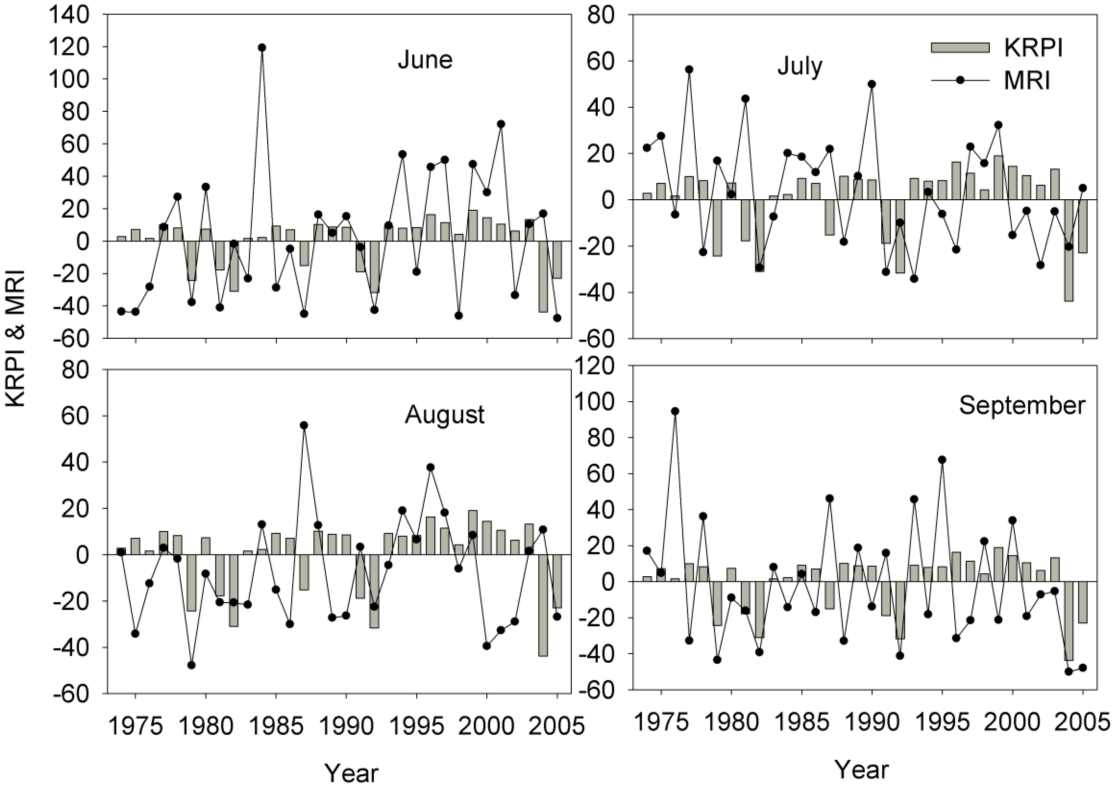

Fig. 4.8: Kharif rice productivity index Vs Monthly monsoon rainfall index for Bihar during 1974-2005

KRPI reached minimum (-43.7 %) during 2004 and MRI reached deficient category during July and September: even MRI during September reached – 50.1 %. The relation between WPI and rainfall index during June-September for Bihar is depicted in Fig. 4.9. Out of eleven deficit WPI years, during seven years, at least two monsoon months received deficient rainfall. It is clear from the graph that August received deficient rainfall in 6 years and in five years each during June and September.

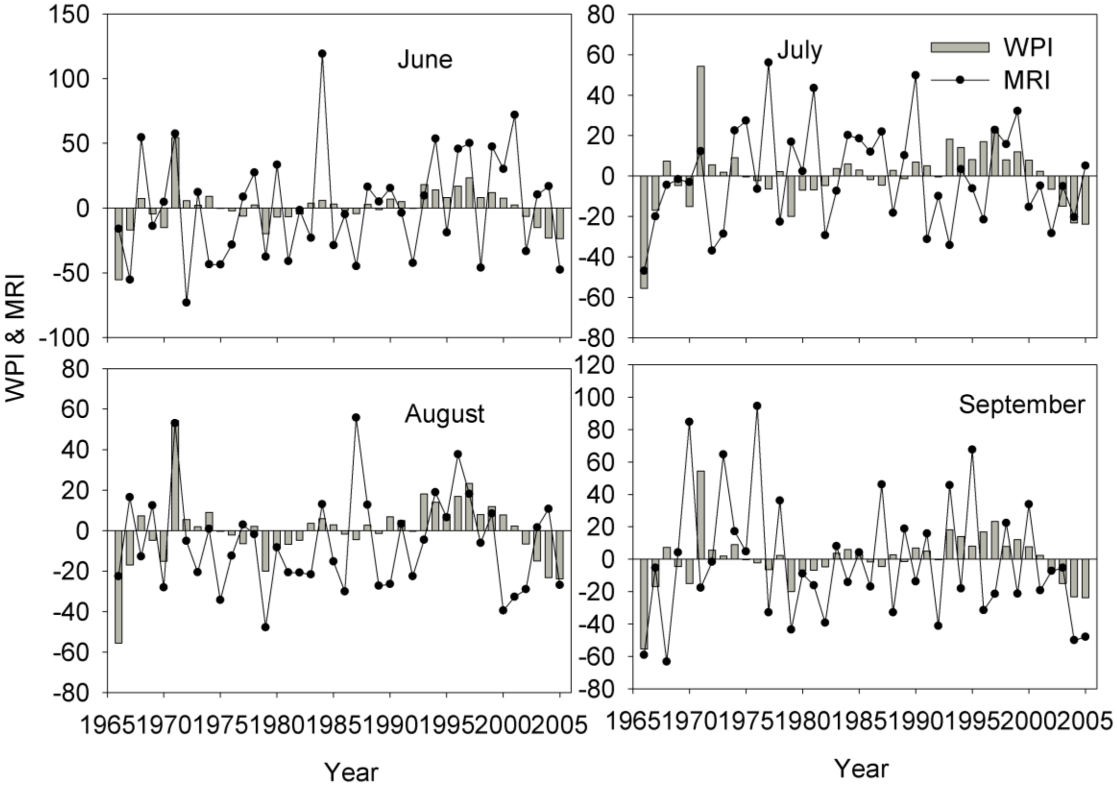

Fig. 4.9: Wheat productivity index Vs Monthly monsoon rainfall index for Bihar during 1966-67 to 2005-06

4.4.4. Use of SPI and MRI for forecasting rice and wheat productivity

The multiple regression equations for KRPI and WPI versus monthly SPI during June to September were developed and are shown in Table 4.5. It is observed that the IGR Kharif rice productivity index and monthly SPI during June to September have a significant (R=0.66) multiple regression at 0.001 level. However, the IGR Kharif rice productivity index and monthly MRI during June to September are also significant (R=0.62) at 0.001 level (Table 4.6). It indicates that the monthly distribution of monsoon rainfall in terms of SPI accounted for 44 per cent variability and in terms of MRI accounted for 38 per cent variability in kharif rice productivity. Among the IGR States, Bihar has high multiple regression coefficient (R=0.70) at 0.001 level between KRPI and monthly SPI.

IGR States	Regression Equation	R – Value
Kharif Rice Productivity Index		
West Bengal	$KRPI=2.652+(2.941*SPI_{June})-(2.783*SPI_{July})+(1.223*SPI_{Aug})+(0.357*SPI_{Sept})$	0.33
Bihar	$KRPI=-1.337+(9.76*SPI_{June})+(4.705*SPI_{July})-(1.456*SPI_{Aug})+(8.303*SPI_{Sept})$	0.70 *
Uttar Pradesh	$KRPI=0.0921+(1.265*SPI_{June})+(2.368*SPI_{July})+(4.945*SPI_{Aug})+(5.141*SPI_{Sept})$	0.63 *
Punjab	$KRPI=0.234+(0.546*SPI_{June})+(0.810*SPI_{July})+(0.0936*SPI_{Aug})-(5.165*SPI_{Sept})$	0.60 *
Haryana	$KRPI=0.363-(0.640*SPI_{June})+(0.179*SPI_{July})+(1.537*SPI_{Aug})+(1.87*SPI_{Sept})$	0.21
IGR	$KRPI=-0.958+(4.022*SPI_{June})+(2.062*SPI_{July})+(2.196*SPI_{Aug})+(3.727*SPI_{Sept})$	0.66 *
Wheat Productivity Index		
West Bengal	$WPI=0.689+(5.738*SPI_{June})+(2.854*SPI_{July})-(1.368*SPI_{Aug})-(1.087*SPI_{Sept})$	0.30
Bihar	$WPI=1.845+(5.198*SPI_{June})+(3.209*SPI_{July})+(4.884*SPI_{Aug})+(3.992*SPI_{Sept})$	0.61 *
Uttar Pradesh	$WPI=0.0578+(0.761*SPI_{June})-(0.208*SPI_{July})+(2.518*SPI_{Aug})+(1.901*SPI_{Sept})$	0.44
Punjab	$WPI=0.241-(0.583*SPI_{June})+(1.551*SPI_{July})-(0.655*SPI_{Aug})-(0.431*SPI_{Sept})$	0.29
Haryana	$WPI=0.839-(1.138*SPI_{June})-(0.411*SPI_{July})+(0.566*SPI_{Aug})+(3.09*SPI_{Sept})$	0.31
IGR	$WPI=-0.515+(2.355*SPI_{June})+(2.96*SPI_{July})+(2.152*SPI_{Aug})+(2.369*SPI_{Sept})$	0.46

**Significant at 0.001 level, Normality test and constant variance test passed for all the multiple regressions.*

Table 4.5: Kharif rice productivity index and wheat productivity and monthly SPI (June to September) relationship regression equations and R-Value for IGR States

At all the IGR States, except West Bengal, the multiple regression coefficients between KRPI and SPI are higher compared to KRPI and MRI. This suggested that the kharif rice productivity of IGR States as well as for the IGR could be estimated based on the monthly SPI values. But for wheat productivity, the multiple regression coefficients between WPI and MRI are higher compared to multiple regression coefficients between WPI and SPI. Thus SPI based multiple regression equations are suitable for estimating kharif rice productivity while MRI based multiple regression equations are suitable for estimating wheat productivity. These indices are purely based on rainfall climatology of the region and its performance on rice and wheat productivity has tremendous implications on aiding water management and thereby enhancing the productivity during deficit rainfall years.

IGR states	Regression Equation	R – Value
Kharif Rice Productivity Index		
West Bengal	$KRPI=2.784+(0.15*MRI_{June})-(0.151*MRI_{July})+(0.0557*MRI_{Aug})+(0.00306*MRI_{Sept})$	0.34
Bihar	$KRPI=-1.206+(0.215*MRI_{June})+(0.189*MRI_{July})-(0.0729*MRI_{Aug})+(0.232*MRI_{Sept})$	0.65 *
Uttar Pradesh	$KRPI=0.350+(0.0299*MRI_{June})+(0.0662*MRI_{July})+(0.182*MRI_{Aug})+(0.0926*MRI_{Sept})$	0.54 *
Punjab	$KRPI=-0.0792-(0.000425*MRI_{June})+(0.00693*MRI_{July})-(0.00288*MRI_{Aug})-(0.0440*MRI_{Sept})$	0.59 *
Haryana	$KRPI=-0.0492-(0.00473*MRI_{June})+(0.0209*MRI_{July})+(0.0222*MRI_{Aug})+(0.00662*MRI_{Sept})$	0.21
IGR	$KRPI=-0.519+(0.103*MRI_{June})+(0.0863*MRI_{July})+(0.0613*MRI_{Aug})+(0.0664*MRI_{Sept})$	0.62 *
Wheat Productivity Index		
West Bengal	$WPI=1.102+(0.271*MRI_{June})+(0.169*MRI_{July})-(0.0723*MRI_{Aug})-(0.0465*MRI_{Sept})$	0.32
Bihar	$WPI=1.561+(0.135*MRI_{June})+(0.133*MRI_{July})+(0.233*MRI_{Aug})+(0.113*MRI_{Sept})$	0.61 *
Uttar Pradesh	$WPI=0.146+(0.0158*MRI_{June})-(0.00672*MRI_{July})+(0.0963*MRI_{Aug})+(0.0394*MRI_{Sept})$	0.42
Punjab	$WPI=0.0215-(0.00302*MRI_{June})+(0.0304*MRI_{July})-(0.0128*MRI_{Aug})+(0.000272*MRI_{Sept})$	0.28
Haryana	$WPI=1.099-(0.000185*MRI_{June})-(0.0143*MRI_{July})+(0.00630*MRI_{Aug})+(0.0482*MRI_{Sept})$	0.34
IGR	$WPI=-0.270+(0.0760*MRI_{June})+(0.0906*MRI_{July})+(0.0545*MRI_{Aug})+(.0624*MRI_{Sept})$	0.48

* *Significant at 0.001 level, Normality test and constant variance test passed for all the multiple regressions.*

Table 4.6: Kharif rice productivity index and wheat productivity and MRI (June to September) relationship regression equations and R-Value for IGR States

The important features emerging from this section is that gamma distribution has been found to provide the best model for describing monthly precipitation over the study region. Even though the annual coefficient of variation (10.5 per cent) as well as the monsoon seasonal coefficient of variation (11.5 per cent) of rainfall is less, the monthly coefficients of variation within the monsoon season are higher; this clearly indicates that there will be large year to year variations in monthly distribution of rainfall during the southwest monsoon. There is an upward trend of rainfall during the period 1906-2005 for

IGR during monsoon season while there is a significant (0.05 level) decreasing trend of 0.8 mm rainfall/year for West Bengal.

The rice productivity over IGR States has increased steadily over the period and none of the States fall under the category of very low productivity (< 1000 kg/ha) during the triennium ending 2005 in IGR. This clearly shows the spreading of “Green Revolution” to the entire IGR, even though at different rates. It is noticed that the kharif rice productivity over IGR has grown at the rate of 45 kg/ha/year while wheat productivity has grown at the rate of 46.7 kg/ha/year during study period.

CHAPTER 5

Use of Remote Sensing Application for Drought Assessment

5.1 Introduction

The monitoring of agricultural drought requires rapid and continuous data and information generation or gathering. Since agricultural droughts that cause huge social and economic disruptions normally affect areas of different scales, it is not possible to effectively collect continuous data on them using conventional methods. The space technology or remote sensing has the capability of collecting data at different scales, global/regional, rapidly and repetitively and the data is collected in digital form. Remote sensing techniques can be used to monitor the current situation – before, during or after agricultural occurrence. Drought indicators assimilate information on rainfall, stored soil moisture or water supply but do not express much local spatial detail. Also, drought indices calculated at one location is only valid for single location. Thus, a major drawback of climate based drought indicators is their lack of spatial detail as well as they are dependent on data collected at weather stations which sometimes are sparsely distributed affecting the reliability of drought indices. Satellite derived drought indicators calculated from satellite-derived surface parameters have been widely used to study agricultural drought. Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) are some of the extensively used Vegetation Indices. Among the indices, NDVI is the most commonly used vegetation index. Therefore, an attempt has been made in this Chapter to analyze the use of NDVI for drought assessment with respect to rice and wheat over Indo-Gangetic Region.

5.2. Analysis of NDVI variability

Fig. 5.1 shows the NDVI variation from February, 2000 to March, 2006 over different States. The monthly value of NDVI ranged from 0.2 to 0.8 in all the States during the period 2000-2005. For Punjab, Haryana and Uttar Pradesh, two peak of NDVI have been observed – one during the rice season and one during the wheat season. Higher value of NDVI has been noticed during wheat season compared to rice season for Punjab and Haryana. For Bihar, the highest value of NDVI was obtained during the rice season, while the value of NDVI never above 0.50 during any of the months in wheat during the period.

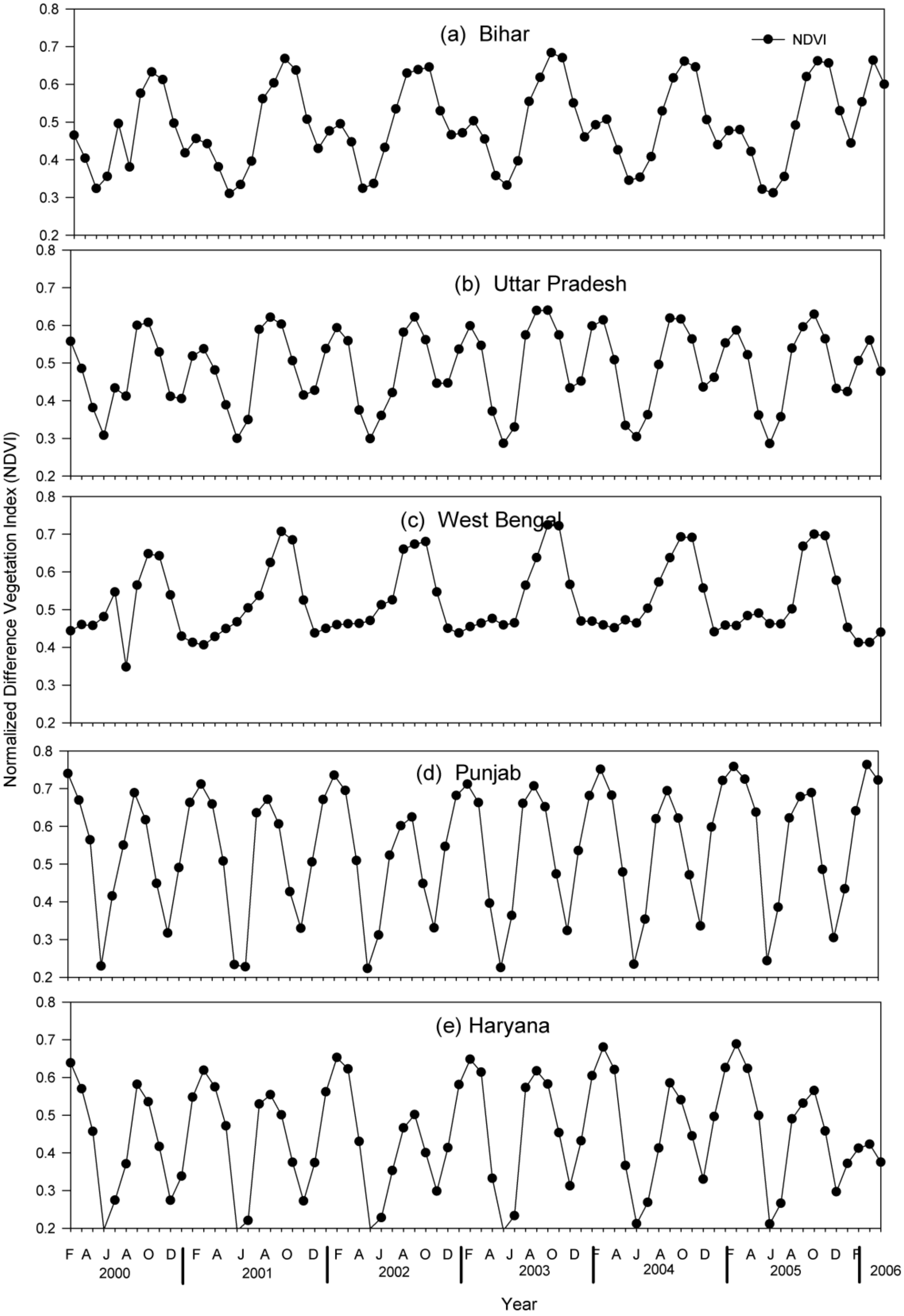

Fig. 5.1: Variability of NDVI during the period 2000-2005 over IGR States

The NDVI statistics such as monthly mean, standard deviation, coefficient of variation (CV), maximum NDVI, mode and median during the period 2000-2005 over IGR States are given in Table 5.1 and 5.2. For West Bengal, higher mean value of 0.69 with a standard deviation of 0.03 was noticed during September and October followed by a value of 0.63 in August. The highest value of standard deviation (0.08) and coefficient of variation (16.3 per cent) indicated that the year-to-year variability is more during July. In the case of Bihar, CV of more than 10 % was noticed in June and July of rice season and February and March of wheat season and a higher NDVI value of 0.66 was observed during September (rice season). As far as wheat season is concerned, a value of 0.51 was noticed in February. For Uttar Pradesh, a NDVI of 0.62 during rice season (September) and 0.58 during wheat season (February) were observed. The higher CV of 15 per cent with a standard deviation of 0.08 was noticed during July.

Months	West Bengal			Bihar			Uttar Pradesh			Punjab			Haryana		
	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV
Jan	0.44	0.02	5.37	0.49	0.03	7.04	0.54	0.03	5.97	0.68	0.03	3.93	0.56	0.08	13.61
Feb	0.44	0.02	5.18	0.51	0.07	14.24	0.58	0.03	4.72	0.74	0.02	2.83	0.62	0.09	14.60
Mar	0.46	0.02	3.93	0.45	0.07	15.99	0.51	0.03	6.35	0.69	0.03	3.96	0.57	0.09	15.65
Apr	0.47	0.01	3.09	0.33	0.02	5.28	0.37	0.02	5.21	0.52	0.08	15.75	0.43	0.06	15.11
May	0.47	0.01	1.65	0.34	0.02	4.74	0.30	0.01	3.04	0.23	0.01	3.14	0.20	0.01	4.06
June	0.50	0.03	6.38	0.41	0.05	11.40	0.37	0.04	9.67	0.34	0.07	19.34	0.25	0.02	9.54
July	0.51	0.08	16.30	0.51	0.07	13.24	0.50	0.08	15.04	0.60	0.05	8.87	0.45	0.09	19.70
Aug	0.63	0.04	5.80	0.61	0.02	3.10	0.61	0.02	3.43	0.67	0.04	5.57	0.56	0.05	9.52
Sept	0.69	0.03	3.88	0.66	0.02	2.90	0.62	0.01	2.21	0.63	0.03	4.80	0.54	0.03	6.14
Oct	0.69	0.03	3.77	0.64	0.02	3.01	0.55	0.03	4.79	0.46	0.02	4.71	0.42	0.03	7.79
Nov	0.55	0.02	3.45	0.52	0.02	3.84	0.43	0.01	3.09	0.32	0.01	3.49	0.30	0.02	7.47
Dec	0.45	0.01	3.12	0.44	0.02	4.10	0.44	0.02	4.80	0.52	0.06	10.74	0.40	0.06	13.86

(M- Mean, SD-Standard Deviation and CV- Coefficient of Variation)

Table: 5.1. NDVI statistics (mean, standard deviation and coefficient of variation) over different IGR States during 2000-2005.

Months	West Bengal			Bihar			Uttar Pradesh			Punjab			Haryana		
	MX	MO	ME	MX	MO	ME	MX	MO	ME	MX	MO	ME	MX	MO	ME
Jan	0.91	0.36	0.43	0.91	0.33	0.46	0.93	0.53	0.55	0.90	0.77	0.70	0.90	0.59	0.60
Feb	0.93	0.33	0.43	0.89	0.32	0.48	0.92	0.65	0.60	0.91	0.82	0.77	0.90	0.77	0.69
Mar	0.88	0.36	0.44	0.86	0.33	0.41	0.89	0.52	0.52	0.89	0.72	0.71	0.88	0.64	0.63
Apr	0.88	0.42	0.47	0.78	0.33	0.32	0.85	0.30	0.34	0.81	0.51	0.52	0.77	0.48	0.44
May	0.93	0.45	0.46	0.81	0.25	0.32	0.87	0.20	0.26	0.75	0.19	0.22	0.66	0.18	0.19
June	0.96	0.45	0.49	0.92	0.35	0.40	0.94	0.27	0.34	0.85	0.23	0.33	0.82	0.19	0.22
July	0.99	0.46	0.51	0.98	0.49	0.50	0.98	0.48	0.50	0.96	0.61	0.61	0.94	0.40	0.44
Aug	0.99	0.70	0.66	0.98	0.63	0.62	0.99	0.63	0.63	0.92	0.70	0.69	0.93	0.55	0.56
Sept	0.98	0.74	0.72	0.98	0.71	0.67	0.96	0.71	0.65	0.88	0.67	0.65	0.88	0.64	0.55
Oct	0.96	0.75	0.71	0.92	0.64	0.65	0.92	0.62	0.57	0.85	0.42	0.45	0.89	0.45	0.43
Nov	0.91	0.51	0.54	0.88	0.49	0.50	0.90	0.35	0.41	0.80	0.29	0.31	0.83	0.29	0.28
Dec	0.90	0.35	0.42	0.92	0.34	0.41	0.93	0.36	0.42	0.89	0.57	0.53	0.85	0.34	0.39

(MX- Maximum, MO-Mode and ME-Median)

Table: 5.2. NDVI characteristics (maximum, mode and median) over different IGR States during 2000-2005.

For Punjab, a high NDVI value of 0.74 was noticed during February and a lower value of 0.67 during August. The CV was more during June and December months and indicating the higher inter annual variability of dates of transplanting of rice as well as sowing of wheat in Punjab. For Haryana, a NDVI value of 0.62 was observed during February and 0.56 during August. The CV was more than 10 per cent in all the months during wheat season.

5.3. Seasonal pattern of rainfall and NDVI

5.3.1. Total monsoon seasonal rainfall and average NDVI

Considering the total monsoon season rainfall and NDVI patterns for the different States of the IGR for the period 2000-2005, it can be seen (Fig. 5.2) that their exist increasing correlation between average NDVI and monsoonal rainfall. As rainfall increases from 500 mm, NDVI increases and reaches up to a range of 0.55 at 1100 mm.

However, it can be analyzed that beyond 1100 mm of rainfall NDVI does not show further significant increase. Since most of the rainfall occurs between July-September with a maximum in July, therefore averaging NDVI data for these months fairly represents the growing season for the region (Anyamba and Tucker, 2005).

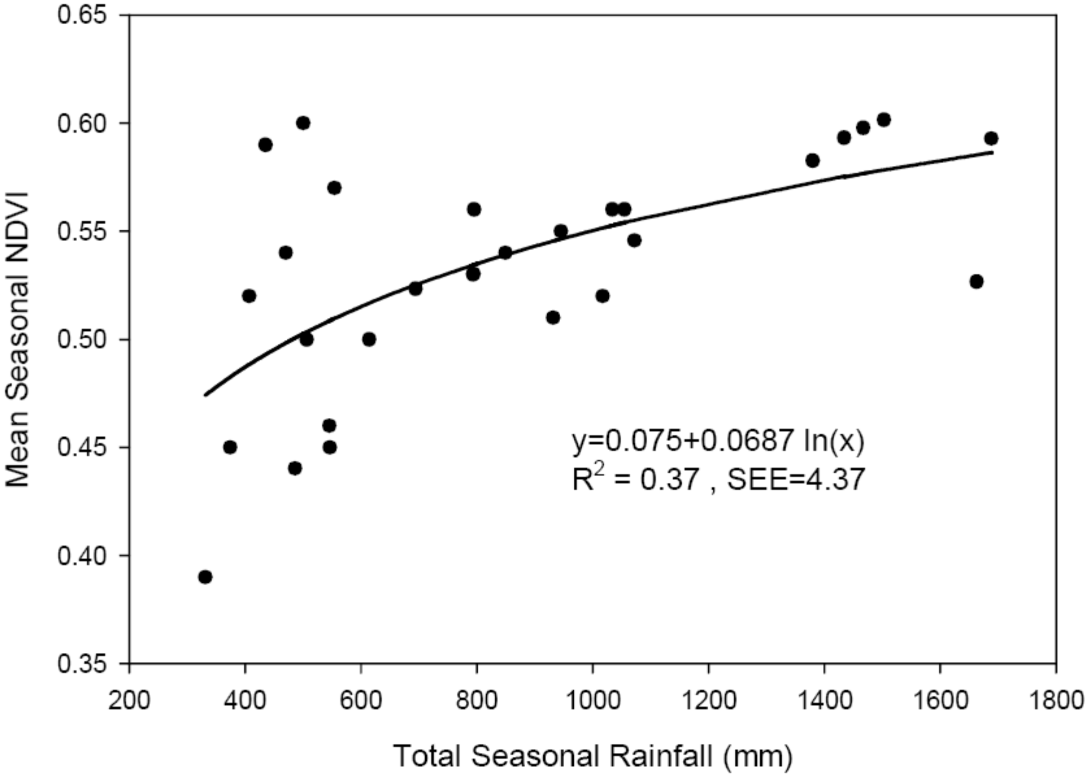

Fig.5.2: Relation between mean seasonal NDVI and total seasonal rainfall

5.3.2. Relation between monthly rainfall and NDVI for different States

The monthly distribution of rainfall during monsoon season and corresponding NDVI over different States for the period 2000-2005 is given in Fig. 5.3. During the 6 year period, considerable year-to-year variation was noticed between rainfall and NDVI.

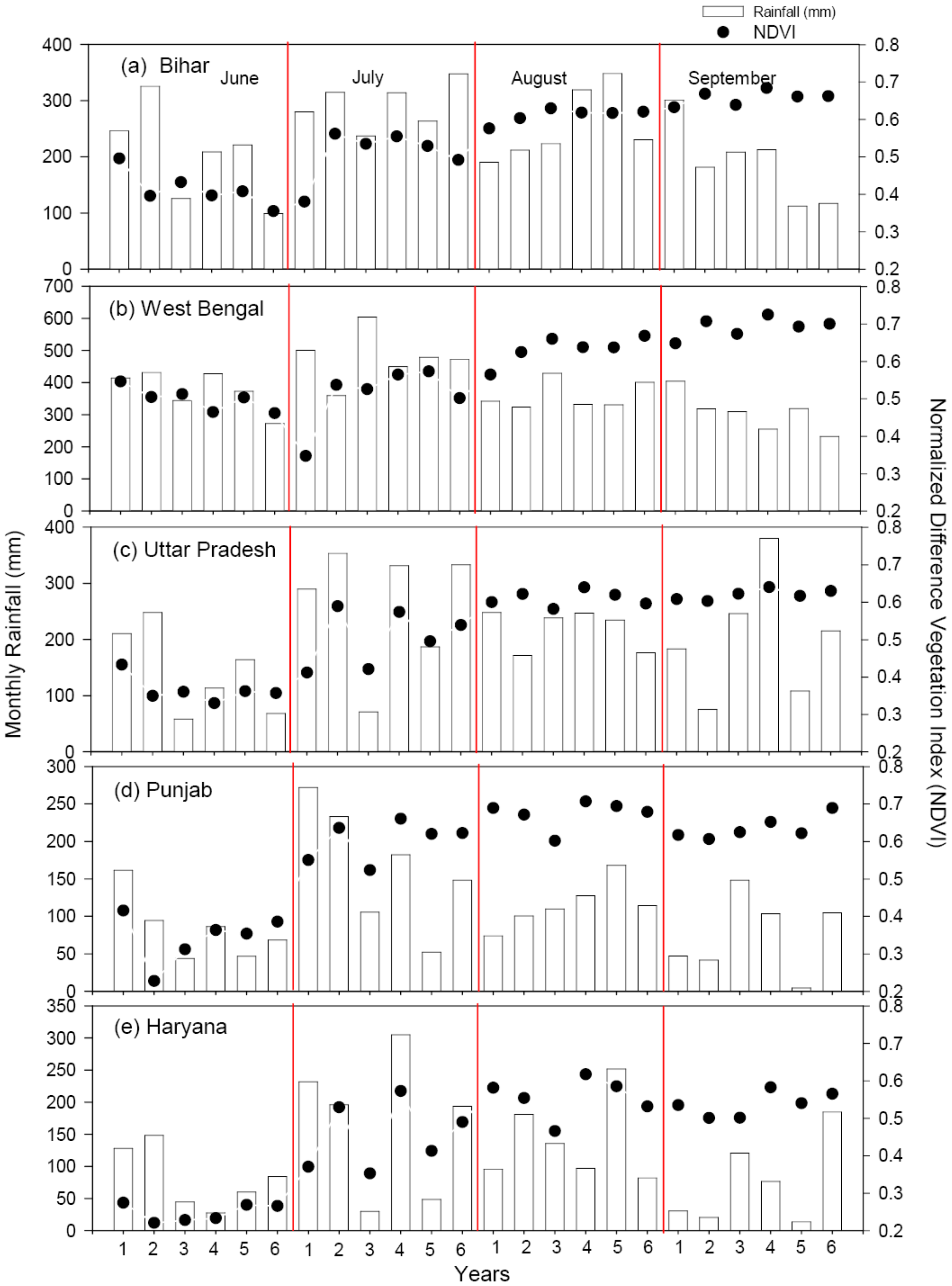

Fig. 5.3: Monthly rainfall during June-September and corresponding NDVI over different States for the period 2000-2005 *(1-2000; 2-2001; 3-2002; 4-2003; 5-2004; 6-2005)*

For Bihar, out of six years, two years (2002 & 2005) received below normal rainfall and though only in 2005 NDVI was below normal during June. No clear trend of any pattern of NDVI and monthly distribution has been noticed for Bihar. In 2005 due to 47.7 % deficit of rainfall during June influenced the vegetation conditions during June as well as July even after a surplus rainfall of 4.9 % received during July; this may be the reason for negative NDVI anomaly during July month. Similarly, during the year 2000, the continuous deficit of 15.4 and 39.5 % for July and August, respectively may be the reason for the negative anomaly of NDVI during July, August and September months even though September received 33.8 % surplus rainfall. No clear picture emerged between monthly rainfall and NDVI over West Bengal due to higher rainfall zone of IGR. For Haryana, out of six years, two years received deficit rainfall during June and these two years NDVI values were below normal. But during July, in the deficit years 2002 & 2004 negative NDVI anomalies were noticed.

In Uttar Pradesh, during the year 2005, due to 31.8 % deficit of June rainfall the vegetative conditions were affected during June and July, even after 20 % surplus rainfall received during July. But this surplus rainfall helps the vegetation to adjust the deficit rainfall of 35.7 % during August. This may be reason for positive anomaly of NDVI during August and September. In Punjab, in the year 2002 all the months except September received deficit rainfall and a negative NDVI anomaly was noticed for these months. But during 2004, even though all the monsoon months received deficit rainfall, only September shows negative NDVI anomaly.

Thus even though there was a positive correlation of seasonal monsoon rainfall and average NDVI, conflicting results were noticed in the monthly distribution pattern of rainfall and monthly NDVI anomaly for different States of IGR, indicating a lag time of one month between NDVI and monthly rainfall. These results are in agreement with those reported by Ferrar *et al*. (1994) for Africa, Li et al., (2004) for China and Chopra (2006) for Gujarat, India.

As far as wheat season is concerned, different States responded differently to season monsoon rainfall and NDVI during wheat season (December to March). For Bihar, during the year 2000, due to high rainfall received in September and a little rainfall during October delayed the sowing of wheat and thereby negative NDVI anomaly was noticed in all the months (December to March). But during 2005, even after the monsoon seasonal rainfall deficit, the NDVI showed higher values in all the months. No clear cut relationship between monthly and monsoon season rainfall and NDVI during wheat season has been noticed for Haryana. During the year 2005, a surplus rainfall of 102 per cent during September delayed the sowing of wheat and thereby negative NDVI anomaly was noticed in all the months during wheat season. But during the year 2004, even after deficit rainfall of 70.4 % and 84.9 % during July and September, respectively, due to good rainfall spells during October, January to March provides sufficient soil moisture led to positive NDVI anomaly for all the months. The same has been noticed for Punjab during 2004. In Punjab, during 2000, a high deficit of 56.8 and 52.4 % during August and September, respectively and insufficient rainfall for the rest of the period affected the vegetation conditions and negative NDVI anomalies were noticed in all the months during wheat season. For Uttar Pradesh, ever after a good spell of monsoon, negative

NDVI anomalies were noticed in all the months during the year 2000. But during 2005 deficit rainfall (35.7 %) during August and absence of any significant rainfall during October to March reduced the vegetation growth and negative NDVI anomalies have been noticed in all the wheat season months except December. In the case of West Bengal during the year 2000, even after good spell of monsoon months, negative NDVI anomaly was noticed during wheat season. During the year 2005, all the monsoon months received deficit rainfall and negative NDVI anomalies have been noticed in all months during wheat season.

5.4. Relation between SPI, NDVI and rice-wheat productivity indices

5.4.1. Relation between SPI and NDVI

Relation between monthly SPI during monsoon season and NDVI anomaly of the corresponding month, next month and after two months indicated that NDVI anomaly and SPI shares no correlation (Fig. 5.4). Large variability in crop physiological conditions exists among the IGR States: for example in June Punjab and Haryana have different rice pheno-phases compared to Bihar and Uttar Pradesh. This may be the reason for the absence of any relation between SPI and NDVI over IGR. When we analyzed the NDVI and SPI for each State separately (Fig. 5.5), it was found that there is a positive correlation between NDVI and SPI for Punjab, Haryana and a negative correlation between NDVI and SPI for West Bengal, though these correlations are not statistically significant. But as far as Bihar and Uttar Pradesh are concerned, it is found that there is no relation between NDVI and SPI.

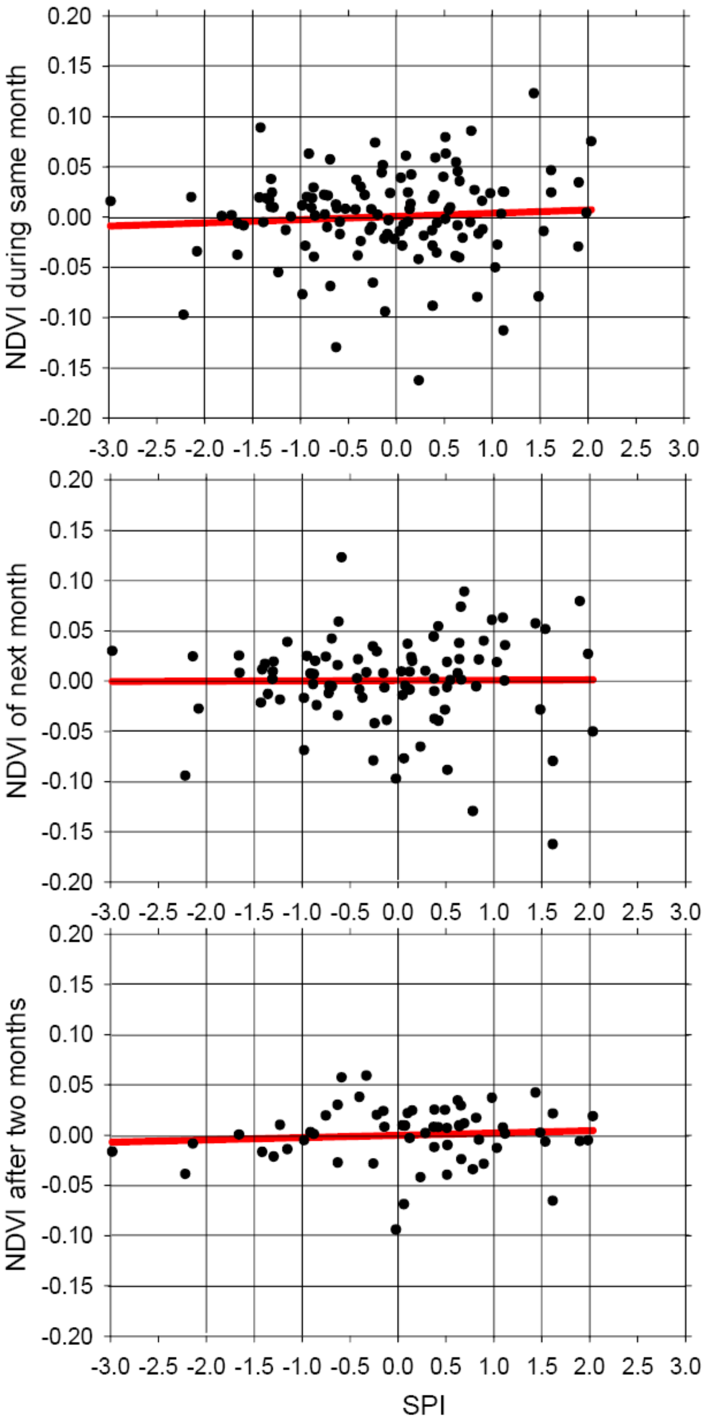

Fig. 5.4: Relation between monthly SPI and NDVI of the same month, next month and after two months

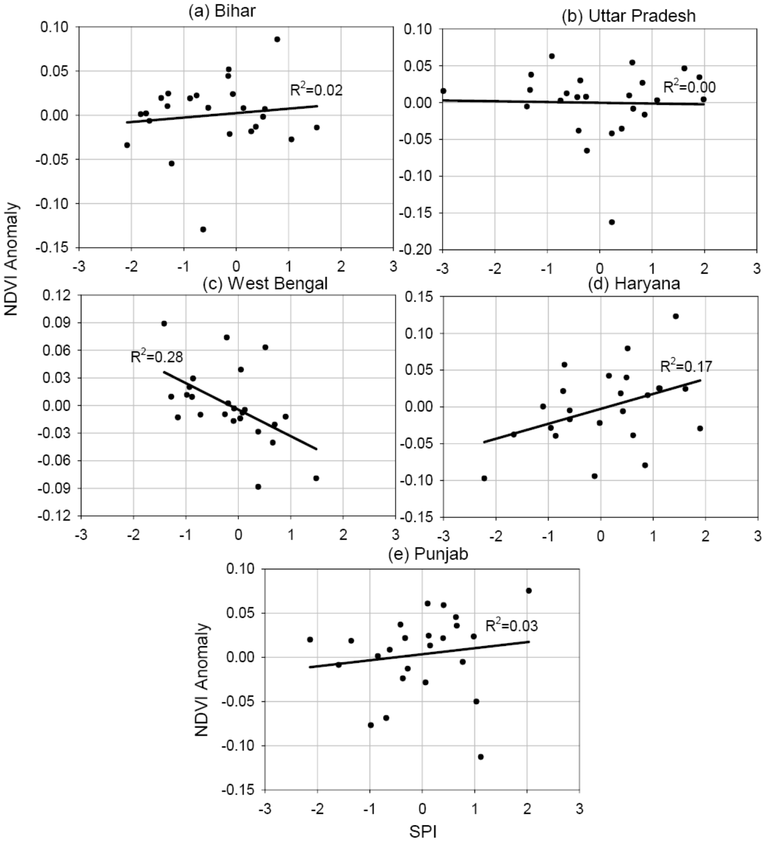

Fig. 5.5: Relation between monthly SPI and NDVI for different IGR States

5.4.2. Relation between NDVI anomaly and Rice and Wheat Indices

The State-wise Kharif Rice Productivity Indices (KRPI) and monthly NDVI anomaly (dif NDVI) for monsoon months during the period 2000-2005 were given in Table 5.3. It is observed that for Bihar, out of six years, two years (2004 & 2005) fall under deficit rice productivity and in these two years at least one of the monsoon months had established negative NDVI anomaly. But even after three continuous negative NDVI anomalies during July to September, positive KRPI was observed in the year 2000. Similarly, for West Bengal, too, no definite pattern has been observed. Three continuous negative NDVI anomalies affected the rice productivity during the years 2000 and 2002.

At least two negative NDVI anomaly months were noticed in all the three deficit rice productivity years (2000, 2002 & 2005). As far as Uttar Pradesh is concerned, out of six years, four years (2000, 2002, 2004 & 2005) fall under the category of deficit rice productivity years and in these years except 2004 at least one negative NDVI anomaly month was noticed. But during 2004, all the months had positive NDVI anomaly. Over Punjab and Haryana, the variation of kharif rice productivity indices never reached ± 10. In the case of Punjab, during deficit rice productivity years, at least two of the months had experienced negative NDVI anomaly.

Months	NDVI anomaly					
	2000	2001	2002	2003	2004	2005
Bihar						
June	0.086	-0.014	0.022	-0.013	-0.002	-0.055
July	-0.130	0.052	0.024	0.044	0.019	-0.019
August	-0.034	-0.007	0.019	0.008	0.007	0.010
September	-0.028	0.008	-0.021	0.024	0.001	0.002
KRPI	14.4	10.5	6.2	13.3	-43.8	-23.0
West Bengal						
June	0.063	-0.021	-0.010	-0.040	-0.008	-0.013
July	-0.088	0.089	-0.079	0.074	-0.005	0.039
August	-0.010	0.011	-0.029	0.029	0.009	-0.014
September	-0.012	-0.017	0.002	0.020	-0.003	0.010
KRPI	-11.30	3.57	-1.66	21.23	10.25	-6.68
Uttar Pradesh						
June	0.046	0.004	0.012	-0.036	0.003	-0.038
July	-0.162	0.027	0.016	0.054	0.063	-0.008
August	-0.065	-0.005	0.030	0.008	0.007	0.038
September	-0.042	0.017	-0.017	0.034	0.003	0.010
KRPI	-3.14	1.52	-13.68	0.47	-19.49	-11.96
Haryana						
June	0.024	-0.030	-0.022	-0.017	0.018	0.016
July	-0.080	0.079	-0.097	0.123	-0.038	0.040
August	0.021	-0.006	-0.094	0.057	0.025	-0.029
September	-0.005	-0.040	-0.039	0.042	0.000	0.025
KRPI	-6.92	-4.13	-2.20	-1.98	4.16	7.33
Punjab						
June	0.075	-0.113	-0.029	0.024	0.013	0.045
July	-0.050	0.036	-0.077	0.061	0.020	0.022
August	0.019	0.001	-0.069	0.037	0.024	0.009
September	-0.013	-0.024	-0.005	0.022	-0.009	0.059
KRPI	-1.93	-1.85	-3.80	0.23	5.92	2.62

Table 5.3: NDVI anomaly during monsoon months and KRPI during the period 2000-2005 for IGR States

At all the IGR States, deficit wheat productivity indices were noticed continuously from the year 2002 to 2005 (Table 5.4). It is clear that the variability of wheat productivity is more in Bihar compared to all other States.

Months	NDVI anomaly					
	2000	2001	2002	2003	2004	2005
Bihar						
December	-0.022	-0.010	0.026	0.020	-0.001	0.004
January	-0.034	-0.014	-0.019	0.002	-0.013	0.063
February	-0.068	-0.015	-0.007	-0.003	-0.031	0.154
March	-0.069	-0.003	0.004	-0.024	-0.028	0.150
WPI	7.71	2.30	-6.63	-15.03	-23.20	-23.85
West Bengal						
December	-0.035	-0.013	0.006	0.011	0.022	-0.016
January	-0.022	-0.003	-0.004	0.058	0.013	-0.034
February	-0.043	0.013	0.019	0.034	0.007	-0.020
March	-0.029	0.048	0.036	-0.002	0.011	-0.033
WPI	10.63	-2.04	-3.83	-6.34	-8.82	-9.15
Uttar Pradesh						
December	-0.021	-0.012	0.000	0.019	-0.009	0.002
January	-0.027	0.010	-0.002	0.029	0.018	-0.028
February	-0.034	0.020	0.015	0.019	0.017	-0.027
March	-0.032	0.002	0.004	-0.008	0.024	-0.020
WPI	4.52	3.96	-3.76	-7.14	-10.40	-7.50
Haryana						
December	-0.062	-0.026	0.013	0.031	0.096	-0.028
January	-0.012	0.002	0.021	0.044	0.066	-0.148
February	-0.001	0.033	0.028	0.060	0.069	-0.197
March	0.005	0.052	0.044	0.050	0.054	-0.195
WPI	4.25	2.21	-0.83	-4.39	-7.82	-10.70
Punjab						
December	-0.030	-0.015	0.027	0.015	0.078	-0.086
January	-0.017	-0.009	0.002	0.001	0.041	-0.039
February	-0.028	-0.005	-0.028	0.011	0.018	0.024
March	-0.031	0.005	-0.027	-0.008	0.035	0.032
WPI	6.88	4.44	-4.75	-6.01	-7.21	-9.53

Table 5.4: NDVI anomaly during wheat season months and WPI during the period 2000-2005 for IGR States

To quantify the relation between NDVI and rice productivity, regression analysis of different combinations of monthly NDVI anomalies during the rice season and KRPI was performed. The same analysis was also done for wheat productivity indices (WPI) and monthly NDVI anomalies during December to March. The regression coefficients are given in Table 5.5. & Table 5.6.

Different combinations	Regression Equation	SEE	R-value
June	KRPI=-1.810+(103.775x dif NDVI $_{\text{June}}$)	12.13	0.31
July	KRPI=-1.890+(22.077x dif NDVI $_{\text{July}}$)	12.68	0.10
August	KRPI=-1.879+(26.457x dif NDVI $_{\text{Aug}}$)	12.71	0.07
September	KRPI=-1.863+(46.740x dif NDVI $_{\text{Sept}}$)	12.68	0.10
June-July	KRPI=-1.858+(120.307x dif NDVI$_{\text{June}}$)+ 43.305xdif NDVI $_{\text{July)}}$	12.13	0.36
June-August	KRPI=-1.833+(147.214x dif NDVI$_{\text{June}}$)+77.888xdif NDVI $_{\text{July)-}}$ (83.657x dif NDVI $_{\text{Aug}}$)	12.19	0.39
June-September	KRPI=-1.835+(148.029x dif NDVI$_{\text{June}}$)+78.742xdif NDVI $_{\text{July)-}}$ (83.173x dif NDVI $_{\text{Aug}}$)-(6.032xdif NDVI $_{\text{Sept}}$)	12.43	0.39
July-September	KRPI=-1.881+(16.634x dif NDVI$_{\text{July}}$)- 5.084xdif NDVI $_{\text{Aug)}}$-(35.351xdif NDVI $_{\text{Sept}}$)	13.13	0.12
August-September	KRPI=-1.869+(9.425x dif NDVI$_{\text{Aug}}$)+ 43.793xdif NDVI $_{\text{Sept)}}$	12.91	0.10

Table 5.5: Regression analysis of KRPI and monthly dif NDVI during monsoon season

It is clear that even though none of the combinations is statistically significant, June dif NDVI contributes more to rice productivity followed by July (Fig.5.6). However, the combined effect of June, July and August, explains 15 % variation of KPRI. Since the KPRI variation for all the States during the study period is < 15 %, except 2004 and 2005 for Bihar, this equation can be used as an indicator of regional rice production.

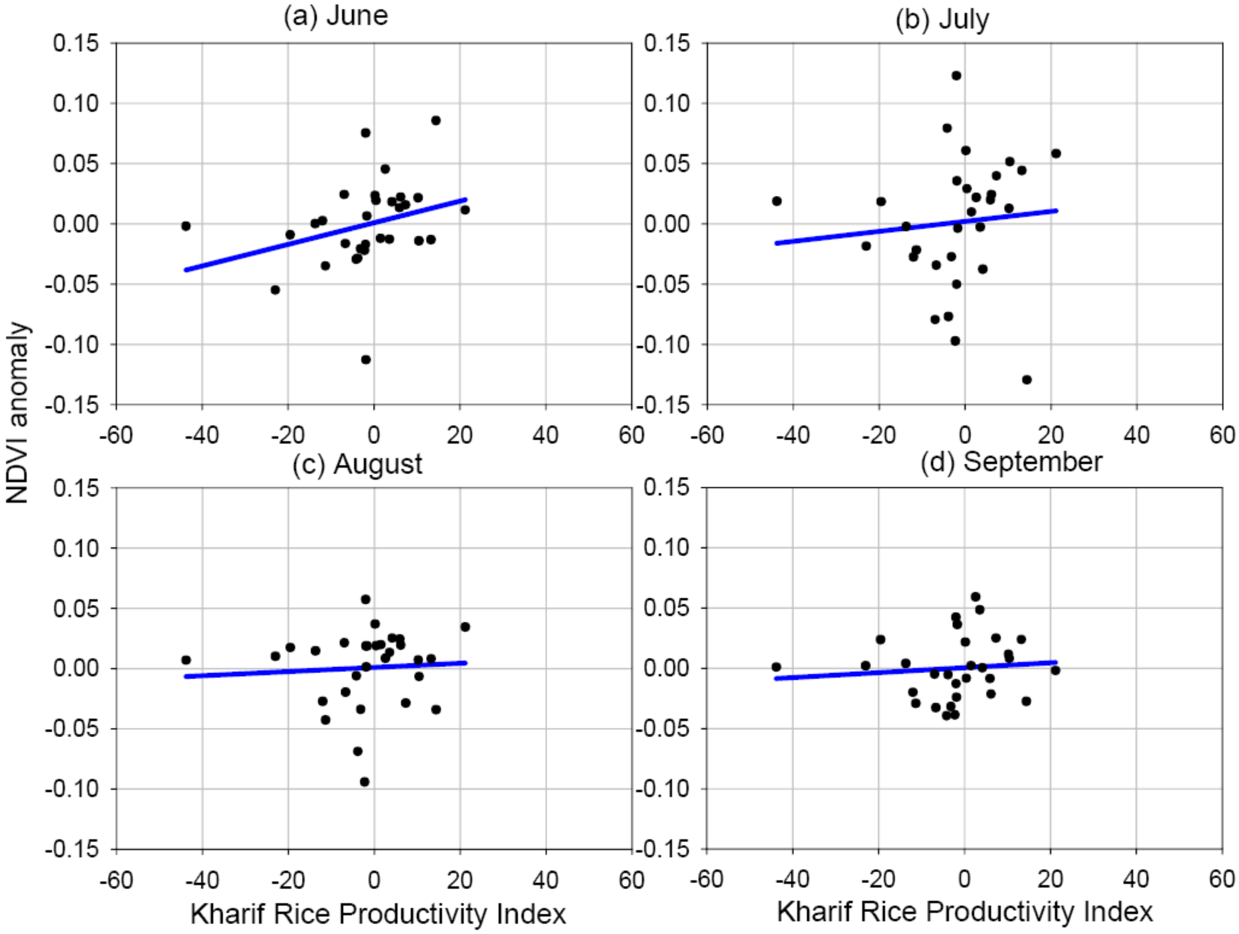

Fig.5.6: Relation between Kharif Rice Productivity Index and monthly NDVI anomaly during June to September.

As far as wheat is concerned, statistically significant relation was found between WPI and dif NDVI during December-March. This explains 35 % variability in WPI and more over all the IGR States during the period 2000-2005 experienced WPI within ± 35 % range. Thus, this equation can be used for predicting/forecasting the wheat productivity over IGR. Among the months, December contributed more control on WPI compared all other individual months (Fig. 5.7).

Different combinations	Regression Equation	SEE	R-value
December	WPI=-4.436-(73.179x dif NDVI $_{Dec}$)	7.91	0.32
January	WPI=-4.465-(34.492x dif NDVI $_{Jan}$)	8.22	0.17
February	WPI=-4.36-(37.598x dif NDVI $_{Feb}$)	8.07	0.25
March	WPI=-4.358-(27.912x dif NDVI $_{Mar}$)	8.19	0.19
December-January	WPI=-4.428-(76.661x dif NDVI$_{Dec}$)+ 5.278xdif NDVI $_{Jan)}$	8.06	0.32
December-February	WPI=-3.875-(147.165x dif NDVI$_{Dec}$)+231.284xdif NDVI $_{Jan)-}$ (154.917x dif NDVI $_{Feb}$)	7.37	0.53*
December-March	WPI=-3.835-(149.366x dif NDVI$_{Dec}$)+275.626xdif NDVI $_{Jan)-}$ (325.503x dif NDVI $_{Feb}$)+(148.398xdif NDVI $_{Mar}$)	7.15	0.59*
January-March	WPI=-4.192+(92.733x dif NDVI$_{Jan}$)- 233.456xdif NDVI $_{Feb)}$+(141.985xdif NDVI $_{Mar}$)	8.02	0.38
February-March	WPI=-4.409-(137.752x dif NDVI$_{Feb}$)+ 104.183xdif NDVI $_{Mar)}$	8.05	0.32

(significant at 0.01 level)*

Table 5.6: Regression analysis of WPI and monthly dif NDVI during wheat season

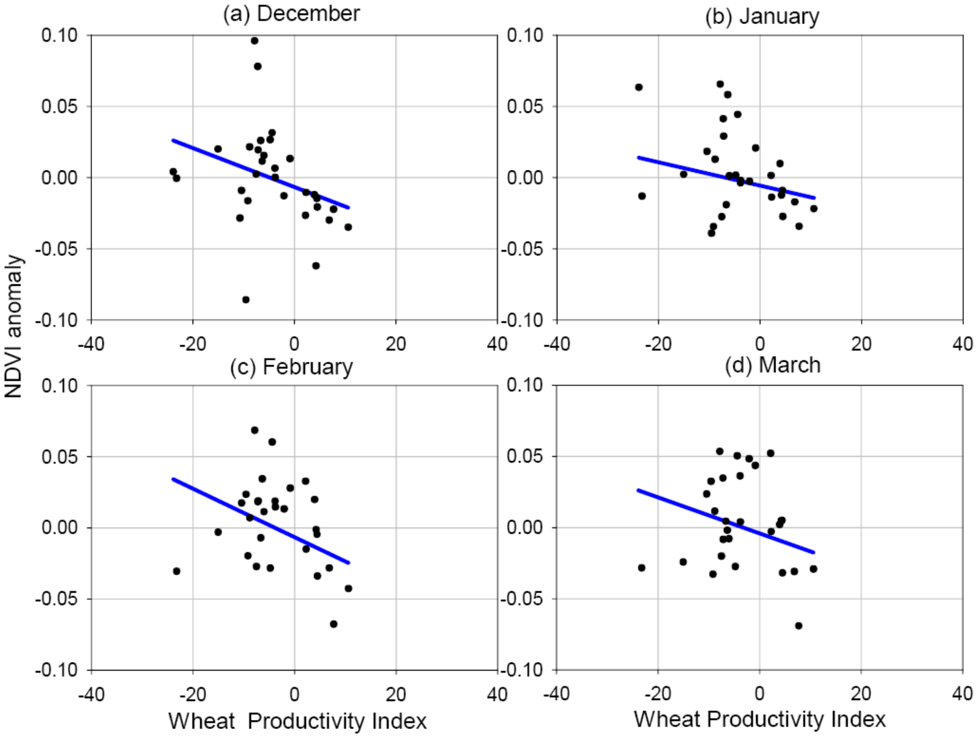

Fig.5.7: Relation between Wheat Productivity Index and monthly NDVI anomaly during December to March.

5.5. Comparison of SPI, dif NDVI and KRPI and WPI – A case study during all-India drought year 2002

5.5.1. The salient features of 2002 monsoon over IGR

The 2002 monsoon set in on time in most parts of the country except Punjab, Haryana and Western Uttar Pradesh of IGR. The monthly rainfall received during 2002 June to 2003 March over IGR States are given in Table 5.7.

Months	West Bengal			Bihar			Uttar Pradesh			Punjab			Haryana		
	RF	ME	%D	RF	ME	%D	RF	ME	%D	RF	ME	%D	RF	ME	%D
June	344.2	373.7	-7.9	125.9	189.4	-33.5	58.3	100.2	-41.9	43.4	51.3	-15.4	44.5	54.2	-17.9
July	604.0	473.5	27.6	237.3	331.1	-28.3	70.8	277.9	-74.5	105.5	186.4	-43.4	30.2	164.2	-81.6
Aug	429.2	403.4	6.4	223.5	314.8	-29.0	238.8	274.7	-13.1	110.0	171.3	-35.8	135.8	159.1	-14.6
Sept	310.4	332.7	-6.7	208.4	224.9	-7.3	246.5	177.7	38.7	148.1	98.8	49.9	120.5	91.2	32.1
Oct	70.0	135.9	-48.5	38.6	76.9	-49.8	17.0	36.5	-53.4	1.7	16.3	-89.6	4.5	13.6	-66.9
Nov	29.2	18.3	59.6	1.0	11.7	-91.5	1.7	4.7	-63.8	0.0	4.8	-100	0	3.8	-100
Dec	1.5	5.8	-74.1	0.5	5.9	-91.5	7.0	7.8	-10.3	8.6	14.2	-39.4	7.3	8.1	-9.9
Jan	4.6	12.2	-62.3	7.2	17.0	-57.6	19.9	18.0	10.6	21.1	27.6	-23.6	25.6	19.2	33.3
Feb	43.2	20.1	114.9	47.0	21.8	115.6	44.5	17.9	148.6	98.5	29.8	230.5	32	18.8	70.2
Mar	53.5	29.9	78.9	30.7	16.0	91.8	4.2	10.6	-60.4	17.0	24.1	-29.5	6.8	13.5	-49.6

(RF-Monthly rainfall (mm); ME-Normal rainfall (mm); %D-per cent deviation from normal)

Table 5.7: Monthly rainfall and per cent deviation from normal during All India drought year 2002-03 (from June 2002 to March 2003) over IGR States

All the IGR States received less rainfall compared to the normal during June: Uttar Pradesh received -41.9 % deviation from the normal followed by Bihar (-33.5 %). In July, all the IGR States except West Bengal received lower rainfall compared to normal. Haryana received a rainfall of 30.2 mm only, which is -81.6 % deviation from the normal followed by Uttar Pradesh - 74.5 % deviation from the normal rainfall. It is for the first time probably in the last 100 years that the month of July received such a low rainfall (Samra and Singh, 2002). Even in the month of August, the situation is not different. Punjab received a deficit rainfall of -35.8 per cent followed by Bihar (-29 per cent). The continuous three months of deficit rainfall caused heavy damage to the transplanted rice crop and withering happened in almost all the States, except West Bengal and Bihar.

5.5.2. Comparison of SPI, MRI, dif NDVI and KRPI – a case study during all-India drought year 2002.

The monthly spatial NDVI during June to November during all-India drought year 2002 over IGR is given Fig. 5.8. It indicated that very low NDVI values were observed over Haryana, southern parts of Uttar Pradesh during July, August and September. But normal values were observed during June-July over most parts of Punjab and a very high value of NDVI has been noticed in eastern and northern parts of Punjab. The spatial map also indicated that Bihar and West Bengal under normal or high NDVI during June-July and most parts of West Bengal exhibited very high NDVI during August and September. Except over Bihar and West Bengal, mean NDVI values during 2002 rice season were higher than the normal (Fig. 5.9). The SPI, MRI, dif. NDVI during all-India drought 2002 over IGR States and corresponding KRPI was given in Table 5.8.

This year, except Bihar, all the IGR States fell under the category of deficit rice productivity status. It is noticed that SPI and MRI followed the same pattern for all the States during June to September. For Punjab and Haryana during all the months, negative NDVI anomaly was observed. Even after continuous three months (June-August) deficit rainfall did not affect the NDVI for the same months, but affected the NDVI of September month and thereby a deficit of KRPI.

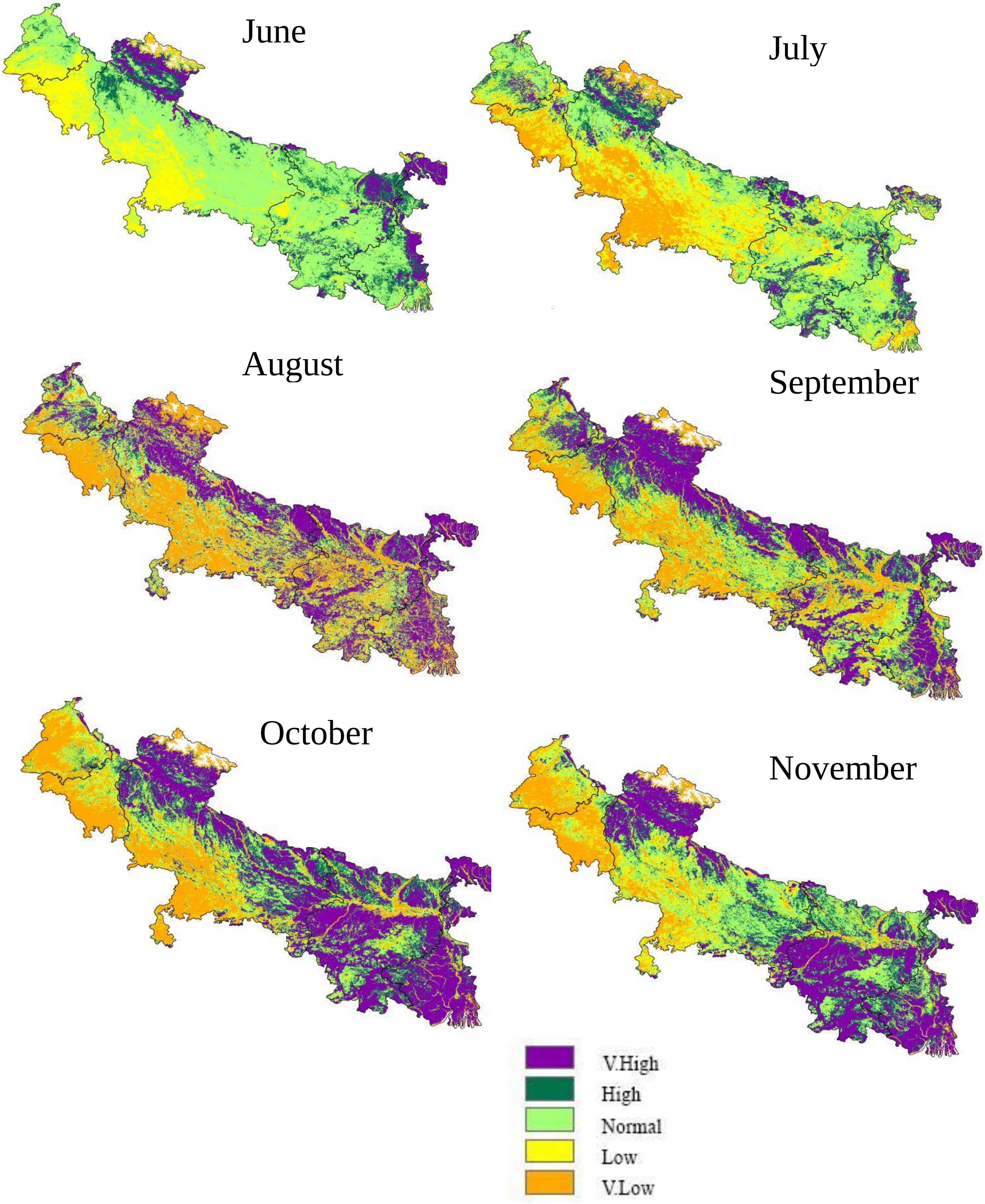

Fig.5.8: Monthly composite NDVI during rice season (June to November) during All India drought year 2002 over IGR

Months	SPI	MRI	dif NDVI	Rice Productivity Index
West Bengal				
June	-0.26	-7.89	-0.010	-1.66
July	1.49	27.56	-0.079	
August	0.38	6.38	-0.029	
September	-0.19	-6.72	0.002	
Bihar				
June	-0.75	-33.55	0.022	6.20
July	-1.30	-28.34	0.024	
August	-1.43	-29.02	0.019	
September	-0.13	-7.34	-0.021	
Uttar Pradesh				
June	-0.63	-41.8	0.012	-13.68
July	-2.98	-74.5	0.016	
August	-0.37	-13.1	0.030	
September	0.86	38.7	-0.017	
Punjab				
June	0.06	-15.40	-0.029	-3.80
July	-0.98	-43.40	-0.077	
August	-0.69	-35.79	-0.069	
September	0.77	49.90	-0.005	
Haryana				
June	-0.02	-17.9	-0.022	-2.20
July	-2.22	-81.6	-0.097	
August	-0.12	-14.6	-0.094	
September	0.62	32.1	-0.039	

Table: 5.8. Comparison of SPI, MRI, dif NDVI during all-India drought 2002 and Rice Productivity Indices over IGR States

Among the States, Uttar Pradesh noticed about -13.7 % deficit in KRPI followed by -3.8 % deficit in Punjab. Even after deficit rainfall for all the monsoon months, KRPI of Bihar falls in the positive side and as far as Bihar is concerned heavy rainfall and floods are the more usual hazard compared to drought during monsoon season. The maximum NDVI was below normal for Punjab, Haryana and Uttar Pradesh and above normal for Bihar and West Bengal during rice season.

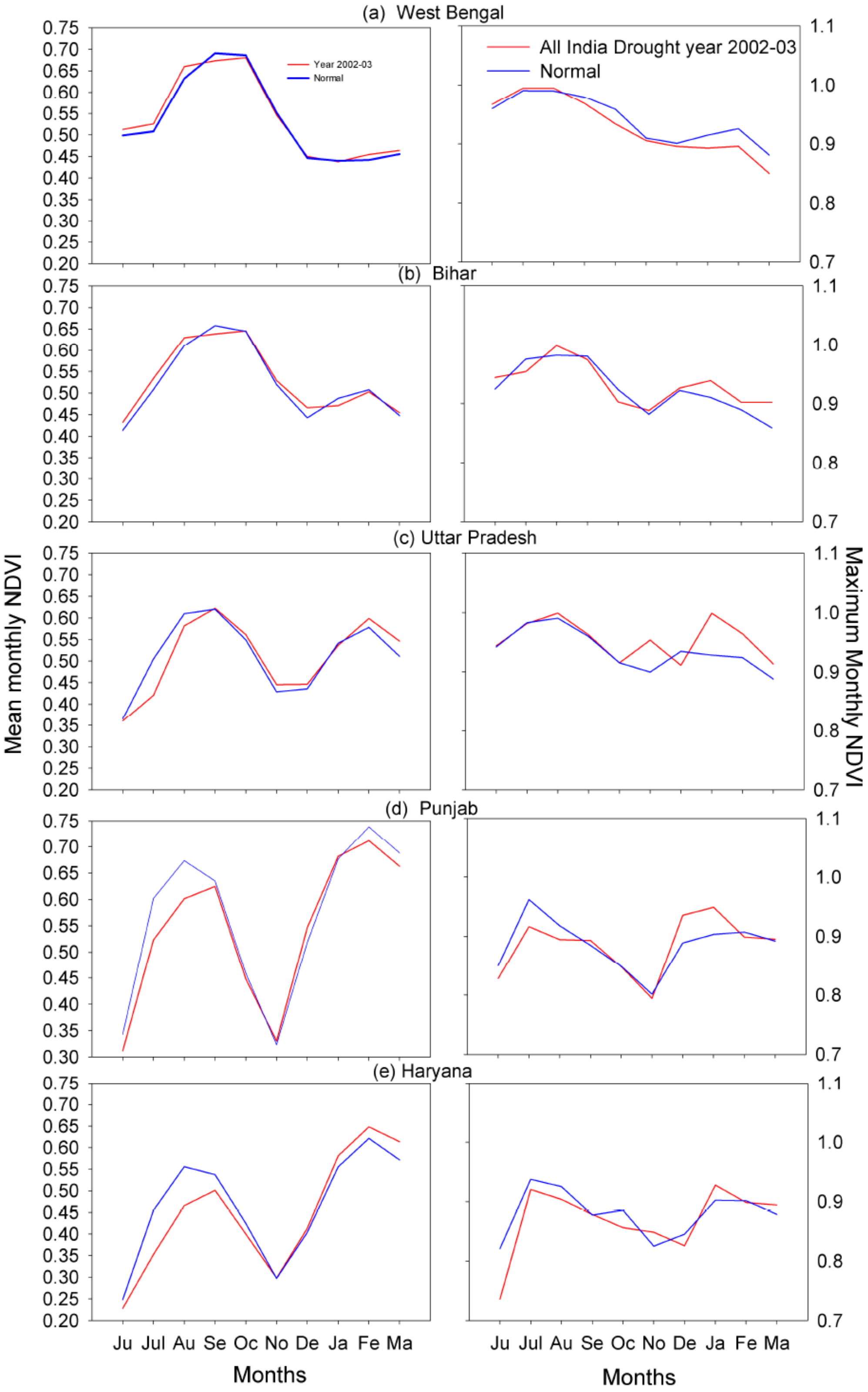

Fig. 5.9: Comparison of monthly NDVI during June to March for all-India drought year 2002 (*red line*) and its normal (*blue line*)

5.5.3. Comparison of dif. NDVI and WPI – a case study during all-India drought year 2002.

Very low NDVI values were noticed over eastern part of West Bengal and western part of Bihar during February-march in the year 2003 and very high values were observed over most parts of Punjab and Haryana during the same period. The rest of the IGR showed normal NDVI (Fig. 5.10). The NDVI spatial map provides the extent and variability of drought severity within the IGR States.

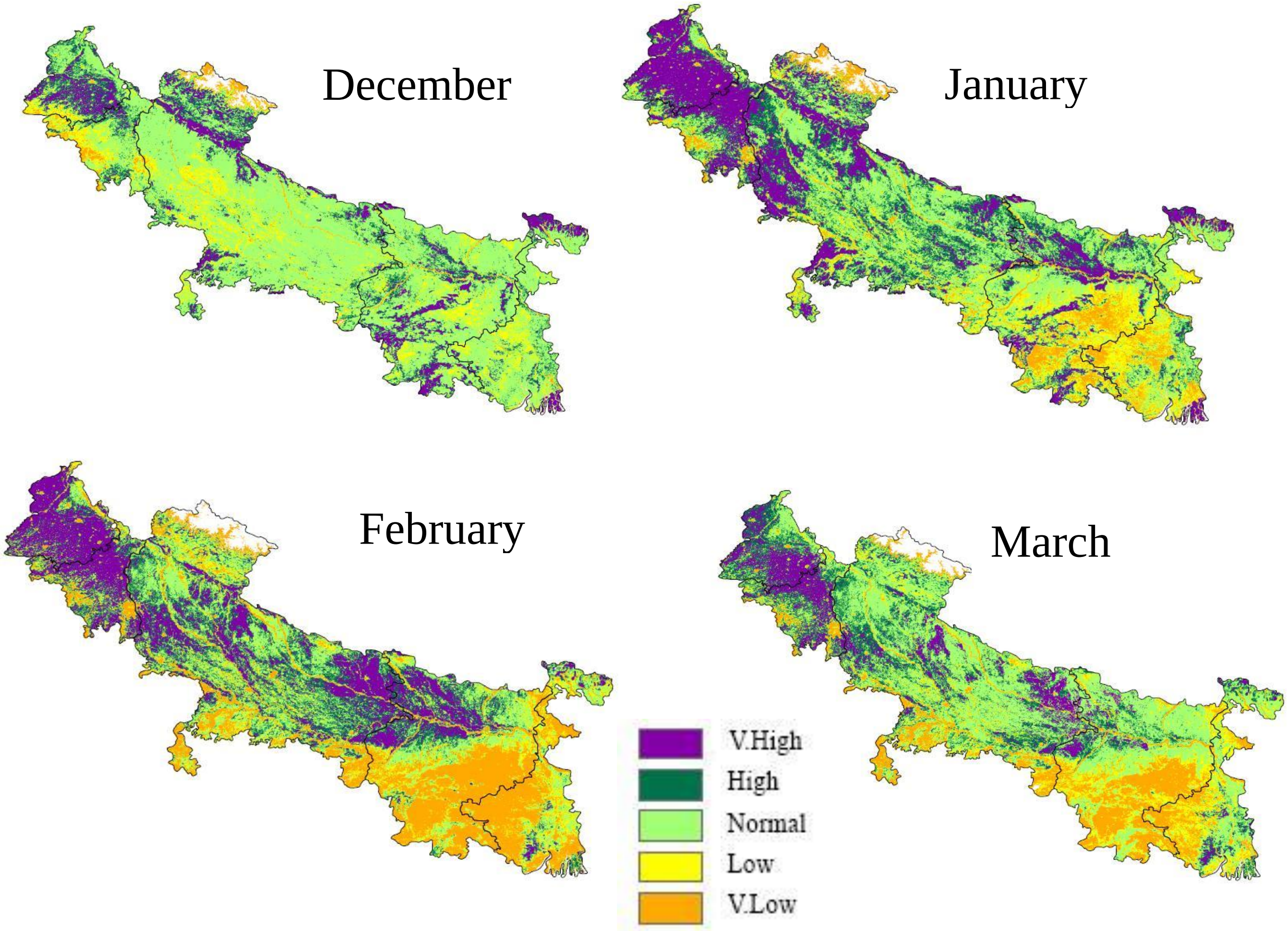

Fig. 5.10: Monthly composites NDVI during wheat season (December to March) during All India drought year 2002-03 over IGR

All the States recorded deficit wheat productivity during the drought year, but these values were below -10. Moreover, all the States except Haryana, at least one negative NDVI anomaly was observed during December to March (Table 5.9). Therefore, it can be concluded that except Uttar Pradesh during rice season, no other State in Indo-Gangetic region was affected with drought with respect to rice and wheat is concerned.

Months	dif NDVI	Wheat Productivity Index
West Bengal		
December	0.006	-3.83
January	-0.004	
February	0.019	
March	0.036	
Bihar		
December	0.026	-6.63
January	-0.019	
February	-0.007	
March	0.004	
Uttar Pradesh		
December	0.000	-3.76
January	-0.002	
February	0.015	
March	0.004	
Punjab		
December	0.027	-4.75
January	0.002	
February	-0.028	
March	-0.027	
Haryana		
December	0.013	-0.83
January	0.021	
February	0.028	
March	0.044	

Table: 5.9. Comparison of dif NDVI during all-India drought 2002 over IGR States and Wheat Productivity Indices

CHAPTER 6

Rainfall and Temperature Variability and Trends over IGR

6.1 Introduction

Local and regional changes - tectonic, climatic, hydrologic, demographic, agricultural, socio-economic - combined with global changes have caused concern regarding sustainability of natural and agricultural ecosystems of many regions in the world in general and Indo-Gangetic Region in particular. Though the entire area is situated in the sub-tropical belt underneath the large scale persistent subsidence motion, it experiences good rainfall activities due to occurrence of the summer monsoon circulation, which is attributed to the unique geographical setting of South Asia. The land-sea-mountain-air configuration provides opportunities for large scale rapid exchanges of mass, momentum, moisture and energy between the hemispheres (northern and southern), the regions (tropics and extra-tropics) and the levels (surface and upper air) through summer monsoon circulation and dynamics of its components. Large inter-annual variability is the intrinsic characteristic of the summer monsoon circulation. Summer monsoon rainfall is of the greatest concern in agriculture and in the utilization of natural resources in the area. Changes affecting ecosystems of the IGR are well documented for different parameters except climate. Most of the climate studies have confined to only seasonal and annual or confined to individual monsoon months for India as a whole or for different homogenous regions. But on a monthly basis studies have been few. In-depth monthly analysis can provide comprehensive assessment of rainfall and temperature trends, which would be highly relevant and useful from agricultural and water management point of view. This study investigates the trends of rainfall in the data series of monthly, seasonal and annual rainfall for IGR States separately as well as for the IGR as a whole using Mann-Kendall (M-K) non-parametric test. The slopes of the trend lines were determined using the method of least square linear fitting. The trends of maximum and minimum temperature of the 3 homogeneous temperature regions fall in IGR were also examined using the same methodology.

6.2. Variation of Rainfall during different normal periods

6.2.1. Variation during 1906-2005

The long-term (1906-2005) mean annual rainfall of IGR is 1099.1 mm (Table 6.1) with a standard deviation of 115.7 mm and coefficient of variation (CV) of 10.5 per cent. The seasonal rainfall distribution indicates that 81 % (890.1 mm) of the rainfall occurs during southwest monsoon (June - September) followed by 8.7 % (95.7 mm) during summer season (March - May). July is the rainiest month (286.6 mm) and obtains about 26.1 % of the annual rainfall followed by August (264.7 mm, 24.1 %). West Bengal receives the highest annual rainfall of 2038.5 mm followed by Bihar (1060.2 mm); Haryana receives the lowest annual rainfall of 570.8 mm. Similarly, all the IGR States receive highest rainfall during July followed by August. Even though the annual CV (10.5 per cent) as well as the monsoon seasonal CV (11.5 per cent) of rainfall is low, the monthly CV within the monsoon season is higher clearly indicating that there will be large year to year variation in monthly distribution of rainfall during the southwest monsoon. It is clear that there is no definite pattern of normal seasonal rainfall for IGR for different normal periods, but shows fluctuating rainfall pattern.

Months/ Seasons	Rainfall (mm)					
	West Bengal	Bihar	Uttar Pradesh	Punjab	Haryana	IGR
J	12.2(0.6)	17.0(1.3)	18.0(1.9)	27.6(4.2)	19.2(3.4)	18.8(1.7)
F	20.1(1.0)	21.8(1.7)	17.9(1.9)	29.8(4.5)	18.8(3.3)	21.7(2.0)
M	29.9(1.5)	16.3(1.3)	10.6(1.1)	24.1(3.7)	13.5(2.4)	18.8(1.7)
A	65.7(3.2)	19.1(1.5)	7.2(0.8)	14.6(2.2)	8.8(1.5)	23.1(2.1)
M	167.2(8.2)	52.9(4.1)	16.0(1.7)	16.2(2.5)	16.4(2.9)	53.7(4.9)
J	373.7(18.3)	189.4(14.8)	100.2(10.6)	51.3(7.8)	54.2(9.5)	153.7(14.)
J	473.5(23.2)	331.1(25.8)	277.9(29.3)	186.4(28.4)	164.2(28.8)	286.6(26.1)
A	403.4(19.8)	314.8(24.6)	274.7(28.9)	171.3(26.1)	159.1(27.9)	264.7(24.1)
S	332.7(16.3)	224.9(17.5)	177.7(18.7)	98.8(15.1)	91.2(16.0)	185.1(16.8)
O	135.9(6.7)	76.9(6.0)	36.5(3.9)	16.3(2.5)	13.6(2.4)	55.8(5.1)
N	18.3(0.9)	11.7(0.9)	4.7(0.5)	4.8(0.7)	3.8(0.7)	8.7(0.8)
D	5.8(0.3)	5.9(0.5)	7.8(0.8)	14.2(2.2)	8.1(1.4)	8.3(0.8)
JF	32.3(1.6)	38.9(3.0)	36.0(3.8)	57.4(8.8)	37.9(6.6)	40.5(3.7)
MAM	262.6(12.9)	88.1(6.9)	33.8(3.6)	54.9(8.4)	38.7(6.8)	95.7(8.7)
JJAS	**1583.3(77.7)**	**1060.2(82.7)**	**830.5(87.5)**	**507.7(77.5)**	**468.7(82.1)**	**890.1(81.0)**
OND	160.0(7.9)	94.5(7.4)	49.0(5.2)	35.3(5.4)	25.5(4.5)	72.9(6.6)
Annual	2038.5	1281.7	949.2	665.4	570.8	1099.1

(Figures in parenthesis indicate the % contribution to annual rainfall)

Table 6.1: Variation of mean monthly and seasonal rainfall over different IGR States and its mean during 1906-2005

6.2.2. Variation during different normal periods 1906-35, 1936-65 and 1966-05

The mean monsoon rainfall for the IGR for the 1st (NP1:1906-1935) and 2nd (NP2:1936-1965) periods were higher, while for the 3rd (NP3:1966-2005) period it was lower compared to long term period average. But same pattern is not followed in the case of individual States (Fig. 6.1). The results show that three States viz., West Bengal, Punjab and Haryana received higher rainfall while Bihar and Uttar Pradesh got lower rainfall during the 3rd period compared to 100 year long term normal.

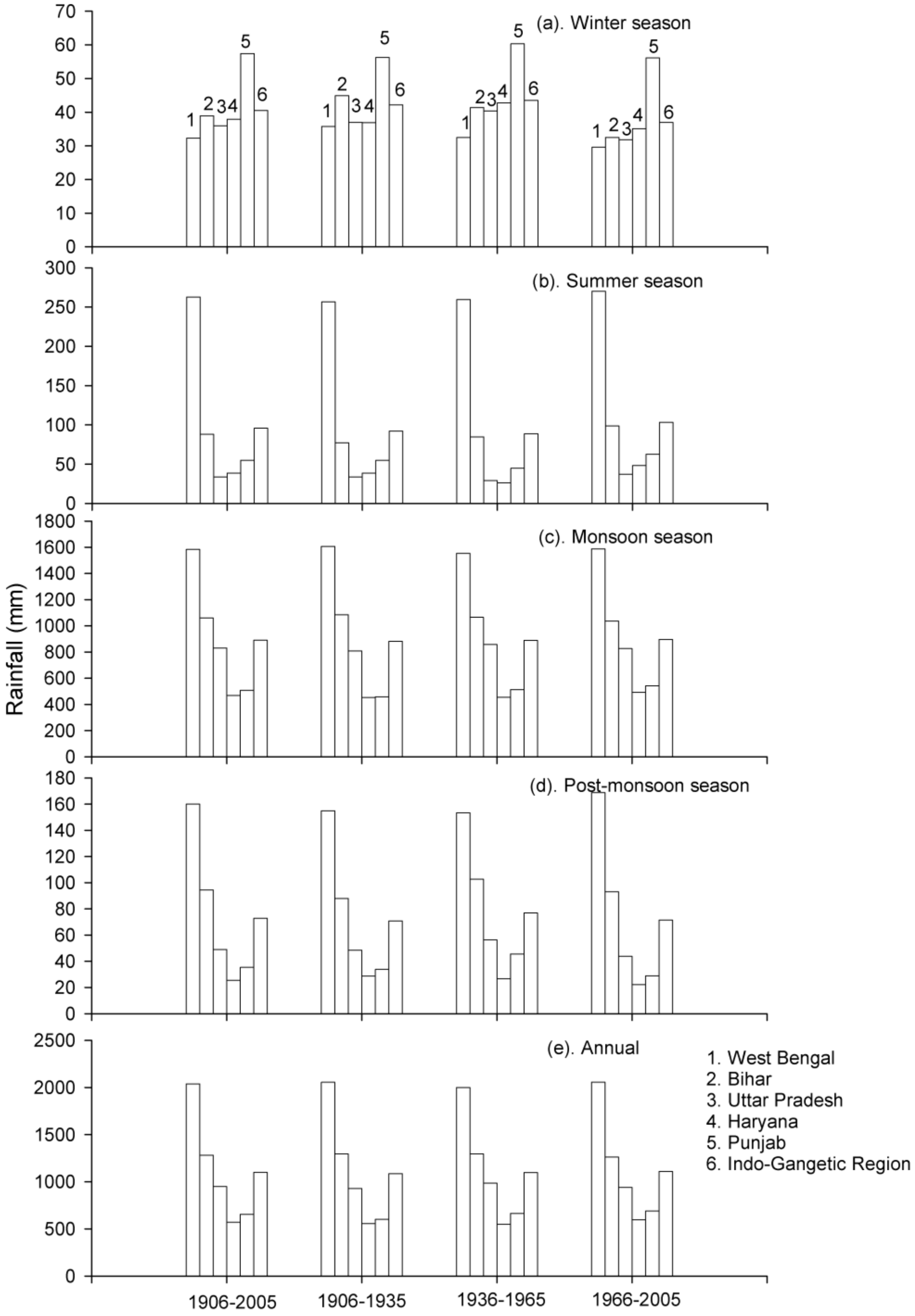

Fig. 6.1 : Mean seasonal rainfall during 1906-2005, 1906-1935, 1936-1965 and 1966-2005 for different states of Indo-Gangetic Region of India

But the monthly distribution during monsoon indicates that June and July received higher rainfall while August and September got lower rainfall compared to long term average during the recent normal period for IGR (Fig. 6.2).

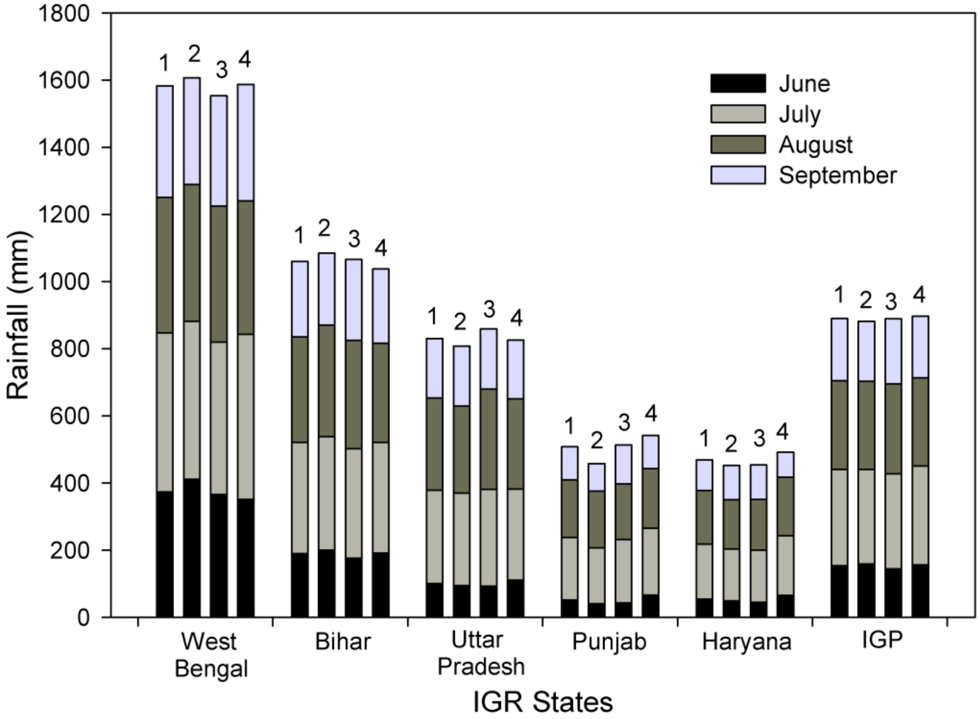

Fig.6.2: Variation of mean monthly rainfall of IGR States and its mean during June to September during different normal periods *(1=1906-2005; 2=1906-35; 3=1936-65;4=1966-2005)*

6.3. Long term trends in monsoon rainfall

6.3.1. Seasonal trends

The results show that there is an upward trend of rainfall during the summer, monsoon and post-monsoon season, while there is a downward trend during the winter season for IGR. These trends are however, statistically not significant. During the last normal period 1966-2005 all the seasons, except post-monsoon season, show an increasing trend of rainfall that are not statistically significant (Fig. 6.3).

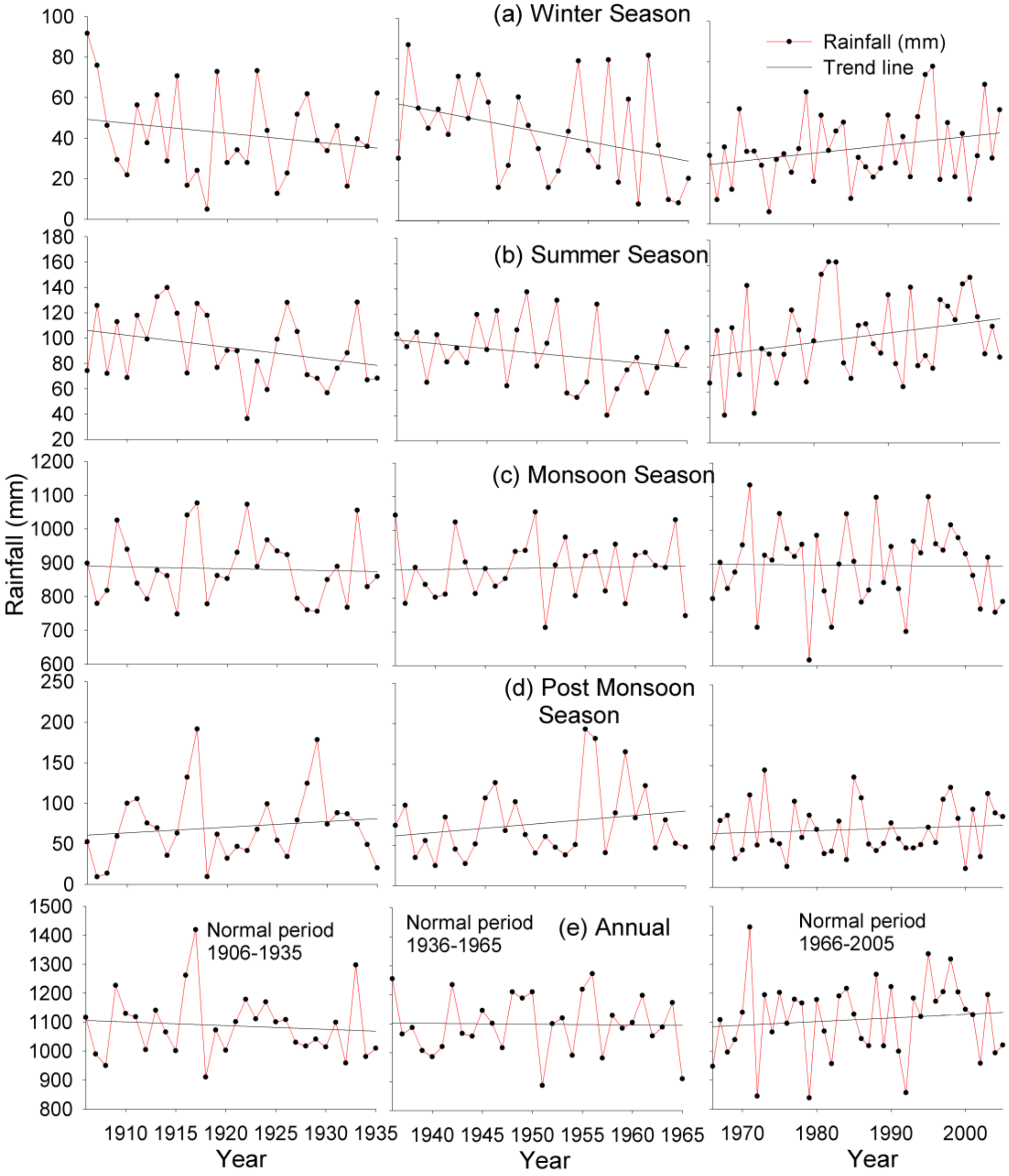

Fig. 6.3: Variability of seasonal and annual rainfall and its trends over Indo-Gangetic Region of India during different normal periods

A significant increasing trend of monsoonal rainfall of 0.7 mm rainfall/year for Haryana and 1.1 mm rainfall/year for Punjab has been noticed during the study period.

But West Bengal, Punjab, and Bihar show an increasing trend while Uttar Pradesh and Haryana show a decreasing trend of rainfall during the recent normal period 1966-2005.

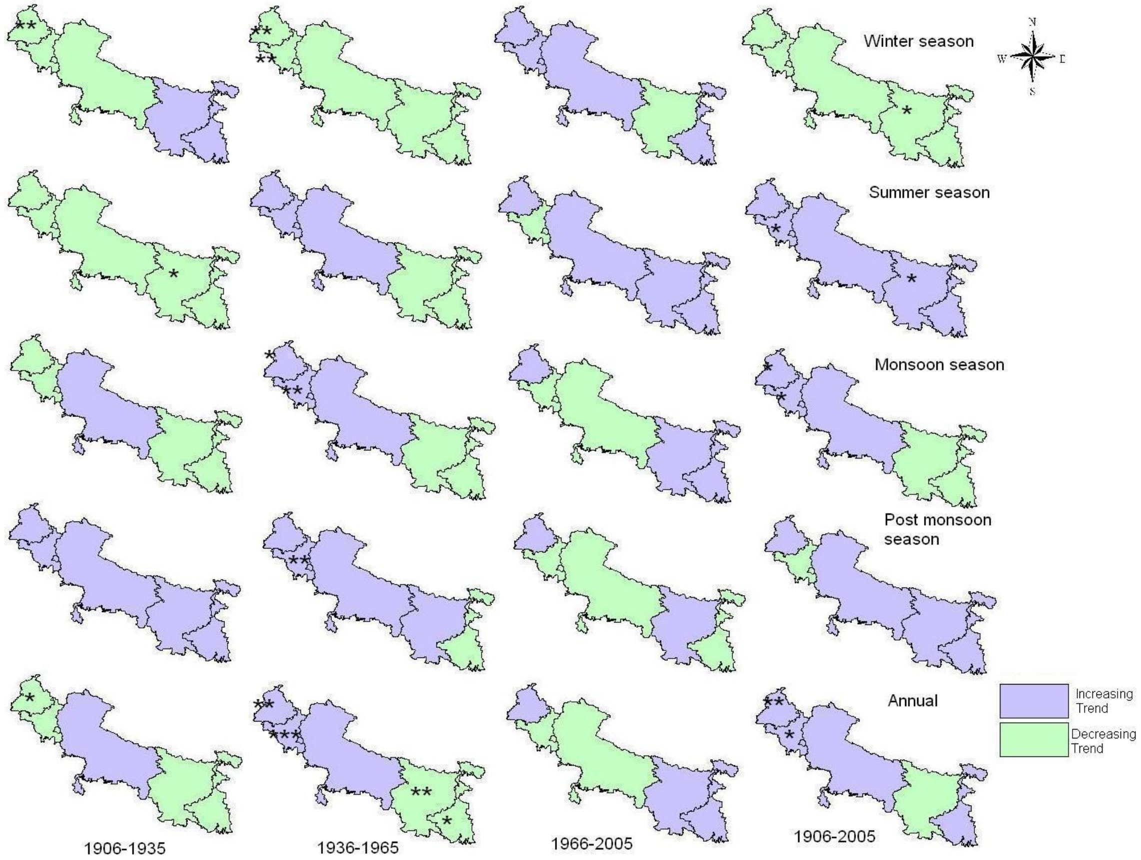

Fig.6.4: M-K test results of different States during different season and annual for different normal periods and during 1906-2005 *(* - significant at 0.10 level, **-significant at 0.05 level and ***-significant at 0.01 level*)

During summer season, all the States recorded an upward trend of rainfall during the period 1906-2005 (Fig.6.4): Bihar and Haryana show an increasing trend of 0.2 mm/year each during the same period. However, except Haryana, all other States show a non-significant increasing trend during the recent normal period 1966-2005. During the post-monsoon season, West Bengal, Uttar Pradesh and Bihar show an increasing trend and Haryana and Punjab show a decreasing trend of rainfall. During winter, all the States show a decreasing trend of rainfall: in Bihar, a significant decreasing trend of rainfall of 0.1 mm/year has been noticed during the same period. The IGR shows an increasing trend of annual rainfall during the period 1906-2005. The same was followed in all the normal periods except 1906-1935. All the States show an increasing trend of rainfall except Bihar during the entire period of consideration. Haryana and Punjab, show a significant increasing trend of rainfall of 0.8 mm/year and 1.1 mm/year, respectively during the period. In the recent normal period 1966-2005, West Bengal, Bihar and Punjab show a non-significant increasing trend of rainfall and Uttar Pradesh and Haryana show a non-significant decreasing trend. However, there is a decreasing trend of rainfall during the 1st period and an increasing trend of rainfall during the 2nd and 3rd periods: but all these trends are insignificant.

6.3.2. Monthly trends

__Indo-Gangetic Region__: The results show that in all the months, except January and August, there is an increasing trend of rainfall during 1906-2005. A significant (0.01 level) increasing trend of rainfall at the rate of 0.1 mm year has been noticed during May. This may be attributed to the increasing extreme events during summer season, particularly pre-monsoon showers during April/May. But as far as different periods are concerned, the recent period NP3 showed an increasing trend of rainfall from January-July, September and December months. But during the period NP2, January-February and April-June months show a decreasing trend of rainfall and a significant decrease of 1.0 mm/year and 2.2 mm/year, respectively have been noticed during February and June. However, during NP1, all months, except January, July and September-December months show a decreasing trend of rainfall, but all are statistically insignificant.

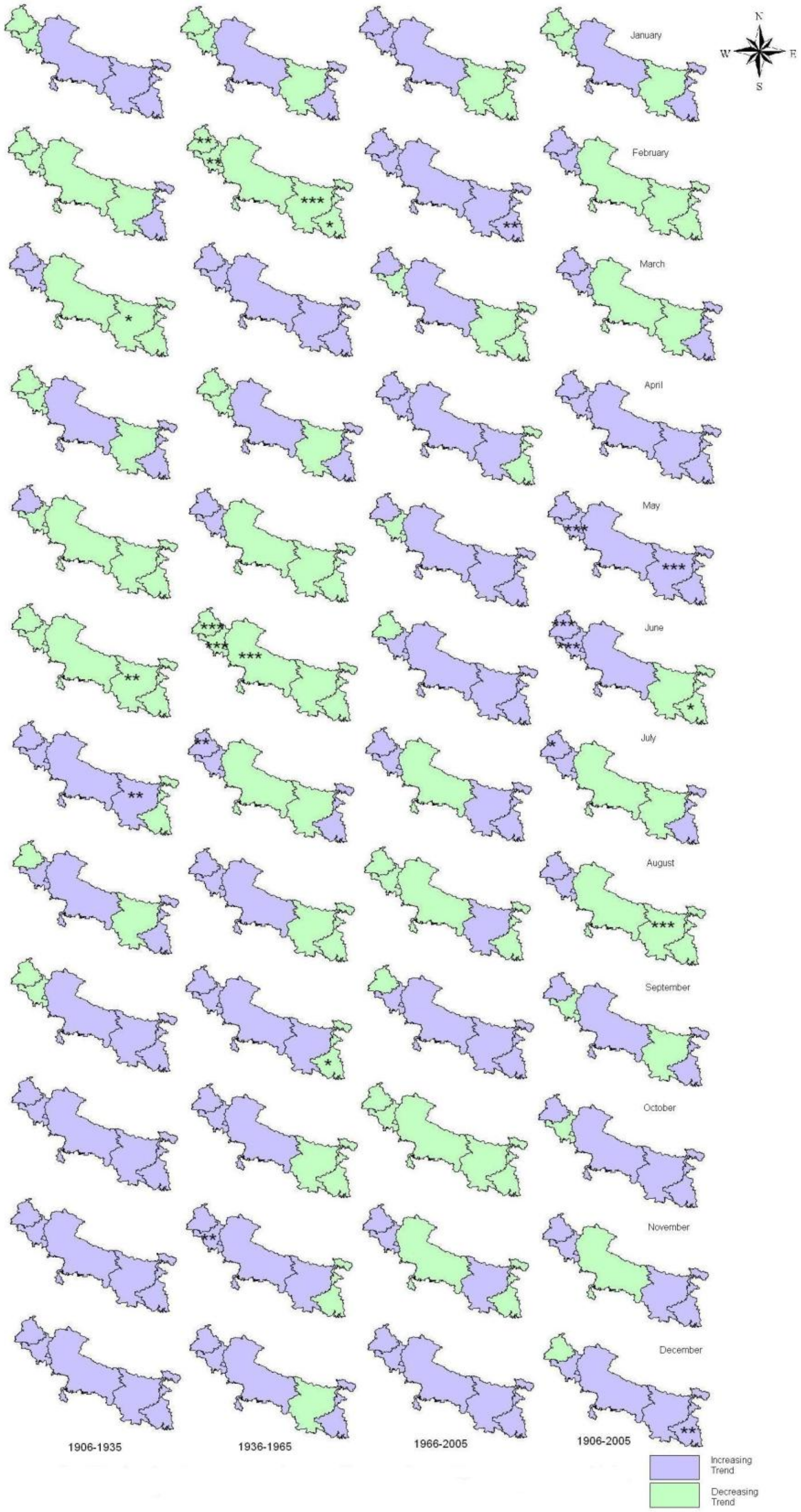

Fig.6.5: M-K test results of Indo-Gangetic States during different normal periods and during 1906-2005 *(* - Significant at 0.1 level, ** - Significant at 0.05 level and *** - Significant at 0.001 level)*

Punjab: The results show that in all the months, except January and December, there is an increasing trend of rainfall during 1906-2005. A significant increasing trend of rainfall at the rate of 0.3 mm/year and 0.6 mm/year, respectively has been noticed during June and July. But as far as different periods are concerned, the recent period NP3 showed an insignificant increasing trend of rainfall from January to May, July and November-December months. The increasing trends of rainfall during April, May and July months clearly indicating that the number of extreme event or pre-monsoon showers may be increasing in this part of the country. But the increasing trend of rainfall over Punjab may have double impact on wheat crop because heavy rain may tamper the sowing operations while small showers after sowing may be beneficial, even though almost 100 per cent of the wheat area comes under irrigated condition. But during NP2, January-February, April and June months show a decreasing trend of rainfall and a significant decrease of 1.4 mm/year and 1.9 mm/year, respectively have been noticed during February and June months. But a significant increasing trend of rainfall at the rate of 3.5 mm/year has been noticed during July. However, during NP1, all months except March, May, July and October-December months show an insignificant decreasing trend in rainfall.

Haryana: The results show that in all the months, except January and September-October, there is an increasing trend of rainfall during 1906-2005. A significant increase of 0.2 mm rainfall/year has been noticed during May and June. But as far as different normal periods are concerned, the recent period NP3 showed an insignificant decreasing trend of rainfall during March, May, August and October months. However, there is an increasing trend of 0.2 mm rainfall/year has been noticed during April. The increasing trends of rainfall during April, June months clearly indicate that the number of extreme events or pre-monsoon showers may be increasing in this part of the country. But the increasing trend of rainfall during November and December may have double impact on wheat crop because heavy rain may tamper the sowing operations while small showers after sowing may be beneficial, even though almost 100 per cent of the wheat area comes under irrigated condition. But during NP2, January-February, April and June months show a decreasing trend of rainfall and a significant decrease of 0.9 mm/year and 2.0 mm/year, respectively have been noticed during February and June. But a significant increasing trend of 4.9 mm rainfall/year has been noticed during August month. However, during NP1, all months, except March, July-August and October-December show an insignificant increasing trend in rainfall.

Uttar Pradesh: The results show that in all the months, except February-March, July-August and November, there is an increasing trend of rainfall during 1906-2005. A significant increasing trend of 0.1 mm rainfall/year has been noticed during May indicating that the number of extreme events or pre-monsoon showers may be increasing in this part of the region. But as far as different normal periods are concerned, the recent period NP3 showed an insignificant decreasing trend of rainfall during July-August and October-November months. This gives an indication that the rice crop will be under more drought risk as the maximum tillering/vegetative phase is in August in these parts. Similarly, the decreasing trends of rainfall during October-November months suggest the necessity of pre-sowing irrigation in wheat. But during NP2, February and April-July months show a decreasing trend of rainfall and even a significant decrease of 0.9 mm/year and 3.2 mm/year, respectively have been noticed during February and June months. However, during NP1, all months, except February-March and May-June months show an insignificant increasing trend in rainfall.

Bihar: The results show that all the months, except January-March and June-September, there is an increasing trend of rainfall during 1906-2005. A significant increasing trend of 0.1 mm rainfall/year has been noticed during May indicating that the number of extreme events or pre-monsoon showers may be increasing in this part of the region. But a significant decreasing trend in rainfall at the rate of 0.1 mm/year has been noticed during August. This gives an indication that the rice crop will be under more drought risk, particularly during the maximum tillering/vegetative phase, which is generally during August in these parts. But as far as different normal periods are concerned, the recent period NP3 showed an insignificant decreasing trend of rainfall during January, March and October months. But during NP2, January-February, May-August, October and December months show a decreasing trend of rainfall and a significant decrease of 1.0 mm/year and 1.1 mm/year, respectively have been noticed during February and August. However, during NP1, all months, except February-June and August, show an increasing trend in rainfall. A significant decreasing trend in rainfall at the rate of 0.4 mm/year (0.05 level) and 2.0 mm/year (0.01 level), respectively have been noticed during March and June. A significant (0.01 level) increasing trend rainfall at the rate of 1.8 mm/year has been noticed during July.

West Bengal: The results show that in all the months, except February, June and August, there is an increasing trend of rainfall during 1906-2005. However, a significant decreasing trend in rainfall at the rate of 0.8 mm/year has been noticed during June. A significant (0.01 level) increase in rainfall at the rate of 0.1 mm/year has been noticed during December. But as far as different normal periods are concerned, the recent period NP3 showed an insignificant decreasing trend of rainfall during January, March-April, August and October-November months. However, a significant increasing trend in rainfall at the rate of 0.3 mm/year has been noticed during February. But during NP2 all months, except January, March, July and December, show a decreasing trend of rainfall and even a significant decrease of 0.6 mm/year, 2.3 mm/year and 2.1 mm/year, respectively have been noticed during February, May and September months. However, during NP1 all months, except January-February, April and August-December, show an insignificant decreasing trend in rainfall.

6.4. Temperature variability and its trends

Indo-Gangetic region consists of three homogenous temperature regions Northwest (NW), North Central (NC) and Northeast (NE). The detailed analysis of trends in this region is given below.

6.4.1. Monthly temperature variability and trends

The long-term (1914-2003) mean annual maximum and minimum temperature of North Central India is 30.7 and 18 ^{O}C, respectively. May is the hottest (39.1^{O}C) month followed by April (36.7^{O}C); January is the coolest (8.5^{O}C) followed by December (8.9^{O}C) during the period. The same pattern was observed during different normal periods; 1914-1943(NPT1), 1944-1973(NPT2) and 1974-2003(NPT3) for maximum and minimum temperature. Similarly, the average maximum and minimum temperature over Northwest

India are 32.1^{O}C and 18.4^{O}C, respectively and over Northeast India 28.7^{O}C and 18^{O}C, respectively. In Northeast India, May (32.8^{O}C) is the hottest month followed by April (32.1^{O}C), while in Northwest India; May (39.6^{O}C) is the hottest month followed by June (38.6^{O}C). The region-wise inferences drawn from the application of M-K test are as follows;

NW region: All months except March show an increasing trend in maximum temperature during 90-year period 1914-2003 (Table 6.2). Linear approximation shows significant (at 0.01 level) rising trend of 0.011^{O}C/yr and 0.012^{O}C/yr, respectively during November and December months (Fig. 6.6). Similarly, significant (0.05 level) rising trend of 0.008^{O}C/yr during August, 0.009^{O}C/yr during September and 0.01^{O}C/yr during October were also noticed in maximum temperature. But minimum temperature shows decreasing trend in all months except February, April and August-December months during the same period. A significant (0.05 level) increase of 0.011^{O}C/yr during November has been observed. As far as different 30-year periods are concerned, during the recent period NPT3 all months, maximum and minimum shows an increasing trend. A significant (0.01 level) upward trend of maximum temperature of 0.048^{O}C/yr and 0.053^{O}C/yr during November and December months has been noticed. A significant (0.05 level) increasing trend of 0.038^{O}C/yr has been observed during August month.

Months/ Seasons	1914-2003		1914-1943		1944-1973		1974-2003	
	Max	Min	Max	Min	Max	Min	Max	Min
Jan	P	N	N	N *	P	N	P	P
Feb	P	P	P	P	P	N	P	P *
Mar	N	N	N	N	P	N	P	P
Apr	P	P	P	N	P	N	P	P
May	P	N	P	P	N	N **	P	P
June	P	N	N	P	N	N **	P	P *
July	P	N	N	N	P	N	P	P
Aug	P *	P	N	N	P	N *	P *	P
Sept	P *	P	P	N	P	N	P	P
Oct	P *	P	P *	N	P	P	P	P
Nov	P **	P *	P *	N	P	P	P **	P
Dec	P **	P	P	N	P	P	P **	P
Winter	P	N	P	N	P	N	P *	P *
Summer	P	N	P	N	P	N	P	P
Monsoon	P *	N	N	N	P	N **	P	P *
Post-monsoon	P **	P	P *	N	P	P	P **	P
Annual	P **	N	P	N	P	N	P **	P **

*P = Positive trend N = Negative trend; * and ** indicate statistically significant at 0.05 and 0.01 level, respectively.*

Table 6.2: M-K test results of maximum and minimum temperature for Northwest (NW) homogeneous region

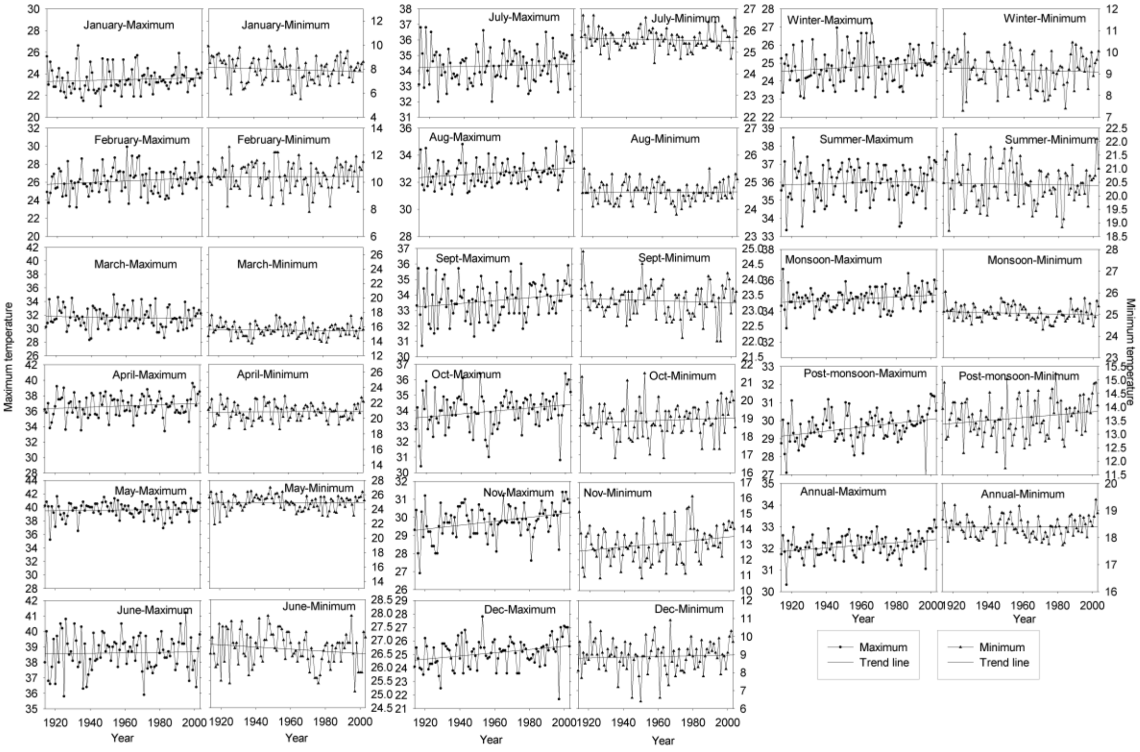

Fig.6.6: Monthly, seasonal and annual maximum and minimum temperature variation during 1914-2003 and its trends over Northwest (NW) homogeneous region

Linear approximation shows significant (0.05 level) upward trend of maximum temperature at the rate of 0.046^{O}C/yr and 0.023^{O}C/yr during February and June have been noticed. Thus increase of maximum temperature and minimum temperature during all months suggest the expansion of irrigation network in this part of the region to meet the increase in water demand of the crop. During NPT2 all months except May and June, an increasing trend of maximum temperature was noticed. But in the case of minimum temperature, all the months except October-December, show a decreasing trend and even a significant (0.01 level) downward trend of 0.058^{O}C/yr and 0.027^{O}C/yr during May and June have been observed. However, during NPT1, all months except January, March and June-August, an increasing trend in maximum temperature has been observed and even a significant (0.05 level) increase of 0.059^{O}C/yr and 0.056^{O}C/yr during October and November months have also been noticed. In the case of minimum temperature, all months except February and May-June, decreasing trends were observed. A significant upward trend of minimum temperature at the rate of 0.044^{O}C/yr during January has also been noticed.

<u>NC region</u>: All months except January show an increasing trend in maximum temperature during 90-year period 1914-2003 (Fig. 6.7). Linear approximation shows significant (0.01 level) rising trend of 0.014^{O}C/yr during July, 0.0097^{O}C/yr during August, 0.012^{O}C/yr during October, 0.019^{O}C/yr during November and 0.011^{O}C/yr during December. Similarly, significant (0.05 level) rising trend of 0.009^{O}C/yr during February, 0.01^{O}C/yr during April and 0.0066^{O}C/yr during September also have been noticed in

maximum temperature. But minimum temperature shows decreasing trend in all months (Table 6.3) except February-March and October-December months during the same period. A significant (0.01 level) increase of 0.019^{O}C/yr and 0.0099^{O}C/yr, respectively have been observed in November and December months and a significant (0.01 level) decrease of 0.005^{O}C/yr and 0.01^{O}C/yr, respectively have been observed in May and September months.

As far as different 30-year periods are concerned, during the recent period NPT3 all months except January, June, and September, maximum temperature shows an increasing trend and even a significant (0.05 level) upward trend of 0.03^{O}C/yr and 0.023^{O}C/yr during February and August, respectively has been noticed. A significant (0.01 level) increasing trend of 0.025^{O}C/yr has been observed during December month also. However, all the months show an increasing trend of minimum temperature during NPT3 and this clearly indicate that increase of minimum temperature contributes more to increase in mean temperature of the region. Linear approximation shows significant (0.01 level) upward trend of 0.05^{O}C/yr during February, 0.034^{O}C/yr during July and 0.024^{O}C/yr during August months. Similarly, a significant (0.05 level) upward trend of 0.016^{O}C/yr has been observed during September. Thus increase in maximum temperature and minimum temperature during July, August increase the evapotranspiration and thereby increase the water requirement of crops.

Months/ Seasons	1914-2003		1914-1943		1944-1973		1974-2003	
	Max	Min	Max	Min	Max	Min	Max	Min
Jan	N	N	N	P	P	N	N	P
Feb	P *	P	P	P	P	N	P	P **
Mar	P	P	P	N	P	N	P	P
Apr	P *	N	P	N	P	N	P	P
May	P	N	P *	P	N	N **	P	P
June	P	N *	P	P	N	N *	N	P
July	P **	N	N	N	P **	N **	P	P **
Aug	P **	N	P	P	P	N **	P *	P **
Sept	P *	N *	P	P	P	N **	N	P *
Oct	P **	P *	P *	N	P	N	P	P
Nov	P **	P **	P *	N	P	P	P	P
Dec	P **	P **	P	P	N	N	P **	P
Winter	P	P	P	P	P	N *	P	P *
Summer	P	N	P	N	P	N *	P	P
Monsoon	P **	N *	N	P	P	N **	P	P **
Post-monsoon	P **	P **	P **	N	P	N	P *	P *
Annual	P **	P	P	P	P *	N **	P	P **

*P = Positive trend N = Negative trend; * and ** indicate statistically significant at 0.05 and 0.01 level, respectively.*

Table 6.3: M-K test results of maximum and minimum temperature for North Central (NC) homogeneous region

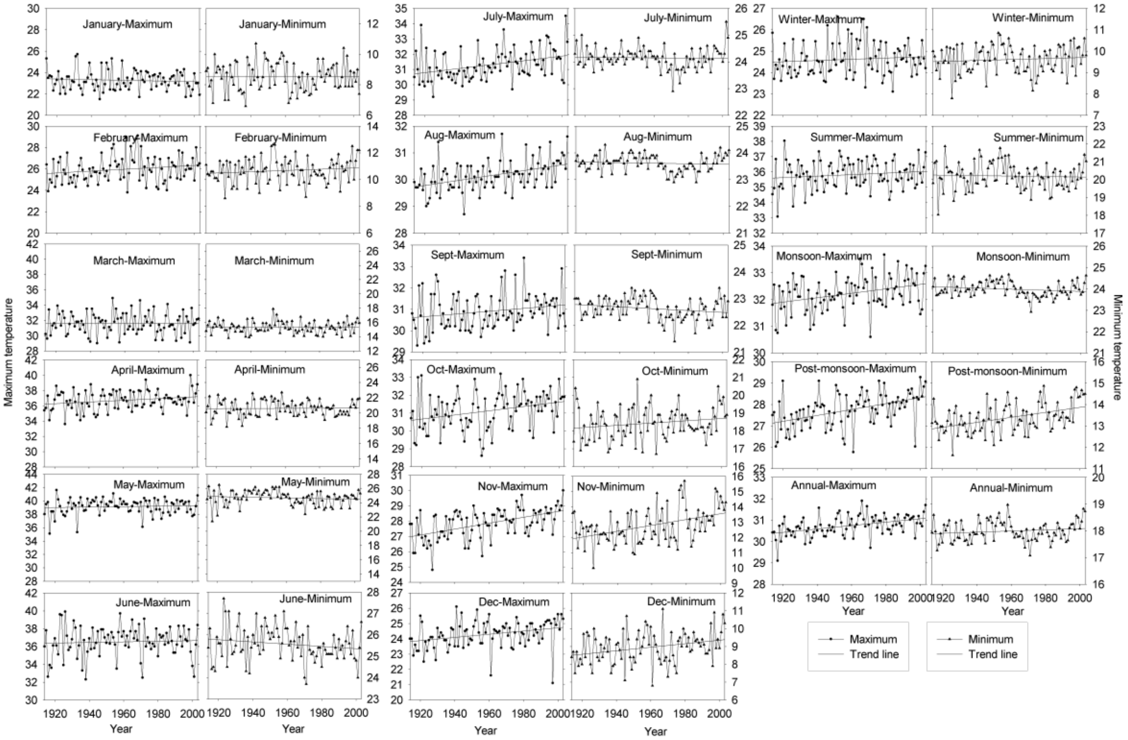

Fig.6.7: Monthly, seasonal and annual maximum and minimum temperature variation during 1914-2003 and its trends over North Central homogeneous region

During NPT2 all months except May-June and December, an increasing trend of maximum temperature was noticed and even a significant (0.01 level) increase of 0.014^{O}C/yr has been observed during July. But in the case of minimum temperature, all the months except November, show a decreasing trend during and even a significant (0.01 level) upward trend of 0.06^{O}C/yr during May, 0.022^{O}C/yr during July, 0.03^{O}C/yr during August and 0.032^{O}C/yr during September have been observed. However, during NPT1, all months except January and July, an increasing trend in maximum temperature has been observed and even a significant (0.05 level) increase of 0.045^{O}C/yr during May, 0.029^{O}C/yr during October and 0.045^{O}C/yr during November has been noticed.

NE region: All months show an increasing trend in maximum temperature during 90-year period 1914-2003 (Table 6.4). Linear approximation shows significant (at 0.01 level) rising trend of 0.014^{O}C/yr during February, 0.007^{O}C/yr during July, 0.012^{O}C/yr during August, 0.018^{O}C/yr during September, 0.015^{O}C/yr during October, 0.02^{O}C/yr during November and 0.014^{O}C/yr during December have been observed. A significant (0.05 level) increase of 0.008^{O}C/yr during June also has been observed. But minimum temperature shows decreasing trends except February and October-December months during the same period (Fig. 6.8). A significant (0.01 level) increase of 0.012^{O}C/yr and 0.009^{O}C/yr, respectively during November and December has also been noticed.

Months/ Seasons	1914-2003		1914-1943		1944-1973		1974-2003	
	Max	Min	Max	Min	Max	Min	Max	Min
Jan	P	N	P	N	P	N	N	P
Feb	P **	P	P	P	P	N	P	P **
Mar	P	N	P	P	P	N	N	P
Apr	P	N	P *	P	P	N	P	P
May	P	N	P	P	P	N *	P	P *
June	P *	N *	P	P	P	N **	N	P
July	P **	N *	P *	P	P *	N	P *	P **
Aug	P **	N	P	P	P	N **	P	P **
Sept	P **	N **	P	P	P	N **	P	P *
Oct	P **	P	P	P	P *	N	P	P
Nov	P **	P **	P	N	P	N	P **	P
Dec	P **	P **	P **	P	P	N	P **	P *
Winter	P **	P	P	N	P	N	P	P **
Summer	P	N	P	P	P	N	P	P **
Monsoon	P **	N *	P *	P	P	N **	P	P **
Post-monsoon	P **	P **	P **	P	P	N	P **	P *
Annual	P **	P	P **	P	P *	N **	P *	P **

*P = Positive trend N = Negative trend; * and ** indicate statistically significant at 0.05 and 0.01 level, respectively.*

Table 6.4: M-K test results of maximum and minimum temperature for Northeast (NE) homogeneous region

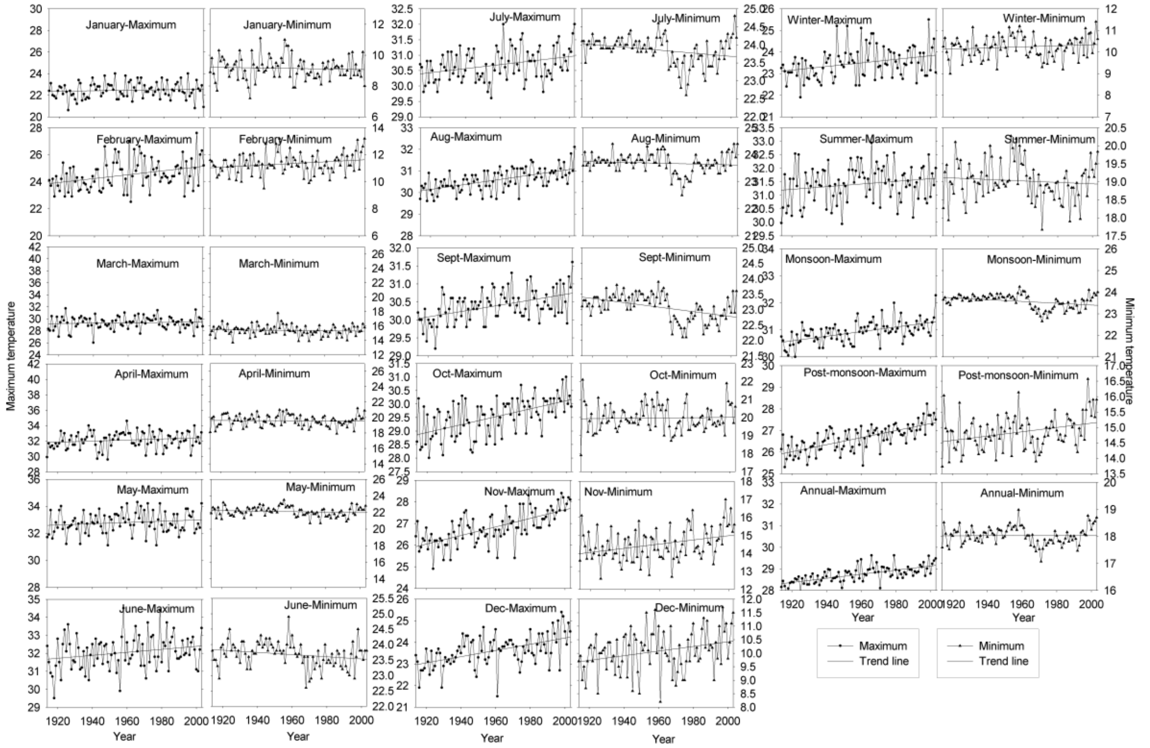

Fig.6.8: Monthly, seasonal and annual maximum and minimum temperature variation during 1914-2003 and its trends over Northeast homogeneous region

However, a significant (0.01 level) downward trend of minimum temperature at the rate of 0.004^{O}C/yr has been noticed during June and July months. A significant (0.01 level) downward trend of minimum temperature at the rate of 0.007^{O}C/yr during September also has been observed.

As far as different 30-year periods are concerned, during the recent period NPT3 all months except January, March and June, show an increasing trend in maximum temperature and even a significant (0.01 level) upward trend of 0.027^{O}C/yr during July, 0.029^{O}C/yr during November and 0.044^{O}C/yr during December have been observed. All months show an increasing trend in minimum temperature during NPT3. Linear approximation shows significant (at 0.01 level) rising trend of 0.046^{O}C/yr during February, 0.037^{O}C/yr during July and 0.027^{O}C/yr during August. A significant (0.05 level) rising trend of 0.031^{O}C/yr during May, 0.019^{O}C/yr September and 0.037^{O}C/yr during December has also been observed. All the months show an increasing trend in maximum temperature while all the months show a decreasing trend in minimum temperature during NPT2. A significant (0.05 level) upward trend in maximum temperature at the rate of 0.03^{O}C/yr and 0.034^{O}C/yr during July and October months has been noticed. In the case of minimum temperature, a significant (0.01 level) decrease at the rate of 0.03^{O}C/yr during June, 0.032^{O}C/yr during August and 0.04^{O}C/yr during September has been noticed. Similarly, a significant (0.05 level) decrease of minimum temperature at the rate of 0.028^{O}C/yr during May has also been observed. During NPT1, all the months show an increasing trend in maximum temperature and even a significant (0.05 level) increase of 0.039^{o}C/yr and 0.018^{o}C/yr during April and July have been observed. All the months except January and November, show an increasing trend in minimum temperature during NPT1, but statistically insignificant.

6.4.2. Seasonal temperature trends

NW-region: Maximum temperature shows significant rising trend of 0.005^{o}C/yr (at 0.05 level) during monsoon season and 0.011^{o}C/yr (at 0.01 level) during post-monsoon season during period 1914-2003. However, it shows insignificant increasing trend during winter and summer season during the study period. The annual maximum temperature also shows significant increasing trend of 0.006^{o}C/yr (at 0.01 level) during the same period. Minimum temperature does not show any significant trends during the study period. When we look into different normal periods analysis, during the recent normal period 1974-2003, maximum temperature shows insignificant increasing trend during summer and monsoon seasons and significant rising trend of 0.039^{o}C/yr (at 0.05 level) and 0.035^{o}C/yr during the winter and post-monsoon season, respectively. However, minimum temperature also shows significant increasing trend of 0.037^{o}C/yr (at 0.05 level) during winter, 0.017^{o}C/yr (at 0.05 level) during monsoon and insignificant increasing trend during summer and post-monsoon season. The annual minimum temperature also shows significant rising trend of 0.024^{O}C/yr (at 0.01 level) during the recent normal period 1974-2003.

NC-region: Maximum temperature shows significant rising trend of 0.008^{O}C/yr (at 0.01 level) during monsoon season and 0.014^{O}C/yr (at 0.01 level) during post-monsoon season during period 1914-2003. However, it shows insignificant increasing trend during winter and summer season during the study period. The annual maximum temperature also shows significant increasing trend of 0.008^{O}C/yr (at 0.01 level) during the same period. Minimum temperature shows significant rising trend of 0.012^{O}C/yr (at 0.01 level) during post-monsoon season and significant falling trend of 0.002^{O}C/yr (at 0.05 level) during monsoon season. This rising feature of both maximum and minimum temperature ultimately increases the mean heating of the atmosphere and favors the cloud formation and eventually increases the rainfall activity. The post-monsoon season rainfall analysis also suggests that rainfall shows an increasing trend in all the States. However, minimum temperature shows insignificant increasing trend during winter and insignificant decreasing trend during summer season during the study period. The annual minimum temperature also shows insignificant increasing trend during the same period. When we look into different normal periods analysis, during the recent normal period 1974-2003, maximum temperature shows insignificant increasing trend during winter, summer and monsoon seasons and significant rising trend of 0.016^{O}C/yr (at 0.05 level) during the post-monsoon season. However, minimum temperature also shows significant increasing trend of 0.026^{O}C/yr (at 0.05 level) during winter, 0.022^{O}C/yr (at 0.01 level) during monsoon and 0.028^{O}C/yr (at 0.05 level) during post-monsoon and insignificant increasing trend during summer season. The annual minimum temperature also shows significant rising trend of 0.023^{O}C/yr (at 0.01 level) during the recent normal period 1974-2003.

NE-region: Maximum temperature shows significant rising trend of 0.008^{O}C/yr (at 0.01 level) during monsoon season and 0.017^{O}C/yr (at 0.01 level) during post-monsoon season during period 1914-2003. However, it shows significant increasing trend (0.008^{O}C/yr, at 0.01 level) during winter and insignificant increasing trend during summer season during the study period. The annual maximum temperature also shows significant increasing trend of 0.01^{O}C/yr (at 0.01 level) during the same period. Minimum temperature shows significant rising trend of 0.007^{O}C/yr (at 0.01 level) during post-monsoon season and significant falling trend of 0.004^{O}C/yr (at 0.05 level) during monsoon season. This rising feature of both maximum and minimum temperature during the post-monsoon season ultimately affects the depletion of soil moisture and there by affect the sowing operation of wheat crop. When we look into different normal periods analysis, during the recent normal period 1974-2003, maximum temperature shows insignificant increasing trend during winter, summer and monsoon seasons and significant rising trend of 0.028^{O}C/yr (at 0.01 level) during the post-monsoon season. However, minimum temperature also shows significant increasing trend of 0.028^{O}C/yr (at 0.05 level) during winter, 0.024^{O}C/yr (at 0.01 level) during monsoon and 0.028°C/yr (at 0.05 level) during post-monsoon and 0.025°C/yr (at 0.01 level) during summer season. The annual minimum temperature also shows significant rising trend of 0.026°C/yr (at 0.01 level) during the recent normal period 1974-2003.

CHAPTER 7

Assessment of Drought using Crop Growth Simulation Models

7.1 Introduction

The production potential of a crop is largely determined by the climatic, edaphic and soil properties and their interactions. Crop Growth Simulation Models (CGSM) deal with interactions of crop growth with climatic factors, soil characteristics, agronomic management, and therefore can be used to estimate climatic limitations to growth and yield (Aggarwal and Kalra, 1994). Agricultural droughts are one such important limitation to crop growth and productivity. The characterization and assessment of agricultural drought is entirely different from other droughts. The deficiency of water in sensitive crop stages, even for short periods can severely affect the agriculture production. The important aspect that differentiates other droughts from agricultural drought is that normalcy is restored once sufficient precipitation occurs. In agricultural drought on the other hand, normalcy cannot be restored for that particular crop season because the damage caused to the crop during any crop stage cannot be repaired at other stages. The drought events should not be seen as an isolated event. At times, the effect of a drought spell may continue to affect the area for several years so there is the need to analyze the drought events on the basis of continuous weather data. In this section we compare, the Standardized Precipitation Index (SPI) – which is weather based index and an Agriculture drought index based on Crop Growth Simulation Model-Drought Index (CGSM-DI). The crop simulation based analysis of drought is necessary for identification of agricultural drought because it accounts for water losses through percolation (soil effect), run off (slope effect), evapotranspiration (temperature effect) and continuing water deficit (from past drought effect) on the crop, from sowing/transplanting stage to harvest.

7.2. Site characterization

Five sites covering important agro-ecological sub-regions of the IGR were selected for the study, based on the availability of soil, weather and crop management data. The sites were distributed from 25.88 to 30.93 ^{0}N latitude and 75.73 to 85.80 ^{0}E longitude (Table 7.1).

Site	Latitude (^{0}N)	Longitude (^{0}E)	Altitude (m)	Period	Annual Rainfall (mm)	Sunshine hours	Temperature (^{0}C)	
							Max.	Min.
Ludhiana	30.93	75.87	247	1970-2007	745.8	8.3	29.8	16.5
Hisar	29.17	75.73	215	1970-2007	920.6	7.1	30.6	16.9
Faizabad	26.78	82.13	133	1986-2006	915.8	7.1	31.3	18.1
Kanpur	26.43	80.37	126	1971-2006	869.2	6.5	31.2	18.7
Samastipur	25.88	85.80	52	1960-2007	1199.5	7.1	30.9	18.9

Table 7.1: Characterization of the study sites in the IGR

The annual maximum temperature ranges from 29.8 ^{0}C at Ludhiana to 31.3 ^{0}C at Faizabad: minimum temperature ranges from 16.5 ^{0}C at Ludhiana to 18.9 ^{0}C at Samastipur. The annual mean sunshine hours are maximum of 8.3 hours/day at Ludhiana and minimum of 6.5 hours/day at Kanpur. The available organic carbon, phosphorous and potassium for these sites are given Table 7.2. It clearly indicated that the available organic carbon is more at Samastipur and least at Kanpur while in the case of potassium, maximum value is obtained at Hisar and minimum value at Samastipur.

Site	Organic $C^{a,b}$ (%)	Olsen P^b (mg kg^{-1})	NH_4OAc K^c (mg kg^{-1})
Ludhiana	0.31	5	46
Hisar	0.32	7	180
Faizabad	0.37	6	161
Kanpur	0.29	6	82
Samastipur	0.47	5	35

Table 7.2: The available carbon, phosphorous and potassium for these sites

[a] Sources from : Abrol et al. (2000); Singh and Swarup (2000); Saha et al. (2000); Bhandari et al (2002); Ladha et al. (2002); Pathak et al. (2002); Pathak et al. (2003).

[b] Organic carbon content of soil was estimated by Walkley and Black (1934) method.

[c] Olsen P content of soil was estimated by Olsen el al. (1954) method.

[d] NH_4OAc K of soil was estimated by ammonium acetate extraction method (CSTPA, 1974)

7.3. Analysis of weather

Analyses of weather data during the period showed that there was no significant change in rainfall over the years in both the rice and wheat growing seasons at all the sites except Hisar. The annual change in the rainfall trend was -28.9 mm/year ($P < 0.05$) and during the rice season it was -20.5 mm/year ($P < 0.01$) for Hisar (Table 7.3 (a-e)). The distribution of rainfall for these sites showed no clear significant trends during June, but negative trends were observed in Kanpur, Ludhiana and Hisar. In July, however, all the sites except Samastipur showed a decreasing trend of rainfall. Negative trends were observed in all the five sites during August, only one (Hisar) of which was statistically significant ($P < 0.01$). The rainfall distribution during the wheat season showed no clear significant trend, but two sites (Kanpur and Samastipur) showed increasing trend while three sites (Faizabad, Ludhiana and Hisar) showed decreasing trend during December, which coincides with the CRI stage in most of the IGR, in which the first irrigation is very much important.

(a) Faizabad

Months/ Crop season	Rainfall		Maximum temperature		Minimum temperature		Sunshine hours	
	Mean (mm)	Change (mm/ year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (hours)	Change (hours/ year)
June	127.3	3.49	37.2	-0.06	26.0	0.06	6.7	0.002
July	255.9	-3.24	33.3	-0.01	25.9	0.12	5.2	-0.022
Aug.	236.6	-2.60	32.7	0.03	25.6	0.11**	5.3	0.033
Sept.	180.9	-4.59	32.4	0.01	24.7	0.10	5.7	0.06
Oct.	38.1	-1.31	31.9	-0.003	19.6	0.08	7.8	0.007
Nov	3.2	0.14	28.8	0.01	13.0	-0.02	7.7	-0.010
Dec	5.2	-0.55	24.2	-0.07	8.3	-0.02	6.4	-0.024
Jan	14.4	0.44	21.4	-0.11	7.2	-0.07	5.8	-0.014
Feb	10.6	-0.05	25.7	0.01	9.8	0.04	8.2	-0.016
Mar	6.0	-0.42	31.5	0.04	13.9	0.03	8.6	-0.003
Annual	915.8	-5.39	31.3	-0.01	18.1	0.06	7.1	-0.005
Kharif	838.8	-8.25	33.5	-0.004	24.3	0.09	6.2	0.004
Rabi	36.2	-0.58	25.2	-0.04	9.3	-0.01	7.0	-0.017

*** Significant at P<0.01, ** Significant at P<0.05,* Significant at P<0.10

Fig. 7.3: Monthly mean rainfall, maximum and minimum temperature and sunshine hours over various sites ((a) Faizabad, (b) Kanpur, (c) Ludhiana, (d) Hisar and (e) Samastipur) of IGR and its trends

(Contd…..)

(b) Kanpur

Months/ Crop season	Rainfall		Maximum temperature		Minimum temperature		Sunshine hours	
	Mean (mm)	Change (mm/ year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (hours)	Change (hours/ year)
June	72.3	-0.21	38.6	-0.01	27.5	-0.04**	5.3	-0.001
July	259.5	-0.60	33.7	0.04	26.5	-0.03	2.9	0.0004
Aug.	243.1	-2.76	32.6	0.05***	25.9	-0.03***	5.1	-0.0003
Sept.	178.3	0.62	32.5	0.04**	24.4	-0.02	6.4	0.00
Oct.	42.8	-0.78	32.2	0.02	19.4	-0.04*	6.9	0.00
Nov	7.3	-0.30	28.2	0.04**	12.8	-0.05**	6.8	0.0001
Dec	8.8	0.18	23.1	0.04**	8.5	-0.03**	5.0	0.0009
Jan	14.3	0.27	21.0	-0.01	7.5	-0.04	6.7	-0.0001
Feb	13.0	0.02	24.6	0.07	10.1	0.01	8.0	0.0004
Mar	11.0	-0.61	30.7	0.03	14.8	0.02	8.8	0.00
Annual	869.2	-3.55	31.2	0.03**	18.7	-0.03***	6.5	0.0004
Kharif	796.0	-3.73	33.9	0.03**	24.7	-0.03***	5.3	0.00
Rabi	47.1	-0.14	24.3	0.03**	9.7	-0.02	6.4	-0.0007

(c) Ludhiana

Months/ Crop season	Rainfall		Maximum temperature		Minimum temperature		Sunshine hours	
	Mean (mm)	Change (mm/ year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (hours)	Change (hours/ year)
June	65.1	-0.78	38.2	-0.03	25.7	0.05***	9.2	0.02
July	216.3	-0.65	34.3	-0.02	26.2	0.07***	6.9	-0.01
Aug.	190.3	-0.07	33.4	0.01	25.5	0.06***	7.3	0.003
Sept.	104.6	2.07	33.5	-0.01	22.7	0.07***	8.8	-0.01
Oct.	8.9	0.31	31.9	-0.01	16.4	0.07***	9.2	-0.04**
Nov	7.3	-0.21	26.6	0.01*	10.6	0.08***	8.4	-0.06***
Dec	16.5	-0.11	20.6	-0.01	6.5	0.06***	6.9	-0.06***
Jan	28.3	0.25	18.3	-0.04*	5.5	0.04**	6.7	-0.04*
Feb	33.8	0.47	21.2	0.03	7.7	0.09***	7.9	-0.02
Mar	23.4	0.01	26.4	0.02	11.6	0.07***	8.6	0.02
Annual	745.8	1.17	29.8	-0.001	16.5	0.07***	8.3	-0.02**
Kharif	585.1	0.88	34.2	-0.01	23.3	0.06***	6.9	-0.01
Rabi	101.9	0.63	21.3	-0.001	7.4	0.06***	7.3	-0.04***

*** Significant at *P*<0.01, ** Significant at *P*<0.05,* Significant at *P*<0.10

Fig. 7.3: Monthly mean rainfall, maximum and minimum temperature and sunshine hours over various sites ((a) Faizabad, (b) Kanpur, (c) Ludhiana, (d) Hisar and (e) Samastipur) of IGR and its trends

(Contd…..)

(d) Hisar

Months/ Crop season	Rainfall		Maximum temperature		Minimum temperature		Sunshine hours	
	Mean (mm)	Change (mm/ year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (hours)	Change (hours/ year)
June	148.7	-4.77	37.3	0.13*	25.4	0.01	6.2	0.04
July	202.6	-4.78**	35.1	0.07*	25.8	0.03*	5.8	-0.01
Aug.	170.4	-6.39***	34.1	0.07***	25.1	0.02	6.6	0.05**
Sept.	119.9	-3.06	33.7	0.05*	23.0	-0.01	7.4	0.03
Oct.	37.2	-1.48**	32.2	0.05	17.5	-0.09*	8.0	0.01
Nov	9.5	-0.69**	28.0	0.04***	11.5	-0.10**	7.7	-0.01
Dec	8.9	-0.27	22.7	-0.02	6.9	-0.08**	6.6	-0.05***
Jan	12.7	-0.09	20.7	-0.11***	6.2	-0.09***	6.5	-0.06***
Feb	23.6	0.11	23.5	-0.02	8.8	-0.08*	7.3	-0.02
Mar	26.8	-0.43	28.2	0.001	12.5	-0.09*	8.0	0.01
Annual	920.6	-28.86**	30.6	0.05*	16.9	-0.04*	7.1	0.004
Kharif	678.8	-20.5***	34.5	0.07**	23.3	-0.01	6.8	0.02
Rabi	72.0	-0.68	23.4	-0.03**	8.0	-0.09**	6.9	-0.04***

(e) Samastipur

Months/ Crop season	Rainfall		Maximum temperature		Minimum temperature		Sunshine hours	
	Mean (mm)	Change (mm/ year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (^{0}C)	Change (^{0}C per year)	Mean (hours)	Change (hours/ year)
June	159.0	1.65	35.4	-0.01	25.6	0.03	7.3	0.001
July	325.2	0.93	32.8	0.01	25.8	0.03***	4.9	-0.001
Aug.	289.8	-1.19	32.6	0.02***	25.9	0.04***	6.4	0.0004
Sept.	225.8	-1.34	32.4	0.003	25.3	0.01***	6.0	0.0
Oct.	70.1	-1.53	31.9	002	21.8	0.03*	7.3	0.0004
Nov	7.8	-0.05	28.9	0.02*	14.8	0.05***	7.2	-0.0001
Dec	5.6	0.06	24.4	0.001	9.5	0.06***	7.0	0.0001
Jan	10.9	-0.07	22.4	-0.06***	8.0	0.02*	5.7	0.0003
Feb	13.2	0.12	25.9	-0.01	10.2	0.06**	7.6	0.0
Mar	7.6	-0.24	31.3	-0.02*	15.1	0.03*	8.8	0.0
Annual	1199.5	-0.68	30.9	-0.01	18.9	0.04***	7.1	0.0001
Kharif	1069.9	-1.48	33.0	0.01	24.9	0.03***	6.4	-0.0002
Rabi	37.2	-0.12	25.5	-0.02*	10.3	0.05***	7.2	0.0002

*** Significant at $P<0.01$, ** Significant at $P<0.05$,* Significant at $P<0.10$

Fig. 7.3: Monthly mean rainfall, maximum and minimum temperature and sunshine hours over various sites ((a) Faizabad, (b) Kanpur, (c) Ludhiana, (d) Hisar and (e) Samastipur) of IGR and its trends

Analyses showed that sunshine hours decreased over the years during rice season at three sites (Faizabad, Ludhiana and Samastipur), though statistically not significant. During wheat season, a significant decreasing trend was noticed for Ludhiana and Hisar ($P < 0.01$) (-0.04 hours/day/year). On the other hand, positive trends were noticed at three sites, though statistically not significant. Sinha *et al*. (1998) observed that there was a 10 % decline in solar radiation in northwestern India during the last two decades. It is widely recognized that in all the major cities of India aerosol concentration has been increasing, resulting in decreased solar radiation and increased minimum temperature (Hundal and Kaur, 1996; Aggarwal *et al*., 2000). In another study, Pathak *et al*., (2003), reported that solar radiation decreased over the years in both the rice and wheat seasons at selected sites of Indo-Gangetic Plains. Besides the effect of global warming, an increase in minimum temperature could be the result of decreased solar radiation. There has also been an increase in the percent particulate matter in the air around cities. This would attenuate the light reaching the plant to higher, red wavelengths that are less photosynthetically active and so lower yields. Since, most weather stations are located in urban areas, it cannot be concluded whether these changes are also occurring in rural agricultural areas.

The minimum temperature in rice showed a negative trend at two stations (statistically significant at Kanpur) whereas three sites showed a positive trend, with two sites, Samastipur and Ludhiana showing significantly positive trend of 0.03 ^{0}C/year and 0.06 ^{0}C/year, respectively. In wheat season, three sites showed a negative trend, Hisar being significantly different from 0 ($P < 0.05$). Two sites (Ludhiana and Samastipur) showed statistically significant positive trend ($P < 0.01$). A similar significant increase in the minimum temperature trend in rice was also recorded in Adampur, located near Jalandhar, Punjab (Bijay Singh, personal communication). The analyses of weather data for more than two decades by Sinha *et al*., (1998) showed that there has been a 1.5 ^{0}C increase in the minimum temperature at many places in northwestern India. The distribution pattern indicated that all sites except Kanpur showed an increasing trend of minimum temperature during June, July and August months and for Ludhiana and Samastipur, it is highly statistically significant for all the months. The minimum temperature change ranges from 0.01 ^{0}C/year (Samastipur) to 0.07 ^{0}C/year (Ludhiana). Interestingly, Samastipur and Ludhiana showed increased minimum temperature trend in all the rice and wheat season months with high statistical significance ($P < 0.01$). During the wheat season, at Hisar, all the months showed statistically significant negative trend in minimum temperatures. But all the sites except Hisar, showed an increasing trend of minimum temperature during February and March, which coincides with the grain filling stage of wheat in IGR. Kukla and Karl (1993) analyzed data from several countries, including the United States, Canada, China, Commonwealth of Independent States, Australia, Sudan, Japan, Denmark, Finland, several Pacific islands, Pakistan, South Africa, and some European countries, covering 50 % of the land in the Northern Hemisphere and 10 % of the land in Southern Hemisphere. The minimum temperature revealed a general rise worldwide, with the exception of the eastern coast of North America, where it decreased. They observed that (a) an increase in natural and anthropogenic clouds, (b) haze from cities, factories, and burning fields and forests, (c) vapor trails of high altitude aircraft, (d) irrigation that keeps the soil surface warmer at night, (e) anthropogenic greenhouse gases and (f) warming of the urban zones, which keeps the night temperature high, are the probable causes of such an increase in minimum temperature.

The maximum temperature in rice remained stable over the years, with two sites (Faizabad and Ludhiana) showing a negative trend and three positive (Kanpur, Hisar and Samastipur): only at Kanpur and Hisar was significant increasing trend The monthly distribution indicated that all sites except Hisar showed negative trend during June, but all are statistically not significant. However, for Hisar a significant change of maximum temperature of 0.13 ^{0}C/year has been noticed during the period. In July, three sites (Kanpur, Hisar and Samastipur) showed increasing trend while two sites (Faizabad and Ludhiana) showed decreasing trend. Moreover, for Hisar a significant change of 0.07 ^{0}C/year has been noticed during the period. But during August and September, all sites showed increasing trend of maximum temperature except in Ludhiana where negative trend was seen in September. This indicated that the grain filling stage or rice in the western part/vegetative phase in the eastern part of the region may coincide with this period. The increase of higher sunshine hours and minimum temperature will definitely increase the water requirement of rice and any break in the monsoon will adversely affect the rice yield. But in wheat growing season, all stations except Kanpur showed negative trend, with trend at Samastipur being statistically significant. The monthly distribution of maximum temperature during wheat season showed that an increasing trend in November for all sites: statistically significant at all the sites except Faizabad. During December, three sites (Faizabad, Ludhiana and Hisar) showed decreasing trend (all statistically not significant) while two sites showed increasing trend. Kanpur showed a significant increasing trend of 0.04 ^{0}C/year during the period ($P < 0.01$). All sites showed decreasing trend during January with three stations Ludhiana, Hisar and Samastipur showing statistically significant decreasing trend ranging from -0.04 ^{0}C/year (Ludhiana) to -0.11 ^{0}C/year (Hisar). The increasing trend during February (Faizabad, Kanpur and Ludhiana) and March (Faizabad, Kanpur, Ludhiana and Hisar) may coincide with the grain filling period of wheat. A decrease in maximum temperature increases the vegetative and grain-filling period and increases crop yield in wheat provided the minimum temperature remains constant (Horie *et al*., 1995; Matthews *at al*., 1995).

7.4. Potential Yield Simulation

7.4.1. Model description

Potential yield is defined as the maximum yield of a variety restricted only by the season-specific climatic conditions. This assumes that other inputs (nutrient, water, etc) are not limiting and cultural management is optimal. Thus, the potential yield of a crop depends on the temporal variation of CO_2 level in the atmosphere, solar radiation/ sunshine hours, maximum and minimum temperatures during the crop season and physiological characteristics of the variety. Mechanistic crop growth models are routinely used to estimate potential yield and assess the effects of climate change (Muchow *et al*., 1990; Jansen, 1990; Penning de Vries, 1993; Boote and Tollenar, 1994; Kropff *et al*., 1994, 1996; Hundal and Kaur, 1996; Aggarwal *et al*., 1997, 2000; Pathak *et al*., 2003). To simulate potential yield, DSSATv4.0 (Hoogenboom et al., 2003) was used. The details of the model were described in Chapter 2. These process oriented, daily time-step, mechanistic models simulate the main processes of crop growth and development such as timing of phenological events, development of the canopy to intercept photosynthetically active radiation and its use to accumulate dry matter. The models calculate net photosynthesis based on a constant radiation use efficiency, leaf area index, extinction coefficient and light absorption by the canopy (Mall and Aggarwal, 2002). The models have the capability to simulate the effect of CO_2 on photosynthesis and water use based on the effects of stomatal conductivity.

7.4.2. Input data requirement of DSSAT model

The popular rice variety PR 106 and wheat variety HD 2329, which are the most dominant varieties in the IGR, were selected for the study. Genotypic coefficients used in the models for rice and wheat cultivars are given in Table 7.4. These coefficients were estimated based on past field experiments by repeated iterations until a close match between simulated and observed phenology and yield was obtained. The data of experiments not used for calibration was used for validation. There is generally a good agreement between the simulated and observed time course in phenological development and grain yield. The performance of the models has been well validated all over the world including rice-wheat growing environments of India (Hundal and Kaur, 1996; Lal, 1999; Aggarwal and Mall, 2002; Mall and Aggarwal, 2002) using data from field experiments. The accuracy of model predictions was estimated using the coefficient of determination between simulated and observed values.

Genetic coefficients	Values
Rice (Variety PR 106)	
P1 – Juvenile phase coefficient, GDD	500
P2R – Photoperiodism coefficient, GDD h^{-1}	150
P5 – Grain-filling duration coefficient, GDD	300
P20 – Critical photoperiod, h	11.5
G1- Spikelet number coefficient	60
G2- Single grain weight, g	0.024
G3- Tillering coefficient	1.0
G4- Temperature tolerance coefficient	1.0
Wheat (Variety HD 2329)	
PIV - Vernalization coefficient	0.5
PID - Photoperiodism coefficient, GDD h^{-1}	3.24
P5 - Grain-filling duration coefficient, GDD	2.6
PHINT – Phyllochron interval	95
G1- Kernel number coefficient	3.24
G2- Kernel weight coefficient	3.5
G3- Spike number coefficient	4.23

(GDD – Growing Degree Days (^{0}C))

Fig.7.4. Genotypic coefficients of rice and wheat varieties used in the DSSAT model

Rice is transplanted on 1 July and wheat sown on 15 November every year. These are the optimum dates of planting rice and wheat in this region (Aggarwal and Kalra, 1994). The experimental data regarding crop phenology, soil characteristics and yield data were collected from these sites for re-calibration and re-validation of the model. The CO_2 concentration in the atmosphere was considered as 330 ppm in 1985 and increasing with an annual increment of 1.5 ppm.

Site	Latitude and longitude, altitude
Weather	Daily global solar radiation or sunshine hours, maximum and minimum temperature and rainfall
Soil	Classification using the local system and (to family level) the USDA-NRCS taxanomic system
Initial conditions	Basic profile characteristics by soil layer; in situ water release curve characteristics (saturated drained upper limit, lower limit); bulk density, organic carbon; pH; root growth factor; drainage coefficient
Management	Previous crop, root, and nodule amounts; numbers and effectiveness of rhizobia (nodulating crop) Water, ammonium and nitrate by soil layer Cultivar name and type Planting date, depth and method; row spacing and direction; plant population Irrigation and water management, dates, methods and amounts or depths Fertilizer (inorganic) and inoculants applications Residue (organic fertilizer) applications (material, depth of incorporation, amount and nutrient concentrations), Tillage Environment (aerial) adjustments Harvest Schedule

Table 7.5: Input data required to run the CERES model

7.4.3. Sensitivity Analysis

Sensitivity of the model to the changes in solar radiation, minimum and maximum temperatures and rainfall on potential yields of rice and wheat was done for Hisar using the weather data of 1990-01, 1991-02 and 1992-03. Every incremental increase of rainfall by 2 mm/day, increased the potential rice yield continuously. However, wheat yield increased up to when the rainfall reached 26 mm/day and after that showed decreasing tendency (Fig. 7.1). Decreased solar radiation by 2 MJm^{-2} per day reduced rice and wheat yields from 11050 to 10230 and 7300 to 7072 kg/ha, respectively (Fig. 7.2). Increased minimum temperature by 2 ^{0}C also decreased yields of rice and wheat from 10920 to 9780 and 8310 to 7830 kg/ha, respectively.

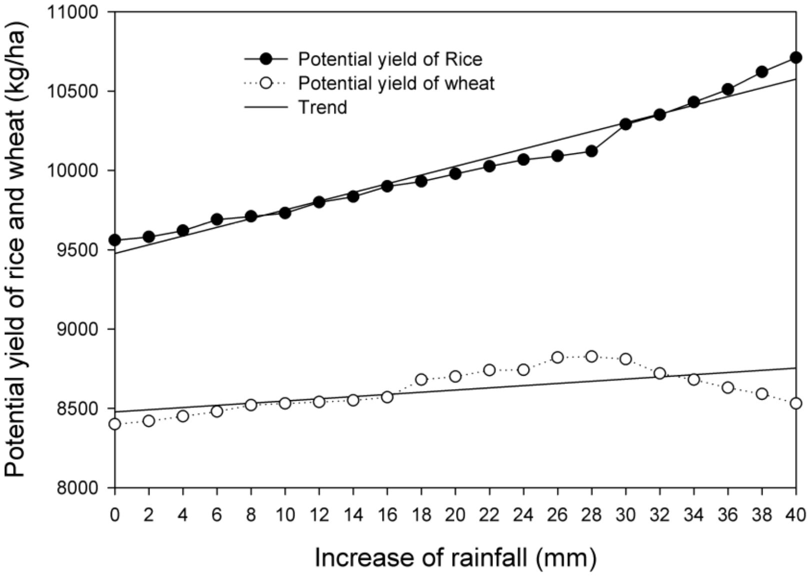

Fig. 7.1: Sensitivity of simulated potential yields of rice and wheat to the increase of rainfall

Increase in maximum temperature increased rice yield marginally, but decreased wheat yield significantly. Increased maximum temperature by 2 ^{0}C decreased the yields of wheat from 7680 to 6800 kg/ha. The analysis showed that the model is sensitive to the changes in radiation, rainfall and temperature, and therefore, could be used for simulating the effect of changes in weather parameters on rice and wheat yields.

7.4.4. Simulated potential yields

The potential yields of rice and wheat in the IGR ranged from 8.7 to 10.7 and 6.2 to 8.5 t/ha, respectively (Table 7.6). The yields of both rice and wheat were the highest in Ludhiana and decreased towards the eastern part of the IGR. The yield declined by 19 % for rice and by 29 % for wheat from Ludhiana to eastern side of IGR. This is because of the lower solar radiation and higher daily minimum temperature in the eastern part of the IGR, resulting in decreased photosynthesis, and a shortened vegetative and grain-filling period.

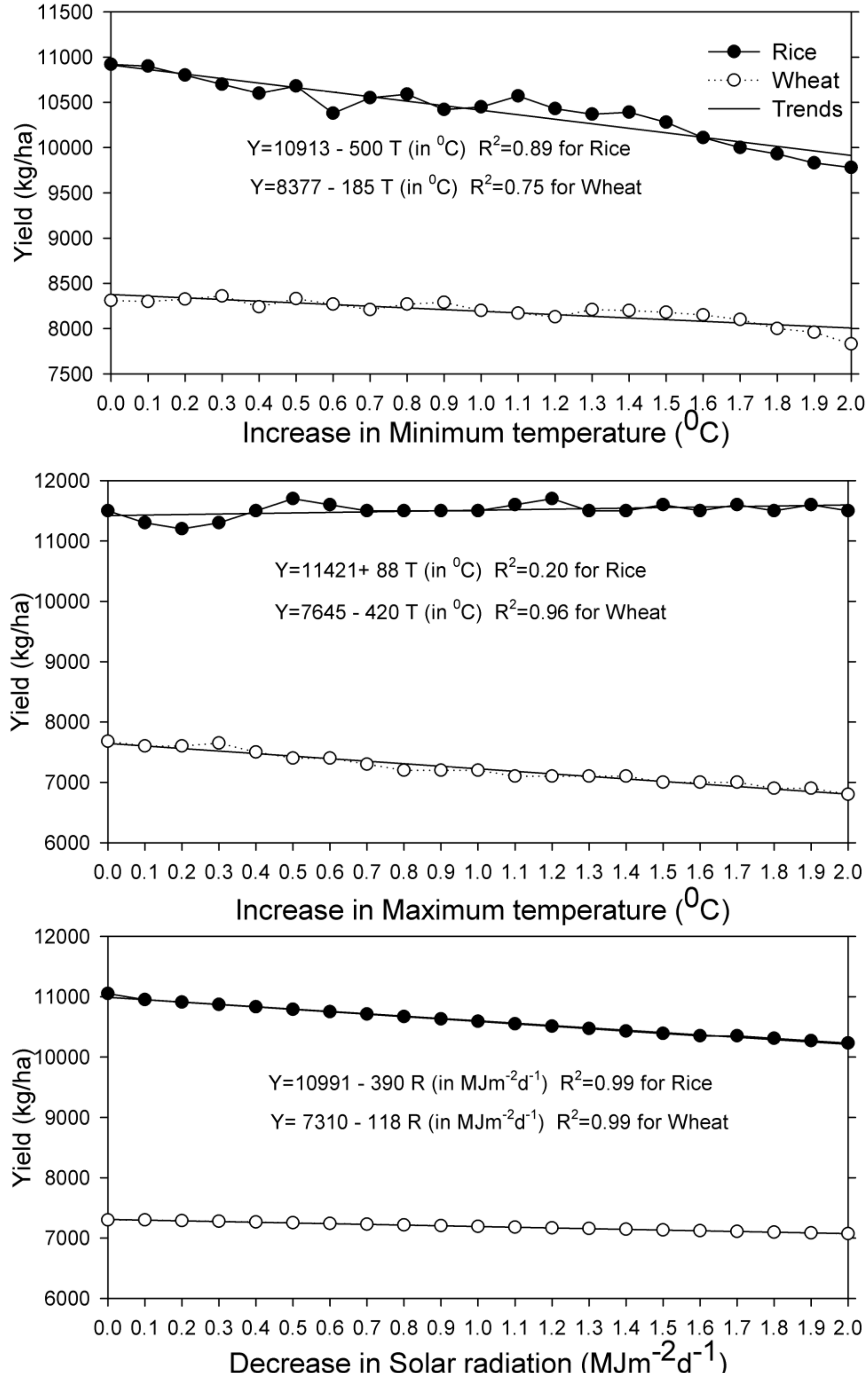

Fig. 7.2: Sensitivity of simulated potential yields of rice and wheat to the changes in solar radiation and minimum and maximum temperatures

Aggarwal *et al*. (2000a) estimated similar potential yields of rice and wheat in the IGP using daily weather data generated from monthly means by WGEN-weather and observed that Punjab and Haryana had 10 t/ha or more potential rice yield, which decreased in an eastward direction in the IGP. The potential yield of wheat was about two-thirds of that of the rice crop and followed the same declining trend from northwest to east. In another study (Mohandas *et al*., 1995), potential rice yield in Kapurthala district of Punjab in the upper Gangetic Plains was estimated to be 10.5 t/ha, whereas in Cuttack, Orissa, located in the southwest of the lower IGP, it was 7.1 t/ha.

Site	Period	Potential yield				District yield			
		Rice		Wheat		Rice		Wheat	
		Yield (t/ha)	Change (t/ha per year)	Yield (t/ha)	Change (t/ha per year)	Yield (t/ha)	Change (t/ha per year)	Yield (t/ha)	Change (t/ha per year)
Ludhiana	1974-2005	10.7	-0.029*	8.5	0.031**	3.8	0.019**	4.1	0.055
Hisar	1974-2005	10.4	0.009	7.1	0.01*	2.8	0.004	3.3	0.096**
Faizabad	1974-2005	8.7	0.025*	7.2	0.036**	1.7	0.055**	2.0	0.045**
Kanpur	1974-2005	9.5	0.048**	7.5	0.057**	1.7	0.043**	2.9	0.059**
Samastipur	1974-2005	9.4	0.039*	6.3	0.016	0.9	-0.023*	1.9	0.010

** Significant at P=0.05, ** Significant at P=0.01*

Table 7.6: Climatic potential and district average yields and yield changes over the years in IGR

The potential yield trend in rice ranged from -0.029 t/ha per year at Ludhiana to 0.048 t/ha per year at Kanpur (Fig. 7.3 and Table 7.6). Negative yield trends were observed in only Ludhiana and which is significantly different from 0 ($P < 0.05$). But all the other four sites, positive yield trends were noticed and at three stations significantly different.

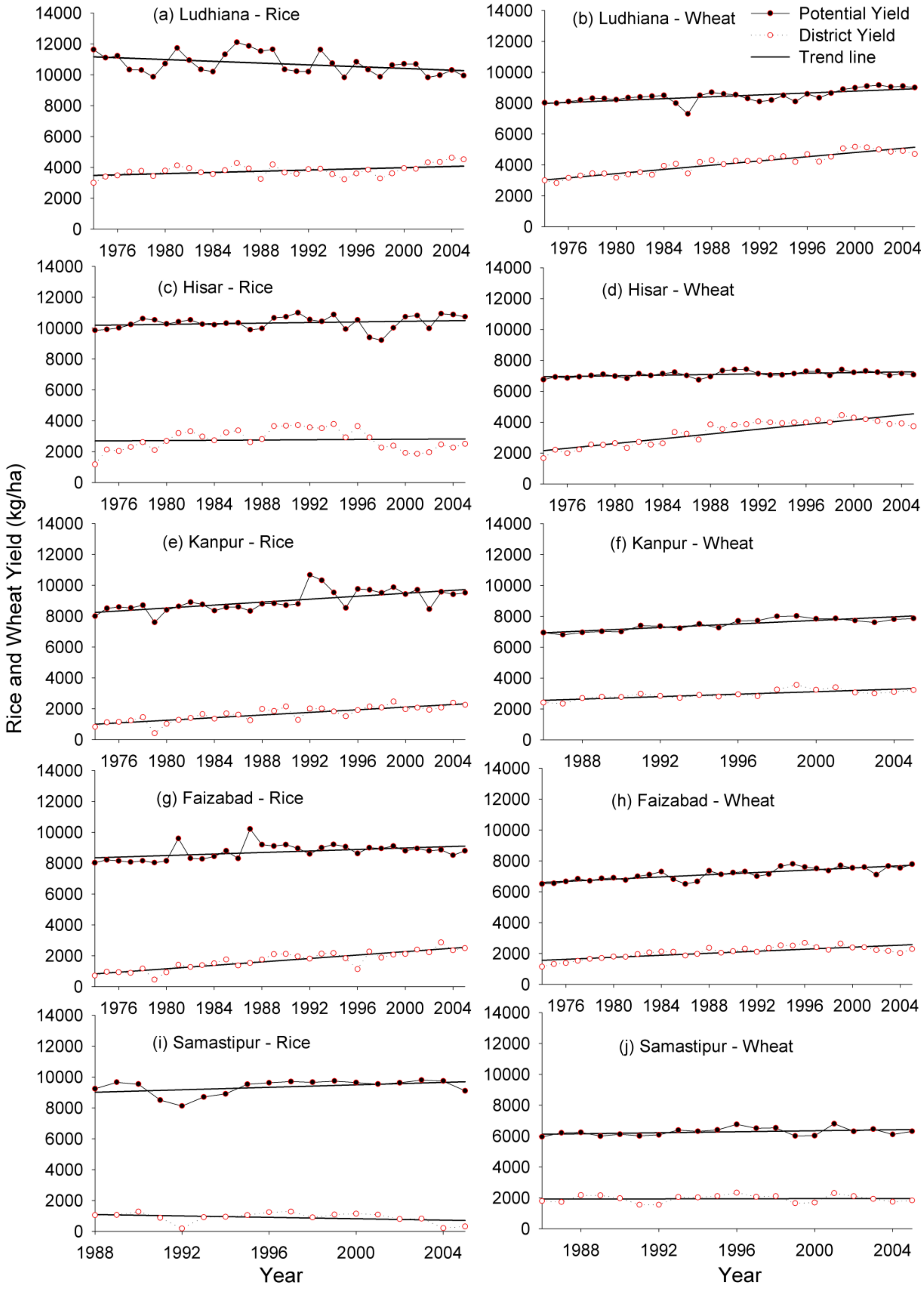

Fig. 7.3: Climatic potential and District yields of rice and wheat and its trends at the various sites of the IGR

The changes in radiation and minimum temperature are the reasons for the potential yield decline of rice for Ludhiana. In wheat, the rate of annual yield change ranged from 0.01 t/ha per year at Hisar to 0.057 t/ha per year for Kanpur. All the stations showed positive trends,

7.4.5. District yield trends

The rice and wheat productivity values were fitted into linear technological trend as described in Chapter 2. The rice and wheat technological trend equations and its regression statistics are shown in Table 7.7.

Sites	Linear Technological Productivity
Rice	
Ludhiana	TRP_{ti}= 3465.19+(19.4*ti) R=0.48 , SEE=342.79
Hisar	TRP_{ti}= 2683.22+(4.30*ti) R=0.06 , SEE=680.77
Faizabad	TRP_{ti}= 776.39+(55.00*ti) $R=0.88^{*}$, SEE=288.55
Kanpur	TRP_{ti}= 957.38+(42.83*ti) $R=0.83^{*}$, SEE=271.89
Samastipur	TRP_{ti}= 1111.39-(22.86*ti) R=0.36 , SEE=325.43
Wheat	
Ludhiana	TWP_{ti}= 3077.63+(55.23*ti) $R=0.66^{*}$, SEE=519.00
Hisar	TWP_{ti}= 1870.83+(95.97*ti) $R=0.95^{*}$, SEE=250.30
Faizabad	TWP_{ti}= 1398.24+(44.54*ti) $R=0.91^{*}$, SEE=172.40
Kanpur	TWP_{ti}= 2395.68+(58.95*ti) $R=0.87^{*}$, SEE=169.70
Samastipur	TWP_{ti}= 1861.40+(10.47*ti) R=0.20 , SEE=261.40

ti = 1,2,3, ……….. for the period from 1974-75 to 2005-06

* *Significant at 0.001 level*

Table 7.7: Linear and technological trend equations for rice and wheat productivity and its regression statistics for study sites

The district average yields of rice varied from 0.9 t/ha at Samastipur to 3.8 t/ha at Ludhiana (Table 7.5). Rice yields decreased from the west to east IGR. As with to rice, farmers in the western IGR harvested more wheat than those in the eastern regions.

Among other factors, favorable climate is responsible for the greater yields in the western part (Narang and Virmani, 2001). The time trend of rice yield ranged from -0.023 t/ha per year at Samastipur to 0.055 t/ha per year at Kanpur. Negative trends were observed in Samastipur and was significantly different from 0 ($P<0.05$). Positive trends were observed at four sites and three (Ludhiana, Faizabad and Kanpur) were statistically significant. The district yield trend resembled the trend of potential yield of rice to a great extent, indicating that climate also affected farmers' yields considerably. For eg., Ludhiana showing negative yield trends also recorded decline in sunshine hours and increase in minimum temperature. Thus the study showed that a reduction in sunshine hours/solar radiation and an increase in minimum temperature may be responsible for the yield decline of rice.

In wheat, the yield trend ranged from 0.01 t/ha per year at Samastipur to 0.096 t/ha per year at Hisar. All the sites had a positive yield trend and at three stations (Hisar, Faizabad and Kanpur) have significantly positive trends ($P<0.05$). Wheat yields appeared to be increasing throughout the IGR.

7.5. Drought Analysis

7.5.1. Simulated rice and wheat yields

The technological advancement factor in observed yield of rice and wheat were removed by linearly regressing the yield with the year and removing the contribution of trend from the observed yield. The mean, standard deviation and coefficient of variation of observed and simulated rice and wheat yields during 1974 to 2005 at the various sites of the IGR were given in Table 7.8. In the case of observed rice yields, the standard deviation was more for Hisar (671 kg/ha) followed by Faizabad (589 kg/ha), but coefficient of variation was higher for Samastipur (37.8 %) followed by Faizabad (35 %). However, Ludhiana which was showing a decreasing trend of observed rice yield showed less coefficient of variation (10.1 %). The same low value of coefficient of variation was also observed in the simulated rice yield of Ludhiana. The results also indicated that the coefficient of variation of simulated rice yields were low compared to observed rice yields in all the sites.

Site	Rice			Wheat		
	Mean Yield (kg/ha)	Standard deviation (kg/ha)	Coefficient of variation (%)	Mean Yield (kg/ha)	Standard deviation (kg/ha)	Coefficient of variation (%)
Observed						
Ludhiana	3786	383	10.1	4087	683	16.7
Hisar	2753	671	24.4	3341	801	24.0
Kanpur	1664	483	29.0	2935	301	10.3
Faizabad	1684	589	35.0	2060	380	18.5
Samastipur	894	338	37.8	1940	238	12.3
Simulated						
Ludhiana	4302	440	10.2	4542	683	15.0
Hisar	3829	687	18.0	3935	700	17.8
Kanpur	2817	441	15.7	3599	304	8.4
Faizabad	3063	554	18.1	3208	337	10.5
Samastipur	2655	371	14.0	2612	104	4.0

Table 7.8: Mean, Standard deviation and coefficient of variation of observed and simulated rice and wheat yield during 1974 to 2005 at various sites of IGR

The standard deviation of the observed wheat yield was higher for Hisar (801 kg/ha) followed by Ludhiana (683 kg/ha). A higher coefficient of variation was observed for Hisar (24 %) followed by Faizabad (18.5 %). The higher standard deviation and coefficient of variation indicated that there were high uncertainties in year-to-year rice yield. The higher coefficient of variation of rice yields over the eastern part of IGR may be due to more rainfed areas in these parts of the region. But in the case of observed wheat yields, higher year-to-year variability was noticed for Ludhiana and Hisar compared to eastern sites.

The observed rice yields ranged from 3000 kg/ha in the year 1974 to 4632 kg/ha in the year 2004 for Ludhiana. However, in the case of simulated rice yields, a higher yield of 5323 kg/ha was observed in the year 2004 and a lowest yield of 3620 kg/ha was observed in the year 1998 (Table 7.9). In the case of Hisar, the observed rice yields ranged from 1168 kg/ha in the year 1974 to 3782 kg/ha in the year 1994 have been noticed. The same pattern was not followed in the simulated rice yields. The same pattern of observed and simulated rice yield has been noticed for Kanpur and Faizabad sites. But as far as Samastipur site is concerned, highest observed rice yield of 1271 kg/ha was observed in 1990 and lowest (307 kg/ha) in 2005. However, simulated rice yields ranged from 1890 kg/ha in 1992 to 3100 kg/ha in 1997.

Site	Observed Rice Yield (t/ha)		Simulated Rice Yield (t/ha)	
	Lowest	Highest	Lowest	Highest
Ludhiana	3000 (1974)	4632 (2004)	3620 (1988)	5323 (2004)
Hisar	1168 (1974)	3782 (1994)	2634 (2002)	5002 (1994)
Kanpur	414 (1979)	2460 (1999)	1980 (1979)	3612 (1999)
Faizabad	448 (1979)	2860 (2003)	1834 (1979)	4234 (2003)
Samastipur	307 (2005)	1271 (1990)	1890 (1992)	3100 (1997)

(Figures in parenthesis indicates the year)

Table 7.9: Lowest and highest observed and simulated rice yield during the period 1974-2995 at various sites of IGR

In wheat, the same range of pattern of observed as well as simulated yields was noticed for all the sites (Table 7.10).

Site	Observed Wheat Yield (t/ha)		Simulated Wheat Yield (t/ha)	
	Lowest	Highest	Lowest	Highest
Ludhiana	2822 (1975)	5169 (2000)	3245(1975)	5578 (2000)
Hisar	1657 (1974)	4448 (1999)	2768 (1974, 76)	5089 (1999)
Kanpur	2337 (1987)	3547 (1999)	2987 (1987)	4089 (1999)
Faizabad	1129 (1974)	2676 (1996)	2456 (1974)	3789 (1996)
Samastipur	1547 (1992)	2335 (1996)	2430 (1992)	2780 (1996)

(Figures in parenthesis indicates the year)

Table 7.10: Lowest and highest observed and simulated wheat yield during the period 1974-2995 at various sites of IGR

The year-to-year deviation in observed and simulated rice and wheat yields were calculated and compared. The comparison of observed and simulated rice and wheat yield shows that there is very good agreement (Fig. 7.4) between them based on Spearman correlation coefficient (rs), significant at $P < 0.05$ level for all the sites except Samastipur (Table 7.11). In the case of Samastipur, the simulated and observed wheat yields follow the same pattern during lower yield years, but not in agreement during higher yield years.

Site	Spearman Correlation Coefficient, rs, between observed and simulated yields of	
	Rice	Wheat
Ludhiana	0.81 *	0.99 *
Hisar	0.98 *	0.97 *
Kanpur	0.96*	0.98 *
Faizabad	0.91 *	0.95 *
Samastipur	0.98 *	0.55

** Significant at $P < 0.05$*

Table 7.11: Spearman correlation coefficient between observed (de-trended) and simulated rice and wheat yields during the period 1974-2005 at various sites of IGR.

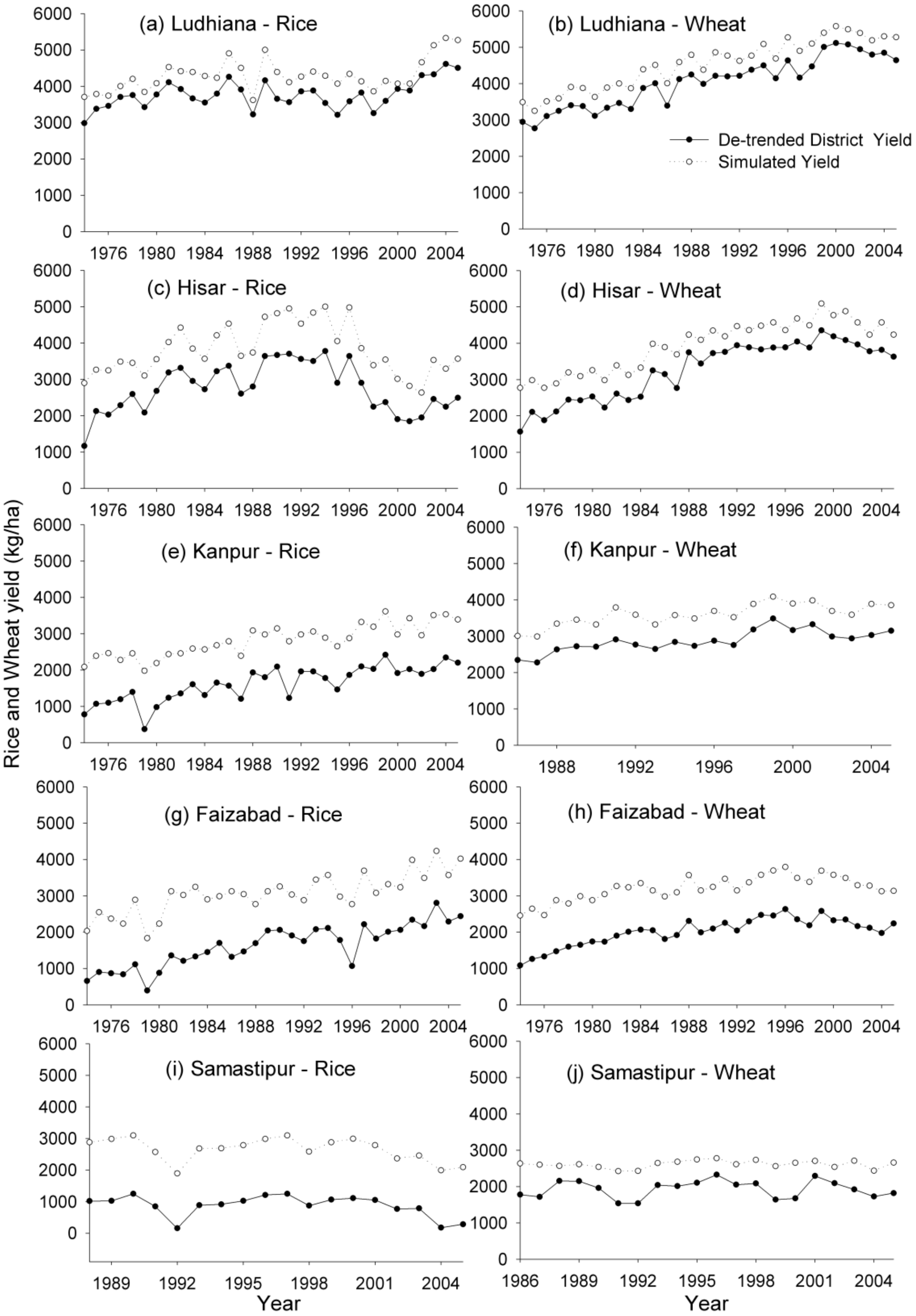

Fig. 7.4: Actual (de-trended) and simulated rice and wheat yields at various sites of the IGR

7.5.2. Crop Growth Simulation Model based Drought Index (CGSM-DI)

The average site conditions were prescribed in the DSSATv4.0, which were kept constant throughout the study period to observe the variation in rice and wheat yield due to differing inter-annual moisture regime. The simulated rice and wheat yields were converted into indices using the gamma distribution. From Fig. 7.5 to 7.9, it is clear that the Crop Growth Simulation Model based Drought Index (CGSM-DI) and Kharif Rice Productivity Index (KRPI) as well as CGSM-DI and Wheat Productivity Index (WPI) follow the same pattern. Even though, the CGSM-DI could capture all the extreme agricultural drought conditions with respect to rice and wheat for all the sites, its intensity differs (Fig. 7.10).

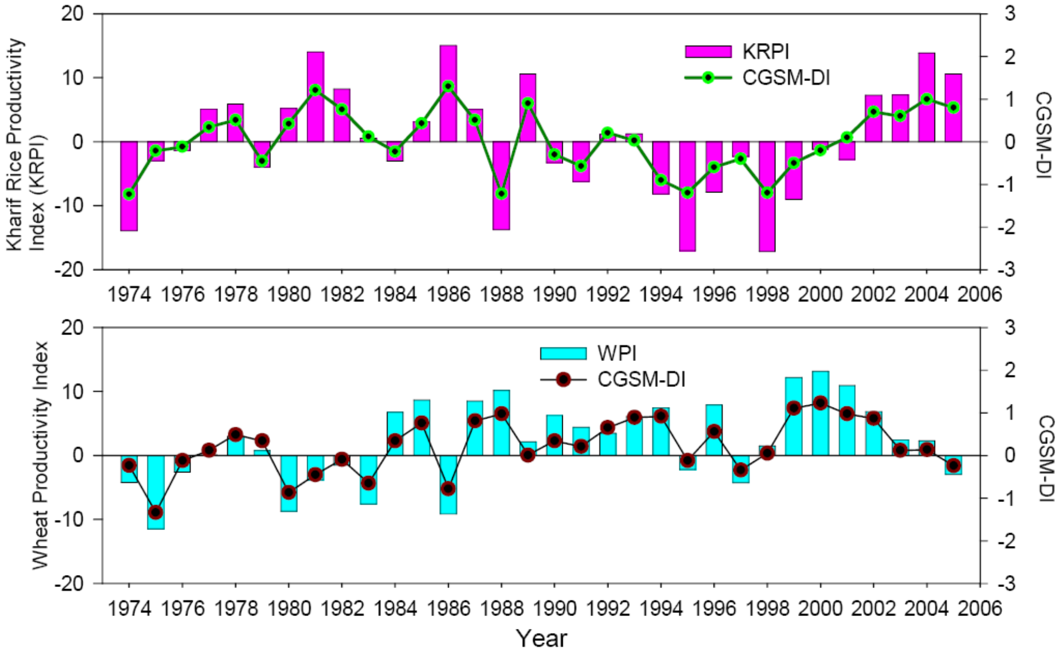

Fig. 7.5: Variability of CGSM-DI and KRPI and WPI for the period 1974-2005 for Ludhiana

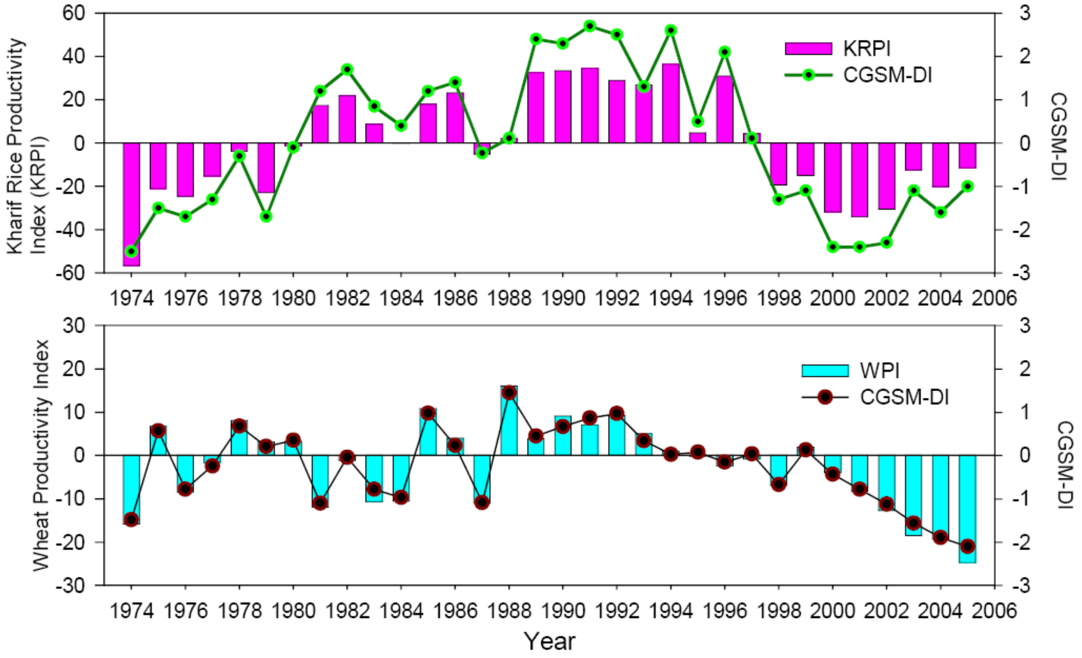

Fig. 7.6: Variability of CGSM-DI and KRPI and WPI for the period 1974-2005 for Hisar

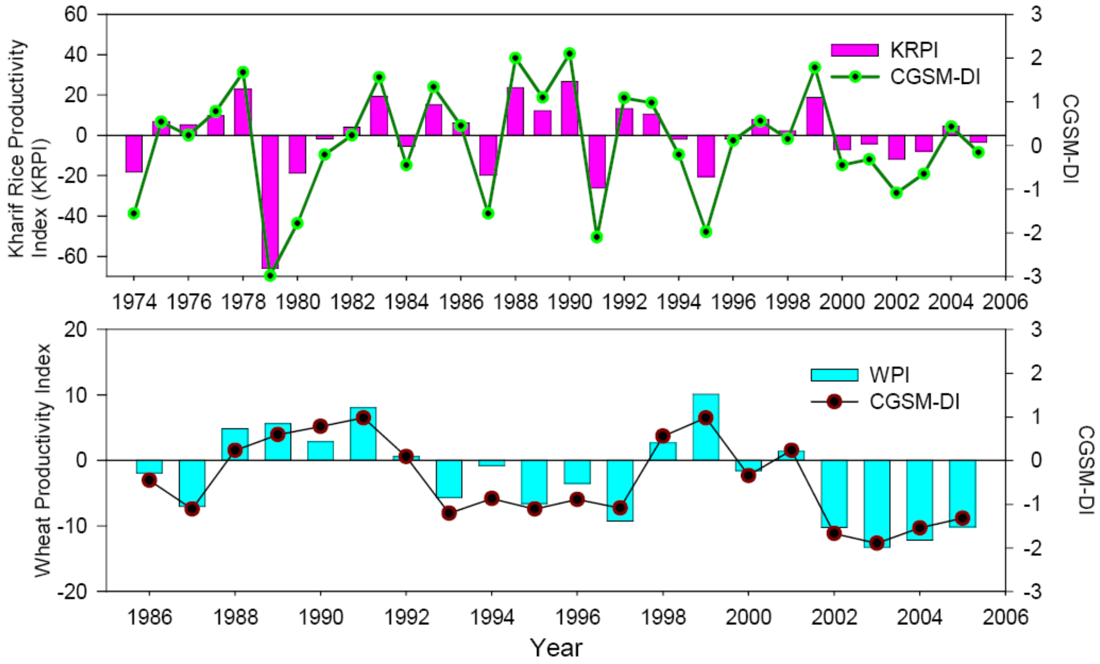

Fig.7.7: Variability of CGSM-DI and KRPI and WPI for the period 1974-2005 for Kanpur

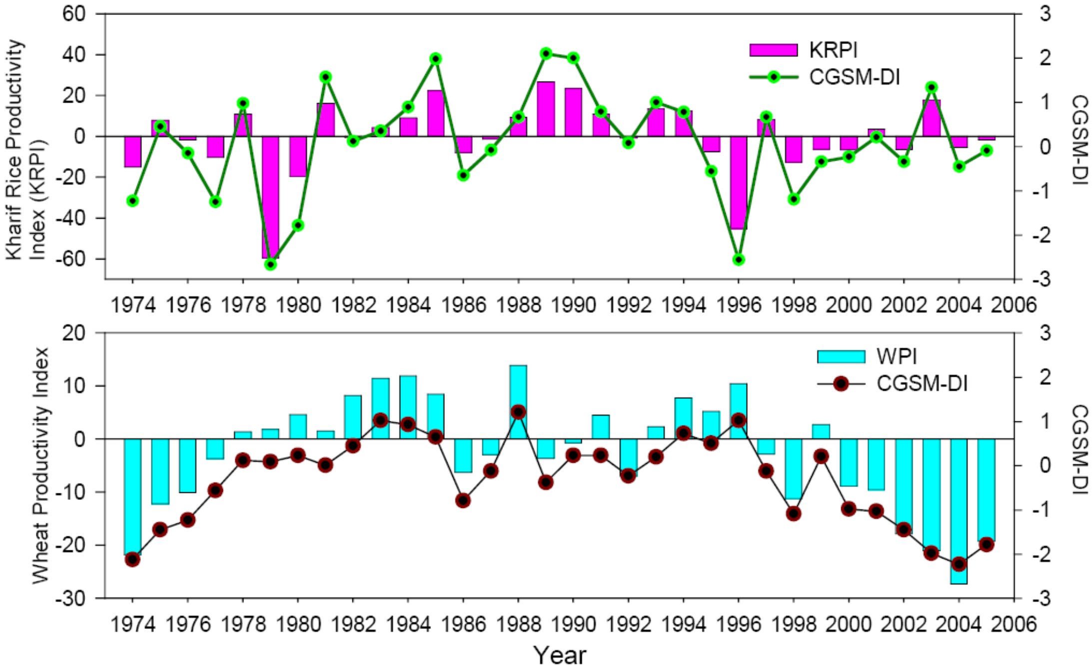

Fig 7.8: Variability of CGSM-DI and KRPI and WPI for the period 1974-2005 for Faizabad

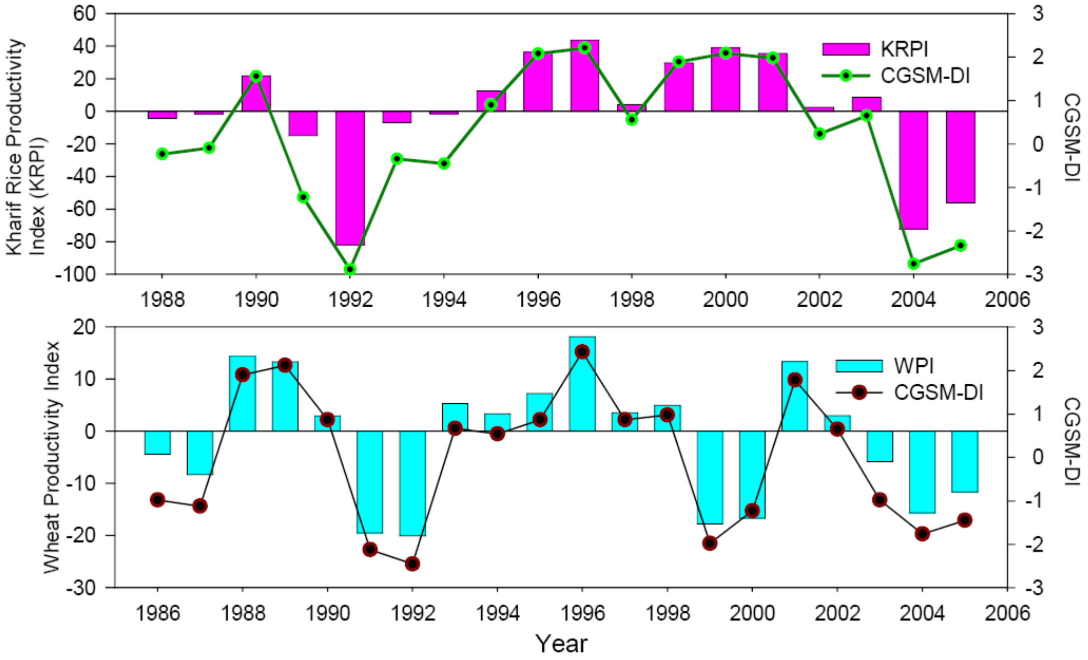

Fig.7.9: Variability of CGSM-DI and KRPI and WPI for the period 1986-2005 for Samastipur

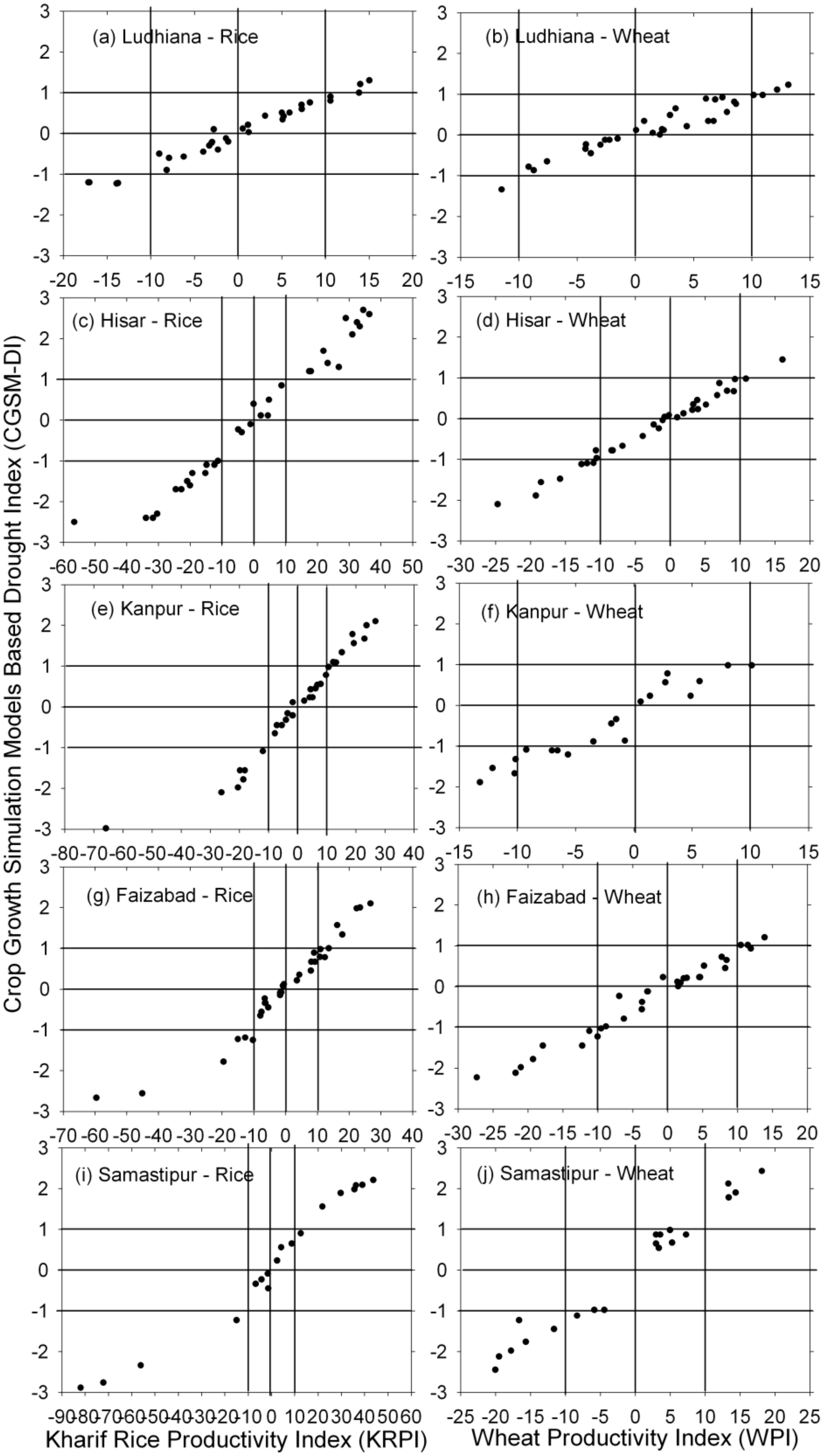

Fig. 7.10: Relation between CGSM-DI and KRPI and WPI for all the sites of IGR

Characterization of drought with crop growth simulation model has advantages that it calculates the water deficiency due to all possible causes including deficient rainfall, runoff, deep percolation and evapotranspiration. Pandey and Sastry (2004) concluded that for the characterization of agriculture drought water balance approach on weekly or less data set is required because water deficiency for even short duration in sensitive growth stage is more harmful than the long duration water deficiency during insensitive growth stages. It is clear from figure 7.10, most of the data points are scattered in the 1st and 3rd quadrant, which indicated that there is a direct relationship between CGSM-DI and productivity indices. Even though, it captures the drought years, but due to variation of intensity indicates that the drought assessment index needs more verification of other parameters also.

7.6. Projected Rice and Wheat yields

Based on the trends in rainfall, maximum and minimum temperature and sunshine hours during 1976-2007, the changes of these parameters for the years 2010, 2015, 2020 and 2025 were obtained by multiplying the yearly trends into number of years from the base year 2007. The changes of rainfall, maximum and minimum temperature and sunshine hours during kharif and rabi seasons 2010, 2015, 2020 and 2025 for the selected stations are given in Tables 7.12 & 7.13. These changes were incorporated into the normal daily weather of these stations for generating daily expected weather data for the years 2010, 2015, 2020 and 2025.

Year	Faizabad				Kanpur				Ludhiana			
	RF	Max	Min	SSH	RF	Max	Min	SSH	RF	Max	Min	SSH
2010	-24.75	-0.012	0.27	0.012	-11.19	0.09	-0.09	0	2.64	-0.03	0.18	-0.03
2015	-66	-0.032	0.72	0.032	-29.84	0.24	-0.24	0	7.04	-0.08	0.48	-0.08
2020	-107.25	-0.052	1.17	0.052	-48.49	0.39	-0.39	0	11.44	-0.13	0.78	-0.13
2025	-148.5	-0.072	1.62	0.072	-67.14	0.54	-0.54	0	15.84	-0.18	1.08	-0.18

Year	Hisar				Samastipur			
	RF	Max	Min	SSH	RF	Max	Min	SSH
2010	-61.5	0.21	-0.03	0.06	-4.44	0.03	0.09	-0.0006
2015	-164	0.56	-0.08	0.16	-11.84	0.08	0.24	-0.0016
2020	-266.5	0.91	-0.13	0.26	-19.24	0.13	0.39	-0.0026
2025	-369	1.26	-0.18	0.36	-26.64	0.18	0.54	-0.0036

Table 7.12: Changes of rainfall, maximum and minimum temperatures and sunshine hours during kharif season for the years 2010, 2015, 2020 and 2025 at selected stations of IGR

Year	Faizabad				Kanpur				Ludhiana			
	RF	Max	Min	SSH	RF	Max	Min	SSH	RF	Max	Min	SSH
2010	-1.74	-0.12	-0.03	-0.051	-0.42	0.09	-0.06	-0.0021	1.89	-0.003	0.18	-0.12
2015	-4.64	-0.32	-0.08	-0.136	-1.12	0.24	-0.16	-0.0056	5.04	-0.008	0.48	-0.32
2020	-7.54	-0.52	-0.13	-0.221	-1.82	0.39	-0.26	-0.0091	8.19	-0.013	0.78	-0.52
2025	-10.44	-0.72	-0.18	-0.306	-2.52	0.54	-0.36	-0.0126	11.34	-0.018	1.08	-0.72

Year	Hisar				Samastipur			
	RF	Max	Min	SSH	RF	Max	Min	SSH
2010	-2.04	-0.09	-0.27	-0.12	-0.36	-0.06	0.15	0.0006
2015	-5.44	-0.24	-0.72	-0.32	-0.96	-0.16	0.4	0.0016
2020	-8.84	-0.39	-1.17	-0.52	-1.56	-0.26	0.65	0.0026
2025	-12.24	-0.54	-1.62	-0.72	-2.16	-0.36	0.9	0.0036

Table 7.13: Changes of rainfall, maximum and minimum temperatures and sunshine hours during rabi season for the years 2010, 2015, 2020 and 2025 at selected stations of IGR

The projected rice and wheat yields were simulated using the DSSATv4.0 model using the above daily weather generated for 2010, 2015, 2020 and 2025 for all the stations, keeping all the management and other initial conditions constant as explained above sections.

Projected rice and wheat yields during 2010: The simulated rice yields for Faizabad, Kanpur and Hisar stations show a decline of 0.2, 2.6 and 1.5 per cent, respectively during 2010 compared to 2007 (Table 7.14). This may be due to the combined effect of decreasing trend in rainfall and increasing trend of maximum and minimum temperature during kharif season. The significant increase of mean temperature increases the degree days and thereby reduces the duration of crops which ultimately results in decrease in grain size as well as yield. Ludhiana and Samastipur showed increase in yields by 1.0 and 1.9 per cent, respectively, perhaps due to increasing trends in rainfall. The simulated wheat yield for Faizabad, Kanpur, Hisar and Samastipur show an increasing tendency of 7.5, 2.7, 7.0 and 1.3 per cent, respectively during 2010 when compared to 2007 (Table 7.15). This may be due to combined effect of decreasing trend in maximum and minimum temperature during the season. The significant decrease of mean temperature increases duration of crops which increase the grain size as well as yield. But as far as Ludhiana is concerned, the significant increasing trends in minimum temperature may have more control over other small changes in maximum and sunshine hours and influence the simulated rice yield causing a decreasing trend of 2.2 per cent from 2007 to 2010.

Year	Rice yield (kg/ha)				
	Faizabad	Kanpur	Ludhiana	Hisar	Samastipur
2007	4010	3620	5210	3567	2090
2010	4000(-0.2)	3526(-2.6)	5261(1.0)	3512(-1.5)	2130(1.9)
2015	3912(-2.4)	3427(-5.3)	5572(6.9)	3420(-4.1)	2220(6.2)
2020	3860(-3.7)	3360(-7.2)	5120(-1.7)	3400(-4.7)	2290(9.6)
2025	3720(-7.2)	3312(-8.5)	5012(-3.8)	3360(-5.8)	2327(11.3)

Table 7.14: Simulated rice yield (kg/ha) during 2007, 2010, 2015, 2020 and 2025 at selected stations of IGR *(Figures in parenthesis indicates the per cent decline/increase over 2007)*

	Wheat yield (kg/ha)				
	Faizabad	Kanpur	Ludhiana	Hisar	Samastipur
2005	3134	3856	5278	4234	2656
2010	3370(7.5)	3960(2.7)	5160(-2.2)	4500(7.0)	2690(1.3)
2015	3412(8.9)	4020(4.3)	5012(-5.0)	4530(6.3)	2830(6.6)
2020	3490(11.4)	4170(8.1)	4927(-6.7)	4620(9.1)	2890(8.8)
2025	3570(13.9)	4412(14.4)	4812(-8.8)	4612(8.9)	2910(9.6)

Table 7.15: Simulated wheat yield (kg/ha) during 2007, 2010, 2015, 2020 and 2025 at selected stations of IGR *(Figures in parenthesis indicates the per cent decline/increase over 2007)*

Projected rice and wheat yields during 2015: The simulated rice yields for Faizabad, Kanpur and Hisar show a decline of 2.4, 5.3 and 4.1 per cent, respectively during 2015 compared to 2007. But Ludhiana and Samastipur show an increase of 6.9 and 6.2 per cent, respectively. The simulated wheat yield for Faizabad, Kanpur, Hisar and Samastipur show an increasing tendency of 8.9, 4.3, 6.3 and 6.6 per cent, respectively during 2015 when compared to 2007. However, at Ludhiana there is a decline of 5.0 per cent.

Projected rice and wheat yields during 2020: The simulated rice yields for Faizabad, Kanpur and Hisar show a decline of 3.7, 7.2 and 4.7 per cent, respectively during 2020 compared to 2007. But at Ludhiana a decline of 1.7 from 2007 to 2020 has been noticed. Samastipur shows an increase of 9.6 per cent from 2007 to 2020. The simulated wheat yield for Faizabad, Kanpur, Hisar and Samastipur show an increasing tendency of 11.4, 8.1, 9.1 and 8.8 per cent, respectively during 2020 when compared to 2007. However, at Ludhiana there is a decline of 6.7 per cent.

Projected rice and wheat yields during 2025: The simulated rice yield for Faizabad, Kanpur, Ludhiana and Hisar show a decreasing tendency of 7.2, 8.5 3.8 and 5.8 per cent, respectively during 2025 when compared to 2007. Samastipur shows an increasing simulated rice yield of 11.4 per cent from 2007 to 2025. Since Samastipur receive an average 1069.9 mm rainfall during kharif season and the area is usually affected by floods during the entire crop season, decrease of rainfall during the season may have helped the rice crop to project a higher simulated rice yield in 2025.

The simulated wheat yield for Faizabad, Kanpur, Hisar and Samastipur show an increasing tendency of 13.9, 14.4, 8.9 and 9.6 per cent, respectively during 2025 when compared to 2007 (Table 7.15). This may be due to combined effect of decreasing trend in either maximum or minimum temperature during the season. The significant decrease of mean temperature increases the growing period and thereby duration of crops and ultimately increases the grain size as well as yield. But as far as Ludhiana is concerned, the significant increasing trends in minimum temperature of the order of 1 ^{0}C may have more control over other small changes in maximum and sunshine hours and influence the simulated rice yield: thus a decreasing trend of 8.8 per cent from 2007 to 2025.

The expected yield decline in the year 2025 is a matter of serious concern and improved germplasm with more adjustability in the changed climate should be developed. Steps to improve the input use efficiency and to adopt modern management technologies such as zero tillage, timely sowing/transplanting, use of irrigation water for nursery preparation during kharif season etc. should be encouraged Since all these five locations are representative sites for the entire IGR, the decreasing trend of rice productivity of four stations and decreasing trend of wheat productivity of one station may adversely affect the food security of the region and measures should be taken to stabilize the productivity under changing climatic scenario. Even though, these projected yields don’t consider the technological advancement as well as the incidence of pest and diseases, they still provide an indication of yield variability under projected climatic conditions.

CHAPTER 8

Rational Integration of SPI, NDVI and CGSM-DI for Assessment of Drought

8.1. Introduction

Crop growth and yields are influenced by a number of factors such as genetic nature of crop cultivar, soil, weather, management practices adopted (date of sowing/transplanting, amount and time of fertilizer and irrigation application) and biotic stresses. In a rainfed agriculture system, the year-to-year variability of yield can be attributed to the dependency of agriculture production to precipitation. The year-to-year variability is so erratic that rainfed agriculture witnesses drought conditions very frequently. However, for a known area, year-to-year yield variability has been mostly modelled through rainfall and other weather parameters as predictors using either empirical or crop growth simulation models. As seen in earlier Chapters, even though meteorological indices explain yield variability to some extent, they generally do not take into account the soil as well as crop parameters. But in the crop growth simulation model, the daily crop growth and development is modelled with an integrated time step approach. The use of remotely sensed information to improve crop model accuracy was proposed as early as three decades ago by Wiegand *et al.* (1979) and Richardson *et al.* (1982). They suggested using spectrally derived Leaf Area Index (LAI) either as direct input to physiological crop model or as an independent check to model calculations for its re-initialization. The main advantage of using remotely sensed information is that it provides a quantification of the actual state of crop for large areas using less labour and material-intensive methods than *in situ* sampling. While crop models provide a continuous estimate of growth over time, remote sensing provides a multispectral assessment of instantaneous crop condition within a given area (Delecolle *et al.*, 1992). The different ways to combine a crop model with remote sensing observations (radiometric or satellite data) were initially described by Maas (1988) and this classification scheme was revised by Delecolle *et al.* (1992) and by Moulin *et al.* (1998). Five methods of remote sensing data integration into the models have been identified (Dadhwal, 2003): (a) the direct use of a driving variable estimated from RS data in the model: (b) the updating of a state variable of the model (e.g., LAI) derived from RS ('forcing' strategy); (c) the re-initialization of the model, i.e., the adjustment of an initial condition to obtain a simulation in agreement with the RS derived observations; (d) the re-calibration of the model, i.e., the adjustment of model parameters to obtain a simulation in agreement with the remotely-sensed derived observations, also called 're-parameterization' strategy; (e) the corrective method, i.e., a relationship is developed between error in some intermediate variable as estimated from remotely sensed measurement and error in final yield. This relationship may be applied to a case in which final yield is not known.

In earlier chapters we have dealt with different approaches i.e., meteorological indices (SPI and MRI), remote sensing index (NDVI) and CSSM-DI independently with respect to rice and wheat for agricultural drought assessment. In this Chapter, we compare the three different approaches for characterizing the agricultural drought conditions with respect to rice and wheat and also make an attempt to improve the drought assessment strategy by rational integration of these approaches.

8.2. Relation between Standardized Precipitation Index (SPI) and Monthly Rainfall Index (MRI) on Kharif Rice Productivity Index (KRPI)

In order to get the influence of monthly distribution of rainfall on yield, the month-wise SPI from June to September were regressed to KRPI (Fig. 8.1). It is found that June, August and September SPI have positive correlation with KRPI while July SPI has no influence on KRPI. The September SPI has significant correlation with rice yield and explains 34 % variability of rice productivity. The combined influence during June to September SPI explains 54 % variations in rice productivity (Table 8.1).

Months	Regression Equation	SEE	R-value
June	$KRPI=-8.862+3.985 \times SPI_{(June)}$	22.61	0.24
July	$KRPI=-5.963+0.241 \times SPI_{(July)}$	23.26	0.02
August	$KRPI=-6.869+5.509 \times SPI_{(August)}$	21.59	0.37
September	$KRPI=-9.844+9.233 \times SPI_{(September)}$	18.30	0.62**
June-July	$KRPI=-8.780+4.316 \times SPI_{(June)}- 0.901 \times SPI_{(July)}$	22.98	0.24
June-August	$KRPI=-9.790+4.175 \times SPI_{(June)}- 0.554 \times SPI_{(July)}+ 5.568 \times SPI_{(August)}$	21.66	0.44**
June-September	$KRPI=-13.907+3.919 \times SPI_{(June)}+1.125 \times SPI_{(July)}+ 4.451 \times SPI_{(August)} +9.014 \times SPI_{(September)}$	16.71	0.74**

Table 8.1: Correlation between monthly SPI and KRPI *(** significant correlation)*

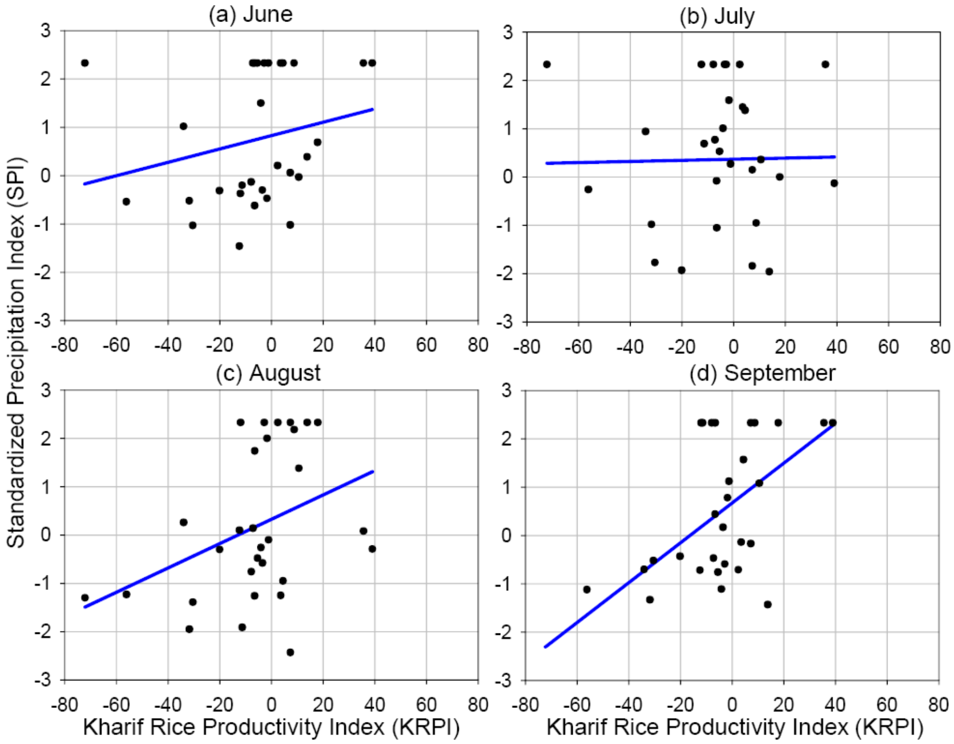

Fig. 8.1: Correlation between monthly SPI and KRPI

Since SPI is a meteorological drought index, it indicates that rainfall climatology alone contributes 54 % variability in rice productivity. The actual kharif rice productivity data contains both irrigated and rainfed rice and on average about 50 % of the area in the IGR is rainfed: this higher per cent contribution of SPI to KRPI offers SPI as a good indicator of rice productivity variations in these parts.

KRPI is better correlated with MRI than with SPI on a monthly basis. Interestingly, the July MRI and KRPI showed a negative correlation, though statistically not significant (Fig.8.2). But combined influence of MRI during June to September with KPRI showed only 46 %, which is lower compared to SPI (Table 8.2). Thus SPI is a good indicator of agricultural drought with respect to rice over the IGR region. The same was noticed in the State-wise study also.

Months	Regression Equation	SEE	R-value
June	KRPI=-6.601+0.103 x $MRI_{(June)}$	22.05	0.32
July	KRPI=-6.255-0.0215 x $MRI_{(July)}$	23.24	0.05
August	KRPI=0.497+0.229 x $MRI_{(August)}$	21.15	0.42**
September	KRPI=-3.696+0.162 x $MRI_{(September)}$	20.61	0.46**
June-July	KRPI=-8.242+0.124 x $MRI_{(June)}$- 0.0844 x $MRI_{(July)}$	22.09	0.36
June-August	KRPI=-2.242+0.113 x $MRI_{(June)}$- 0.0921 x $MRI_{(July)}$+ 0.218 x $MRI_{(August)}$	20.40	0.53**
June-September	KRPI=-0.274+0.112 x $MRI_{(June)}$-0.0577 x$MRI_{(July)}$+ 0.195 x $MRI_{(August)}$ +0.149 x $MRI_{(September)}$	18.08	0.68**

Table 8.2: Correlation between monthly MRI and KRPI *(** significant correlation)*

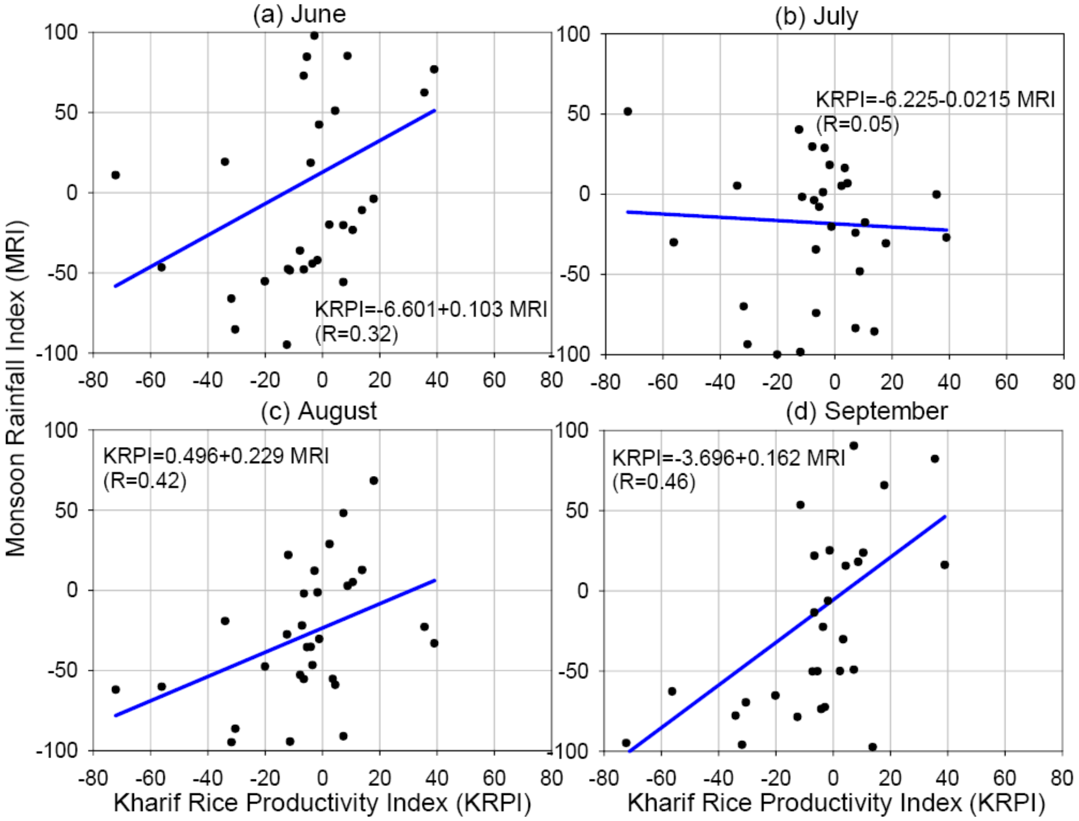

Fig. 8.2: Correlation between monthly MRI and KRPI

8.3. Relation between SPI and MRI on Wheat Productivity Index (WPI)

Even though, wheat crop is not directly linked with monsoon season, around 90 per cent of the wheat area over IGR is under irrigated class. Irrigation options such as surface water (i.e., reservoirs and canals) and subsurface water (i.e., ground water), are affected due to variation of rainfall pattern during the monsoon season. Thus, the monthly SPI and MRI during the monsoon season during June to September were regressed with WPI. It is noticed that June, July and August SP have positive correlation with WPI, but not statistically significant (Fig. 8.3). However, it has been noticed that the September SPI has negative correlation with WPI.

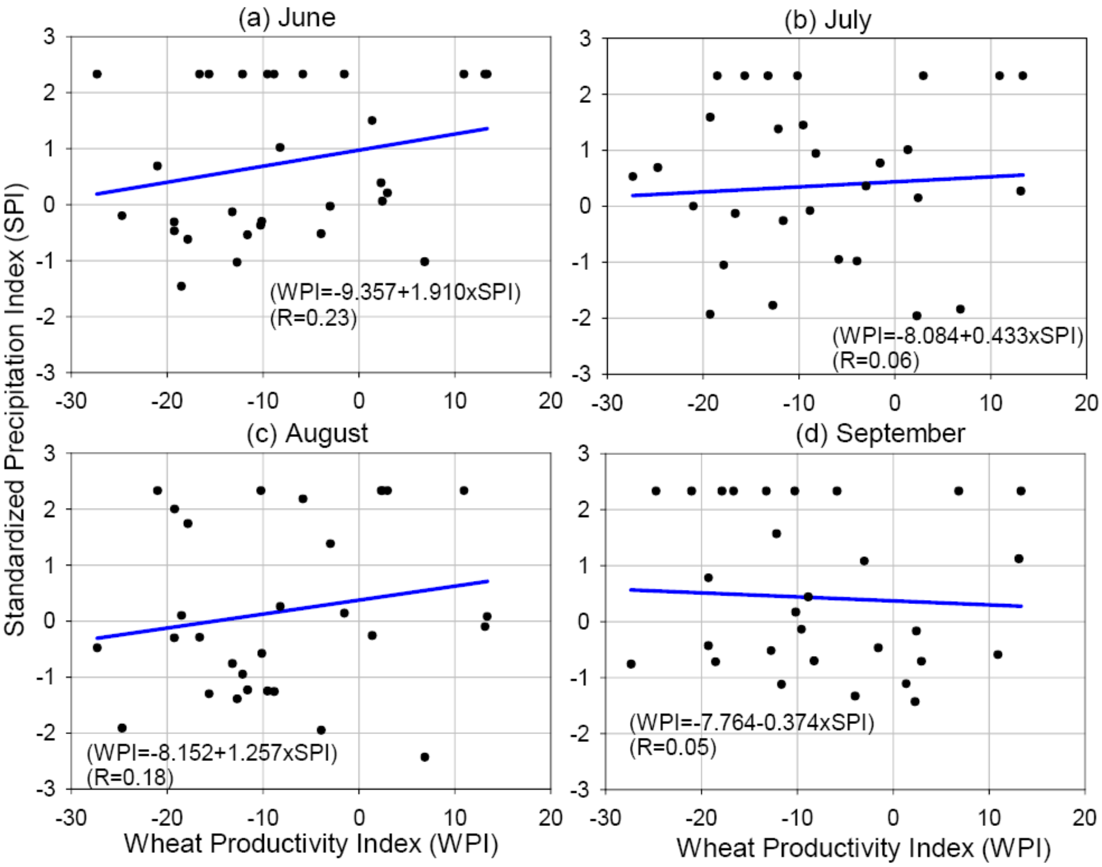

Fig. 8.3: Correlation between monthly SPI and WPI

Higher rainfall during September may delay the rice harvest and thereby subsequent delay of sowing operations of wheat and this eventually may affect the wheat crop in two ways. The delay of wheat sowing may affect the germination of wheat and it will extend the Crown Root Initiation (CRI) stage and finally expose the milky stage to higher maximum temperature during summer season. This may be the reason for negative correlation of September SPI with WPI. The combined effect of SPI during June to September showed that SPI explains only 9 % variability in wheat productivity (Table 8.3).

Months	Regression Equation	SEE	R-value
SPI			
June-July	WPI=-9.350+1.939 x SPI$_{(June)}$- 0.0803 x SPI$_{(July)}$	11.07	0.23
June-August	WPI=-9.581+1.907 x SPI$_{(June)}$- 0.0.000707 x SPI$_{(July)}$+ 1.254x SPI$_{(August)}$	11.09	0.29
June-September	WPI=-9.353+1.921 x SPI$_{(June)}$-0.0938 x SPI$_{(July)}$+ 1.310 x SPI$_{(August)}$ -0.499 x SPI$_{(September)}$	11.29	0.30
MRI			
June-July	WPI=-8.187+0.0345 x MRI$_{(June)}$- 0.00105 x MRI$_{(July)}$	11.11	0.22
June-August	WPI=-7.091+0.0326 x MRI$_{(June)}$- 0.00246 x MRI$_{(July)}$+ 0.0398 x MRI$_{(August)}$	11.19	0.27
June-September	WPI=-7.117+0.0326 x MRI$_{(June)}$-0.0029 x MRI$_{(July)}$+ 0.0401 x MRI$_{(August)}$ -0.00192 x MRI$_{(September)}$	11.41	0.27

Table 8.3: Correlation between monthly MRI and WPI

The correlation between MRI and WPI also follows the same pattern of SPI (Fig. 8.4), but the negligible increase of coefficient is not statistically significant. The combined effect of MRI during June to September explains only 7 % variations in wheat productivity. But in the State-wise study, we found that the MRI explains larger variability compared to district-wise study. However, MRI drought indices might not explain the yield variations in wheat.

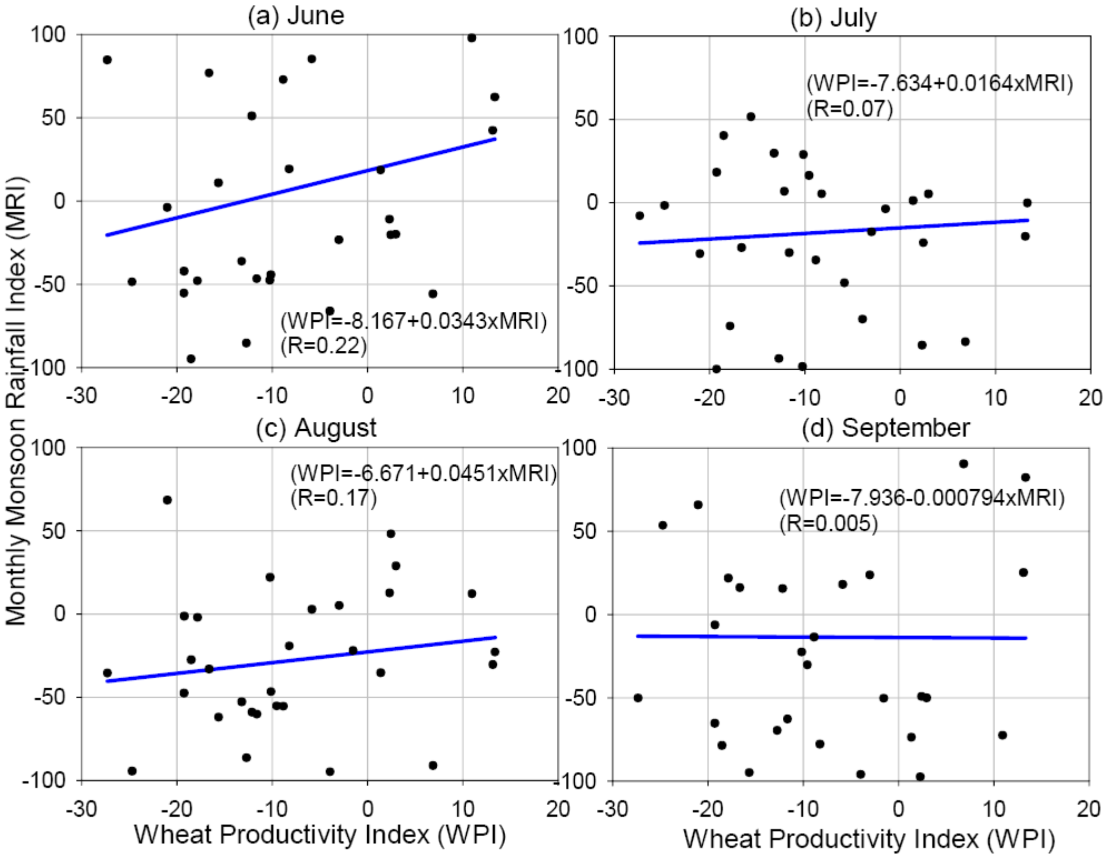

Fig. 8.4: Correlation between monthly MRI and WPI

8.4. NDVI analysis over selected stations

8.4.1. Historical monthly mean NDVI pattern over selected stations

The monthly composite NDVI values during 2000-2005 showed high spatial variability and temporal variability (Fig. 8.5). For Ludhiana, it ranged from 0.20 to 0.80 while for Samastipur it ranged from 0.30 to 0.70. It is also noticed that the higher values of NDVI for Ludhiana followed by Hisar and lower values for Samastipur during rice and wheat seasons are closely linked with the productivity of these crops. As discussed earlier, the productivity has a decreasing trend towards eastern region and NDVI pattern also supports the observation.

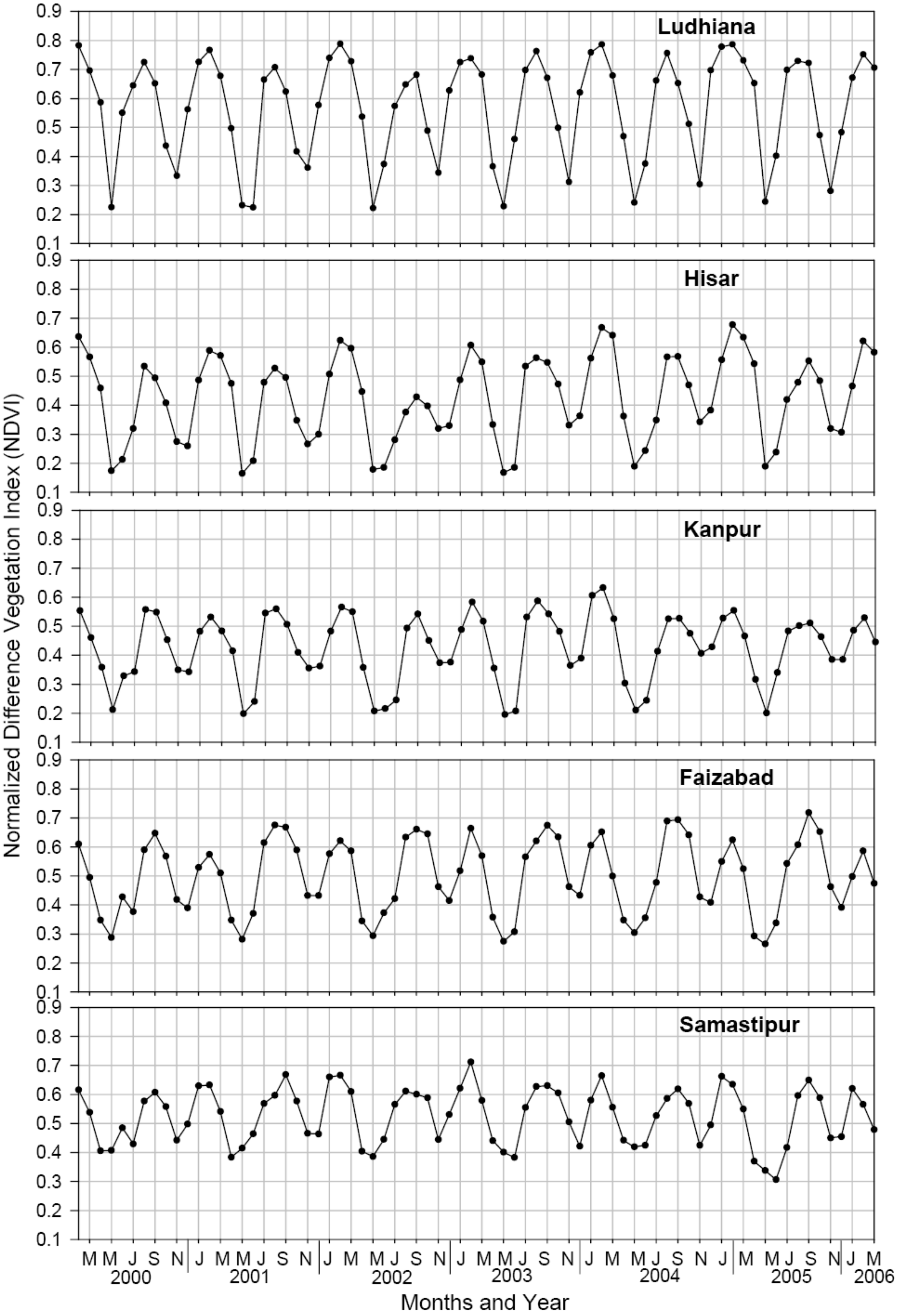

Fig.8.5: Monthly composite NDVI during the period 2000-2005 over IGR States

Maximum NDVI was attained during wheat season for Ludhiana and Hisar while for Faizabad and Samastipur, it was attained during the rice season. For Ludhiana maximum NDVI of 0.77 was reached during February followed by 0.73 during January and higher coefficient of variation(CV) of 24.8 % was noticed during June (Table 8.4).

Months	Ludhiana			Hisar			Kanpur			Faizabad			Samastipur		
	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV	M	SD	CV
Jan	0.73	0.03	4.53	0.51	0.04	7.05	0.51	0.04	8.76	0.55	0.04	6.62	0.63	0.03	4.39
Feb	0.77	0.02	2.38	0.63	0.03	4.68	0.56	0.03	5.82	0.62	0.03	4.86	0.64	0.04	6.62
Mar	0.70	0.02	2.99	0.59	0.03	5.46	0.49	0.04	7.27	0.52	0.04	7.24	0.55	0.04	6.80
Apr	0.52	0.09	17.45	0.44	0.07	16.08	0.35	0.04	10.14	0.34	0.02	6.34	0.41	0.03	6.59
May	0.23	0.01	3.47	0.18	0.01	5.44	0.20	0.01	3.21	0.28	0.01	4.37	0.39	0.03	6.95
June	0.40	0.10	24.78	0.21	0.02	10.61	0.26	0.05	19.86	0.36	0.04	10.14	0.42	0.06	14.20
July	0.66	0.04	6.38	0.40	0.09	22.49	0.43	0.11	24.91	0.50	0.08	16.57	0.51	0.06	12.41
Aug	0.72	0.04	5.25	0.51	0.07	12.95	0.54	0.03	6.25	0.64	0.04	5.59	0.60	0.02	2.71
Sept	0.67	0.03	4.58	0.51	0.05	9.25	0.53	0.02	3.09	0.68	0.02	3.41	0.63	0.02	3.75
Oct	0.47	0.03	7.16	0.43	0.05	11.46	0.46	0.02	5.14	0.62	0.03	5.08	0.58	0.02	2.64
Nov	0.32	0.03	8.25	0.31	0.03	9.15	0.37	0.02	5.21	0.44	0.02	4.22	0.46	0.03	5.58
Dec	0.59	0.07	11.07	0.32	0.04	12.62	0.38	0.03	6.93	0.41	0.02	4.23	0.48	0.04	7.35

(M- Mean, SD-Standard Deviation and CV- Coefficient of Variation)

Table 8.4: NDVI statistics (mean, standard deviation and coefficient of variation) over selected districts of IGR

Higher CV was noticed during June-August (> 10 %) for Hisar. For Kanpur, higher CV of 24.9 % was noticed during July followed by 19.9 % during June. Similarly, high year-to-year variability has been noticed during June and July for Samastipur and Faizabad. Thus the high year-to-year variability of NDVI during rice season suggests that the variability of rainfall pattern within a normal month may influence the vegetative growth of rice plants. During rainy season, maximum NDVI was attained during August for Ludhiana, Hisar and Kanpur while it was during September for Faizabad and Samastipur (Table 8.5).

Year	Maximum NDVI during rice season				
	Ludhiana	Hisar	Kanpur	Faizabad	Samastipur
2000	0.73 (Aug)	0.53(Aug)	0.56(Aug)	0.65(Sept)	0.61(Sept)
2001	0.71(Aug)	0.53(Aug)	0.56(Aug)	0.68(Aug)	0.67(Sept)
2002	0.68(Sept)	0.43(Sept)	0.54(Sept)	0.66(Sept)	0.61(Aug)
2003	0.76(Aug)	0.56(Aug)	0.59(Aug)	0.67(Sept)	0.63(Sept)
2004	0.76(Aug)	0.57(Aug)	0.53(Aug)	0.69(Sept)	0.62(Sept)
2005	0.73(Aug)	0.55(Sept)	0.51(Sept)	0.72(Sept)	0.65(Sept)

Table 8.5: Maximum NDVI occurred during rice season for selected districts of IGR during the period 2000-2005.

This indicates that maximum tillering phase was during August in the western part of the region while it was September in the eastern part of the IGR. This may be due to the one month difference in dates of transplanting of rice – June in western parts and July in the eastern parts. Due to well developed canal network and irrigation facilities, the resource rich farmers of western part start their field operations and nursery preparation before the onset of monsoon. But in the eastern region, the resource crunch farmers wait for the onset of monsoon to start their nursery preparation. In the case of wheat, maximum NDVI was obtained during February at all the stations except Samastipur during the years 2004 and 2005 (Table 8.6).

Year	Maximum NDVI during wheat season				
	Ludhiana	Hisar	Kanpur	Faizabad	Samastipur
2000	0.77(Feb)	0.59(Feb)	0.53(Feb)	0.57(Feb)	0.63(Jan,Feb)
2001	0.79(Feb)	0.62(Feb)	0.57(Feb)	0.62(Feb)	0.67(Feb)
2002	0.74(Feb)	0.61(Feb)	0.58(Feb)	0.66(Feb)	0.71(Feb)
2003	0.79(Feb)	0.67(Feb)	0.63(Feb)	0.65(Feb)	0.66(Feb)
2004	0.79(Feb)	0.68(Feb)	0.55(Feb)	0.62(Feb)	0.66(Jan)
2005	0.75(Feb)	0.62(Feb)	0.53(Feb)	0.59(Feb)	0.63(Jan)

Table 8.6: Maximum NDVI occurred during wheat season for selected districts of IGR during the period 2000-2005.

8.4.2. Relation between Maximum NDVI and Rice and Wheat Productivity

Since the NDVI measures the vegetative vigour of the crop, the maximum NDVI during the crop season is more indicative of plant growth compared to monthly variation of NDVI during the season. The maximum NDVI during the rice crop season has a positive correlation with KRPI between them, though not statistically significant. But as a single factor/variable, it contributes about 14 per cent variation in rice productivity. Moreover in wheat, the maximum NDVI and WPI have a significant correlation coefficient of 0.49 and explain about 24 % variations in WPI (Fig. 8.6 and Fig. 8.7).

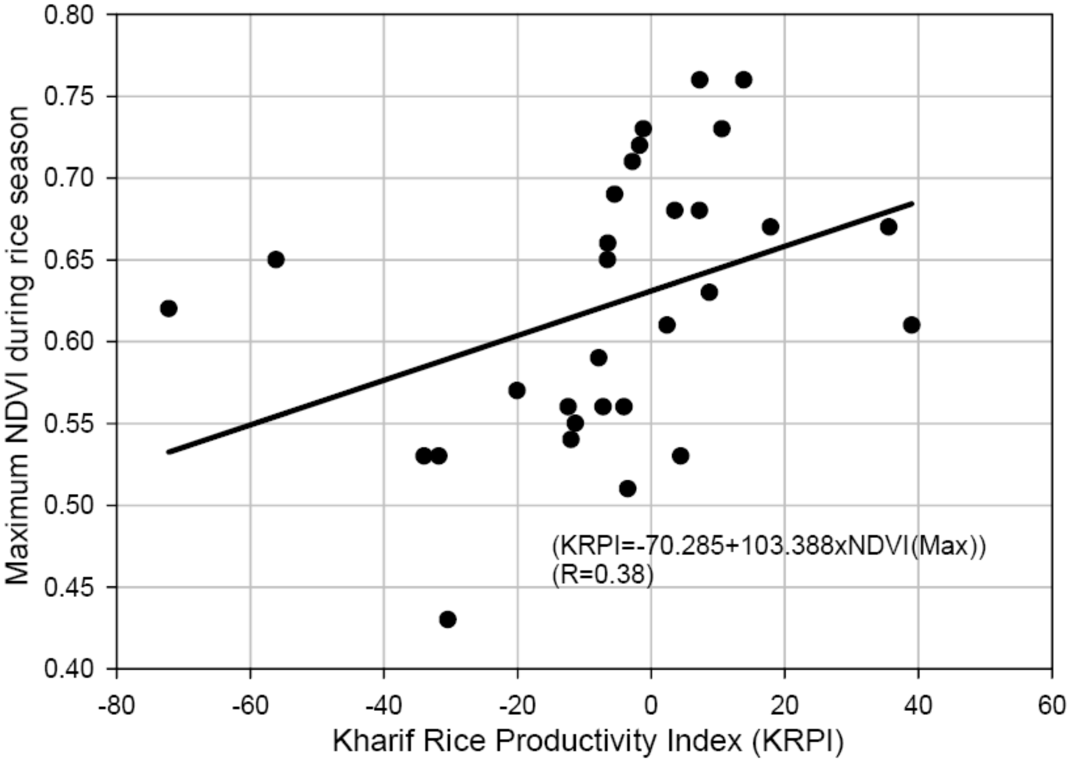

Fig. 8.6: Relation between maximum NDVI and kharif rice productivity index

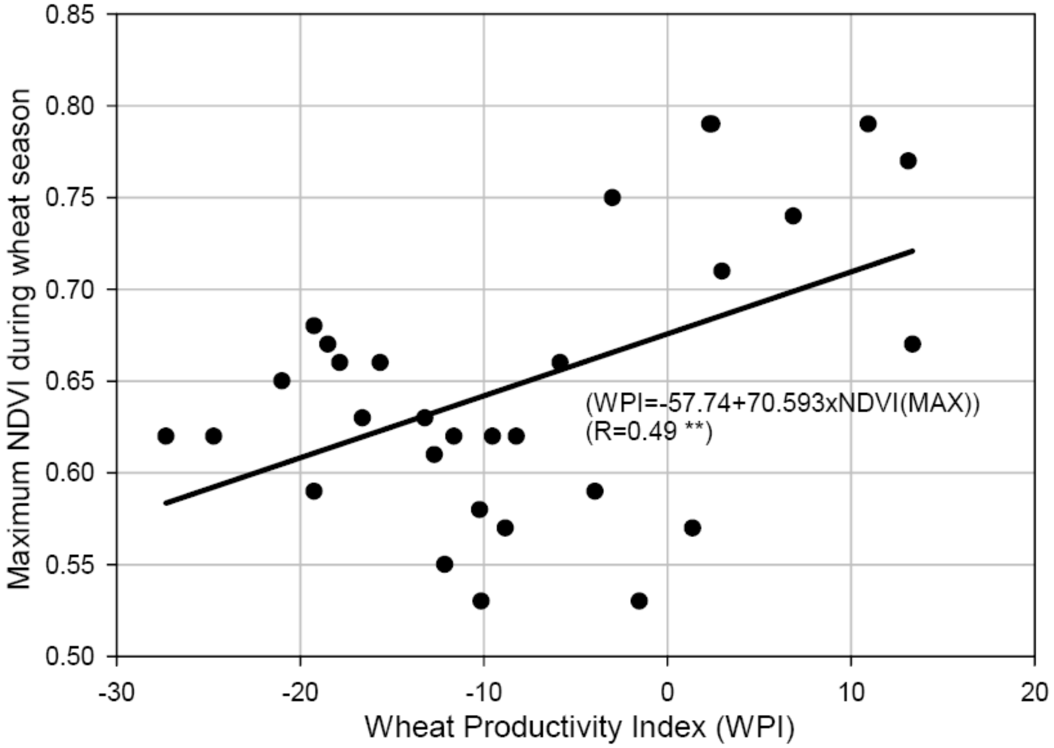

Fig. 8.7: Relation between maximum NDVI and wheat productivity index

8.4.3. Variation of NDVI during drought and normal years

The extent of negative deviation of NDVI from its long-term mean for a pixel, district or region, and the duration of continuous negative deviations are powerful indicators of drought magnitude and persistence. Fig. 8.8 shows NDVI conditions during the drought year (2002-03) and the normal year (2004-05) over selected stations of IGR. A year is considered normal if seasonal rainfall is within ± 1 standard deviation from the climatological mean. NDVI values for each month from June to March for the selected study stations of IGR were plotted. At all the stations, except Samastipur, the NDVI values during drought year are below the values during normal year during the rice season. During the wheat season NDVI values at Ludhiana and Hisar, in the drought year were below the NDVI value during normal year. However, the NDVI values at

Kanpur, Faizabad and Samastipur were higher in the drought year as compared to the normal year.

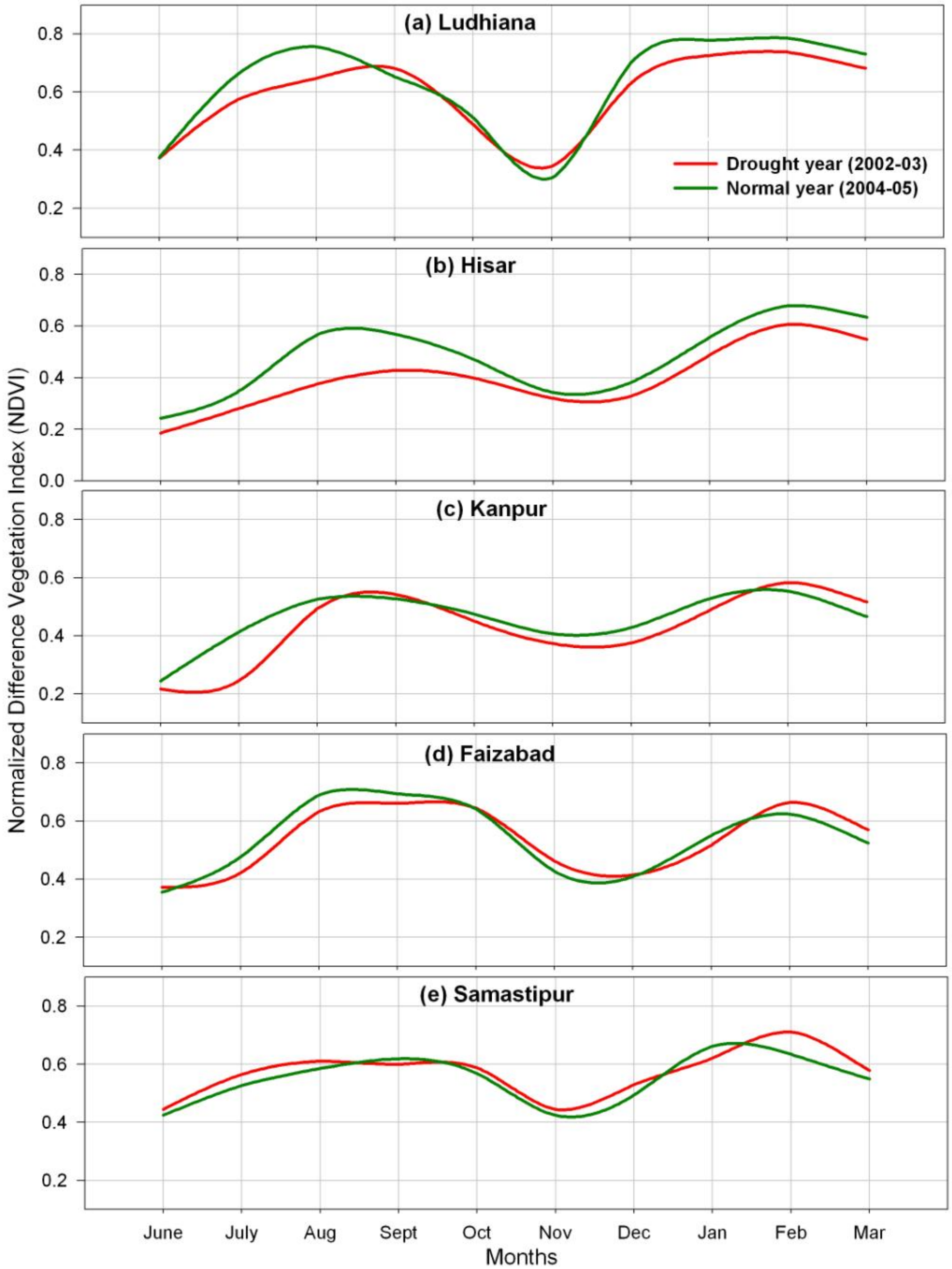

Fig. 8.8: Variation of NDVI during drought (2002-03) and normal year (2004-05) for selected study stations of IGR

8.5. Rational Integration of SPI, NDVI and CGSM-DI for drought assessment

From the results and discussion of preceding chapters, it is found that agriculture drought monitoring with crop simulation models has an edge over other conventional and spatial drought monitoring approach. Though there is flexibility in SPI and indices can be generated periods ranging from weeks to years, there are also limitations that it cannot account for water deficit caused by evapotranspiration, deep percolation and run off. The CGSM-DI has an additional advantage that it also accounts for the type and stage of crop on evapotranspiration losses. SPI does not consider the intensity factor and temporal distribution of rainfall within the base unit, for example, month. The intensity factor is necessary to calculate the water losses through runoff, while temporal distribution is necessary to calculate the water stress during the crop growth cycle. A good amount of precipitation in very early stages may be followed by drought like condition in later phase, while similar amount of precipitation well spread over the month may save the crop from moisture stress. SPI cannot differentiate between the two conditions as it considers only the total amount of precipitation during the base unit such as month. Maximum NDVI provides a good indicator of drought because it is directly linked with the crop growth and vigour and thereby yields. Thus a combination of these indices would provide a better understanding of drought assessment of crops.

Different drought indices SPI, NDVI and CGSM-DI are able to explain rice and wheat productivity variabilities upto different levels. Since all these indices are based on separate variables, the summation or averaging of these indices definitely removes the year-to-year variability. Since SPI and CGSM-DI ranged between -3.0 to 3.0 and NDVI ranged between 0 and 1, the summation of averaging lose individual character of the variable and will not reflect the actual variability of the rice and wheat productivity. The values of SPI during June to September, maximum NDVI during rice and wheat season, CGSM-DI of rice and wheat and KPRI and WPI during 2000-2005 over selected study stations are given in Table 8.7. It is found that the year-to-year variability of productivity of rice is more compared to that of wheat in all the stations.

To improve the drought assessment index, we have tried different combinations such as SPI from June to September, MRI from June to September, NDVI anomaly during June to September, Maximum NDVI during the crop season and Crop Growth Simulation Model based drought index (CGSM-DI). We found that the combination of SPI from June to September, Maximum NDVI during the crop season, CGSM-DI constitutes the best fit. Hence, to improve the drought assessment methodology, we have rationally integrated all the three indices and carried out multi-regression analysis for rice and wheat productivity. The Rational Integrated Drought Assessment Index (RIDAI) is a simple combination of SPI during June to September, maximum NDVI during the season and drought index based on crop growth simulation models.

$$\text{RIDAI} \quad = \text{Combination of } (\text{SPI}_{\text{during June-September}}, \text{NDVI}_{\text{Maximum}}, \text{CGSM-DI})$$

Integration of all these indices overcomes most of the limitations of each index and provides a complete picture of crop growth from sowing to harvest.

Year	SPI				Max. NDVI		CGSM-DI		KRPI	WPI
	June	July	August	Sept.	Rice	Wheat	Rice	Wheat		
Ludhiana										
2000	2.33	0.27	-0.1	1.12	0.73	0.77	-0.20	1.23	-1.13	13.14
2001	2.33	2.33	2.33	-0.59	0.71	0.79	0.10	0.98	-2.78	10.94
2002	-1.02	-1.84	-2.43	2.33	0.68	0.74	0.70	0.87	7.27	6.85
2003	0.06	0.15	2.33	-0.17	0.76	0.79	0.60	0.12	7.30	2.44
2004	0.39	-1.96	2.33	-1.43	0.76	0.79	1.00	0.14	13.87	2.30
2005	-0.03	0.36	1.38	1.08	0.73	0.75	0.80	-0.24	10.58	-2.99
Hisar										
2000	-0.52	-0.98	-1.95	-1.33	0.53	0.59	-2.40	-0.43	-31.78	-3.95
2001	1.02	0.94	0.26	-0.7	0.53	0.62	-2.40	-0.78	-33.99	-8.23
2002	-1.03	-1.77	-1.39	-0.52	0.43	0.61	-2.30	-1.12	-30.45	-12.70
2003	-1.46	2.33	0.1	-0.72	0.56	0.67	-1.10	-1.56	-12.41	-18.51
2004	-0.31	-1.93	-0.3	-0.43	0.57	0.68	-1.60	-1.89	-20.08	-19.26
2005	-0.2	0.69	-1.91	2.33	0.55	0.62	-1.00	-2.10	-11.33	-24.71
Kanpur										
2000	2.33	0.77	0.14	-0.47	0.56	0.53	-0.45	-0.34	-7.18	-1.52
2001	1.5	1.01	-0.26	-1.11	0.56	0.57	-0.32	0.23	-4.06	1.38
2002	-0.37	-3.47	2.33	2.33	0.54	0.58	-1.09	-1.67	-11.97	-10.24
2003	-0.13	2.33	-0.76	2.33	0.59	0.63	-0.65	-1.89	-7.81	-13.21
2004	2.33	1.38	-0.95	1.57	0.53	0.55	0.43	-1.54	4.46	-12.14
2005	-0.3	2.33	-0.58	0.17	0.51	0.53	-0.16	-1.32	-3.47	-10.15
Faizabad										
2000	2.33	-0.08	-1.26	0.44	0.65	0.57	-0.23	-0.98	-6.52	-8.84
2001	2.33	1.45	-1.25	-0.14	0.68	0.62	0.21	-1.03	3.57	-9.54
2002	-0.62	-1.05	1.74	2.33	0.66	0.66	-0.34	-1.45	-6.47	-17.84
2003	0.69	0	2.33	2.33	0.67	0.65	1.34	-1.98	17.87	-21.01
2004	2.33	0.53	-0.48	-0.76	0.69	0.62	-0.45	-2.23	-5.42	-27.31
2005	-0.47	1.59	2	0.78	0.72	0.59	-0.09	-1.78	-1.71	-19.25
Samastipur										
2000	2.33	-0.13	-0.29	2.33	0.61	0.63	2.09	-1.23	39.02	-16.62
2001	2.33	2.33	0.08	2.33	0.67	0.67	1.98	1.78	35.58	13.36
2002	0.21	2.33	2.33	-0.71	0.61	0.71	0.23	0.65	2.40	2.97
2003	2.33	-0.95	2.18	2.33	0.63	0.66	0.65	-0.98	8.76	-5.85
2004	2.33	2.33	-1.3	-3.03	0.62	0.66	-2.76	-1.76	-72.19	-15.64
2005	-0.54	-0.26	-1.23	-1.12	0.65	0.62	-2.34	-1.45	-56.14	-11.63

Table 8.7: SPI during June to September, maximum NDVI during rice and wheat season, CGSI-DI of rice and wheat and KRPI and WPI during 2000-2005 over selected study sites of IGR

The results statistics of the multiple regressions are given in Table 8.8 and 8.9.

	Coefficient	Std. Error	t	P
Constant	-49.524	21.457	-2.308	0.030
SPI $_{\text{June}}$	0.171	2.218	0.0770	0.939
SPI $_{\text{July}}$	-1.001	1.819	-0.550	0.588
SPI $_{\text{Aug}}$	1.068	1.94	0.550	0.587
SPI $_{\text{Sept}}$	4.080	2.207	1.849	0.077
NDVI $_{\text{Max}}$	79.537	37.711	2.227	0.036
CGSM-DI	9.693	2.795	3.468	0.002

R=0.84 Rsqr = 0.72 SEE=13.661
F = 9.697 P <0.001
Normality test and constant variance test passed.

Table 8.8: Multiple Regression Statistics of RIDAI of rice

	Coefficient	Std. Error	t	P
Constant	5.561	7.035	0.790	0.437
SPI $_{\text{June}}$	0.203	0.477	0.425	0.674
SPI $_{\text{July}}$	-0.332	0.398	-0.833	0.413
SPI $_{\text{Aug}}$	0.330	0.421	0.785	0.440
SPI $_{\text{Sept}}$	-0.168	0.396	-0.423	0.676
NDVI $_{\text{Max}}$	-8.775	10.202	-0.860	0.399
CGSM-DI	9.864	0.666	14.805	0.001

R=0.97 Rsqr = 0.94 SEE=3.156
F = 54.735 P <0.001
Normality test and constant variance test passed.

Table 8.9: Multiple Regression Statistics of RIDAI of wheat

Thus multiple regression equations are suitable for estimating kharif rice productivity and wheat productivity. The actual and estimated KRPI showed that most of the points are centered on 1st and 3rd quadrant (Fig. 8.9). But some points fall in the 2nd and 4th quadrant indicating that even with this high regression coefficient, in some of the years the actual and estimated values were far apart.

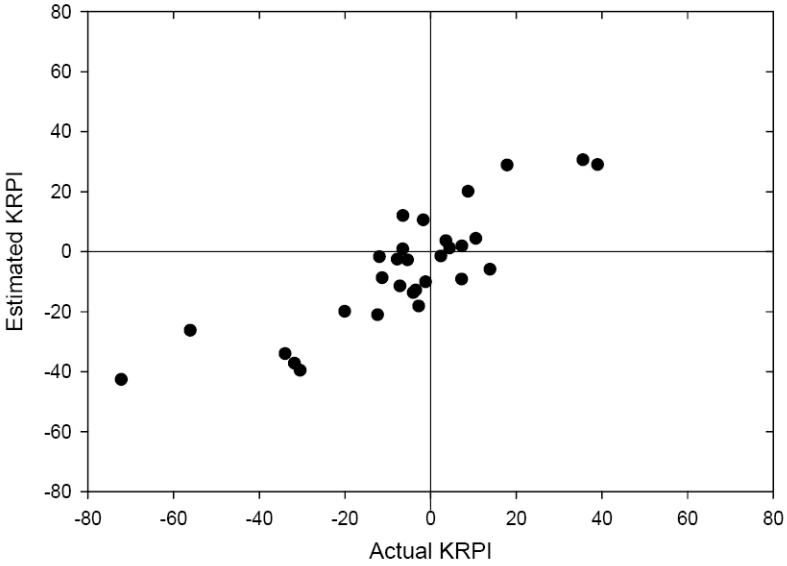

Fig.8.9: Actual and estimated values of KRPI

But in the case of wheat, all the points centered on 1st and 3rd quadrant (Fig. 8.10). This implies that this multiple regression equation explains very well to year-to-year variation of weather changes and can be used for assessing the yield variability in wheat due to weather fluctuations.

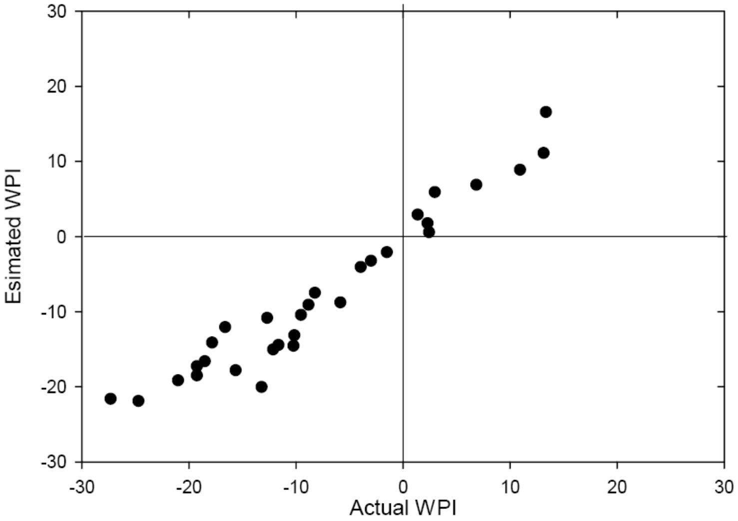

Fig.8.10: Actual and estimated values of WPI

It is found that for Hisar, out of six deficit kharif rice productivity years (KRPI < 10) the Rational Integrated Drought Assessment Index (RIDAI) captures five years and for Samastipur, RIDAI captures all the two deficit kharif rice productivity years. However, RIDAI has failed to capture one deficit kharif rice productivity year noticed in Kanpur. But in the case of wheat, RIDAI captures all the deficit wheat productivity years in all the selected stations of IGR. Thus combined drought assessment tool can be used for characterization of the agricultural drought with respect to rice and wheat over the entire region, if the input data sets are available. The Rational Integrated Drought Assessment Index explains 72 % variations in rice productivity while it explains 94 % variations of wheat productivity. Thus, this combined drought index tool regressed dynamical index, spatial index and rainfall index and captures all the drought years in the region.

CHAPTER 9

Summary and Conclusions

The Indo-Gangetic Region (IGR), situated in the north of India, occupies nearly 20% of the total geographical area of India. The IGR of India primarily encompasses five states: West Bengal, Bihar, Uttar Pradesh, Haryana and Punjab. The IGR has comes into existence as a result of continuous deposition of alluvium from the hills and mountains from both sides of the Plains, i.e. the Himalayas in the north and the ranges of the Deccan Plateau in the south. It is one of the most fertile agricultural regions of the country and is also densely populated region. Rice-wheat cropping system is the major cropping system in the IGR. With the advent of the “Green Revolution”, these two crops have come to occupy a significant area in the region, which is the food bowl of India. Historical records indicate that drought occurs every year in any form of severity in one or more States in the IGR. Rainfed rice predominates in the abundant rainfall zones of the eastern part where there is scope for growing rice under ponded water conditions during the rainy season, while irrigated rice is grown in the western part. Wheat assumes greater prominence in the western part, where it is normally grown with irrigation in the winter, in rotation with rice.

There are four major reasons for droughts in these areas – delay in the onset of monsoon/failure of monsoon, variability of monsoon rainfall, long breaks in monsoon and spatial variation in the persistence of monsoon rains. Even though there has been a significant increase in the application of water-conserving technologies and in water storage facilities, a recurrence of multiyear droughts would result in greater impacts on agriculture today because of the rapid expansion and urbanization of the region's population during the past several decades and the associated increased pressure on water and other natural resources.

At present, several drought indices, simulation models and modern tools such as remote sensing are available to assess and monitor the droughts: in this investigation, a detailed study on the topic has been carried out with a rational integrated approach to the problem. A summary of the results of these studies are presented in this Chapter.

In **CHAPTER 1**, a general introduction including the background of the topic, justification for the study and its objectives are given. The general geographical characteristics of the Indo-Gangetic Region of India, general climatology, agro-ecological zones and the major cropping systems in this part of the country are presented.

CHAPTER 2 includes a detailed survey of literature in the field of drought climatology, definitions of droughts, their categorization and the different drought indices available for their assessment, crop-weather modelling and remote sensing. The data used and the methodology adopted in the study are also given in this Chapter.

In **CHAPTER 3,** an attempt has been made to estimate the expected rainfall at 50, 60, 70, 80 and 90 per cent probability levels during 18th to 44th Standard Meteorological weeks for selected representative stations in each agro-ecological zone of the IGR India. The Moisture Availability Indices (MAI) at 50, 60, 70, 80 and 90 per cent probability levels have also been computed for these representative stations. The salient results of the study are given below:

The mean annual rainfall varies from 552.0 mm at Karnal to 1589.6 mm at Dhanbad. It has been noticed that the eastern part of the IGR receives more rainfall compared to western part. The weekly rainfall distribution highlights the availability of rainfall during pre-monsoon period as well as retreating period in the eastern part of the region with high year-to-year variability. This helps the farmers of this region to start nursery growing early with the help of some assured irrigation, so that they can start transplanting operations with the start of the onset of monsoon rainfall. Gamma distribution was found to fit the weekly rainfall of all the 18 study sites. When compared the weekly potential evapotranspiration with estimated expected rainfall at 60 % probability level, it has been noticed that the estimated expected rainfall at 60 % probability level never reaches above PET over Hisar, Ludhiana, Kanpur and Karnal. This indicates the importance of assured irrigation in this part of the region during the monsoon season.

The rainfall analysis indicate that the western part of the region is having more probability of water stress period (dry: MAI<0.5) during the critical phenophases of the crop. It is also noticed that none of the weeks of Hisar, Ludhiana and Karnal during the rice season, MAI value above 0.5 at 70 % probability level. At the same time, Dhanbad gets 15 continuous weeks having MAI above 0.50 at 70 % probability level. Considering the values of MAI at all the different probability levels, a suitable level for crop-growing can be selected for each district/block/taluk depending upon the duration of adequacy of moisture.

There are 37 districts with high rice productivity (> 2500 kg/ha), 52 districts with medium productivity (2000-2500 kg/ha), 38 districts with medium-low productivity (1500-2000 kg/ha), 51 districts with low productivity (1000-1500 kg/ha) and 13 districts with very low productivity (< 1000 kg/ha). The low productivity is a result of bio-physical factors like low level of irrigation facilities, undulating physiography and extreme climatic events like floods and droughts on one side and poor socio-economic status farmers leading to poor crop management on the other.

Based on rainfall probability and MAI, appropriate crop management strategies have been suggested for each important agro-ecological sub-region of IGR. Supplemental irrigation is recommended to meet the crop water requirements and mitigate water deficits during the critical growth periods. Hence, in addition to the site specific management strategies, adoption of run-off rainwater management conservation measures suited to small and marginal farmers, which enables to provide life saving irrigation to the crop wherever possible during long dry spells is also recommended to increase the rice productivity of the region. Since most of the farmers in this region are poor, the adoption of non-monetary inputs like timely sowing, application of balanced dose of fertilizers, timely irrigation and timely harvesting of crops may also increase the productivity.

In **CHAPTER 4**, the drought climatology of Indo-Gangetic States is explained using Standardized Precipitation Index (SPI) and Monsoon Rainfall Index (MRI). Frequency and intensity of meteorological droughts over the region with reference to rice crop during kharif season and wheat crop during rabi season are assessed using the two indices. An attempt is made here to assess the effectiveness of monthly SPI and MRI from June to September on rice-wheat productivity over the region. An attempt is also made to employ monthly SPI and MRI values for forecasting kharif rice and rabi wheat productivity in these States. The important features of this study are as given below:

It has been found that in 14 per cent of the years, the SPI class falls under the dry category during June for West Bengal. However, in 17 per cent of the years SPI falls below -1 during July and August and in 18 per cent of years during September. But for Bihar, in17 per cent of the years the values of SPI reach dry category during June and August and 18 per cent during September. In 21 and 20 per cent of the years, the June MRI fall below -60 % for Punjab and Haryana, respectively. Similarly, in 32 and 33 per cent of the years the September MRI was below -60 % for these States. The important inferences draw from the influence of SPI on KRPI and WPI are:

In West Bengal, out of 32 years under study, nine years (1979, 1981, 1982, 1986, 1995, 1998, 1999, 2000 & 2005) fell under deficit rice productivity (KPRP< -5) category. During these deficit years, except 1995, SPI value of one of the monsoon months was negative. But in the case of wheat, 12 years fell under deficit wheat productivity and during all these years SPI values of one of the monsoon months were negative. In Uttar Pradesh, eight years (1979, 1981, 1982, 1987, 1991, 1992, 2004 & 2005) fell under deficit productivity (KPRP< -5) category. During these deficit years SPI value of at least one of the monsoon months were < -1 and June and September SPI contributed more to KPRI. The SPI values during August (r: 0.38) showed significant relation with wheat productivity. In Bihar, nine years (1974, 1979, 1980, 1981, 1982, 1987, 2002, 2004 & 2005) fell under deficit productivity (KPRI< -5) category. During these deficit years, except 1995, SPI value of one of the monsoon months was negative; June, July and August SPI contribute more to KPRI. However, SPI values during June (r=0.36) and August (r = 0.41) have more influence on wheat productivity. In Haryana, six years (1974, 1975, 1995, 1998, 1999 & 2000) fell under deficit productivity (KPRP< -5) category. High rainfall during September helps the timely sowing of the wheat crop in this region. In Punjab, six years (1974, 1979, 1988, 1995, 1998, 1999) fell under deficit productivity (KPRP< -5) category. Since 99.3 % rice area was under irrigation during 2005-06, effect of dry spells during the monsoon season did not affect the productivity. Also found that SPI values during July and August may influence the WPI.

There is significant (5 % level) correlation between June and September MRI and KRPI for Bihar. However, the influence of September rainfall on KRPI for Uttar Pradesh and Punjab is high. During the eight deficit productivity years (except 2004), June rainfall index falls under the deficient drought class indicating that June rainfall is crucial for timely sowing of rice in this region. But during July, only four years received deficient rainfall. During the year 1982, July to September received deficient rainfall and the productivity index reached 31 %.

KRPI reached minimum value (-43.7 %) during 2004 and MRI reached deficient category during July and September: MRI during September reached – 50.1 %. Out of eleven deficit WPI years, during seven years, at least two monsoon months received deficient rainfall.

The percentage increase in triennium rice productivity ending 1976 to 2005 was 119 per cent for IGR. A higher value of 140 per cent increase in triennium productivity was noticed for West Bengal while a very low 26 per cent increase was noticed for Bihar. It is also noticed that the rice productivity showed a linear growth rate of 45 kg/ha/year during the study period. But in the case of wheat, the percentage increase in triennium productivity ending 1968 to 2005 was 117.6 per cent for IGR. One important aspect emerging from the study is the slight 5.1 per cent decrease of triennium productivity from 1999 to 2005. After green revolution, the productivity of rice and wheat have increased tremendously, but this marginal decrease has had serious implications on food security of the region.

The monthly distribution of monsoon rainfall in terms of SPI explains 44 per cent variability while MRI explains 38 per cent variability in kharif rice productivity of IGR. Even though, more than 75 % of the region consists of well developed irrigation systems, the performance of SPI to capture 44 per cent variability is highly significant. But in the case of wheat, even after more than 90 % coverage of irrigation, SPI accounted for 21 per cent and MRI accounted for 23 per cent variability in productivity. Thus monthly SPI based multiple regression equations are suitable for estimating kharif rice productivity while MRI based multiple regression equations are suitable for estimating wheat productivity for IGR States.

CHAPTER 5 deals with the use of MODIS data for drought assessment and monitoring over the IGR. The changes in the monthly composite NDVI values during the period 2000 to 2006 have been studied in detail. The NDVI values during drought year and normal year during kharif and rabi seasons have been compared. An attempt has been made to relate NDVI with rice and wheat yields. The important features of this study are as given below:

Higher values of NDVI have been noticed for wheat compared to rice in western region while they are comparable in the eastern region. Moreover, the higher maximum NDVI during the rice and wheat season over western region closely follow the productivity pattern in this region. The relation between monsoon rainfall and NDVI showed that at around 1100 mm rainfall, the NDVI reached saturation point and no further significant increase in NDVI with an increase of rainfall is noticed. Even though, there was a positive correlation of seasonal monsoon rainfall and average NDVI, conflicting results were noticed in the monthly distribution of rainfall with monthly anomaly of NDVI over IGR states. This may be due to the one month lag time between NDVI and monthly rainfall.

It is noticed that June dif NDVI (actual NDVI – mean NDVI) contributes more to rice productivity followed by July. However, the combined effect of June, July and August, explains 15 % variation of KPRI. As far as wheat is concerned, statistically significant relation was found between WPI and dif NDVI during December-March. This explains 35 % variability in WPI.

CHAPTER 6 deals with rainfall and temperature trends during the last 100 years over the region. A detailed in-depth monthly analysis of the trends in all the months of the year has been done to bring out a comprehensive assessment, which would be highly relevant and useful from the agricultural and water management points of view. The trends in the monthly, seasonal and annual rainfall data series of 5 Indo-Gangetic States using Mann-Kendall non-parametric test have been analyzed. The slopes of the trend lines have been determined using the method of least square linear fitting. The trends of maximum and minimum temperatures of the region have also been examined using the same methodology. The summary of the results are given below:

- Insignificant increasing trend in annual, summer, monsoon and post-monsoon rainfall and insignificant decreasing trend in winter rainfall.
- All the States show an increasing trend in summer rainfall and Bihar and Haryana show an increasing trend of 0.2 mm/year.
- All the States show a decreasing trend in winter rainfall and Bihar shows a significant decreasing trend of rainfall at the rate of 0.1 mm/year from 1905.
- All the States except Bihar show an increasing trend of annual rainfall and Haryana and Punjab, show a significant increasing trend of rainfall of 0.8 mm/year and 1.1 mm/year, respectively.
- A significant (0.01 level) increasing trend of rainfall at the rate of 0.1 mm/year has been noticed during May. This may be attributed to the increasing extreme

events during summer season, particularly pre-monsoon showers during April/May.

- During the recent period 1966-2005, an increasing trend of rainfall from January to May, July and November-December was observed, though statistically not significant. The increasing trends of rainfall during April, May and July months clearly indicate that the greater occurrence of extreme events or Pre-monsoon showers may also be increasing in this part of the country.
- In all the months, except January and December, there is an increasing trend of rainfall during 1906-2005 in Punjab. A significant increasing trend of rainfall at the rate of 0.3 mm/year and 0.6 mm/year, respectively has been noticed during June and July. In all the months, except January and September-October, there is an increasing trend of rainfall during 1906-2005 in Haryana and a significant increase of 0.2 mm rainfall/year has been noticed during May and June.
- A significant decreasing trend in rainfall at the rate of 0.1 mm/year has been noticed during August in Bihar. This gives an indication that the rice crop will be under greater drought risk, particularly during the maximum tillering/vegetative phase, which is during August in these parts.
- Important features of the IGR seasonal temperature fluctuations are : significant (0.01 level) maximum temperature increase over NC-region at the rate of 0.008 ^{0}C/year during monsoon season, 0.014 ^{0}C/year during post-monsoon season, 0.008 ^{0}C/year during annual, significant rising trend of minimum temperature at the rate of 0.012 ^{0}C/year during post-monsoon; significant rising trend in maximum temperature over NE-region at the rate of 0.008 ^{0}C/year during

monsoon season, 0.017 ^{0}C/year during post-monsoon season, 0.008 ^{0}C/year during winter; significant rising trend of minimum temperature at the rate of 0.007 ^{0}C/year during post-monsoon, decreasing trend at the rate of 0.004 ^{0}C/year during monsoon season; significant rising trend of maximum temperature over NW-region at the rate of 0.005 ^{0}C/year during monsoon season, 0.011 ^{0}C/year during post-monsoon. Thus all the regions show significant increase in maximum temperature during monsoon season and post-monsoon season and this indicates that if this condition persists, it will affect the heating of the atmosphere and more convective activity can occur over the region.

CHAPTER 7 deals with use of the CERES crop growth simulation model for drought assessment in selected districts of the region. The model has been calibrated and validated based on farm / experimental data sets. Using model simulations, influence of the various meteorological variables rainfall, maximum and minimum temperature and solar radiation on the potential yields of rice and wheat during the period 1974 to 2005 has been investigated. The changes in the potential yields of rice and wheat resulting from each unit of increase or decrease of maximum and minimum temperature, rainfall and solar radiation have also been simulated. The actual district yield trends of rice and wheat during the study period for all these five districts have also been investigated. The projected rice and wheat yields in 2010, 2015, 2020 and 2025 have also been simulated for these five districts. The important features of the results are given below:

Recent trends of a decline or stagnation in the yield of rice and wheat in the region have serious repercussions on food security of the region. The effect of possible climate change on crop production adds to the already complex problem. Analyses of weather data during the period showed that there was no significant change in rainfall over the years in both the rice and wheat seasons. Analyses of sunshine hours during the period showed that this decreased over the years during rice and wheat seasons, but these trends were statistically not significant. The minimum temperature in rice showed a negative trend at two sites, with one (Kanpur) statistically significant whereas three sites showed a positive trend, with two sites, Samastipur and Ludhiana showing significantly positive trend of 0.03 ^{0}C/year and 0.06 ^{0}C/year, respectively. In wheat season, three sites showed a negative trend, Hisar being significantly different from 0 ($P < 0.05$). Two sites (Ludhiana and Samastipur) showed statistically significant positive trend ($P < 0.01$).

The maximum temperature in rice remained stable over the years, with two sites (Faizabad and Ludhiana) showing a negative trend and three positive (Kanpur, Hisar and Samastipur). But during August and September, most of the sites showed increasing trend of maximum temperature. These significant changes in weather parameters during different stages of the crop result in declining trend of potential simulated yield of rice. Sensitivity analysis shows that every incremental increase of rainfall by 2 mm/day, increased the potential rice yield continuously. However, wheat yield increased up to when the rainfall reached 26 mm/day and after that showed decreasing tendency. Decreased solar radiation by 2 MJm^{-2} per day reduced rice and wheat yields from 11050 to 10230 and 7300 to 7072 kg/ha, respectively. Increased minimum temperature by 2 ^{0}C also decreased yields of rice and wheat from 10920 to 9780 and 8310 to 7830 kg/ha, respectively. Increase in maximum temperature increased rice yield marginally, but decreased wheat yield significantly. Increased maximum temperature by 2 ^{0}C decreased the yields of wheat from 7680 to 6800 kg/ha. A comparison of observed and simulated rice and wheat yields shows that there is a very good agreement between them, significant at $P < 0.05$ level for all the sites except Samastipur.

The simulated rice yield for Faizabad, Kanpur, Ludhiana and Hisar show a decreasing tendency of 7.2, 8.5 3.8 and 5.8 per cent, respectively during 2025 when compared to 2007. Samastipur shows an increasing simulated rice yield of 11.4 per cent from 2007 to 2025. Since Samastipur receive an average 1069.9 mm rainfall during kharif season and the area is usually affected by floods during the entire crop season, decrease of rainfall during the season may have helped the rice crop to project a higher simulated rice yield in 2025.

The simulated wheat yield for Faizabad, Kanpur, Hisar and Samastipur show an increasing tendency of 13.9, 14.4, 8.9 and 9.6 per cent, respectively during 2025 when compared to 2007. This may be due to combined effect of decreasing trend in either maximum or minimum temperature during the season. The significant decrease of mean temperature increases the growing period and thereby duration of crops and ultimately increases the grain size as well as yield. But as far as Ludhiana is concerned, the significant increasing trends in minimum temperature of the order of 1 ^{0}C may have more control over other small changes in maximum and sunshine hours and influence the simulated rice yield: thus a decreasing trend of 8.8 per cent from 2007 to 2025. The simulated rice and wheat yields were converted into indices using the gamma distribution. It is clear that the Crop Growth Simulation Model based Drought Index

(CGSM-DI) and Kharif Rice Productivity Index (KRPI) as well as CGSM-DI and Wheat Productivity Index (WPI) follow the same pattern. Even though, the CGSM-DI could capture all the extreme agricultural drought conditions with respect to rice and wheat for all the sites, its intensity differs and still need verification with other parameters.

CHAPTER 8 deals with the development of a new rational integrated drought assessment model combining the NDVI, Crop growth model and SPI for the above five districts during the study period. The important results arrived from this study is given below:

The study successfully demonstrated that the scope of applicability of rational integration of meteorological drought index – Standardized Precipitation Index (SPI), remote sensing derived index – Normalized Difference Vegetation Index (NDVI) and Crop Growth Simulation Model based Drought Index (CGSM-DI) for year-to-year variations of rice and wheat productivity over Indo-Gangetic Region. This combined drought assessment tool, Rational Integrated Drought Assessment Index (RIDAI) can be used for characterization of the agricultural drought with respect to rice and wheat over the entire region, if the input data sets are available. The RIDAI explains 72 % variations in rice productivity while it explains 94 % variations of wheat productivity. Thus, this drought index regressed dynamical index, spatial index and rainfall index and captures all the drought years in the region.

Recommendations for overall Agricultural Development of IGR

Based on rainfall probability and MAI, the following appropriate crop management strategies for different agro-ecological sub-regions have been recommended for IGR,

- Medium (110-130 days) to long duration (140-150 days) varieties can be grown in *Sub-regions 15.1.* Timely nursery raising and transplantation has to be ensured in transplanted rice. Field bunding should be done to conserve rain water.

- Long duration varieties can be grown in low-land (water stagnation during crop period) region where there is stagnant run off water in *Sub-regions 13.1 and 13.2.* Timely planting is important as some areas face inundation from runoff water.

- Direct seeded upland rice is the major crop in *Sub-regions 11 and 12.3,* which is suited to the rainfall distribution and topography. Medium duration varieties are ideal for this region. Introduction of direct-seeded and transplanted aerobic rice varieties in this region can increase productivity. In uplands, in case of delayed sowing, short duration (90-100 days) varieties may be preferred. In case of delayed sowing, pre monsoon tillage will help to conserve moisture and check weeds. Closer spacing is ideal for delayed sown conditions.

- Summer ploughing can help conserve soil moisture in *Sub-regions 4.3, 4.4 and 9.2.* Only short duration varieties can be taken up in these areas, which are purely rainfed. Long and medium duration varieties may suffer water stress from flowering period. Also this region has suitability for medium duration varieties.

In situ water harvesting and runoff collection measures are important to provide the crop with lifesaving irrigation.

- Moisture availability is a constraint in *Sub-region 2.3, 4.1 and 9.1* and hence supplementary irrigation is essential for raising short duration rice varieties.

In addition to the site specific management strategies, adoption of run-off rainwater management conservation measures, which provide life saving irrigation to the crop during long dry spells, are also recommended to increase the rice productivity of the region. Since most of the farmers in this region are poor, the adoption of non-monetary inputs like timely sowing, application of balanced dose of fertilizers, timely irrigation and timely harvesting of crops are also recommended. Crop diversification with the advantage of flooded and ground water in eastern part of the region should also be explored.

Site-specific resource conservation technologies should be evolved to increase farmers' participation. Resource conservation technologies (RCTs) such as zero-tillage, reduced tillage, surface seeding, bed-planting and the associated agronomic practices promote precision agriculture, timely farming operations, save water and energy, improve factor productivity and improve soil health.

Growing of legumes in the rice-wheat fields will enhance natural resource conservation and increase the income and nutrition of the poor and marginal farmers. Promoting the rotation of rice and pigeon pea in the rainy season and wheat and chickpea in the post-rainy season may enrich the soil through nitrogen fixation and this ultimately increases the productivity for the rice and wheat crops too.

The projected yield decline by the year 2025 is a matter of serious concern and improved germplasm with more adaptability to the changed climate should be developed. Ways to improve the input use efficiency and to disseminate modern management technologies to the farmers, such as zero tillage, timely sowing/transplanting, use of irrigation water for nursery preparation during kharif season etc. The decreasing trend of rice and wheat productivity may adversely affect the food security of the region and hence measures should be taken to stabilize the productivity under changed climatic change scenario. Even though these projected yields do not consider the technological advancement as well as the incidence of pest and diseases, they still provide an indication of yield variability under projected climatic conditions. Climate change and climatic variability and increasing non-farm demands for water affect supply-demand and the resulting vulnerability of the rice-wheat production system of this region. Adoption of efficient water management, water conservation and land use strategies and energy-efficient technologies are essential to reduce the vulnerability of rice-wheat system to climatic stresses.

The study successfully demonstrated the scope of applicability of RIDAI (Rational integration of drought assessment index) for estimating year-to-year variations of rice and wheat productivity over Indo-Gangetic Region. This drought index tool needs to be used to characterize agricultural droughts of the region with respect to rice and wheat.

Since Indo-Gangetic Region consists of several ICAR Research Institutes and Agricultural Universities, efforts should be made to coordinate all the agrometeorological observatories in this region to develop an Agro-meteorological Data Bank. Space technology, particularly the use of MODIS 250 m resolution data, which is available free of cost through internet, for crop monitoring and yield forecasting, should be employed in the IGR. The possibility of dynamic linking of space technology and crop growth simulation models should be explored.

Future line of work

Since along with rainfall, soil characteristics and physiography of the place also influence the productivity of rice, more accurate results can be achieved by super-imposing the soil and physiography map of the region with moisture availability map of the region using GIS. Supplemental irrigation during the critical growth periods rather than continuous irrigation is valuable for increasing production and gives the maximum economic benefits to resource poor, marginal to small land holding farmers for better livelihoods. Since the moisture sensitive phenophases of rice and wheat crop are limited to 1-2 weeks, it is necessary to analyze the weekly/biweekly rainfall to capture and quantify the drought impacts on productivity. Another characteristic emerging out of this study is that even though IGR is classified as four similar agro-ecological zones, there is large scale variation of rainfall within the IGR States and hence future research work should focus on smaller grid areas – perhaps district level.

The other forms of remote sensing vegetation indices such as EVI, VCI and TCI should be explored for drought assessment with respect to rice and wheat. Similarly, 8-day composite NDVI, EVI, VCI or TCI could be used to delineate agricultural droughts. Efforts should be made to use spatially high resolution of 250 m satellite imageries rather than 1 km resolution. Since MODIS data set is available from the year 2000 onwards, this has limitation to capture different types of agricultural droughts during this short span of period, the possibility of relationship between AVHRR data and MODIS data of the region should be explored.

Even though, there is good agreement of actual and simulated rice and wheat yields, the district yield data represents the average of all the varieties of that district. Hence, sampling methods should be adopted to collect yield data pertaining to popular varieties. Regular monitoring of crops and climatic factors in farmer’s fields would help in predicting problems and allowing measures to be taken to improve productivity.

Establishment of early warning systems with the help of space technology and modelling are necessary in areas vulnerable to droughts and floods.

If the above suggestions and recommendations are pursued the overall development of the IGR would be possible confirming its status as the food bowl of India and ensured the food security of our country.

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