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Spatio-temporal Variation of Hydrological Drought in the Indo-Gangetic Plains

Manoj Khanna[1], Mukesh Kumar[2], Rekha Rani[3] and Himanshu Pathak[4]

[1]Principal Scientist, [2]Research Associate, [3]Research Associate, Water Technology Centre, Indian Agricultural Research Institute, New Delhi 110012; [4]Director, National Rice Research Institute, Cuttack (Odisha) 753 006. Corresponding author e-mail address: Khanna_manoj2001@yahoo.com.au

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ABSTRACT

The Indo-Gangetic plains (IGP) encompass a large alluvial track consisting of multi-tier aquifer system. Due to stride developmental activities and intensification of agriculture with higher irrigation water requirement, shallow groundwater regime is getting depleted causing hydrological drought. Spatio-temporal variation of seasonal drought pattern and drought severity in the IGP region was analysed for the period of 2005-2009, using Standardized water level index (SWI) with topo to raster methods of interpolation in geographic information system (GIS). Analysis of hydrological drought indicated that 40-60 % area in the IGP was affected by mild hydrological drought, whereas 2-7 % of the area was affected by extreme hydrological drought because of excessive and indiscriminate groundwater pumping leading to decline in groundwater level. SWI categories were correlated with the irrigation activity for better irrigation planning. Irrigation planning for the IGP was suggested for different SWI drought categories.

Drought is a natural hazard adversely affecting agriculture, socio-economic activities, livelihood, human and animal health and sustainability of natural environments (IPCC, 2007; Mishra and Singh, 2010). Hydrological drought is defined as a significant decrease in the availability of water appearing in the land phase of the hydrological cycle (Nalbantis, 2009). It may be a result of long term meteorological drought that resulted in the drying up of reservoir, lake, streams and rivers and a decline in groundwater levels (Rathore, 2004).

Groundwater drought is a particular type of hydrological drought that occurs when groundwater recharge deviates negatively from the normal events (Tallaksen and Van Lanen, 2004).Groundwater drought adversely affects water availability for agriculture, public supply and industry; and unlike the surface water groundwater takes significantly longer time to be replenished (Aggarwal *et al*., 2012). Groundwater levels can be used as a key variable to assess hydrological drought.

The total geographical area of Indo-Gangetic Plains (IGP) is 255 Mha. The IGP region in India is extended to five states of Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal. It is one of the most densely populated regions in the world with extensive agricultural activities. During the last three decades, the region has witnessed large scale growth in agriculture, industrialization and population explosion leading to excessive stress on both surface and groundwater resources, quantitatively as well as qualitatively. Increased variability in precipitation and the frequent drought events that have recently occurred have highlighted the need for an improvement of the current strategies for mitigating drought impacts on irrigation activities (Mendicino *et al*., 2008; Mishra and Singh, 2010). Researchers have also emphasized the monitoring and characterization of long-term drought trends and development of drought warning system for mitigating its impacts (Mendicino *et al*., 2008; Florillo and Gudaguo, 2012).

Agriculture in the arid and semi-arid regions depends on the groundwater irrigation. Around 45- 60 % water for irrigation in most of the districts of the IGP region is exploited from groundwater. Central Water Commission (2009) reported that the ratio of surface and groundwater use for total irrigated agriculture had changed drastically in the last two decades in the IGP region. The contribution of groundwater to irrigation has increased many folds as compared to surface water. Excessive withdrawal of groundwater to irrigate crops under drought condition has depleted groundwater in large parts of the IGP region. It is an irreversible loss in many cases due to lack of recharging possibilities. Farmers excessively consume electricity and fossil fuels for pumping groundwater in order to offset rainfall deficiency (Shah, 2009; Pathak *et al*., 2014).

The objectives of the present study were to (1) characterize hydrological drought conditions through SWI in IGP categories, and (2) establish a relationship between SWI drought categories and irrigation planning for sustainable use of groundwater.

MATERIALS AND METHODS

Study Area

The present study was carried out in the IGP, which lies between the east longitudes 73°30' to 89°0' and north latitudes 22°30' to 31°30' (Fig. 1). The IGP region covered a distance of 400-800 km wide, low relief, east-west zone between the Himalaya in the north and the Peninsula in the south. The IGP region climate is characterized as sub-tropical climate with three distinct seasons (summer, monsoon and winter) with average mean daily temperature ranging from 20°C to 32°C. The highest and lowest temperature range of about 45 °C and 4 °C are recorded in the months of June and January, respectively. The region receives an average annual rainfall ranging from 300 to 800 mm. Rainfall activity happens mostly during south-west monsoon (June to September). The rainfall is generally adequate for summer-grown crops, but majority areas depend on surface and groundwater resources. As surface water availability is not certain, groundwater is the major source of irrigation.

Fig. 1: Study area map of the Indo-Gangetic plains

The IGP region forms the largest consolidated area of irrigated food production on the globe with a net cropped area of 114 Mha. The development of tube well irrigation was an important factor in increasing food production and reducing poverty. However, much of the groundwater use in the region is not sustainable; therefore, the area is being confronted with major groundwater management challenges. Over-exploitation of groundwater and declining water tables in the drier eastern and western part of the region is the major problem. This leads to hydrological drought in the IGP region.

Standardized Water level Index (SWI)

Spatio-temporal variation of seasonal hydrological drought pattern and severity in the IGP region was analysed using the groundwater levels. The variation of hydrological drought was carried out by dividing the year into two main seasons of pre-monsoon and post-monsoon based on monsoonal pattern of rainfall. The pre-monsoon period indicates groundwater level during the month of May, while post-monsoon period indicates groundwater level during the month of November. The groundwater levels of these two months were used to characterize hydrological drought in the region.

Hydrological drought variation was analysed using Standard Water-Level Index (SWI), which is based on groundwater level. SWI was proposed to monitor anomaly in groundwater level as a correspondent of aquifer-stress (Bhuiyan, 2004). The SWI was computed by normalising seasonal groundwater level, and dividing the difference between the seasonal water level and its long-term seasonal mean, by standard deviation. The SWI is given by:

$$SWI = (Wij - Wim)/\sigma \quad \ldots(1)$$

Where,

SWI = Standardised water level index,

Wij = Seasonal water level for the i^{th} well and j^{th} observation, m,

W_{im} = Seasonal mean, m, and

σ = Standard deviation.

The SWI value has been classified and used as a measure of hydrological drought intensity. Since groundwater level is measured down from the surface, positive anomalies correspond to drought and negative anomalies correspond to 'no-drought' or normal condition.

SWI Hydrological Drought Category

SWI is an indicator of water table decline and an indirect measure of recharge, and thus an indirect reference to drought. For interpretation, categories of hydrological drought were defined (Bhuiyan *et al.*, 2006) and given in Table 1.

Table 1. SWI hydrological drought categories

Sl. No.	Drought category	SWI	
1.	Extreme drought	>2.0	
2.	Severe drought	>1.5	
3.	Moderate drought	>1.0	
4.	Mild drought	>0.0	
5.	No drought	<0.0	

Data Source

Data analysis was carried out for the period ranging from the year 2005 to 2009 from the network of 3187 observation wells. Groundwater level data were collected from the Central Ground Water Board, Faridabad (Haryana), India. Out of 3187 observation wells, 261 were located in the state of Punjab, 426 in the state of Haryana, 1218 in the state of Uttar Pradesh, 373 in the state of Bihar and 909 in the state of West Bengal. However, water level data were grouped according to four seasons viz. post-monsoon *rabi* (January to March), pre-monsoon (April to June), monsoon (July to September) and post-monsoon *kharif* (October to December).

After sorting the groundwater level data season-wise, point data shape files were generated in GIS. These point data shape files were average value of total number of observation wells of the districts that had been used for calculation of SWI using Eqn. (1). These SWI values were added in topo to raster interpolation technique, and 2D maps were generated to show spatial variation of pre- and post-monsoon water levels along with water level fluctuations at 5-year (2005 and 2009) interval.

RESULTS AND DISCUSSION

SWI Hydrological Drought in IGP Region

Time series analysis of SWI maps revealed that hydrological drought in the Indo- Gangetic plain regions during the pre-monsoon and post-monsoon period followed an alternate pattern with minor local variations. During the pre-monsoon period, many discrete pockets all over the IGP regions experienced mild to extreme hydrological drought for the period of 2005 to 2009 (Fig. 2). However, during the year 2005-06, most of the parts of IGP regions showed no drought, but the drought situation aggravated gradually in the following years. During the year 2005, post-monsoon water level was normal or near normal in major parts of the IGP regions, except in some discrete pockets in the western and eastern parts. Before commencement of the 2006 monsoon, most parts of the IGP region were hit by the moderate to severe drought; and major pockets

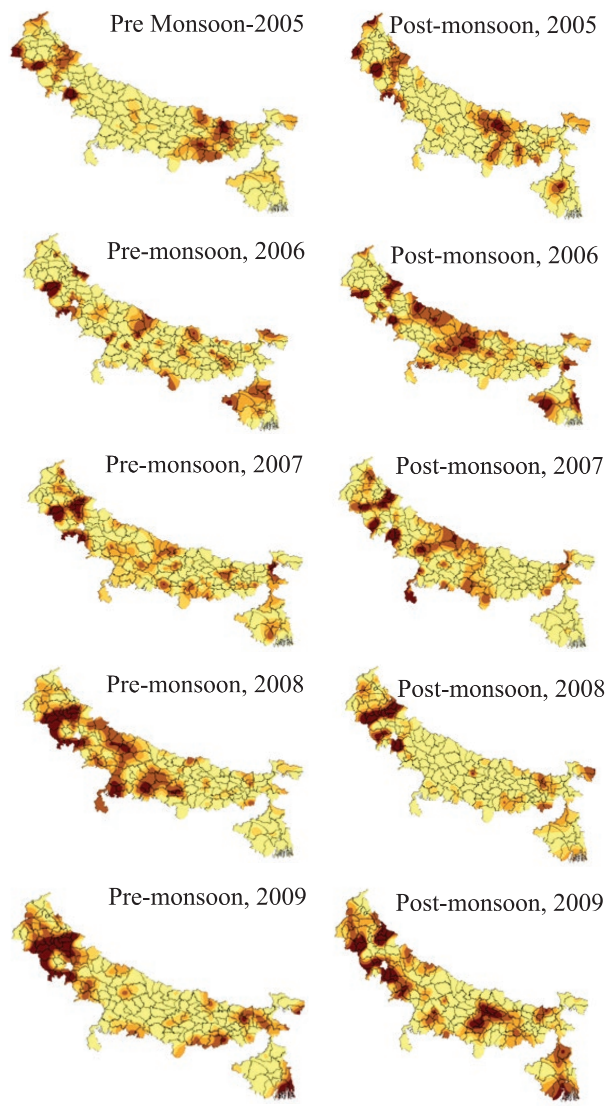

Fig. 2: Year-wise (2005 to 2009) spatio-temporal variation of hydrological drought during pre- and post-monsoon in IGP

were observed in the southern, eastern and western parts suffering from extreme hydrological drought (Fig. 2).

The drought situation further aggravated in the IGP regions and showed affected by moderate to severe hydrological drought during the monsoon period of 2007, but the western part represented no drought. The western parts of IGP underwent a temporary recovery from the water stress during the monsoon of 2008. However, in the year 2008, some parts of the IGP showed drought situation that shifted from western region to southern region (Fig. 2). Although, the drought situation worsened for the period of 2008 (pre-monsoon) and 2006 (post-monsoon), the maximum part of the IGP regions was represented as in acute drought. Severe hydrological droughts had appeared in the region during 2005-2009, as rain-clouds failed to precipitate (Fig. 2). As revealed by the post-monsoon ground water level, the drought condition was worst during the monsoon period of 2009 when most of the wells and reservoir had dried up.

Groundwater drought in the study area is caused both by the reduction of supply and increase of demand. Therefore, the SWI maps shows that some pockets, particularly in the western sector of the regions, frequently suffered from water stress either during the monsoon or non–monsoon period. A continuous spell of poor rainfall in successive years in combination with high temperature affected ground water recharge and imparts stress on ground water resources leading to severe drought in many parts of the IGP region (Kondoh *et al*., 2004).The drought perception varies significantly among regions of different climates (Dracup *et al*., 1980), while rainfall, soil moisture, stream flow, reservoir storage and groundwater level are the main parameters reflecting drought impacts (Bhuiyan *et al*. 2006). The pictorial results generated through various drought indices have been studied, analysed, compared and correlated. Apart from drought intensity, drought duration in different parts of the IGP region has been monitored and interpreted through usual observation of the resultant maps. These results are discussed in following paragraph.

Susceptible Districts to Hydrological Drought in IGP Region

The SWI was categorized into different types of drought categories at district level in the Indo-Gangetic plain regions (States under IGP). The area under different categories of SWI drought category was estimated after drawing the contour of each category in GIS environment. The area analysis indicated that 40-60 % of the area under IGP was under mild drought condition. The area under extreme hydrological drought increased from 2 % to 7 % during the period under study.

Most of the districts of different states in the IGP region such as Gurdaspur and Firozpur in Punjab; Hisar, Fatehabad, Rewari and Mahendragarh in Haryana; Gorakhpur and some parts of Deoria in Uttar Pradesh and district Barddhaman in Bihar state fell in the category of extreme drought during the year of 2005. But, during the year 2006, 2007 and 2008 spatial and temporal variations in hydrological drought were also observed in different district of IGP states. The hydrological drought in different parts of the districts in Punjab and Haryana state showed extreme and severe drought condition during the year of 2008 (Fig. 2). Some agriculturally important districts such as Rohtak, Bhiwani, Sirsa, Jhajjar, Hisar, Rewari, Jind and Kaithal in Haryana faced severe to extreme drought situation, while Bhatinda, Amritsar, and Sangrur, Kapurthala and Patiala districts in Punjab also faced the severe to extreme drought situation in Punjab. The middle parts of the IGP belonging to Uttar Pradesh state also faced the situation of hydrological drought, and consequently a large number of districts as Hamirpur, Jhansi, Mahoba, Fatehpur and some parts of the district Badaun and Lakhimpur were facing the problem of severe to extreme drought conditions. Rest of the parts of districts of Uttar Pradesh under IGP showed mild drought.

During the period of pre-monsoon 2009, most of the districts suffered from mild, moderate, severe and extreme hydrological drought categories in the IGP region. During this period, the adversely drought affected districts in Haryana state were Jhajjar, Mahendargarh, Bhiwani, Hisar, Fatehabad, Kaithal and Sirsa and Mansa and peripherial parts of Sangrur in Punjab. In Uttar Pradesh, the extremely drought affected districts were Saharanpur and north-east parts of Aligarh. Jamui and Banka districts in Bihar state and South 24 Parganas, North 24 Parganas, Koch Bihar and Nawada districts in West Bengal state were facing the problem of hydrological drought in the IGP region (Table 2). Severe hydrological drought situations are very critical for livelihood and agriculture ecosystems. In IGP region Gurugram, Mansa, Patiala, Sangrur, Nawasahar, Yamuna Nagar, Gaya, Rohtas, Aurangabad, Purnea, Kishanganj and Purba Champaran districts suffered from severe drought. During the period of post-monsoon season 2009, 30 districts belonged to severe hydrological drought conditions and 24 districts were categorized to extreme drought (Table 3).

Table 2. State-wise most susceptible districts of the IGP region in different categories of hydrological droughts and stress during pre-monsoon, 2009

Drought Class	State-wise SWI drought category (Pre-monsoon, 2009)				
	Punjab	Haryana	Uttar Pradesh	Bihar	West Bengal
Mild	Gurdaspur, Muktsar, Bhatinda		Bareilly, Pilibhit, Badaun, Moradabad, Etah, Lakihmapur, Hardoi, Lalitpur, Jhansi, Hamirpur, Bijnor, Bullandshahar, Mainpuri,Etawah, Jalaun, Fatehpur, Kanpur Nagar, Unnao, Lucknow, Pratapgarh, Rae Bareli, Barabanki, Bahariach, Shrawasti, Gonda, Balrampur, Allahabad, Jaunpur, Azamgarh, Ambedkar Nagar		
Moderate	Amritsar, Firozpur, Faridkot, Bhatinda, Moga, Ludhiana		Gautam Budh Nagar, Jyotiba Phule Nagar, Ghaziabad, Baghpat, Meerut, Kheri, Sitapur, Barabanki, Lucknow, Faizabad, Sultanpur		West Medinipur, Birbhum
Severe	Patiala, Sangrur, Rupnagar, Nawasahar, Fatehgarh Sahib	Gurugram, Kurukshtrea, Yamuna Nagar,		Sheikhpura, Gaya, Rohtas, Jehanabad, Araria, Purnia, Kishanganj	Purba Chimparan
Extreme	Mansa	Jhajjar, Mahendargarh, Bhiwani, Hisar, Sirsa, Fatehabad, Kaithal	Saharanpur	Jamui, Banka,	South 24 Parganas, North 24 Parganas, Nawada, Cooch Bihar

The pre-monsoon groundwater level variation mostly reflects the water stress side, *i.e.* the human impact and air temperature. In contrast, the pre-dominant control of the post –monsoon water level could be of recharge side, *i.e.*, the availability of recharge and the capacity of different aquifers to respond to the recharge during and after the rainy season. The human activities effect could be secondary in this period. Despite the human stress and temperature impacts, the pre-monsoon water level may better reflect the impact of rainfall in the previous rainy season through lagged recharge than the post-monsoon water level because it contains less random noise of high frequency from surface water infiltrations. However, it is difficult to separate the human stress and temperature impacts from the time lagged recharge effects in the pre monsoon water table.

Relationship Between SWI Drought and Irrigation Planning

A scheme of SWI hydrological drought categories related to irrigation planning was proposed for representing the requirement of groundwater for irrigation in the IGP regions (Table 4). In practice, as soon as drought reaches the category of 2, 3 and 4; it indicates extreme level drought. Irrigation is needed when decline of water level grades reach 4th and 5th (severe drought), and 2nd and 3rd (moderate, mild drought). Irrigation needs are difficult to be satisfied with groundwater level. In that case, irrigation has to depend on canal water supply. Table 4 proposes the relationship between SWI category of extreme drought and action on irrigation using either canal water or groundwater. Under the category of extreme drought, application of life saving irrigation or use of

Table 3. State-wise most susceptible districts of IGP region in different categories of hydrological droughts and stress during post-monsoon, 2009

Drought class	Statewise SWI drought category (Post-monsoon, 2009)				
	Punjab	Haryana	Uttar Pradesh	Bihar	West Bengal
Mild	Gurdaspur, Hoshairpur	Jind, Panipat	Bijnor, Meerut, Bareilly, Moradabad, Rampur, Lalitpur, Jhansi, Hamirpur, Jalaun, Unnao, Rae Bareilly, Balrampur, Bahariach, Gonda, Basti, Fatehpur, Sonhbhadra, Sitamarhi, Gorakhpur	West Champaran	Darjeeling, Jalpaiguri, Puruliya, Bankura, Cooch Bihar
Moderate	Jalandhar, Ludhiana, Moga, Sangrur, Mansa, Muktsar, Patiala	Ambala,	Pilibhit, Lakhimpur, Badaun, Sitapur, Hardoi, Allahabad, Mahoba, Sonbhadra, Ballia	Saran, Vaishali, Jamui, Banka, Munger, Lakhisarai, Katihar	
Severe	Amritsar, Faridkot, Fariozpur, Kapurthala, Moga, Rupnagar	Panchkula, Sonipat, Jind, Bhiwani	Mathura, Agra, Etawah, Moradabad, Rampur, Chitrakoot	Supaul, araria, Purnia, Saharsa, Nalanda, Bhagalpur, Madhepur	Murshidabad, Birbhum, Barddhaman, Hoogly, Midenipur, Howrah, Kolkata,
Extreme	Patiala	Hisar, Sirsa, Karnal, Fatehabad, Gurugram, Mahendargarh, Jhajjar, Mewat	Saharanpur, Muzzafarpur, Mathura, Etah, Aligarh, Bullandsahar, Firozabad, Jaunpur, Mau, Deoria	Siwan	South 24 Parganas, East Medinipur

Table 4. Relationship between the standardized water level index (SWI) drought categories and irrigation planning

Sl. No.	SWI drought category	Related drought severity and irrigation
1.	No drought	For "normal", no operation needed
2.	Mild drought	Only 25-30 % of ground water pumping
3.	Moderate drought	Only 50 % of ground water pumping and delaying the time of first irrigation; another 50 % irrigation from other source (water catchment/canal)
4.	Severe drought	Delay time of first irrigation, and appropriate extraction of ground water
5.	Extreme drought	Use of life saving irrigation from ground water (drip and sprinkle irrigation)

efficient irrigation methods as drip or sprinkler system is suggested.

However, development of surface water resources for irrigation is essential to reduce growing pressure on ground water table. In addition, water conservation programme is required, which would contribute to the recharging of groundwater to maintain better hydrological cycle. Steps are required to regulate the extraction of water in the area for sustaining rechargeable groundwater aquifer with full public knowledge. Quantitative information about groundwater recharge and groundwater management is based on sustaining rechargeable groundwater aquifer may prevent groundwater scarcity in the region. In addition, the spatial and seasonal differences of the rainfall and temperature pattern, and the seasonal anthropogenic water demands could have influenced the drought results. Urbanization is more concentrated in the semi-consolidated and unconsolidated formation having population density. Drinking water demand in these densely populated regions increases in the summer season, and the dry and warm climate further aggravate the situation (Rejani *et al*., 2003). However, it is difficult to separate the factors that precisely influence the ground water level from the existing drought results due to regional variation of the climate, recharge pattern, anthropogenic influence and ground water pumping.

Therefore, it can be concluded that recurrent droughts, rapid expansion of groundwater based irrigation projects and cross-boundary anthropogenic interventions are the main causes of groundwater droughts in the IGP region. As groundwater declination is not only due to deficit of rainfall, but also due to over exploitation of groundwater resources, groundwater droughts in the area is mainly human-induced droughts which is better to term as groundwater scarcity.

CONCLUSIONS

Hydrological drought index help to develop relatively simple but consistent measures or the status of groundwater drought indices that can be applied between different observation sites, in different aquifers, as well as that enable groundwater drought to be compared with hydro-meteorological aspect of drought. However, there are still no commonly accepted indices to quantify groundwater drought phenomenon for wider drought assessment. Therefore, it is expected that this study will help local water resources management, irrigation and agricultural planning organizations as well the developmental authorities to enhance their understanding for sustainable groundwater resources management in the IGP region of India through the use of groundwater drought indices.

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REFERENCES

Aggarwal P K; Palanisami K; Khanna M; Kakumann K R. 2012. Climate change and food security of India adaptation strategies for the irrigation sector. World Agric., 3, 20-26.

Bhuiyan C. 2004. Various drought indices for monitoring drought condition in Aravalli terrain of India. In: Proceedings of the XXth ISPRS Conference. Int. Soc. Photogram. Remote Sens., Istanbul, 1-6.

Bhuiyan C; Singh R P; Kogan E N. 2006. Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data. Int. J. Appl. Earth Obs. Geoinform., 8, 289-302.

CWC. 2009. Annual Report. Central Water Commission, Ministry of Water Resources, Government of India, pp: 143.

Dracup J A; Lee K S; Paulson E G. 1980. On the definition of drought. Water Resour. Res., 16, 297-302.

Fiorillo F; Guadagno F M. 2012. Long karst spring discharge time series and drought occurrence in Southern Italy. Environ. Earth Sci., 65, 2273–2283.

IPCC. 2007. Climate change 2007: the physical science basis. In: Solomon S; Qin D; Manning M; Chen Z; Marquis M; Averyt KB; Tiguor M; Miller HL (Eds.) Contribution of Working Group I to The Fourth Assessment Report of the Inter-governmental Panel and Climate Change, Cambridge University Press, Cambridge, pp: 996 .

Kondoh A; Harto A B; Eleonora R; Kojin T. 2004. Hydrological region in monsoon Asia. Hydrol. Process, 18, 3147-3158.

Mendicino G; Senatore A; Versace P A. 2008. Groundwater resource index (GRI) for drought monitoring and forecasting in a Mediterranean climate. J. Hydrol., 357, 282-302.

Mishra A K; Singh V P. 2010. A review of hydrological drought concepts. J. Hydrol., 391, 202-216.

Nalbantis I. 2009. Assessment of hydrological drought revisited. Water Resour. Manage., 23, 881–897.

Pathak H; Pramanik P; Khanna M; Kumar A. 2014. Climate change and water availability in Indian agriculture: Impacts and adaptation. Indian J. Agric. Sci., 84, 671-679.

Rathore M S. 2004. State level analysis of drought policies and impacts in Rajasthan, India. Working paper 93, Drought Series, Paper 6, International Water Management Institute, 1-35.

Rejani R; Jha M K; Panda S N; Mull R. 2003. Hydrologic and hydrogeological analysis in a coastal groundwater basin, Orissa, India. Appl. Eng. Agric., 19**,** 177–184.

Shah T. 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environ. Res. Letter, pp: 13.

Tallaksen M L; Van Lanen H A J. 2004. Hydrological Drought Process and Estimation Methods for Streamflow and Groundwater. Elsevier Sciences, The Netherlands, pp: 579.