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Anomalies in terrestrial hydrological cycle – India

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सार – इस शोध–पत्र में यह बताया गया है कि समूचे विश्व में विद्यमान प्राकृतिक संसाधनों के दोहनों (ट्रेस्ड फुटप्रिंट) के फलस्वरूप विश्व जलवायु पद्धति अव्यवस्थित हो जाती है। जो क्षेत्रीय समस्याओं समेत विश्व जलीय चक्र को और अधिक तीव्र करने के लिए उत्तरदायी मानी जा सकती है। इस शोध–पत्र में जल संतुलन निदर्श के माध्यम से भारत में जलीय क्षेत्र के मामले में इस तथ्य को समझने का प्रयास किया गया है। इस संबंध में की गई जाँच से मुख्यतः समूचे भारत के जलीय फलक्सों पर इनसो/लनसो सिग्नल के जलवायु संबंधी दूर संपर्क के प्रभावों की जानकारी प्राप्त हुई है।

ABSTRACT. It is reported that the traced footprints across the world are the consequences of the perturbed world climate system that might be responsible in intensifying the world hydrological cycle with regional implications. An attempt is made here to understand this fact in case of hydrological regime over India through water balance model. The investigation mainly addresses the climate teleconnection impacts of ENSO/LNSO signal on the hydrological fluxes for All India.

Key words – Water balance model, Hydrological regime, Hydrographs, ENSO / LNSO events.

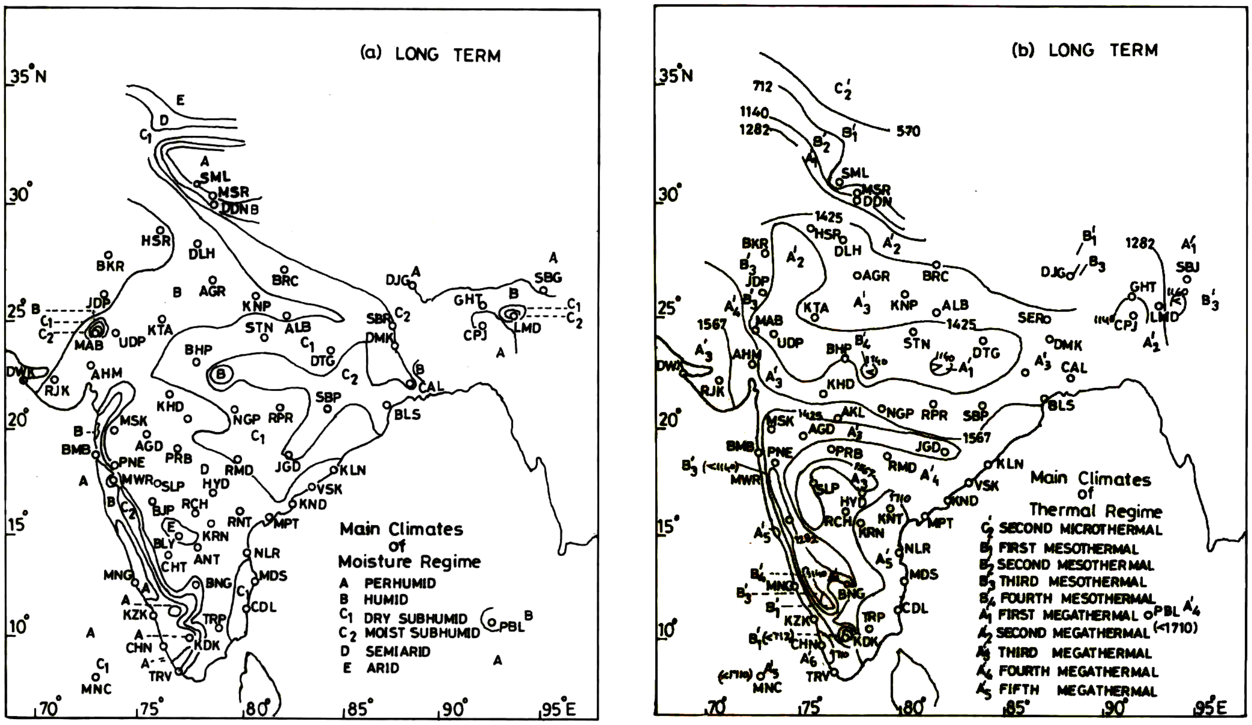
1. Introduction

It is widely accepted that the gravity from the industrial, urban, deforestation, damming of river systems and ever increasing population pressure since their dawn to the present timings is multiplied and is aggravating the management of water systems of both global and regional scales. Global impacts of ElNino – Southern Oscillation (ENSO) are recognized as one of the important modes of the earth's year-to-year climate variability [Ropelewski and Halpert (1987), Glantz *et al*. (1991) and Kripalani and Kulkarni (1997)]. The effects of equatorial Pacific sea surface temperatures (SSTs) are considered as a reliable predictor of the SW monsoon (Palmer, 1994) was of the opinion that the low frequency Pacific SST variability pre-disposes the monsoon to either a strong or weak season. The teleconnection between ElNino and monsoon performance is through Walker circulation. The seasonal cycles of Nino-3 region SSTs unfold the strength of the S-E trades and on which the monsoon has a bearing. Most of the major drought years are also years of low index phase of southern oscillation (Sikka 1980, Ramusson and Carpenter 1983).

The investigations on ENSO signal with reference to SW monsoon performance was reported by Sikka (1980), Pant and Parthasarathy (1981) and the epochal changes in the monsoon studied by Joseph (1976) and Thapliyal and Kulshresta (1991). Sikka (2000) made use of the monsoon rainfall series of Parthasarathy *et al*. (1995) in examining not only the climatology of monsoon floods but also simultaneous occurrence of these events over different homogeneous regions over India as a whole. The prime concern of global water system is to meet the water needs of the world population (Shukla, 1998). The investigations of Simpson *et al*. (1993) and Sarma *et al*. (1999) were clear-cut examples in highlighting the ENSO/LNSO impact on river flows. An exercise is made here to extend the work of Sarma and Srinivas (2005b) & Sarma *et al*. (2005a) on the aberrated climate impacts and aspects of the intensification of the terrestrial (land phase) of the hydrological cycle with reference to the variability of the hydrological fluxes in the climate spectrum of India through water balance model.

2. Materials and methods

The revised water balance model of Thornthwaite and Mather (1955) is followed in obtaining the basic water budget elements from All India data set (mean monthly temperature and rainfall) that is downloaded from the website of Indian Institute of Tropical Meteorology : tropmet.res.in, for a period of 90-years commencing from 1901. To understand the proneness of the region to varied climate stress, sixty-six (66) stations (Appendix) are drawn from the varied geographical settings of India



Figs. 1(a&b). Climate pattern – India

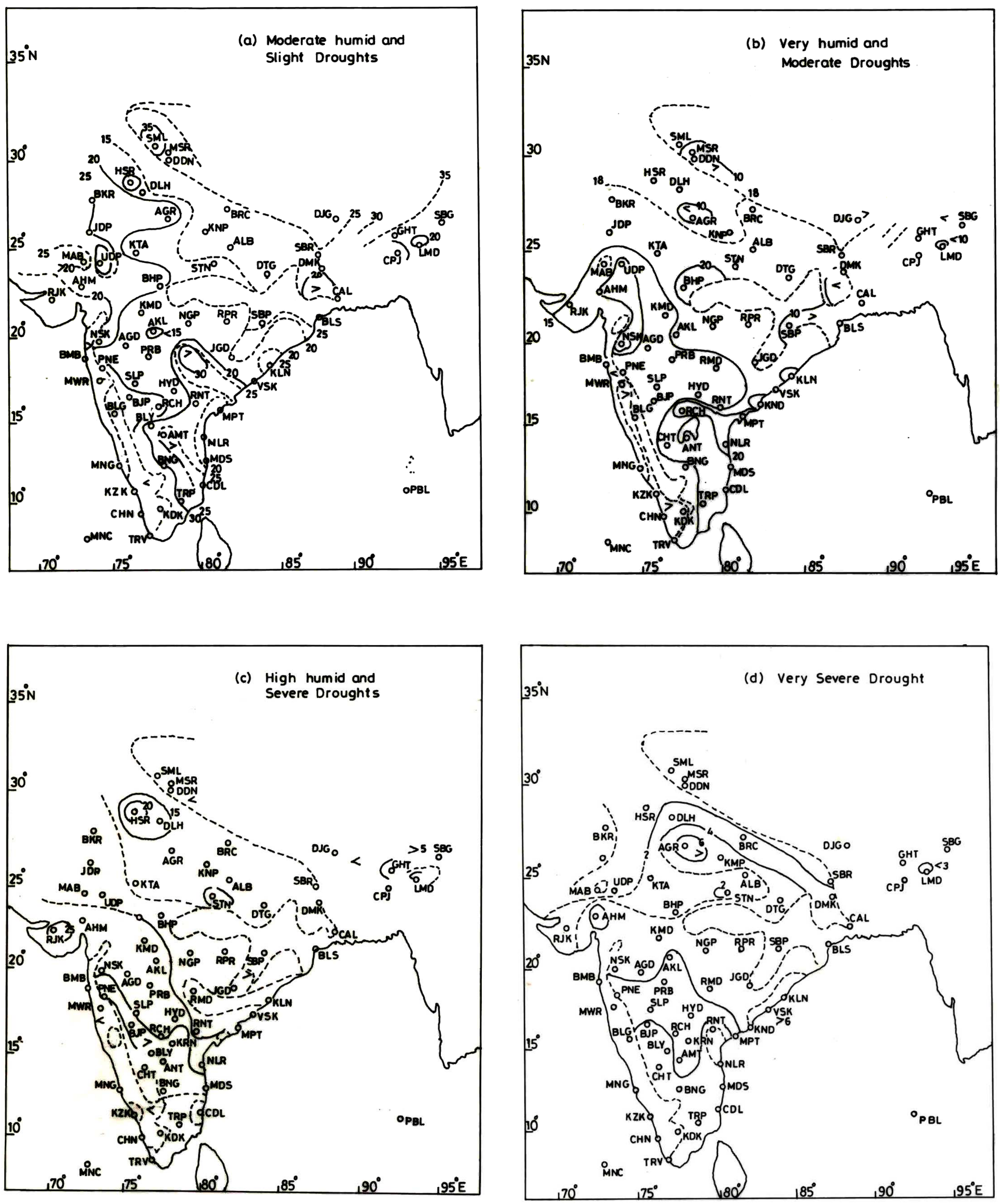
covering its length and breadthwise. The climate indices of aridity, humidity and moisture are determined on annual basis.

The water balance model uses rainfall and potential evapotranspiration on a monthly basis through the year along with the field capacity of the soil as input in obtaining water deficit and water surplus as output in calculating the indices of humidity [(annual water surplus/annual water need) $\times$ 100], aridity [(annual water deficit/annual water need) $\times$100] and moisture ($I_h - I_a$) for the selected stations for the period of study as mentioned in Appendix. The prevalence of humid and drought events in the moist (perhumid, humid and moist sub-humid) and dry (dry sub-humid, semi-arid and arid) climates are according to the percentage departures of the humidity and aridity index from the median respectively. The percentage departures of humidity and aridity from the respective median of the stations are taken to determine the severity of the event and further these are normalized with respect to median for an inter-comparison. The standard deviation of the humidity and aridity indices for the moist and dry climate stations respectively are used to categorize the humid and drought events respectively.

The schema of Sarma *et al*. (1999) are followed for identifying the events of humid and drought respectively.

Limit	*Humid*	*Limit*	*Drought*
0 to σ	Moderate humid	0 to 1/2σ	Slight
σ to 2σ	Very humid	1/2σ to σ	Moderate
$\geq$ 2σ	High humid	σ to 2σ	Severe
		$\geq$2σ	Very severe

Liability of the station to humid or drought event of a particular category is as was reported by Subrahmanyam and Sarma (1975) by expressing the total number of that event as a percentage of the total number of years studied. In determining the moisture status for the selected stations, the revised expression of Carter and Mather (1966) is followed. In understanding the trends, the 5th order polynomial fit is approximated for the 30-year central moving averages (CMAs) of moisture index of All India, Southern Oscillation Index and SSTs (Sea Surface Temperatures) of Nino-3 region. Sea surface temperature (SST) anomaly time series is from Simpson *et al*. (1993)



Figs.2(a-d). Proneness to varied degrees of humid and drought years in moist and dry climates respectively. Areas enclosed by dashed curve refer to moist while solid ones for dry climates for the SSTs of Nino-3 region for the present study in making a correlative study with that of SOI (Southern Oscillation Index) and seasonal moisture index of All India. The seasonal moisture index for the period June to September is obtained and the procedure is same as that of the annual concept except considering the water deficit, water surplus and water need of this period.

3. Results and discussions

3.1. *Moisture and thermal regimes*

Normal main climate pattern in terms of moisture and thermal regimes over India are shown in Fig. 1. The strength and the depth of the monsoon systems (SW and NE) in relation to the physiography of India imparting the complete climate spectrum consisting of perhumid to arid through humid, sub-humids and semi-arid climatic regimes over it. In the north, the main moisture regime commences from moist to dry climates from east to west and this pattern is from west to east in the south. Perhumid and humid provinces are confined to NE India and are very narrow and close along the west coast. Isolated pockets of perhumid and humid climates are appeared both in north and south over hill stations [Fig. 1(a)].

The water need or potential evapotranspiration is also the representation of the thermal regime of the landscape since the water need is also a measure of energy units required for vegetation development. The water need over India is varied from 469 mm (over Jammu & Kashmir) to 1846 mm at Cuddapa. Mesothermal climates appeared as isolated pockets over elevated hill stations in north as continuous strip over parts of Punjab, Himachal Pradesh and southern portions of Jammu & Kashmir wherein the water need ranges from 572 mm to 680 mm. It is clear from the present investigation that three fourths of Jammu and Kashmir records second micro-thermal type of thermal regime with an annual water need that varies from 427 mm to 570 mm [Fig. 1(b)]. Even though elevated stations like Shimla, Missouri, Darjeeling, Mahabaleswar, Mount Abu from perhumid and humid zones of India are under mesothermal type of annual thermal efficiency, their summer concentrations are of megathermal and this might be supporting the forest cover with luxuriant vegetation of the respective geographical locations.

The present climate analysis unfolds that more than three fourth's of the Indian landscape is influenced by varied degrees of megathermal regime that supports luxuriant vegetal cover provided enough moisture is available and is the limiting factor due to spatiotemporal variations in monsoonish currents over India.

3.2. *Proneness to humid and drought events*

(*i*) *Moderate humid events - Moist climates*

Cherrapunji from Meghalaya has recorded the maximum number (43.9%) of moderate humid events while the minimum (25%) is at Darjeeling [Fig. 2(a)]. Mount Abu, the hill station amidst of dry climates from Rajasthan is subjected 32.1% of the study period with moderate humid events. The moist climate zones from the western ghats indicated a frequency that ranges from 32.6% to 38.6%. At and around the adjoins of Balasore, Sambalpur and Jagdalpur are harbored moderate humid events with a frequency of 34%, 32.5% and 37.8% respectively.

(*ii*) *Slight drought events - Dry climates*

Ramgundam from south and Udaipur from north are vulnerable to slight drought with a frequency of 31.1% and 28.8% respectively. It is interesting to note that the frequency of slight droughts increased from east to west in the north but it is from west to east in the south [Fig. 2(a)].

(*iii*) *Very humid events - Moist climates*

The hill stations Darjeeling from north and Kodaikanal from south registered very humid category events with a frequency of 18.5% and 15.2% respectively [Fig. 2(b)]. The frequency of very humid events is varied from 8% to 11% along the west coast.

(*iv*) *Moderate drought events - Dry climates*

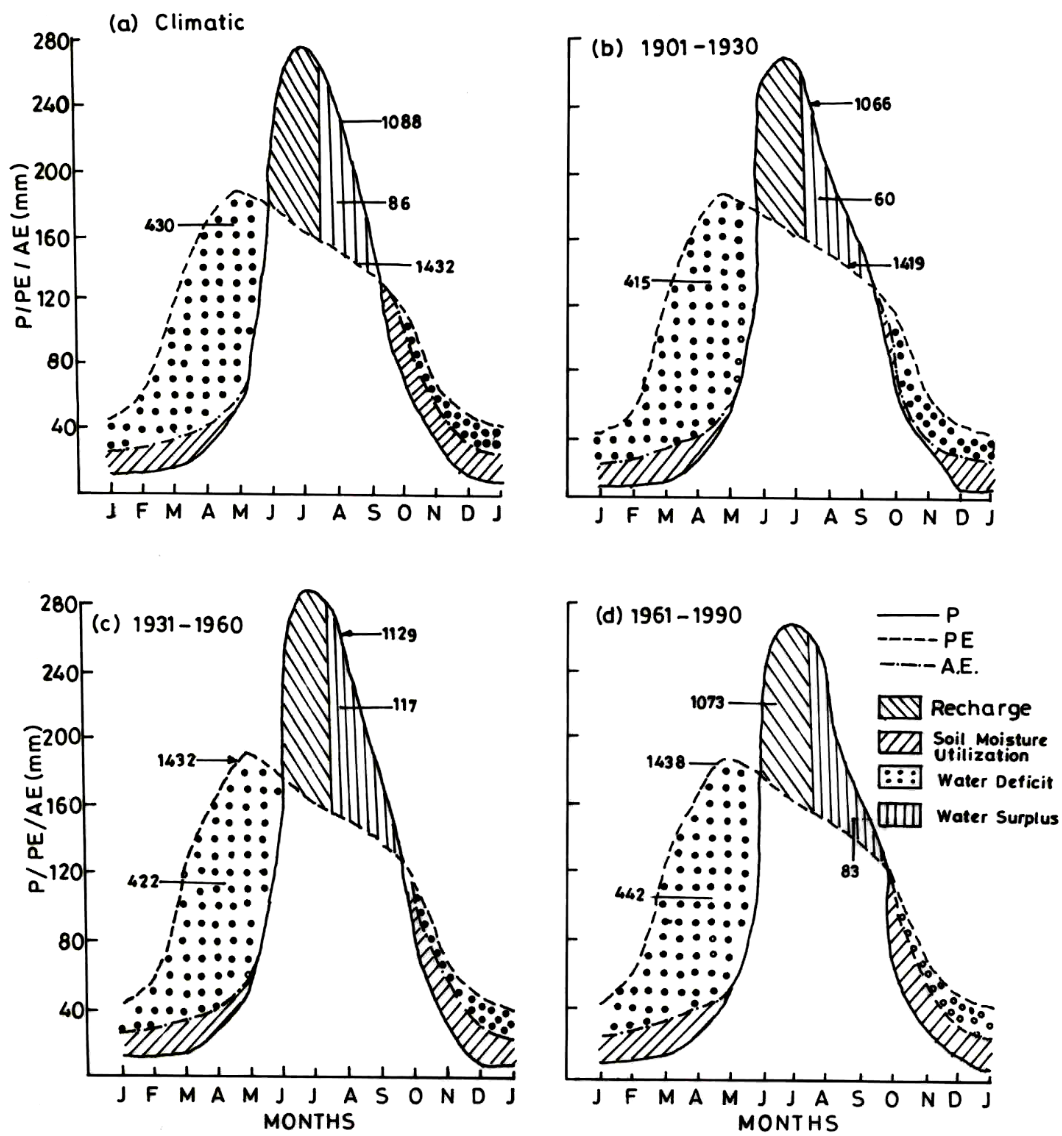
A narrow sector in the south that is protruding from Masulipatam to Raichur and from there to Nellore is subjected to moderate droughts with a frequency of greater than 20% [Fig. 2(b)]. The frequency of moderate droughts is increasing from NW part of India to central Madhya Pradesh in north and from west to east coast that stretches from Kalingapatnam down to Cuddalore [Fig. 2(a)].

(*v*) *High humid events - Moist climates*

The frequency of high humid events is slightly higher (8%) at Guwahati and Sibsagar from Assam compared to 7% at Mount Abu and Kozhikode from Rajasthan and Kerala respectively [Fig. 2(b)].

(*vi*) *Severe droughts events - Dry climates*

Hissar and its adjoins from arid zone recorded severe droughts with a frequency of about 23% while the lee side of the western ghats harboured 15% to 19.7%. Lumding



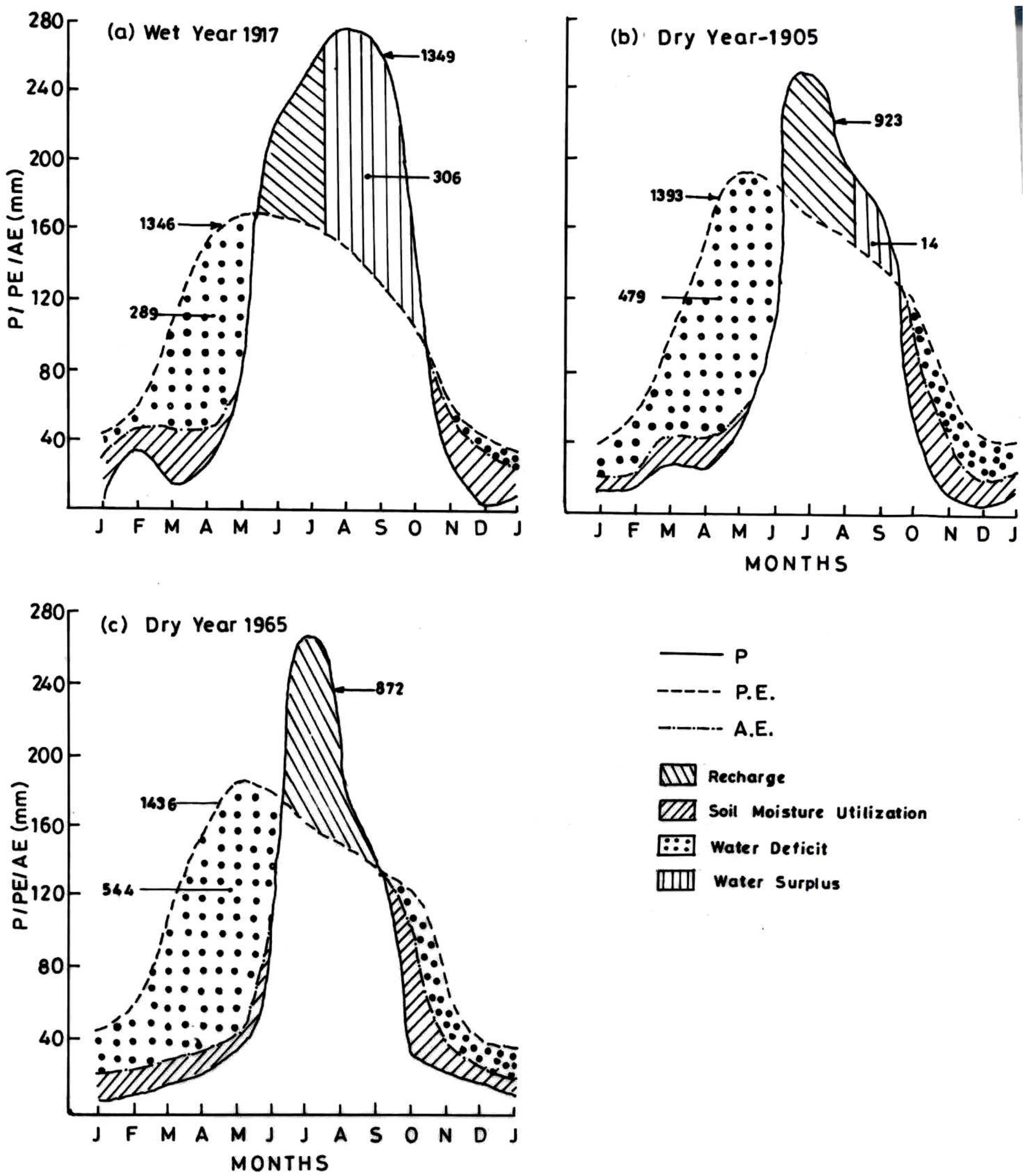
Figs. 3(a-d). Water balances of All India – Distinct epochs (a) Climate, (b) 1901-1930, (c) 1931-1960 and (d) 1961-1990

a dry subhumid station amidst of moist climates from Assam subjected to severe droughts on the order of 14.7%. The frequency of severe droughts varied from 2% to more than 15.6% from northern sectors, down to Coromandel coast and is maximum at Madras and its adjoins [Fig. 2(c)]. Frequency of more than 15% is also observed as isolated pockets over Rajkot and Satna. It appears that the dry climatic provinces of India are subjected to severe droughts.

(*vii*) *Very severe drought events*

Very severe droughts with a frequency of about 6% only appeared highly as isolated pockets at and around Kalingapatnam, Agra, Ahmedabad and Kakinada [Fig. 2(d)].

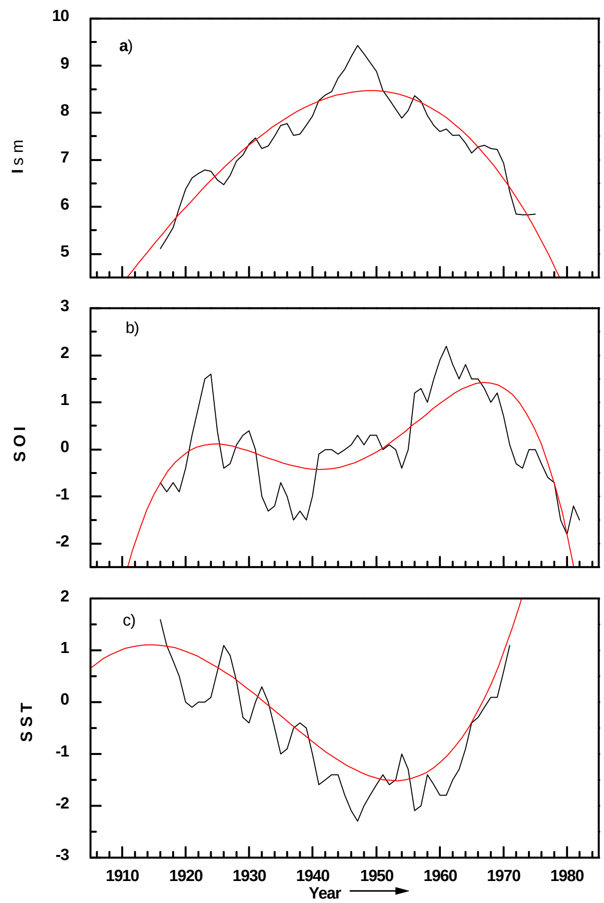
The study of proneness to humid events in the moist climates of India unfolds that the frequency of moderate humid events is high over Assam and its adjoins compared to west coast of India. The northwestern part of India is subjected to high number of severe droughts compared to any other part of India. The occurrence of very severe droughts appears highly as isolated pockets. It is very important to note here that the occurrence of humid and drought events govern the surface hydrologic fluxes which in turn control the flows in regional water system projects.



Figs. 4(a-c). Water balances of All India – Extremities (a) Wet year 1917, (b) Dry year 1905 and (c) Dry year 1965

4. Anomalies in All India terrestrial hydrological cycle - Distinct epochs

Figs. 3 and 4 present All India water balances not only during distinct epochs but also in climate extremities along with the ENSO and LNSO periods. The tendency in All India water balances in distinct epochs is highly skewed and any perturbation in the input from the normal ultimately leads to mismatch with the water need and manifest in its hydrological regime as an anomaly and there by paving ways to flood or drought. All India basic water budget elements that are presented in eleven case studies indicated that its hydrologic regime was moist-subhumid one time only, seven times in dry subhumid and three times in semiarid status (Table 1). The range and variation in thermal efficiency (potential evapotranspiration or water need) are small compared to rainfall as the thermal efficiency maintains conservatism but the range in water surplus is high compared to the variation and range in rainfall. The matching of rainfall with the



Figs. 5(a-c). Polynomial fit for 30-yr normalized CMAS of All India moisture status of (a) SW monsoon, (b) SOI of June to September and (c) SST of September to November of NINO3 region

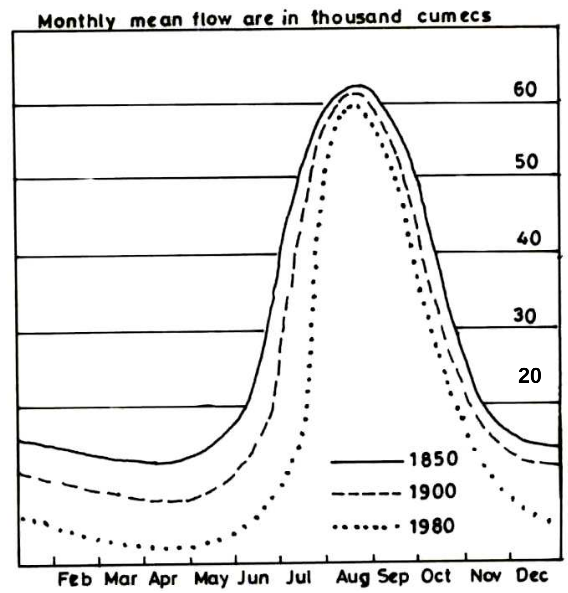


Fig. 6. Mean monthly hydrographs of the Ganges river (Ref: The Earth as transformed by Human Action, 1990)

water need through the year together with the relative difference between water deficit and water surplus determine the hydrologic regime (year / season climate) of the station under question. Figs. 3(a-c) depicts the epochal variability in the basic water balance components of the terrestrial hydrologic cycle of All India. All India had a water surplus of 1.3 times of the normal during the epoch 1931-1960 while that of 1901-1930 witnessed a reduction of 0.6 times of normal (Table 1). In an attempt to understand the extent of perturbation in the hydrologic regime of All India, from epochal mean, the water balances of it are presented in Figs. 4(a-c) for the extremities. The stretching and shrinking not only in amount but also in duration of the rainfall excess period (that is rainfall is greater than water need of the place) are clearly brought out in cases of wet and dry years [Figs. 4(a-c)] compared to epochal mean [Figs. 3(a-d)] accompanied by diminished and increased magnitude of water deficit respectively. It is evidenced from the present investigation that the All India hydrologic regime is in dry subhumid and in extreme climate shifts of 1917 and 1905, its regime is improved and deteriorated by one grade that is moist and dry subhumid type respectively. The ENSO years of 1965, 1972 and 1987 triggered wide spread of droughts all over India with a semiarid status to it (Table 1). It is well known that the waxing and waning circulation patterns of the SW and NE monsoon systems govern the nature of the hydrologic regime of India and is well reflected in the good monsoon year of 1975 by elevating All India's water surplus by 2.3 times of the normal (Table 1), while the extreme wet year of 1917 recorded a water surplus of 3.5 times the normal. It is worth mention here that the hydrologic regime of All India was perturbed during the 1961-1990 epoch since it harboured one good monsoon, one La Nina and four El Nino years (Table 1).

All the ENSO years over India either recorded a zero water surplus with an exception to the year 1982 that witnessed a reduction of more than 5 times the normal. The overall improvement in All India's hydrological regime during the monsoon period continued till 1948 from 1901 accompanied by an increase in SOI and decrease in SSTs of Nino-3 region of Pacific Ocean [Figs. 5(a-c)]. It is worthwhile to mention here that inspite of an increase in SOI beyond 1948-1968, the decrease trend in the hydrological regime did not change since the rise of warming trend commenced at Nino-3 from 1949 which clearly shows that the warm sea surface temperature of Pacific has a greater control over SOI which intern influence the performance of SW monsoon over India.

TABLE 1

All India basic water budget elements (mm) – Distinct epochs – La Nina and El Nino years

Category of Epoch/Year	Annual Rainfall	Annual PE	Annual WD	Annual WS	Climate Type
Normal	**1088**	**1432**	**430**	**86**	**-24 (C_1)**
1901-1930	1066	1419	415	60	-25 (C_1)
1931-1960	1129	1432	422	117	-21.3 (C_1)
1961-1990	1073	1438	442	83	-25 (C_1)
Extreme wet year (1917)	**1349**	**1346**	**289**	**306**	**1 (C_2)**
Good Monsoon Year (1975)	1201	1400	421	205	-15 (C_1)
LaNina Year (1988)	1160	1467	498	199	-20 (C_1)
Extreme dry year (1905)	**923**	**1393**	**479**	**14**	**-33 (C_1)**
El Nino (1965)	872	1436	544	0	-37 (D)
El Nino (1972)	850	1435	536	0	-37 (D)
El Nino (1982)	980	1439	464	15	-31 (C_1)
El Nino (1987)	967	1475	516	0	-34 (D)

C_1 – Dry sub-humid climate
C_2 – Moist sub-humid climate
D – Semiarid climate

TABLE 2

Mean river discharges (Thousand Cumec) of the Ganges at Farakka point – Distinct epochs

Period / Epoch	Annual	March to May	June to September	November to December
1850	28.1	13.8	49.5	16.5
1900	23.8	8.5	45.2	14.0
1980	15.9	1.9	34.6	7.9

5. Trends in river system flows - SOI and SSTs of Nino-3

Coupled ocean-atmosphere interactions such as ENSO/LNSO have been playing a significant role in the variations of the available global hydrological fluxes. But, regional changes due to human interference with the environment might have aggravated the spatio-temporal distribution of fresh water resources across the world.

Fig. 6 shows the seasonal cycles of hydrograph for the Ganges river at Farakka barrage. The hydrographs for the years 1850, 1900 and 1980 are constructed for the Ganges in relation to irrigated area for 1850 and 1900 and is taken from the book authored by Harry *et al*. (1990). Fig. 6 depicts the enormous range (35.1×10^3 cumec) between the monsoon (43.1×10^3 cumec) and lean (8.0×10^3 cumec) epochal flows. It is clear that large amounts of flow were diverted for consumption and might be due to the effects of human intervention, especially in the low flow season (Table 2). The mean annual flow of 28.1×10^3 cumec for the year 1850 is reduced to 15.9×10^3 cumec by 1980 through 23.8×10^3 cumec for the year 1900.

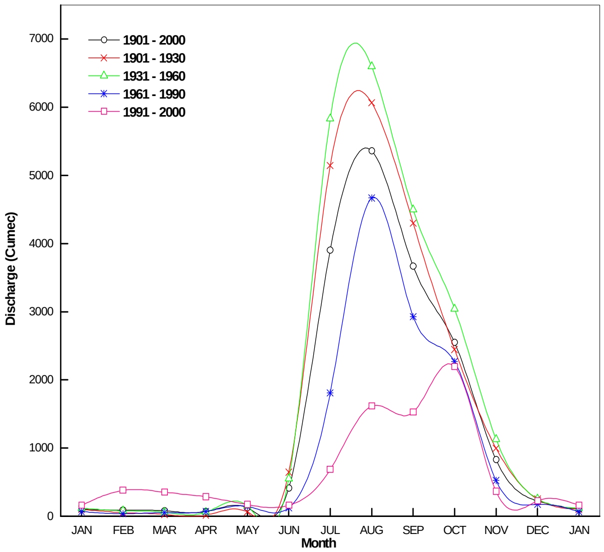


Fig. 7. Hydrograph of Krishna river basin at Vijayawada point – Distinct epochs

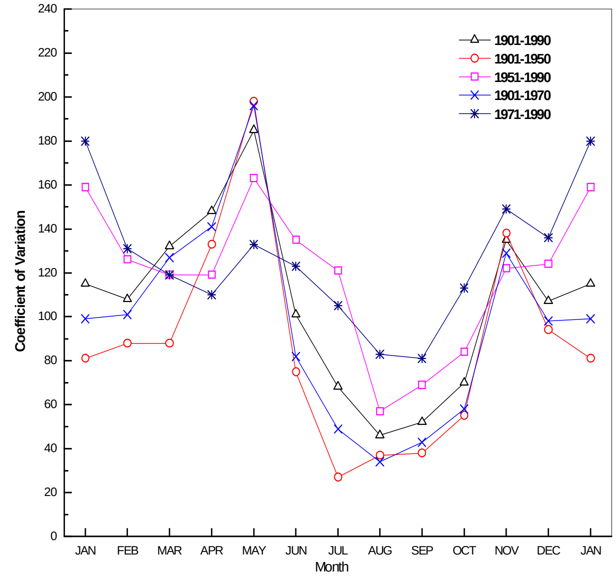


Fig. 9. Coefficient of Variation of the hydrograph of Krishna river basin at Vijayawada point – Distinct epochs

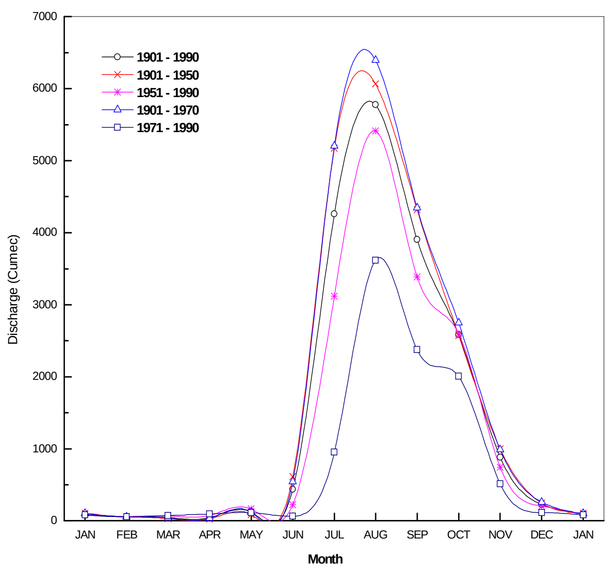


Fig. 8. Hydrograph of Krishna river basin at Vijayawada point – Distinct epochs

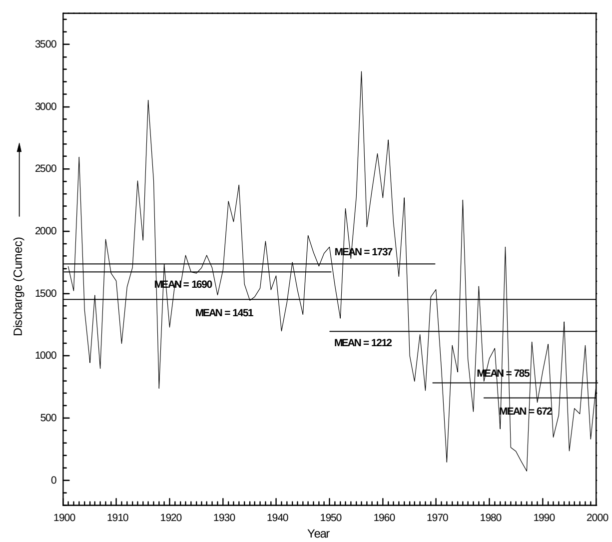


Fig. 10. March of mean annual Krishna river flows at Vijayawada point – Distinct epochs

It is reported that the world wide increased frequency of ENSO events commenced from 1970 (Anonymous, PAGES, News, 1997) and to understand this feature, the catchment's scale rainfall hydrographs and the coefficient of variation in river flows of Krishna river are presented in different epochs (Figs. 7 to 9).

The long-term rainfall of the Krishna river basin as a whole is 910.4mm (2357.4×10^8 m^3) for the period 1901-1990. The rainfall of Krishna river basin as a whole varied from 97.1% of the normal during the period 1971-1990 to 106.2% of the normal for the period 1951-1990 (Table 3). A comparative study of mean annual discharge

TABLE 3

Mean rainfall of the Krishna river basin and river discharges at Vijayawada point – Distinct epochs

Period / Epoch	Rainfall (mm)	Rainfall ($10^8 \times m^3$)	Discharge (Cumec)
1901-2000	-	-	1451.0
1901-1990	910.4	2357.4	1537.2
1901-1950	864.5	2238.5	1690.0
1901-1970	917.9	2376.8	1736.7
1951-1990	967.6	2505.5	1345.6
1971-1990	884.1	2289.3	838.8
1981-2000			672.0

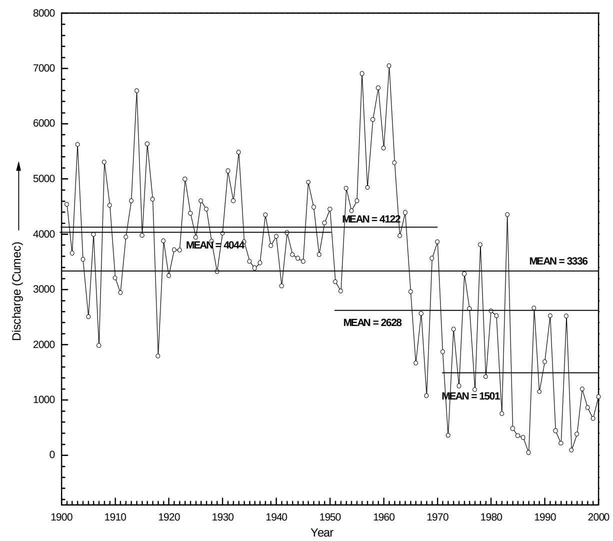


Fig. 11. March of mean monsoon season river flows of Krishna at Vijayawada

of Krishna river at Vijayawada point with the basin rainfall unfolds the human interferences on the river flows from its head and upstream waters (Table 3). The historic mean annual discharge at Vijayawada point is 1451 cumec for the period 1901-2000 (Table 3). The river flow at Vijayawada point varied from 46.3% and 119.6% of the normal during the periods 1981-2000 and 1901-1970 respectively. This clearly shows the increased reduction due to human interference on the river flows compared to the variability in rainfall due to vagaries of monsoon systems in relation to the short-term climate signal. In spite of a drastic reduction in the hydrograph from 1961-1990 to 1991-2000, the flows during August and October months of 1991-2000 recorded the double maxima (Fig. 7) and might be attributed to vigorous monsoon activity and prevalence of weather systems of the retreat monsoon period or frequency of storms and deep depressions respectively (Figs. 7&8). The increased discharge of 114.4% of the normal for 1931-1960 for the months of July to October compared to 1901-1930 and 1961-1990 was due to the increased annual rainfall of July to October (Table 4). Table 4 presents annual rainfall of Krishna river basin and the river discharge from July to October. The mean discharge of 1961-1990 for the July to October was 4990.7 cumec, which was 128.9% of the normal of 3869.5 cumec. It is interesting to note that the discharge of 1991-2000 for the period July to October was 1504.4 cumec, which was 43.8% of the normal only. This reduction of discharge since 1961 to 2000 during the months of July to October is a clear indication of diversion of head and upstream waters by human activity or interference through Srisailam and Nagarjuna Sagar reservoirs. The mean coefficient of variation of river flows of 1901-1990 and 1901-1970 for June to September were 66.7% and 52% compared to 98% during 1971-1990, while the lean flow season of 1951-1990 recorded a

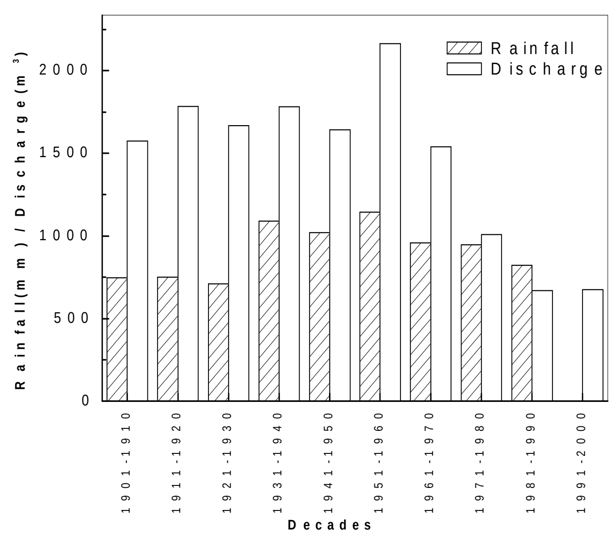


Fig. 12. Decadal rainfall of Krishna river basin and discharge at Prakasam barrage (Vijayawada)

variation of 133.6% compared to 154% of 1901-1970 (Fig. 9).

Figs. 10 and 11 describe the interannual variation in annual and monsoon period flows of Krishna river at Vijayawada point. The march of annual and monsoonal flow showed a decreasing trend. Further, the interannual variation in flows is high and especially the means of the period 1981-2000 of annual and monsoonal are less by two and half times and more than 2.5 times respectively

TABLE 4

Mean river discharges (Cumec) of Krishna river basin at Vijayawada point for the selected months – Distinct epochs

Period/Epoch	Annual rainfall (mm) ($10^8 m^3$)	River Discharge (Cumec)			
		July	August	September	October
1901-2000	-	3902	5361	3669	2546
1901-1930	737.2 (1908.9)	5142	6067	4298	2425
1931-1960	1084.7 (2808.7)	5830	6594	4498	3041
1961-1990	909.1 (2354.0)	1808	4669	2928	2269
1991-2000	-	683	1618	1524	2194

compared to the corresponding means of 1901-1970 period. It is a clear-cut case apart from the effects of climate teleconnections, human interference with the river systems under consideration.

A comparative study of Krishna river basin rainfall with the river flows at Prakasam Barrage at Vijayawada point (Fig. 12) on decadal wise substantiates the features of Tables 3 and 4. The decades of 4^{th} to 6^{th} experienced higher rainfall compared to the remaining decades of the 20^{th} century. Even though the decades of 7^{th} and 9^{th} recorded higher rainfall compared to the first three, the flows at Vijayawada are drastically reduced with the commissioning of upstream reservoirs of Nagarjuna Sagar (6^{th} decade) and Srisailam (7^{th} decade). The river flows at Vijayawada point are markedly started declining since 1981 and is the proof of the impacts of human intervention on the hydrograph of the downstream point, Vijayawada.

6. Conclusions

The study of proneness to humid events in moist climates of India indicates that the frequency of moderate humid events is high over Assam compared to the west coast. The very humid events frequency is same at these two geographical locations. Hissar and its adjoins from Haryana subjected to higher number of severe droughts compared to any other part of India. Parts of Uttar Pradesh, Madhya Pradesh, Gujarat, Maharashtra, Karnataka, Andhra Pradesh are subjected to very severe droughts. The frequency of very severe droughts concentrated with a value of greater than 6 not only at interior places like Agra and Ahmedabad but also the coastal places of Kalingapatnam and Kakinada.

The normal hydrological regime of All India is dry subhumid and is subjected to improvement or deterioration in relation to LNSO or ENSO signal. It is observed that the ENSO signal triggers countrywide droughts with a simultaneous deterioration in its regime to semi-arid (1965, 1972 and 1987 years) but the LNSO signal elevates country's annual water surplus (1988 year).

Human intervention effects are clearly detailed from the hydrographs of Ganges and Krishna rivers in distinct epochs indicating that large amounts of flow are diverted for consumption.

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References

Anonymous, 1997, "Editorial, Past Global Changes (PAGES)", News, Bern, Switzerland, 5,3.

Carter, D. B. and Mather, J. R., 1966, "Climatic Classification for Environmental Biology", Publ. In Clim, Druxel Inst., **19**, 4, 341-352.

Glantz, M. H., Katz, R. W. and Nicholls, N., (eds) 1991, "Teleconnections linking world wide climate anomalies", Cambridge University Press.

Harry, E. S., Jacques, E., William, J. D., Peter, R. and John, T., 1990, (Ed) Turner II, B. L., William, C. C., Robert, W. K., John, F. R., Jessica, T. M. and William, B. M., "The earth as transformed by human action", Cambridge Univ. Press with Clark Univ., 253-270.

Joseph, P. V., 1976, "Climatic change in monsoon and Cyclones 1891-1974", Proceedings of Symposium on Tropical Monsoons, IITM, Pune, 378-387.

Kripalani, R. H. and Kulkarni, A., 1997, "Climatic impacts of LaNina on the Indian monsoon : A new Perspective", *Weather*, **52**, 2, 39-49.

Pant, G. B. and Parthasarathy, B., 1981, "Some aspects of an association between the Southern Oscillation and the Indian summer monsoon", *Arch. Meteor. Geophys. Bioklim*, **B29**, 245-252.

Parthasarathy, B., Munot, A. A. and Kothawale, D. R., 1995, "Monthly and seasonal rainfall series for All India homogeneous regions and meteorological sub-divisions", Res. Rep, RR-065, IITM, Pune, 1871-1994.

Palmer, T. N., 1994, "Chaos and Predictability in forecasting the monsoons", *Pre. Indian Natl. Sci. Acad*., **60**, 57-66.

Ramusson, E. M. and Carpenter, T. H., 1983, "The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka", *Mon. Wea. Rev*., **111**, 517-528.

Ropelewski, C. F. and Halpert, M. S., 1987, "Global and regional scale precipitation associated with ENSO", *Mon. Wea. Rev*., **115**, 1606-1626.

Sarma, A. A. L. N., Srinivas, S. and Karthikeya, A., 2005a, "Studies on aberrations in climate impacts – Water balance model", *Jour. Indian Geophysical Union*, **9**, 3, 209-218.

Sarma, A. A. L. N. and Srinivas, S., 2005b, "Studies on some aspects of the intensification of hydrological cycle", *Jour. Indian Geophysical Union*, **9**, 4, 297-311.

Sarma, A. A. L. N., Padma Kumari, B. and Srinivas, S., 1999, "Studies on hydrological extremities – ENSO signal", IAHS Publ. No. **255**, 73-80.

Shukla, J., 1998, "Seasonal Prediction: ENSO and TOGA", Proc. of World Climate Research Programme: Achievements, Benefits and Challenges, WMO/TD No. **904**, 37-48.

Sikka, D. R., 1980, "Some aspects of the large scale teleconnection of summer monsoon rainfall over India in relation to the planetary and regional scale circulation parameters", Proc. Ind. Acad. Sciences (Earth. Planet. Sci.), **89**, 179-195.

Sikka, D. R., 2000, "Monsoon floods in India", Joint COLA/Care Tech.Tep.4, COLA/IGES, Calverton, Md, USA, p172.

Simpson, H. J., Cane, M. A., Herczeg, A. L., Zebiak, S. E. and Simpson, J. H., 1993, "Annual river discharge in southern Australia related to El Nino-Southern Oscillation forecasts of Sea Surface Temperatures", *Water Resources Research*, **29**, 11, 3671-3680.

Subrahmanyam, V. P. and Sarma, A. A. L. N., 1975, "Incidence of aridity and droughts in the climatic spectrum of the south India region", *Trop. Ecol*., **16**, 2, 120-127.

Thapliyal, V. and Kulshresta, S. M., 1991, "Climatic changes and trends over India", *Mausam*, **42**, 333-338.

Thornthwaite, C. W. and Mather, J. R., 1955, "The Water Balance", Publ. Clim, 8,1.

Appendix

Selected stations and the climate types – India

S. No.	Station	Latitude	Longitude	a.m.s.l.	Period	Climate type
1.	Cherrapunji	25° 15'	91° 44'	1313	1901-1990	A
2.	Sibsagar	26° 59'	94° 38'	97	1891-1992	A
3.	Guwahati	26° 11'	91° 45'	55	1903-1992	B_2
4.	Lumding	25° 45'	93° 11'	149	1949-1992	C_1
5.	Calcutta	22° 32'	88° 20'	6	1891-1990	C_1
6.	Darjeeling	27° 03'	88° 16'	2127	1901-1984	A
7.	Balasore	21° 30'	86° 56'	20	1901-1993	C_2
8.	Sambalpur	21° 28'	83° 38'	148	1901-1992	C_2
9.	Daltonganj	24° 03'	84° 04'	221	1901-1991	C_1
10.	Dumka	24° 16'	87° 15'	149	1901-1991	C_1
11.	Jamshedpur	22° 49'	86° 11'	129	1924-1990	C_1
12.	Sabour	25° 14'	87° 04'	37	1932-1990	C_1
13.	Agra	27° 10'	78° 02'	169	1901-1990	D
14.	Allahabad	25° 27'	81° 44'	98	1901-1990	D
15.	Bahraich	27° 34'	81° 36'	124	1901-1990	C_1
16.	Dehradun	30° 19'	78° 02'	682	1901-1990	B_4
17.	Kanpur	26° 26'	80° 22'	126	1901-1991	D
18.	Mussorie	29° 28'	79° 39'	2311	1901-1986	A
19.	Hissar	29° 10'	75° 44'	221	1901-1991	E
20.	New Delhi	28° 35'	77° 12'	216	1891-1995	D
21.	Shimla	31° 06'	77° 10'	2202	1901-1989	A
22.	Mount Abu	24° 36'	72° 43'	1195	1901-1990	B_2
23.	Bikaner	28° 00'	73° 18'	224	1891-1990	E
24.	Jodhpur	26° 18'	73° 01'	224	1901-1992	E
25.	Kota	25° 11'	75° 51'	257	1901-1990	D
26.	Udaipur	24° 35'	73° 42'	582	1901-1988	D
27.	Bhopal	23° 17'	72° 21'	523	1949-1999	C_1
28.	Jagdalpur	19° 05'	82° 02'	553	1910-1990	C_2
29.	Khandwa	21° 50'	76° 22'	318	1901-1991	D
30.	Raipur	21° 14'	81° 39'	298	1901-1991	C_1
31.	Satna	24° 34'	80° 50'	317	1901-1991	C_1
32.	Ahmedabad	23° 04'	72° 38'	55	1893-1992	D
33.	Dwarka	22° 22'	69° 05'	11	1901-1992	E

Appendix (*Contd.*)

S. No.	Station	Latitude	Longitude	a.m.s.l.	Period	Climate type
34.	Rajkot	22° 18'	70° 47'	138	1891-1990	D
35.	Nasik	20° 00'	73° 45'	598	1965-1986	D
36.	Akola	20° 42'	77° 02'	282	1901-1991	D
37.	Aurangabad	19° 53'	75° 20'	581	1902-1990	D
38.	Mahabaleswar	17° 56'	73° 40'	1382	1932-1995	A
39.	Bombay	18° 54'	72° 49'	11	1891-1992	C_2
40.	Nagpur	21° 06'	79° 03'	310	1901-1992	C_1
41.	Parbhani	19° 08'	76° 50'	423	1951-1991	D
42.	Pune	18° 32'	73° 51'	559	1891-1995	D
43.	Solapur	17° 40'	75° 54'	479	1901-1991	D
44.	Anantapur	14° 41'	77° 37'	350	1947-1992	D
45.	Hyderabad	17° 27'	78° 28'	545	1901-1992	D
46.	Kakinada	16° 57'	82° 14'	8	1901-1992	D
47.	Kalingapatnam	18° 20'	84° 08'	6	1911-1992	D
48.	Kurnool	15° 50'	78° 04'	281	1901-1990	D
49.	Machilipatnam	16° 11'	81° 08'	3	1891-1992	D
50.	Nellore	14° 27'	79° 59'	20	1901-1992	D
51.	Ramagundam	18° 46'	79° 26'	156	1948-1992	C_1
52.	Rentachintala	16° 33'	79° 33'	106	1939-1990	D
53.	Visakhapatnam	17° 43'	83° 14'	3	1891-1996	D
54.	Madras	13° 00'	80° 11'	16	1891-1995	C_1
55.	Cuddalore	11° 46'	79° 46'	12	1901-1992	C_1
56.	Kodaikanal	10° 14'	77° 28'	2343	1901-1992	A
57.	Tiruchirapalli	10° 46'	78° 43'	88	1901-1992	D
58.	Bangalore	12° 58'	77° 35'	921	1891-1992	C_1
59.	Belgaum	15° 51'	74° 32'	753	1901-1990	C_2
60.	Bellary	15° 09'	76° 51'	449	1891-1992	E
61.	Chitradurga	14° 14'	76° 26'	733	1901-1991	D
62.	Mangalore	12° 52'	74° 51'	22	1891-1992	A
63.	Raichur	16° 12'	77° 21'	400	1901-1992	D
64.	Cochin	09° 58'	76° 14'	3	1891-1994	B_3
65.	Kozhikode	11° 15'	75° 47'	5	1891-1992	B_4
66.	Thiruvananthapuram	08° 29'	76° 57'	64	1891-1990	C_2