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# Understanding the Decadal Variation of the Groundwater Resources along the Coastal Aquifers of Pondicherry – A Climate Change Perspective

**R. Thilagavathi[1], S. Chidambaram[2]*, Banaja Rani Panda[1], K. Tirumalesh[3], N. Devaraj[1] and Anil Kurmana[4]**

[1]Department of Earth Sciences, Annamalai University, Annamalai Nagar (Tamil Nadu), India
[2]Research Scientist, Water Research Center, Kuwait Institute for Scientific Research, Kuwait
[3]SOE, Isotope Hydrology Section, Isotope Application Division, BARC, Mumbai
[4]GITAM University, Visakhapatnam, Andhra Pradesh, India
✉ chidambaram_s@rediffmail.com

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**Abstract:** Groundwater and their regional variations are controlled by long-term climate conditions. Climate change will therefore have a great impact on groundwater resources. In this study, long term rainfall (1900 to 2016) and water level changes (1989 to 2009) from Pondicherry region were observed. The rainfall pattern shows cyclic changes of high and low rainfall over decadal period and in particular up to 2011 from 1998 and then decreases, whereas the groundwater level has decreased drastically from 1998 onwards until 2003 and subsequently there is an increasing trend. The changes in climate have resulted in deviation in amount of rainfall, shift in rainfall period, variation in water level and enrichment of stable isotopes in the region. Further the land use pattern has increased in the urban regions due to increase in population which has resulted in the excessive pumping of groundwater in Pondicherry coastal aquifer, thereby enhancing the salinity in major portion of the study area. The geochemical factors like EC and isotopes give an insight in understanding the variation in climate change and its effects on groundwater quantity and quality. Hence the careful land use planning only will help to conserve the groundwater resource which is precious and finite, and will help to protect recharge zones mechanisms.

**Keywords:** Climate change; Rainfall; Water level; Chemistry; Isotopes; Land Use.

## Introduction

Climate change on groundwater relates to the impact in its recharge and discharge rates. It also changes the quantity and quality of groundwater (BGR, 2008; Panwar et al., 2013; Green, Bate et al., 2007; Green et al., 2007). It refers to the long-term changes in the components of climate such as temperature, precipitation, evapotranspiration, etc. The aquifer response to climate change may be lesser in contrast to surface water, though it is still a matter of concern because groundwater is one of the largest available resources of freshwater and potable water on Earth. Ground water plays a major role in sustaining ecosystems and facilitate human variation to climate change and variability (Taylor et al., 2012). The temperature of the earth is constantly increasing and from 1990 to 2005, the temperature has risen by 0.15–0.3 °C / decade; 11 of the 12 warmest years were noticed from 1995 to 2006 and in upcoming decades its rise of 0.2 °C/decade is predictable (IPCC, 2007).

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*Corresponding Author

Climate change has an undesirable impact on the Indian groundwater reservoirs, therefore, better management and improved strategies are required to reduce the threats. Rate of rainfall and evapotranspiration directly affect the groundwater condition. The impacts of climate change on fresh groundwater resources has been evaluated by Ranjan et al. (2006) by discussing the salinity intrusion in the stressed coastal aquifers. Crosbie et al. (2010) assessed the changes in groundwater recharge under a future climate. He has estimated the groundwater recharge rate for 2030 using the dataset of 1990 climate. The climate is estimated not only to concern the recharge and discharge, but also to influence the quality of the groundwater. Long-term changes in monitoring of rainfall and groundwater quality is required to understand the impacts of climate (Dragoni, 2009). Climate change also makes variation in rainfall patterns leading to higher uncertainty and difficulties in management of both water scarcity and flood events (Bhaskar Narjary et al., 2014).

The past climatic episode also register the association of particular ions during the specific rock water interaction process during weathering. Hence a proper understanding of the geology as well as hydrogeology is essential to unravel the impact of climate change on environment. Preferably, the long time period study of groundwater resources must be based on a consistent, constant and dense database of hydrometeorological data and soil moisture (Dragoni, 2009). Environmental isotope analyses in hydrogeochemical studies helps in understanding the paleo climatic sea level changes (Geriesh et al., 2015). They were also used to fingerprint the climatic changes on the groundwater flow and the management of this resource. The chemical and stable isotope composition of groundwater helps to understand the hydrological processes in semiarid basins and current relationships between the hydrology and water chemistry (Acheampong et al., 2000; Herczeg et al., 2001; Harrington et al., 2008).

The climate change on the groundwater resources are thus identified by the quantity and quality of water in the aquifer. The cause and effect is mainly governed by the external drivers live meteorological parameters, which are reflected on landuse/landcover change and ultimately on groundwater resources. The general groundwater qualities of the Pondicherry region based on the major ion distribution were reported by Thilagavathi et al. (2012) and Pethaperumal et al. (2010). Detailed subsurface investigations have also been carried out in this region to further understand subsurface geology and geomorphology (Thilagavathi et al., 2013, 2014). Study on the groundwater chemistry with limited number of samples (Pethaperumal et al., 2008) show that there is a significant spatial variation with respect to season. Later the study was extended with more number of samples representing different aquifers and season by Thilagavathi et al., (2012) to understand its spatial and temporal variability. Earlier the variations of log $pCO_2$ in the aquifer were studied with respect to season (Chidambaram et al., 2011). Further studies were carried out to understand the variation of saturation index in groundwater (Chidambaram et al., 2012). Subsequently the ion migration study was carried out with phase mole transfer in groundwater using geochemical data and isotopes were studied by Tirumalesh et al. (2012). Hence in this study an attempt has been made to understand the decadal variation in groundwater resources relating to the external drivers in the Pondicherry region.

## Study Area

Pondicherry is the capital city and the largest city of the Indian union territory of Puducherry. The city of Pondicherry is situated in Puducherry district of the union territory. It is located on the east coast of South India and lies between 11º 45' and 12° 0' North Latitude and 79° 37' and 79° 50' East longitudes (Figure 1). The region covers 293 sq.km consisting of five villages Ariyankuppam, Bahour, Mannadipet, Nettapakkam and Villiyanur. The mean monthly temperature ranges from 22 °C to 33 °C. The relative humidity varies between 70% and 85%. with an average annual rainfall of 1254.4 mm.

The study area is of two monsoon climates, such as Southwest monsoon climate – (June, July, August and September) and Northeast monsoon climate (October, November, December). The region receives rainfall from both the monsoons having an annual rainfall spread over a period of eight months. The southwest monsoon precipitation occurs from June to September accounting for 29% of the annual rainfall and the northeast monsoon rainfall occurs from October to December constitutes 63% of the annual rainfall. During 2011 the study region was highly affected by the cyclone "Thane" which was formed by northeast monsoon on Dec 30th and during 2015 Puducherry received around 55.7 mm of rainfall over the 24-hour period on 14–15 November.

The alluvial plain, which occupies a major portion of Pondicherry region, is formed due to two major rivers, namely Gingee and Ponnaiyar. The Pondicherry region is covered by sedimentary formations, ranging in age

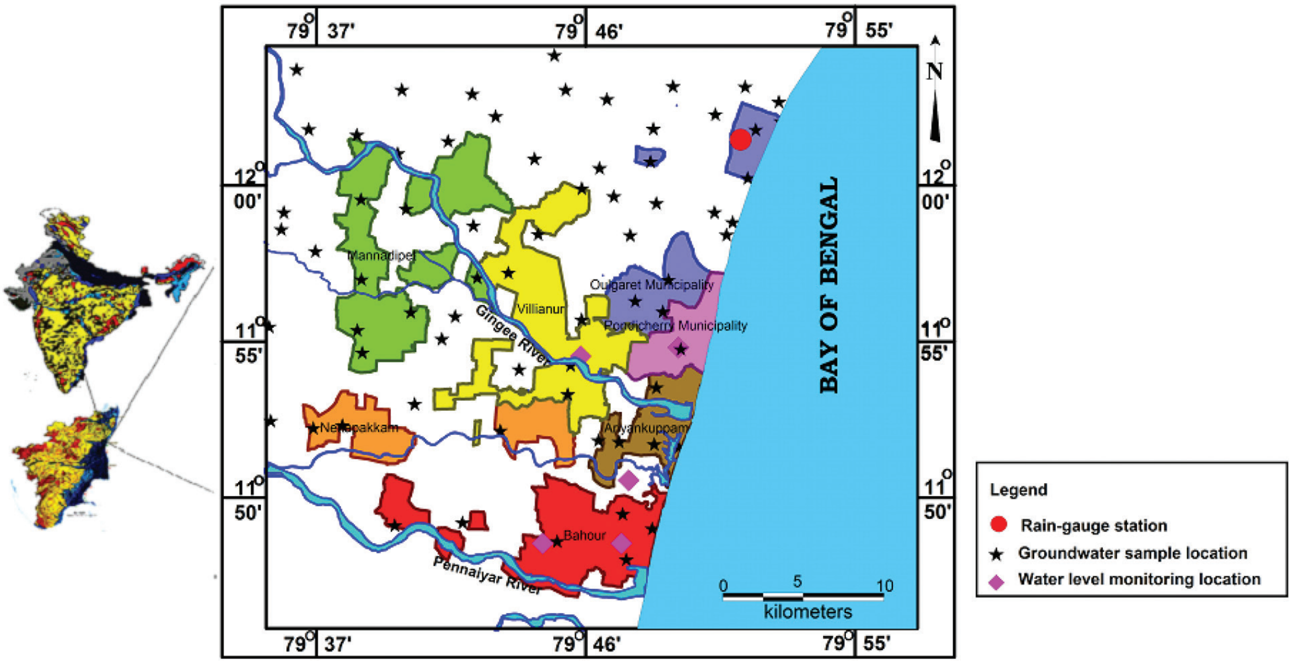

**Figure 1: Location map of the study area.**

from Cretaceous to Recent. The oldest sedimentary formations are the Cretaceous sediments exposed in the northwestern part of the study area and north of Gingee river (it is also named as Sankarabarani River), except a small extent of Archean Formations in the northwestern part of Pondicherry. The general strike of the Cretaceous and Tertiary formations trends NE-SW with gentle dip. The Cuddalore formations—though maintain the same strike—shows a dip up to 10°. The stratigraphic succession with their aquifer parameter of the study area is given in Table 1.

The water level of the bore wells in the study area during Pre-monsoon ranges between 1.8 mbgl and 34 mbgl and deeper water levels are noticed in the central, northwest and south western parts of the study area (Pethaperumal, 2010; Thilagavathi et al., 2015). Similar trend was also noticed during the Post-monsoon, except for the variation in depth of water level, which ranges between 1.6 m and 37.6 mbgl. The decadal mean water level (January 2006 to January 2015) when compared with January 2016 water level, shows that 71% of observed bore wells have reported with rise in water level, ranging 0-2 m. Other 29% show decline in water level and all in 0-2 m range (CGWB, 2016). The Pondicherry region in general is a flat plain with an average elevation of about 15 m above the mean sea level (MSL). The three major physiographic units generally observed are coastal plain (younger and older), alluvial plain and uplands (Ramesh et al., 2011; Mani Murali, 2013; Thilagavathi et al., 2013c).

## Data and Methodology

A study on the long term variation (5 years) in water level and rainfall was observed in Pondicherry region to understand the relationship between the water level fluctuation and rainfall and its response to climate change. The required data is downloaded from the website http://www.cgwb.gov.in/GEMS/. The data was studied for five years interval from 2006 to 2016 and each measurement includes meteorological variables such as temperature and rainfall. It also considers the response of average rainfall to monthly precipitation. Besides the rainfall data, water levels are also used in decadal interval 2006, 2011 and 2016. Long-term changes in groundwater composition in Pondicherry region was carried out for the same interval from 2006 to 2016. Groundwater samples were collected for three different seasons of November 2006, 2011 and 2016 from each site for a period of 10 years to identify the seasonal variations and its temporal changes in the groundwater resource quality. The collected samples were analyzed for in situ measurements for pH and EC done by using thermo ion electrode. The major cations and anions such as Ca, Mg, Na, K, Cl, $SO_4$, $PO_4$ and $H_4SiO_4$ were measured by Tritrimetry,

**Table 1: General stratigraphic succession with their aquifer parameter of the study area**

| *Era* | *Period* | *Formation* | *Lithology* | *Transmissivity value $m^2$/day* | *Storage coefficient* |
|---|---|---|---|---|---|
| Quaternary | Recent | Alluvium laterite | Sands, clays, silts, Kankar and gravels laterite. | 275 | |
| | Mio-Pliocene | Upper Cuddalore formation | Pebbly and gravelly and coarse grained sandstones with minor clays and siltstones with thin seams of lignite. | 2000 | $8.9\times10^{-4}$ |
| | | Lower Cuddalore formation | Dirty white, pale gray sandstone, siltstones marcasite abundant of clay thin seams of lignite. | | |
| | | | *Unconformity* | | |
| Tertiary | Paleocene | Manaveli formation | Yellow and yellowish brown, grey calcareous siltstone and claystone and shale with bands of limestone | 2000 | $9.583\times10^{-5}$ |
| | | Kadaperikuppam formation | Yellowish white to dirty white sandy hard fossiliferrous limestone, calcareous sandstone and clays | | |
| | | | *Unconformity* | | |
| Mesozoic | Upper Cretaceous | Turuvai limestone | Highly fossiliferrous limestone, conglomerate at places, calcareous sandstone and clays | 2000 | $9.583\times10^{-5}$ |
| | | Ottai clay stone | Greyish to grayish green claystones, silts with thin bands of sandy limestone and fine grained calcerous sandstone | | |
| | | Vanur sandstone | Quartzite sandstone hard coarse grained occasionally feldspathic or calcareous with minor clays | | |
| | Lower Cretaceous | Ramanathapuram formation (unexposed) | Black carbonaceous silty clay and fine to medium grained sands with bands of lignite and medium to coarse grained sandstones | 1925 | $1.36\times10^{-4}$ |
| | | | *Unconformity* | | |
| Archaean | | Eastern Ghat complex | Charnockite and biotite hornblende gneiss. | 92 | $2.93\times10^{-5}$ |

*Source:* CGWB, 1993; Nair et al., 1971

Spectrophotometer and flame photometer using standard procedure (APHA, 1998).

Deuterium and oxygen-18 were measured by using Isotopic Ratio Mass Spectrophotometer (Finnigan Delta$^{plus}$ Xp, Thermo Electron Corporation, Germany; the standard deviation of our measurements is ±1.72‰ for oxygen and ±0.8‰ for hydrogen). All the measurements were carried out against laboratory sub-standard that were periodically calibrated against the international isotope water standards recommended by the IAEA (V-SMOW).

Stable isotope results were expressed with respect to VSMOW, where

$$\delta(‰) = (R_{sample} - R_{SMOW} / R_{SMOW}) \times 10^3 \quad (1)$$

$$R = D/H \text{ or } {}^{18}O/{}^{16}O \quad (2)$$

Tritium was determined on electrolytically enriched water samples by low-level proportional counting and the results are reported as $^3H$ units with a typical error of $^3H$ 1TU. The $\delta^{13}C$ and tritium were analyzed for selective samples. The water level, rainfall, landuse pattern change and change in hydrogeochemical data for the period of five years were correlated and plotted graphically to identify the climate variability and change with respect to time.

## Long-term Rainfall Monitoring

Several studies have been carried out by many researchers which show that the trend and magnitude of warming over India and the Indian sub-continent more than the preceding century is broadly reliable with the global trend and magnitude (Hingane, 1995; Arora et al., 2005, Dash et al., 2007). Numerous studies relating to rainfall variation all over India have concluded that the yearly rainfall has not clearly shown the increasing and decreasing trend through the country (Mooley et al., 1984; Lal, 2001). Various case studies from all over the world (Khan et al., 2000; Mirza, 2002; Lal, 2003; Goswami et al., 2006; Dash et al., 2007) proved that the frequency of more intense rainfall events in most parts of Asia have increased, whereas the amount of rainy days and total number of yearly precipitation has decreased. Goswami et al. (2006) used daily rainfall data to confirm the essential increasing tendency in the frequency and magnitude of extreme rain events, and a significant declining trend in the frequency of modest actions over central India throughout the monsoon seasons during 1951 to 2000. Any changes in precipitation patterns can affect surface water processes and resources. Warming trends may also affect global evapotranspiration patterns, which have direct implications for the sustainability of surface- and subsurface-water resources. The cyclones that caused heavy rainfall in Tamil Nadu are listed in Table 2.

Trend analysis of rainfall data of 116 years (1900–2016) indicated significant trend for annual rainfall. The mean annual rainfall over Pondicherry showed a long-term significant declining and increasing trend.

However, the declining trend in average annual rainfall was significant if the annual rainfall is considered between 1945-1960. The amount of annual rainfall in recent years from 2000 to 2015 is observed to be higher than the previous decades. A relatively excess rainfall was seen in earlier decades of 1913 and recent decades of 2004 to 2010 (Figure 2). A decrease of average annual rainfall 49.9 mm was noticed during 1945 in the observation of 100 years. The average annual rainfall increased during 1930, declined in 1945, subsequently increased in 1964, decreased around 1998 and increased in 2004. Hence it is inferred that in 30 years interval there is a high downpour. Moreover there exists a trend of repetition of lower rainy periods and higher intensity rainfall periods.

**Table 2: List of cyclones that caused heavy rainfall in Tamil Nadu**

| *S.No* | *Name of cyclones* | *Year* | *Date* | *Remarks* |
|---|---|---|---|---|
| 1 | Fanoos | 2005 | 08/12/2005 | Increase in the intensity of rainfall and the frequency of depressions in Bay of Bengal |
| 2 | Nisha | 2008 | 26/11/2008 | |
| 3 | Jal | 2010 | 11/06/2010 | |
| 4 | Thane | 2011 | 29/12/2011 | |
| 5 | Nilam | 2012 | 31/10/2012 | The amount of rainfall was less and the frequency of depression was lesser |
| 6 | Madi | 2013 | | |
| 7 | Chennai Floods | 2015 | 08/11 to 04/12/2015 | |

*Source*: www.skymetweather.com/

Three water level records from the Pondicherry region (Pondicherry, Ariyankuppam and Embalam) for 20 years from 1989 to 2009 show variation in water level trend, with a general increasing trend (Figure 3). Although the mean annual water level showed a long-term significant declining deeper water level record spanning a period of time in earlier decades with less than average rainfall, increasing shallow water level in recent decades is due to the increase in rainfall. Hence the rainfall declining trend was significant in earlier decades of deeper water level 1989-1996 and increasing rainfall from 2004 has resulted in the shallow water level. The fact of variation in rainfall pattern and the repose to water level reflect the impact of climate change in groundwater.

The maximum, minimum and average rainfall of Pondicherry region from 2006 to 2016 are given in Table 3. The highest and lowest amount of rainfall is 426.8 mm and 188.2 mm observed during October 2006 and August 2016 respectively; during 2011 significant

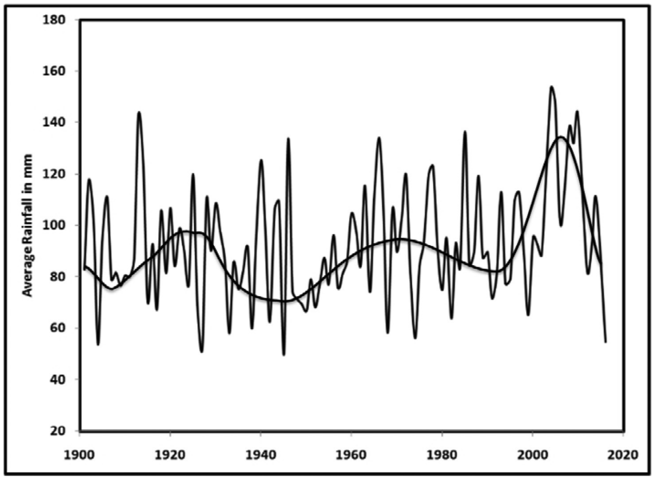

Figure 2: Total average annual precipitation for 1900–2016.

Figure 3: Total average annual water level for 1989–2009.

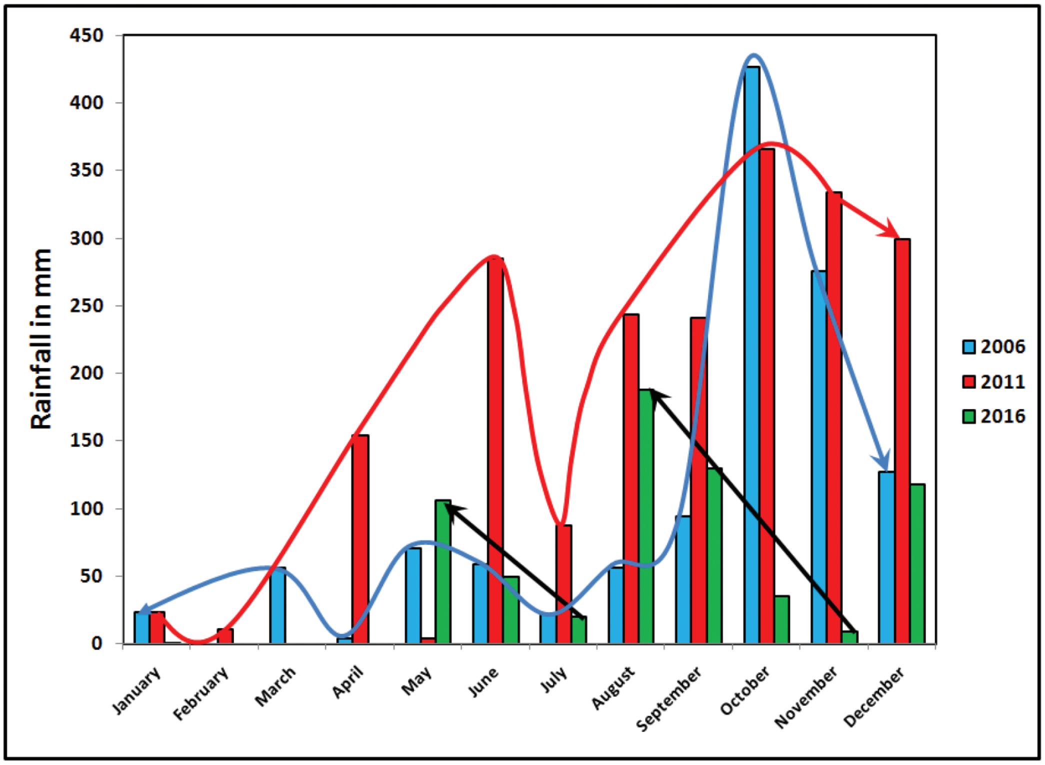

Figure 4: Monthly rainfall in millimetre for the years 2006 to 2016.

amount of rainfall 366 mm was received in October. The predominant month of rainfall during 2006 and 2011 is October and August in 2016. In general there are two monsoon seasons in India, June, July, August, September (Southwest Monsoon) and October (Northeast Monsoon). Most of the rain shower along the east coast of India are predominant during NEM (North East Monsoon) and few spells in SWM (South West Monsoon). This preliminary observation shows that there is a shift in the amount of rainfall from NEM to SWM in the Pondicherry region. The data also reveals the fact that during the period of observation of 10 years (Figure 4), there is an increasing trend in the first half from 2006 to 2011 and followed by a decreasing trend from 2011 to 2016.

Summer rain shower have increased in 2016, which helped in recharge of the aquifer during March and May 2016. This shift is peak from June (2006) to May (2016) and from October (2006) to August (2016) can also be an indicator for the advancement of both Monsoon (SWM and NEM) periods.

The history of the extreme rainfall events due to the depression events shows that the frequency of the events was more from 2005 to 2011 and lesser during 2011-2016. It is to be noted that the rainfall due to the depression in Bay of Bengal serves as one of the major source of recharge of the coastal aquifers, especially in the Pondicherry region.

**Table 3: Maximum, minimum and average rainfall of Pondicherry region for years 2006 to 2016 (in mm)**

| | *2006* | *2011* | *2016* |
|---|---|---|---|
| Maximum | 426.8 | 366.0 | 188.2 |
| Minimum | 0.0 | 0.0 | 0.0 |
| Average | 117.4 | 172.4 | 60.4 |

Examination of monthly rainfall for the period 2006 to 2016 (Figure 4) revealed that there has been a significant increase in the incidence of prolonged monsoon during the core monsoon rainy months of July and August in 2006 and 2011 (Figure 4). Sandstrom (1995) showed that a 15% reduction in precipitation, with no change in temperature, resulted in a 40–50% reduction in recharge. Monsoon depressions are the main rainfall-producing synoptic weather system over India (Vijay Kumar et al., 2010). Studies on the amount of monsoon depressions showed a significant decrease in their seasonal frequency, with a maximum decrease in January followed by February, October and November (Dash et al., 2004). Precipitation and evapotranspiration are particularly important because they directly affect groundwater recharge and indirectly affect human groundwater withdrawals or discharge. Even small changes in precipitation may lead to large changes in recharge in some semiarid and arid regions (Woldeamlak et al., 2007).

## Isotopes are the Indicator of the Climate Change

Isotopes in groundwater are indicators of the climate change (Negrel et al., 2012). The composition of isotopes in water ($\delta^2$H and $\delta^{18}$O) can change (isotopic fractionation) during its travel from the atmosphere, as rainwater, to groundwater, and sometimes within the aquifer (Negrel et al., 2012). These potential changes are controlled by evaporation and exchange processes. The observation of these stable isotope signature shows that $\delta^{18}$O ranges from –6.91% to –2% during 2006 (Table 4) and during 2011 $\delta^{18}$O ranges between –6.85 and –2.15‰ and δD ranges between –43.94 and –19.41‰ (Thilagavathi et al., 2016). Among these the most enriched values, very close to that of the rain inputs observed in Pondicherry region, reflect a modern recharge. The composition of isotopes $\delta^2$H and $\delta^{18}$O in groundwater in Katterikuppam, Poothurai and Manapattu depleted during 2006 and got enriched during 2011 (Table 3). Isotopes from Bahour enriched during 2006 and were depleted during 2011.

The earlier year 2006 waters show the largest $\delta^{18}$O and δD depleted values and were related to other recharge areas. Waters showed enriched $\delta^2$H-$\delta^{18}$O values in 2011 (Figure 5), in agreement with the mean annual precipitation. Long term changes in the input

**Table 4: Stable Isotope values of groundwater in different time period**

| *Location* | *2006** | | *2011*** | | *2016**** | |
|---|---|---|---|---|---|---|
| | $\delta^{18}O$ | $\delta D$ | $\delta^{18}O$ | $\delta D$ | $\delta^{18}O$ | $\delta D$ |
| Katterikuppam | -5.56 | -42.1 | -4.61 | -35.03 | -4.32 | -28.26 |
| Karasoor | -5.61 | -38.4 | -5.11 | -38.75 | -4.72 | -30.75 |
| Poothurai | -6.47 | -42 | -5.29 | -34.12 | -5.11 | -37.12 |
| Manapattu | -6.91 | -55.28 | -3.73 | -26.64 | -4.62 | -29.64 |
| Kaduvanoor | -3.97 | -26.4 | -3.86 | -28.51 | -3.57 | -20.51 |
| Bahour | -2.2 | -8.2 | -4.73 | -31.90 | -1.67 | -10.85 |

*Pethaperumal et al., 2008, **Thilagavathi et al., 2016 ***Present study

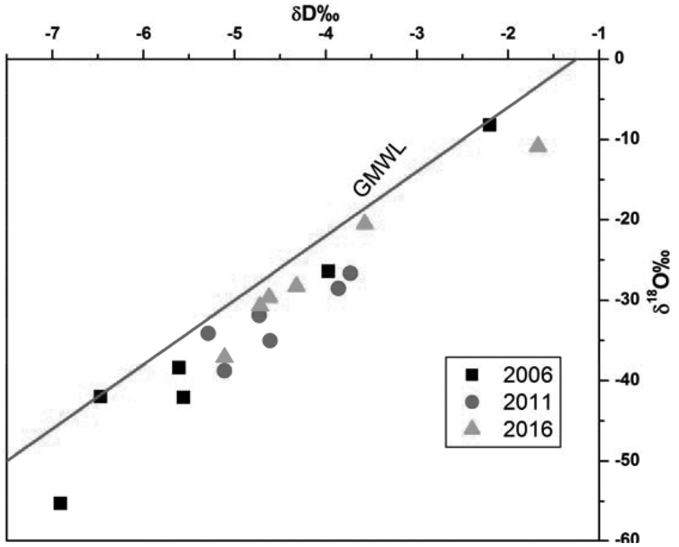

**Figure 5: Plot for $\delta^{18}$O versus δD for groundwater samples.**

function of isotopes are related to climatic evolution yield to the lowermost $\delta^2$H-$\delta^{18}$O values and enriched values in the aquifer originates from fractionation processes due to variation in the recharge signal as the rain input (Philippe Negrel et al., 2011).

The overall analysis of the isotope values in the region indicated that there is an enrichment of the values during 2011 and depletion at Bahour region. This enrichment may be due to the recharge of the evaporated water from the agricultural return flow or tank recharge. But during 2016 there was enrichment in almost all locations of study indicating either variation in source vapour of rain or recharge conditions. This variation may also be a result of the change in the flow direction of groundwater due to excessive pumping of groundwater. Meyboom (1967) has shown on a seasonal basis how the decrease or absence of recharge changes in the flow relationships of groundwater; this has been mainly resulted due to the scarce rainfall. Further Bahour showed enriched rainfall than other locations irrespective of time period indicating the recharge from the tank near the sampling location.

The significant amount of groundwater has tritium units <0.8 and they are sub modern waters. Some groundwater is comparatively younger with >2 TU they are designated as modern waters (Thilagavathi et al., 2015). Parameter scheming the isotopic signature in groundwater conditions prevailing at the moment of the recharge are preserved. Thus the isotope signature may reflect environmental recharge with hydrogen and oxygen isotope values in the range of rainwaters or recharge under colder climate.

## Long-term Water Level Monitoring

The ground-water occurrence can be generally categorized into two hydrogeological units as fissured and fractured crystalline formations and sedimentary formations. The yield of dug and tube wells depends on the topography, geology, rainfall and prevailing groundwater withdrawal pattern. The tube wells are common in sedimentary terrain (CGWB, 2011). Water levels in various aquifers of the Pondicherry region follow a normal cyclic pattern of seasonal fluctuation, on an average rise during the winter and spring due to greater precipitation and recharge, then declining during the summer and fall owing to less recharge and greater evapotranspiration (Taylor et al., 2001).

According to the India-WRIS the water level data have been grouped in 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). A total of seven wells were monitored for pre-monsoon (March/April/May), monsoon (August) and post-monsoon kharif (November). The water level for pre-monsoon (2006) ranges from 2.25 to 16.96 mbgl (Figure 6) while the water level data ranges from 2.7 to 17.02 mbgl (Table 4) in monsoon and from 0.65 to 27.3 mbgl during post-monsoon. The observations of water level during pre-monsoon (2011) ranges from 0.37 to 13.69 mbgl (Figure 6) whereas during post-monsoon it ranges from 01.22 to 14.58 mbgl and during monsoon it varies from 3.09 to 36.12. During pre-monsoon water level data for 2016 ranges between 3.2 and 24.68 mbgl (Figure 6) though during Monsoon it varies from 1.37 to 15.9 mbgl and that of post-monsoon is from 1.52 to 16.86 mbgl (Table 5). When compared, the decadal mean water level (January 2006 to 2015) with January 2016, 71% of observation wells are showing rise in water level, all in the range of 0-2 m. Other 29% show decline in water level and all in 0-2 m range.

Climate change and variability will likely have numerous effects on recharge rates and mechanisms (Vaccaro, 1992; Green et al., 2007a; Kundzewicz et al., 2007; Aguilera and Murillo, 2009). Many climate-change studies have predicted reduced recharge (Herrera-Pantoja and Hiscock, 2008); however, the effects of climate change on recharge may not necessarily be negative in all aquifers during all periods of time (Jyrkama and Sykes, 2007; Doll, 2009; Gurdak and Roe, 2010). However, there is abundant evidence that water resources, especially in many semiarid and arid regions, are particularly vulnerable to the effects of

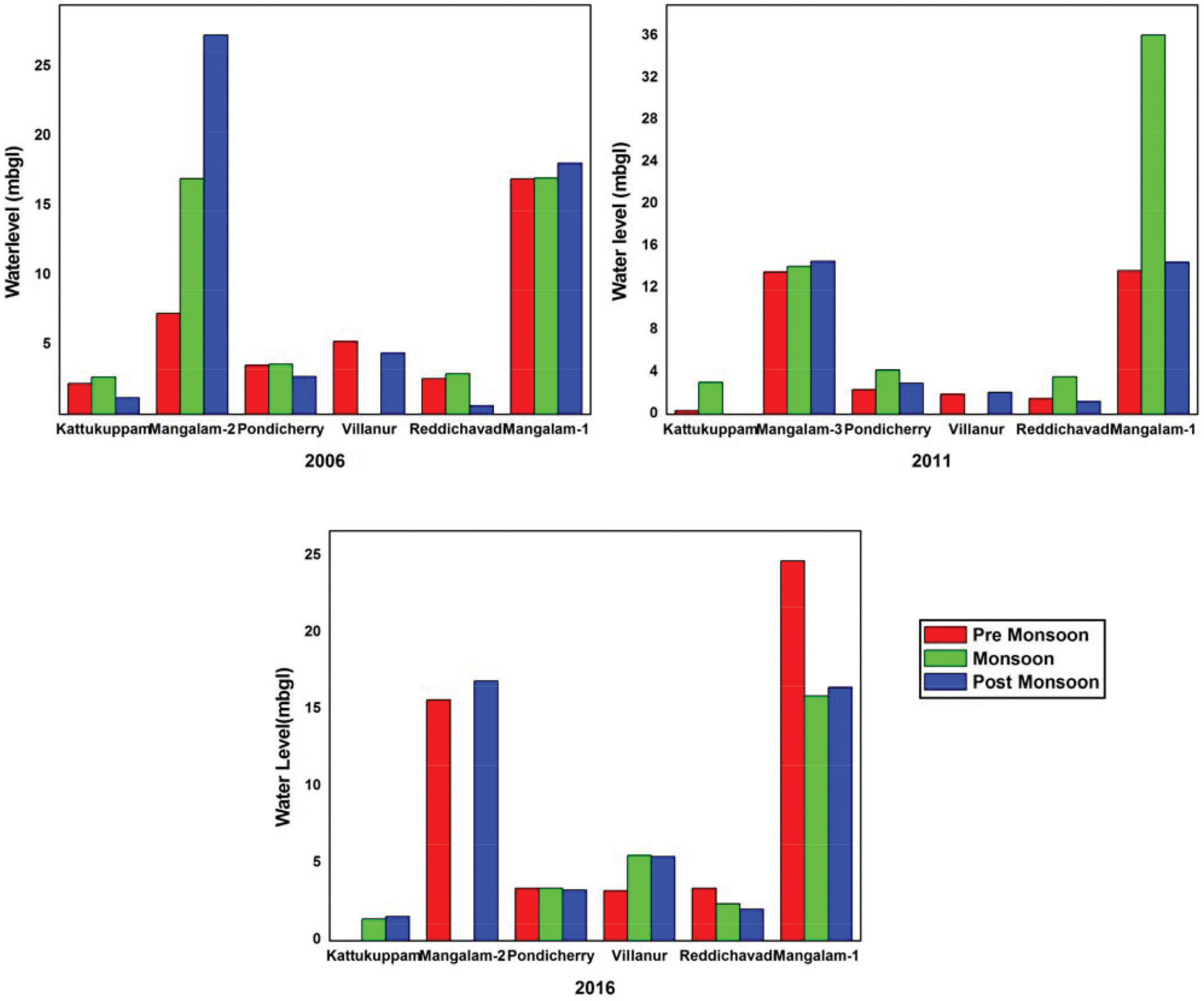

**Figure 6: Water level variation for different periods.**

**Table 5: Water level observations for different seasons and different time periods (mbgl)**

| *Year* | *Pre-monsoon* | *Monsoon* | *Post-monsoon* |
|---|---|---|---|
| 2006 | 2-17 | 3-17 | 0.6-27 |
| 2011 | 0.3-14 | 3-36 | 1.2-14.8 |
| 2016 | 3-24 | 1.3-16 | 1.5-16 |

climate change, especially if recharge conditions change or worsen (Aguilera and Murillo, 2009; Barthel et al., 2009; Novicky et al., 2010). The use of groundwater to offset declining surface-water availability will be hampered by declining recharge rates, especially in the most water-stressed regions (Kundzewicz et al., 2007).

The maximum depth of water level in these bore wells were observed to be about 5 mbgl, except for that of Mangalam as it is predominated by clay and silt and hence deeper water level is noted in the region irrespective of season. In general the POM groundwater levels are shallow as the NEM is predominant and the rain showers have greater intensity and helps in recharging the aquifers.

The SWM during June, July, August and September is less significant and due to the onset of agricultural activities the water level goes deeper.

It was observed that the monsoon (August-2016) water level had become shallow due to significant shift in monsoon period from November to August, thereby resulting in the rise of water level during this period. Similarly, there was a shallow water level observed during PRM of 2011, though lesser rain showers were noted during this period. This is mainly due to the impact of Thane depression during December, 2010 to January 2011. But the subsequent rain event in Chennai has not brought noticeable impact in ground waters of Pondicherry. Since the rainfall event was similar to a normal POM event it was not reflected in the water level observations.

During post-monsoon (November Kharif) of 2006, Reddichavadi received the heavy rainfall of 275.2 mm with the rise of water level upto 0.65 mbgl whereas during 2011 moderate to heavy rainfall was observed in June, October and November. The shallow water level was noted in Kattukuppam during 2011 pre-monsoon (June) and 2016 monsoon. Hence it is inferred that this region is influenced by the rainwater recharge. The groundwater-level response to high-frequency events may indicate the existence of highly permeable channels or preferential-flow paths from land surface to the water table (Chen et al., 2002).

The level of fluctuations in water levels can differ significantly from season to season and from year to year in response to varying climatic conditions. Changes in groundwater recharge and storage caused by climatic variability normally happen over decades, and water levels in aquifers generally contain a late response to the increasing effects of drought. The range and timing of seasonal water-level fluctuations might differ in various aquifers in the same geographic area, depending on the source of recharge to the aquifers and the physical and hydraulic properties of each. Cohen et al. (2006) also noted that groundwater supported evapotranspiration varied with topography and aquifer-hydraulic conductivity, and indicated that small yet important feedbacks exist between groundwater and atmospheric processes on decadal and longer time scales. Coastal aquifers with all but the smallest topographic gradients are more vulnerable to groundwater extraction than to sea-level rise.

## Long-term Electrical Conductivity Monitoring

The Intergovernmental Panel on Climate Change (IPCC) has a very high confidence that sea-level rise, spatiotemporal changes in precipitation and evapotranspiration, which affect recharge, and increased groundwater pumping will result in more groundwater salinisation in many coastal regions (Oude Essink, 1996, 2001, 2004; Klein and Nicholls, 1999; Sharif and Singh, 1999; Pierson et al., 2001; Beuhler, 2003; Ranjan et al., 2006 a, b; IPCC, 2007a; Kundzewicz et al., 2007; Moustadraf et al., 2008; Barrocu and Dahab, 2010; Oude Essink et al., 2010; Yechieli et al., 2010).

The main part of the world population's livelihood is in coastal zones. In those areas the groundwater is susceptible to saline intrusion which can make the water undrinkable. Agriculture, industrial states, urbanization process, the climate change and the pumping of groundwater can alter the coastal aquifer equilibrium between salt and fresh water. Most of the samples in the Pondicherry region have the conductivity during pre-monsoon of 2006 ranges from 209 μs/cm to 2360 μs/cm (Table 6) and post-monsoon represents a range from 144 μs/cm to 1888 μs/cm. During 2011, pre-monsoon samples show the ranges from 186 μs/cm to 2713 μs/cm and post-monsoon represents a range from 168 μs/cm to 2352 μs/cm. During 2016 the electrical conductivity varies from 536 μs/cm to 3657 μs/cm during pre-monsoon and during post-monsoon EC ranges from 469 μs/cm to 3256 μs/cm. The groundwater levels were generally decreased and most of this decrease was attributed to increased pumping. The electrical conductivity values of groundwater were high in the groundwater of Pondicherry region which were indicative of the saline water instruction, anthropogenic contamination and progressive groundwater quality deterioration.

The observation of the EC values of pre- and post-monsoon season data of Pondicherry region shows that the pre-monsoon have obviously higher values irrespective of the time period. In general there is an increasing trend of EC during 2006-2016 irrespective of season. An increase in EC is observed in northwestern and southwestern parts of the study area during pre- and post-monsoon in 2011; higher EC may be due to seawater intrusion (Thilagavathi et al., 2012), effect of pH and intense long-term agricultural practices in the area of study (Sarath Prasanth et al., 2012; Ramesh et al., 2012). With changing facies, which is attributed to contribution from backwater present in the area, the higher EC is noted in northwestern part of the study area during pre-monsoon 2016.

Inference from the data reveals that there is an increase in both maximum and minimum values of EC during 2011 and 2016 (Table 6) indicating the increase in the ionic concentration with time, represented by weathering, agriculture, urabanisation or industrialization as one of the drivers. Due to increasing concentration of human settlements, agricultural development and economic activities, the shortage of fresh groundwater for domestic, agricultural, and industrial purposes becomes more striking in coastal low-lying deltaic areas (Oude Essink, 1996). Climate change may also affect groundwater quality by causing

**Table 6: Maximum, minimum and average of the chemical constituents analysed in groundwater samples in different periods (All values in mgl$^{-1}$ except EC in µscm$^{-1}$ and pH)**

| *PRM 2006* | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | $Cl^-$ | $HCO_3^-$ | $NO_3^-$ | $PO_4^-$ | $SO_4^{2-}$ | $H_4SiO_4$ | *TDS* | *EC* | *pH* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max | 81.6 | 531.8 | 892.3 | 84.0 | 786.8 | 390.4 | 39.9 | 15.0 | 72.6 | 300.0 | 1780 | 2360 | 1760.0 |
| Min | 2.4 | 0.0 | 3.1 | 3.0 | 0.0 | 0.0 | 0.6 | 0.1 | 0.3 | 0.1 | 107 | 7 | 5.9 |
| Average | 30.1 | 88.4 | 218.7 | 22.6 | 209.0 | 165.5 | 6.7 | 6.9 | 8.7 | 61.1 | 577 | 426 | 378.0 |
| POM 2006 | | | | | | | | | | | | | |
| Max | 88.0 | 67.2 | 344.8 | 18.8 | 390.0 | 573.4 | 18.9 | 0.9 | 224.0 | 171.8 | 1360 | 1943 | 8.0 |
| Min | 8.0 | 0.0 | 39.1 | 11.5 | 53.2 | 61.0 | 0.0 | 0.0 | 12.0 | 3.0 | 101 | 144 | 5.7 |
| Average | 31.9 | 13.1 | 173.0 | 16.2 | 171.5 | 276.1 | 3.4 | 0.4 | 55.4 | 80.5 | 676 | 965 | 7.1 |
| PRM 2011 | | | | | | | | | | | | | |
| Max | 172.0 | 62.4 | 567.5 | 47.2 | 904.0 | 475.8 | 21.9 | 2.0 | 44.0 | 202.0 | 1976 | 2713 | 7.8 |
| Min | 12.0 | 0.0 | 6.8 | 0.0 | 26.0 | 73.2 | 0.0 | 0.0 | 0.0 | 2.0 | 174 | 187 | 6.2 |
| Average | 62.2 | 23.9 | 187.7 | 8.8 | 321.6 | 223.5 | 9.6 | 0.3 | 9.6 | 92.6 | 809 | 1098 | 7.2 |
| POM 2011 | | | | | | | | | | | | | |
| Max | 168.0 | 91.2 | 764.0 | 83.0 | 1524.4 | 878.4 | 57.6 | 2.7 | 250.0 | 106.0 | 1269 | 2352 | 8.3 |
| Min | 20.0 | 0.0 | 20.0 | 1.0 | 35.5 | 61.0 | 0.0 | 0.1 | 1.0 | 10.0 | 107 | 168 | 6.3 |
| Average | 76.7 | 35.4 | 166.5 | 26.2 | 352.0 | 351.0 | 14.9 | 0.6 | 91.3 | 61.8 | 593 | 1033 | 7.4 |
| PRM 2016 | | | | | | | | | | | | | |
| Max | 218.0 | 76.0 | 614.0 | 81.0 | 956.0 | 621.0 | 50.0 | 15.0 | 64.0 | 243.0 | 2090 | 3657 | 7.9 |
| Min | 12.0 | 0.0 | 18.0 | 1.0 | 35.0 | 22.0 | 0.0 | 0.0 | 0.0 | 5.0 | 254 | 536 | 6.2 |
| Average | 84.2 | 18.0 | 167.0 | 19.0 | 421.0 | 249.0 | 12.0 | 2.0 | 13.0 | 131.0 | 684 | 1252 | 7.1 |
| POM 2016 | | | | | | | | | | | | | |
| Max | 228.0 | 84.0 | 561.0 | 88.0 | 914.3 | 512.4 | 134.7 | 11.9 | 2.5 | 265.0 | 2090 | 3256 | 7.9 |
| Min | 20.0 | 0.0 | 11.4 | 0.5 | 53.2 | 24.4 | 0.0 | 0.0 | 0.0 | 6.0 | 310 | 469 | 6.7 |
| Average | 93.7 | 19.0 | 173.6 | 25.7 | 359.2 | 270.0 | 15.8 | 0.6 | 0.4 | 122.1 | 1084 | 1676 | 7.3 |

a decline of fresh groundwater through reduced recharge and (or) increased pumping. This may disrupt the current balance of the freshwater/saline water boundary, resulting in saline water intrusion beyond coastal basins (Grasby and Betcher, 2002; Chen et al., 2004).

There has been an increase in the recharge of the evaporate water with time indicating the influence of tanks, sewers or saline water. As during the process of evaporative enrichment, there is a possibility for the increase of ions or because of the recharge of the sewers, agricultural return flow or saline water intrusion increases the EC along with the isotopic enrichments (Fasong Yuan et al., 2008; Gómez et al., 2016). An indirect effect of climate change is increased groundwater pumping, which could affect hydraulic heads in many aquifers, allowing upward leakage of groundwater with poorer water quality (McMahon et al., 2007). Hence it is inferred that there is an influence of this process with time which may be triggered by anthropogenic influence or change in rainfall patterns.

## Land Use Changes and Climate

The microclimate changes are governed by land-use pattern changes (Zhong et al., 2016). Vice versa as the climate changes can also have a significant impact on the land-use pattern (Oliver et al., 2014). The effect of land-use on the climate primarily depends on the type of land cover present within an area. The results of land use/land cover (LULC) assessment based on interpretation for two different years of data between 2005-2006 and 2011-2012 as shown in Figure 7. It has a total area of about 293 sq km.

The dominant land-use categories in 2005-2006 were urban land, rural area, crop land, fallow land and reservoir/lakes/ponds which occupied 15.38%, 8.05%, 50.22%. 12.13% and 5.97% of the study area while other land-use features occupied a negligible area (Table 7). The industrial area is classified in the urabanisation. The agricultural land are seen to be occupied by nearly 63.24% of the study area in both 2005-06 and 2011-12,

**Table 7: Land-use/Land-cover change from 2005-06 to 2011-12**

| *Land-use/Land-cover category* | *Classes* | *Area in square kilometres* | | *Percentage (%)* | |
|---|---|---|---|---|---|
| | | *2005-2006* | *2011-2012* | *2005-2006* | *2011-2012* |
| Buildup, urban | Build-up Land | 45.04 | 49.76 | 15.38 | 16.98 |
| Buildup, rural | | 23.57 | 19.41 | 8.05 | 6.62 |
| Buildup, mining | | - | 0.08 | - | 0.03 |
| Agriculture, crop land | Agriculture Land | 147.1 | 149.53 | 50.22 | 51.03 |
| Agriculture, plantation | | 5.54 | 10.43 | 1.89 | 3.56 |
| Agriculture, fallow land | | 35.53 | 28.37 | 12.13 | 9.68 |
| Forest, deciduous | Forest | 0.17 | 0.17 | 0.06 | 0.06 |
| Forest, forest plantation | | 2.37 | 0.03 | 0.81 | 0.01 |
| Barren/ uncultivable/wastelands/salt affected lands | Barren or waste lands | 0.1 | 0.1 | 0.03 | 0.03 |
| Barren/uncultivable/wastelands. Gullied/ ravenous land | | - | 0.04 | - | 0.01 |
| Barren/ uncultivable/wasteland, scrubland | | 3.98 | 3.73 | 1.36 | 1.27 |
| Barren/uncultivable/ wastelands, sandy area | | 3.17 | 2.43 | 1.08 | 0.83 |
| Barren/ uncultivable/wastelands, barren rocky | | 0.06 | - | 0.02 | - |
| Wetlands/water bodies, inland wetland | Wetlands or water-bodies | - | 0.86 | - | 0.29 |
| Wetlands/water bodies, coastal wetland | | 1.13 | 4.26 | 0.39 | 1.45 |
| Wetlands/water bodies, river/stream/canals | | 7.67 | 7.25 | 2.62 | 2.47 |
| Wetlands/water bodies, reservoir/lakes/ponds | | 17.49 | 16.55 | 5.97 | 5.65 |
| Total geographical area | | 293 | 293 | 7.68 | 8.85 |

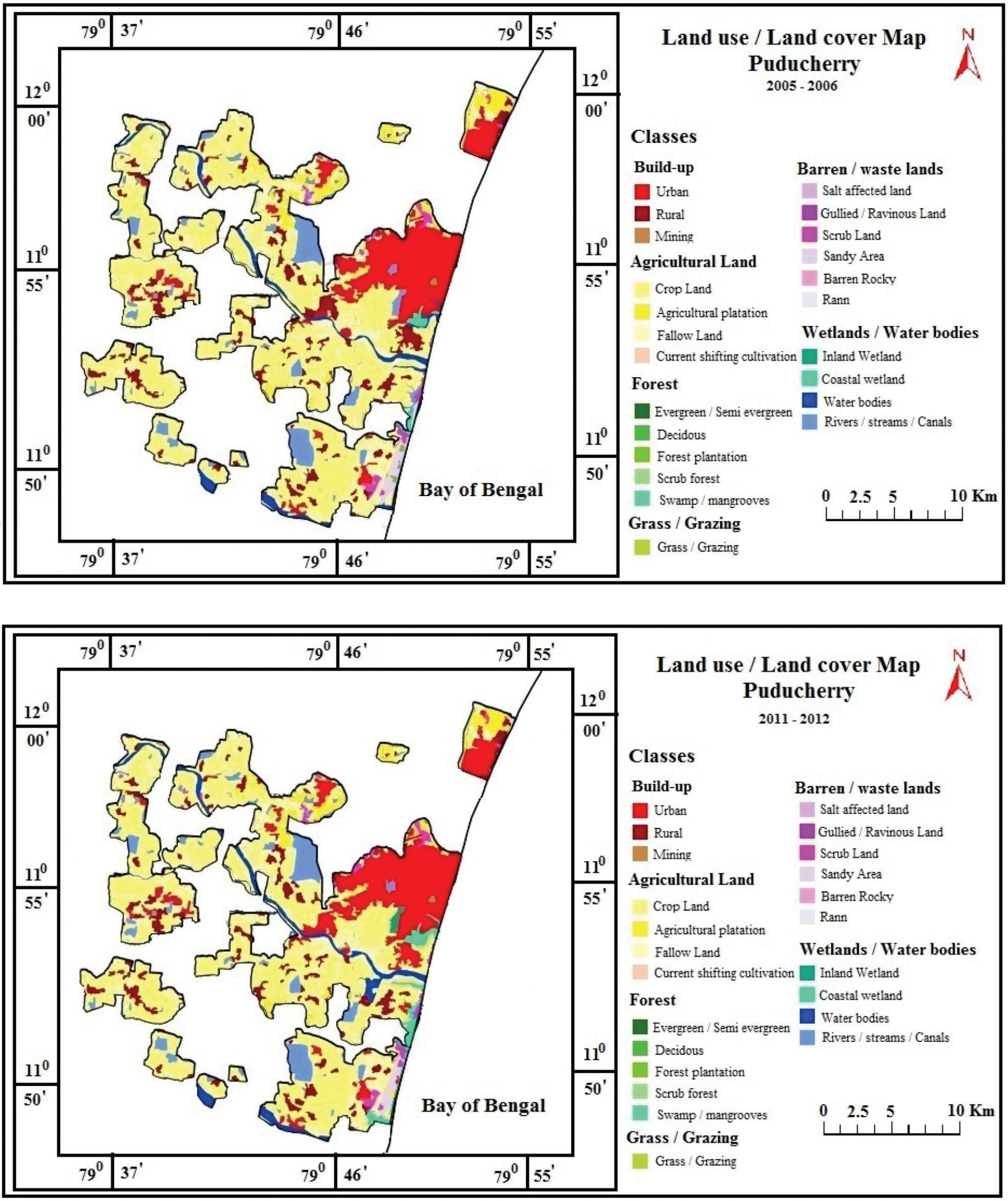

**Figure 7: Land use/Land cover map of Pondicherry region during the years: (Top) 2005-2006; (Bottom) 2011-2012.**

which is the major land-use activity. The percentage of agricultural area may decrease during the years to come as over population and the setting up of more industries in the vicinity (Nobi, 2009). It is noted that 12.13% in 2005-06 and 9.68% in 2011-12 are fallow land. There is a decrease in variations in area covered under agriculture and fallow land attributed to changes in crop rotation, harvesting time and conversion of these lands into plantation. Population density is a reasonable proxy for overall water use, except where industry and agriculture use unusual amounts of water per capita. Although this estimate of water use does not discriminate between surface water and ground water (Grant and Tom, 2012).

Urbanization is another change in land-use that can affect the climate, sometimes significantly. Local climates tend to be warmer due to the increased amount of heat released within a densely populated area. Build-up land showed an increase in percentage from 23.43% (2005-2006) to 24.63% (2011-12). This increase is due to population explosion and the construction of buildings and factories. Increasing population and industrialization along the coastal areas are adding pressure on the coastal ecosystems (Navalgund, 2007; Madan, 2006). Bloomfield et al. (2006) identified that the main climate drivers for changing pesticide fate and behaviour are changes in rainfall seasonality and intensity, and increased temperatures. However, indirect impacts, such as land-use change, are likely to have a more substantial effect on pesticides in surface water and groundwater than the direct effects of climate change on pesticide fate and transport. The area covered with wetlands/water bodies increases from 7.68% to 8.85% during the period of study. A very significant change is noticed in coastal wetland which shows an increasing trend from 0.39 sq.km in 2005-2006 to 1.45 sq.km. Variation in coast may be due to coastal erosion (Nagamani, 2003) or increase of sea level and progressive of sea water.

In general, LULC pattern for 2005-06 has continued to be similar in 2011-12 with lesser intensity of change (Figure 7). However, agriculture with plantation, urban land in build-up area, and coastal wetland showed an increasing tendency while cropland, rural area and fallow land showed a significant reduction. The important factors that drive climatic change are alter land-use through higher mean annual temperatures, altered precipitation patterns, and more frequent and extreme weather events.

## Relationship of EC to the Land-use Pattern

The spatial data of electrical conductivity gives a general trend of the characteristics of the anions and cations present in water which is overlaid on the land-use. The EC of the pre-monsoon seasons are alone considered as they represent higher values irrespective of the time period. The study area has higher EC of above 1500 µs/cm in the northwestern part and in the northcentral part. Agriculture is predominant in the land-use practice in the regions with the higher EC (Figure 8). There is dissolution and leaching in the study area

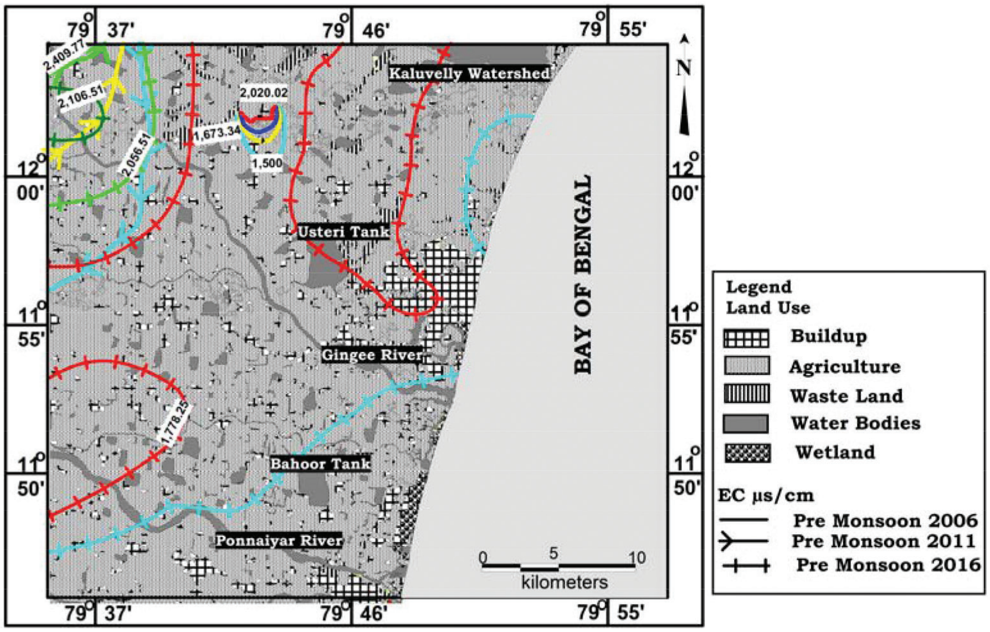

**Figure 8: Electrical conductivity during pre-monsoon during different periods over lay on the land-use.**

which increase the ions (Thilagavathi et al., 2013). Electrical conductivity can also be influenced by the presence of fine sediments (Fenn, 1987).

Similarly the EC values greater than 1500 µs/cm is represented in the northwestern region and in the central part of the study area as that of the pre-monsoon 2006. There is a slight increase in the region with higher EC than the pre-monsoon 2006. It is also interesting to note that the regions with higher drainage intensity also influence the EC values of groundwater. The EC in the pre-monsoon observed during 2016 is 469 to 3256 µs/cm. The EC above 1500 µs/cm is noted in northwestern, eastern and southern parts (Figure 8) of the study area, may be due to seawater intrusion or due to the change in groundwater flow directions. This change in groundwater flow directions may be influenced by two major factors: (1) lesser amount of recharge and (2) excessive pumping of groundwater due to agricultural practices. But the decadal variation shows that there is higher amount of rainfall observed in the study area during this period and hence it is mainly due to the excess groundwater extraction which induces the sea water intrusion. The spatial distribution of EC shows that there is a considerable increase in the area represented by higher EC along the coast and in major portion of the study area, indicating an alarming situation.

## Conclusion

An integrated study has been attempted to get an insight into the climate variations by considering long-term rainfall, water level, groundwater chemistry and land-use resources over a range of temporal and spatial scales. Rainfall trends show a large variability in period of rainfall and it reveals the fact that rainfall has been decreasing over the last five years from 1900 and has cyclicity whereas water table has no correlation with it due to the climate change and land-use pattern changes over the recent years. The monthly rainfall observations show that there is variation in the amount and period of rainfall. Hence, it is inferred that this shift in the monsoonal rainfall is an indicator of climate change. This variation has resulted in the change of recharge pattern and indirectly influence the variation in flow direction. The water level variation in region are mainly governed by rainfall and over exploitation. Maximum depth of water level in majority of the bore wells were observed to be about 5 mbgl. The variation in the enrichment of the isotopes values during 2011 and depleted isotopes in 2006, is a result of the recharge of the evaporated water during 2011 or change in the flow direction of groundwater due to excessive pumping of groundwater. This indicates that the process of recharge has also changed over time. An increase in EC may be due to seawater intrusion, effect of pH and intense long-term agricultural practices in the area of study. Increase in EC in the western region is also due to the excess pumping and groundwater flow direction variation. The land use pattern for 2005-06 has continued to be almost similar in 2011-2012 with lesser intensity of change in agriculture build-up area and coastal wetland.

The change in climate has resulted in variation of amount of rainfall, variation in water level, recharge of the agricultural return flow and increase of population has influenced the excess pumping. The dissolution of minerals in the aquifer matrix and lack of fresh water recharge has resulted in increase of EC. Hence this study shows that the climate change along with other anthropogenic factors has initiated its signature in the groundwater resources of Pondicherry region.

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