# Trends and Patterns in Hydrology and Water Quality in Coastal Ecosystems and Upstream Catchments in Tamil Nadu, India

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# Beyond the Tsunami

# Trends and Patterns in Hydrology and Water Quality in Coastal Ecosystems and Upstream Catchments in Tamil Nadu, India

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# Executive Summary

The Indian Ocean tsunami, which struck the nations in South and Southeast Asia on 26 December 2004, brought about incalculable damage to both humans and the environment. In India, Tamil Nadu was the second worst affected state next to the Andaman and Nicobar Islands. The high intensity waves devastated the Tamil Nadu coast from Chennai to Kanniyakumari and the effects were most pronounced in Cuddalore, Nagapattinam and Kanniyakumari districts. Besides, innumerable human casualties, the impact of the tsunami was also evident in its effects on natural resources such as the coastal and marine ecosystems. Coastal and marine ecosystems provide a wide range of ecosystem services that directly or indirectly sustain livelihoods of millions. Understanding the vulnerability and resilience of these social-ecological systems to climatic shock, large-scale and gradual changes in climate and land use is essential for adaptive management in the future.

## Specific Objectives

1. Assessment of the current status of the quantity and quality of ground and surface water resources in both inland and coastal zones and identify short- and long-term trends.

2. Identify the major drivers of change in water quality and quantity in the coastal zone including emerging land use/water use such as aquaculture.

This study has attempted to integrate the changes in land cover/land use and hydrology of upstream coastal ecosystems within the tsunami affected region over the past few decades with the ecological and environmental status of these ecosystems, and their ability to maintain their ecological functions and ecosystem services that they generate for large numbers of people.

## Our major findings are:

1. The major land use and land cover transformations that are evident in the upstream regions of the coastal ecosystems are a major increase in fallow land, decrease in regular cultivation and increases in area under urban category.

2. There is a pattern of association between ground water resources and area under cultivation. Areas with high recharge of ground water from rainfall are able to sustain cultivation, whereas in other areas, cultivated land has been left fallow, and this is linked to decrease in recharge and/or over-exploitation of ground water.

3. The inflow of fresh water from surface and sub-surface discharges into coastal ecosystems has reduced considerably due to upstream abstraction and diversion, and there is an increasing discharge of untreated sewage, saline effluents from aquaculture, and industrial effluents into these coastal wetlands and estuaries. As a result of reduction in fresh water inflows, coastal wetlands and estuaries are increasingly becoming more marine in their water chemistry through increase in salinity and pH.

## Our recommendations are:

- Maintenance of minimum ecological and environmental flows in rivers that drain into these coastal ecosystems is essential to sustain their productivity, ecological resilience and ability to generate a diversity and abundance of ecosystem services. This can be achieved only through release of water from reservoirs whenever feasible, and through regulation of ground water extraction and adoption of water efficient crops.
- Ground water use must be regulated in the coastal zone and sand mining from river beds must be prohibited and this must be enforced.
- There must be a major awareness campaign launched amongst coastal scientists, coastal communities, government agencies and political parties about the threat to coastal ecosystems and their ecosystem services from upstream land use and water use. The need to maintain minimum environmental flows in rivers discharging into the coastal wetlands and estuaries must be highlighted.

# 1. Introduction

The Indian Ocean tsunami, which struck the nations in South and Southeast Asia on 26 December 2004, brought about incalculable damage to both humans and the environment. In India, Tamil Nadu was the second worst affected state next to the Andaman and Nicobar Islands. The high intensity waves devastated the Tamil Nadu coast from Chennai to Kanniyakumari and the effects were most pronounced in Cuddalore, Nagapattinam and Kanniyakumari districts. Besides innumerable human casualties, the impact of the tsunami was also evident in its effects on natural resources such as the coastal and marine ecosystems. Coastal and marine ecosystems provide a wide range of ecosystem services that directly or indirectly sustain livelihoods of millions. Understanding the vulnerability and resilience of these social-ecological systems to climatic shock, large-scale and gradual changes in climate and land use is essential for adaptive management in the future.

To identify the potential impacts of such natural calamities and to facilitate necessary protection from such disasters, baseline information on the changing patterns of natural resources like changes in the course of rivers, increase or decrease in the availability of fresh water, sediment flow through the rivers to the sea, etc, is very important.

Rapid changes in hydrology, in the past as well as in the future, both within the coastal zone as well as in upstream areas (reduction in fresh water flows due to construction of major reservoirs), from where fluxes of water, nutrients, sediments and pollutants flow into the coastal and marine environment will have major impacts on these coastal ecosystems including ecosystem services, biodiversity, productivity and livelihoods. There has been no comprehensive and systematic study of these impacts, and baseline data is lacking for most indicators of change to enable monitoring. Over and above this, the potential effect of global climate change on the coastal and marine ecosystems of the east coast of India is largely unknown. Assessing the current status and analyzing the impacts of changes in the last few decades will enable a baseline to be established for future monitoring and for formulating effective management measures.

# 2. Objectives

To study the impacts of upstream modifications of the hydrologic, sediment and nutrient fluxes due to reservoir construction on downstream coastal and marine ecosystems, and the likely impacts of these changes on marine and coastal ecosystems on ecosystem services, biodiversity and livelihoods.

## 2.1 Specific objectives

1. Assessment of the current status of the quantity and quality of ground and surface water resources in both inland and coastal zones and identify short- and long-term trends.

2. Identify the major drivers of change in water quality and quantity in the coastal zone including emerging land use/water use such as aquaculture.

# 3. Methodology

## 3.1 Study area

The present study is focused on the impact of land use and hydrological changes at select sites in the coastal zone of the tsunami affected state of Tami Nadu, the worst affected state of the Indian mainland. This analysis will look at changes in land use patterns over the last few decades at select sites. It will additionally look at changing vulnerability patterns, and spatio-temporal hydrological status along the coastal zone, and the potential implications of these changes on human communities and coastal ecosystems. The scope of the study included four main river systems of Tamil Nadu namely, the Cauvery, the Tambraparani, the Vaigai and the Gingee. The sites studied were concentrated around these river systems to identify potential hydrological trends in their due course of flow over a period of 10–15 years from upstream areas till they fall into the sea. Figure 3.1 shows the location of the districts in Tamil Nadu identified for the study.

The objectives highlighted in this report were studied under three sections:

1. Land cover/land use change
2. Status/trends in water resources
3. Snapshot of water quality in coastal areas

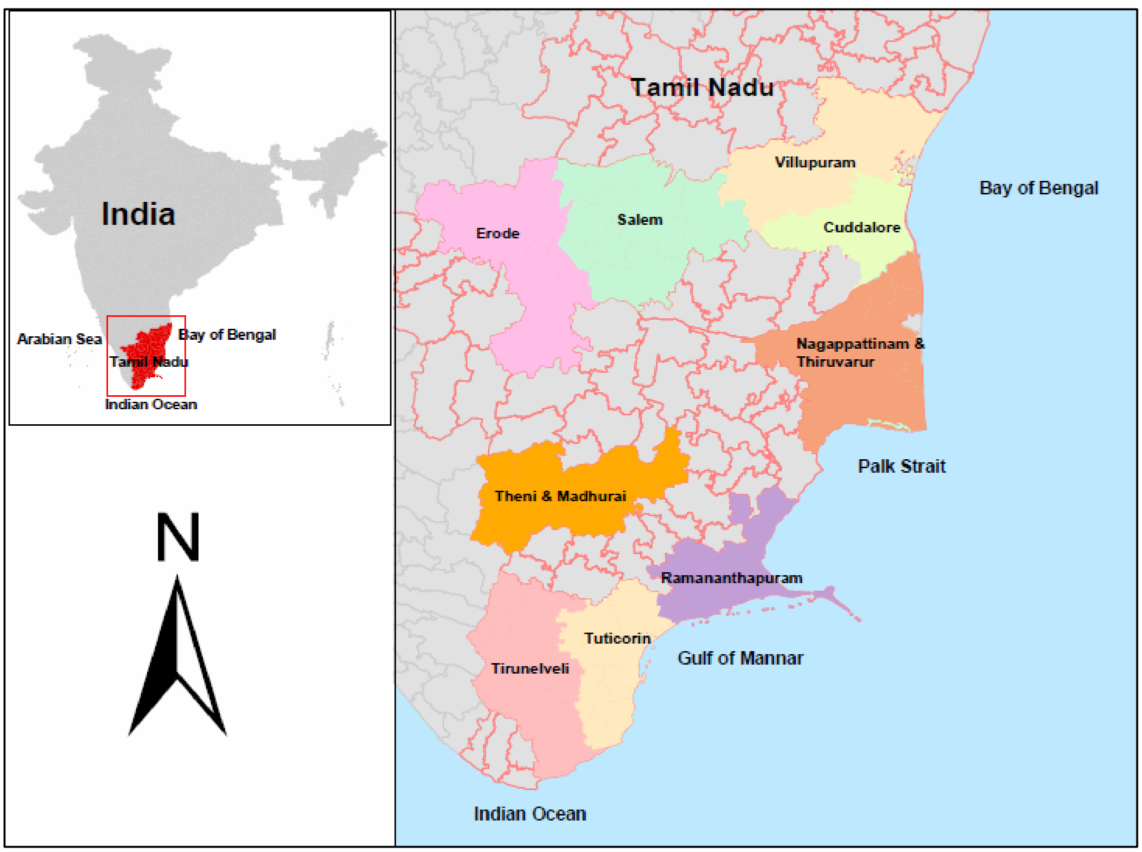



**Figure 3.1:** Location map of study areas in Tamil Nadu

## 3.2 Assessment of trends in water resources

The Central Ground Water Board is the apex organisation for development and management of ground water resources of the country. The Central Ground Water Board has a regional office at Chennai for attending to work in Tamil Nadu and in the union territory of Puducherry.

The entire area of the state has been already covered by systematic hydro-geological surveys. Ground water regime studies were also carried out by establishing Hydrograph Network Stations that are distributed over the state. The studies commenced in 1969 and over the years the number of stations has increased. Presently there are 785 National Hydrograph Stations in Tamil Nadu and Puducherry. These stations are monitored four times a year, i.e., during January, May, August and November.

Annual time series of ground water levels in metres below surface were obtained for Tuticorin, Tirunelveli, Ramanathapuram, Theni, Salem, Erode, Thiruvarur, Nagapattinam, Villupuram, and Cuddalore districts of Tamil Nadu from 1970 to 2006. A few stations from these districts were selected corresponding to the catchment areas and the outlet areas of the above mentioned rivers**.**

Figure 3.2 shows the ground water monitoring sites in Tamil Nadu selected for the study. The stations identified for ground water monitoring were:

- Tuticorin: Nazareth, Tuticorin, Srivaikundam, Tiruchendur
- Tirunelveli: Cheranmadevi, Alwarkurichi, Alangulam
- Ramanathapuram: Sayalkudi, Sikkal, Mandapam, Nadumunaikadu, Perungulam, Thangachchimadam, Uchipuli, R.S.Mangalam, Solandur, Kilakkarai, U.Kosamangai, Tiruvadanail
- Theni: Andipatti
- Salem: Sankaridrug, Nangavalli, Jalakandapuram
- Erode: Bhavani
- Thiruvarur: Muthupet
- Nagapattinam: Velanganni, Sirkazhi, Nannilam
- Villupuram: Alvarupet
- Cuddalore: Vridachalam

The data consisted of measurements of the ground water levels made every 3 months in a year which were divided into pre- and post-monsoon periods. The corresponding data for rainfall nearest to the ground water monitoring station or rainfall for the sub-region in which the ground water monitoring well was located were also obtained.

The robust non-parametric Seasonal Trend Decomposition with Loess (STL) (Cleveland 1990) method in R-statistical software was used to plot and extract the cyclic and trend components in the time series of ground water levels and rainfall. This technique decomposes a time series into a quasi-cyclic component, a trend component and a residual remainder.

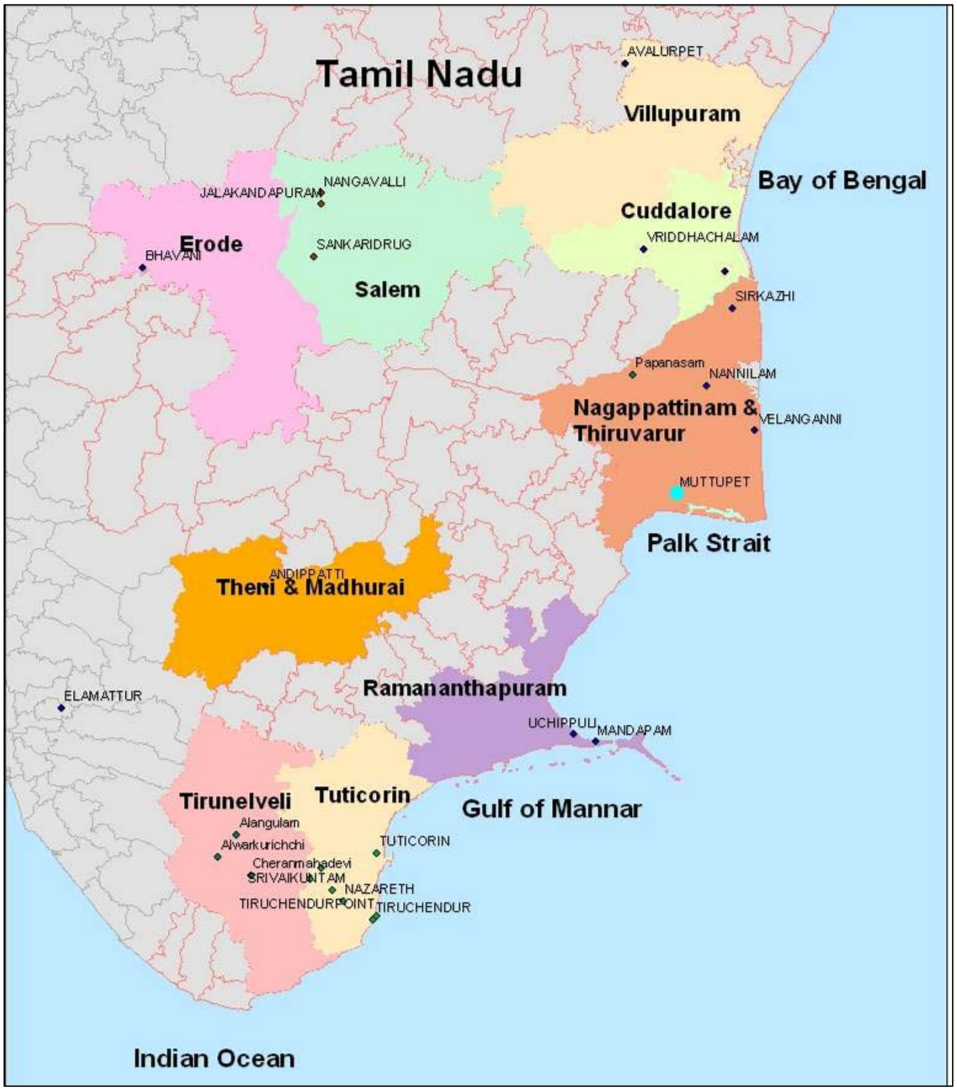



**Figure 3.2:** Selected groundwater monitoring stations in Tamil Nadu

The trend components in ground water for both pre- and post-monsoonal periods were plotted along with the trend component in the corresponding rainfall. In order to correspond with the pre-monsoon (dry season) ground water level data, the preceding monsoon rainfall data was used in the comparisons of trends.

In addition, the trend component in the ground water level was the response variable with corresponding rainfall as the covariate in a linear regression model.

Negative trends in ground water at the stations that were not explained by corresponding trends in rainfall were analysed with respect to land use changes in those districts (see section 3.3 below).

## 3.3 Assessment of land use or land cover change

The watershed areas or the catchment areas, immediately below the dams built on the identified rivers and a few selected sites in the coastal areas of Tamil Nadu, were assessed in terms of their land use patterns. Two sets of land use maps for two time periods, 1996–97 and 2003–04, were studied to identify significant changes during that period; these would provide background information about the alterations in the hydrological trends from the upstream areas to the downstream coastal areas where the rivers flow into the sea. This assessment was essential to understand the factors contributing to the overall hydrological behaviour of rivers and the potential impacts of these factors, which have caused subsequent changes in the course, and status of water resources in Tamil Nadu. The land use changes due to the impact of the tsunami along the coastline were also identified.

The important classes of land use patterns identified under this section were: agricultural uses such as crops, mangroves, fallow land used for grazing and harvesting, non-agricultural activities such as industries, construction of dams for irrigation, urbanization, aquaculture and salt pans, forest land, and water bodies such as lakes, streams, ponds and estuaries.

The changes in the land use patterns of the respective districts were assessed and identified for any significant change from the size of the land area under a particular use observed over a time period of 20–30 years. The change observed in any specific class of the land use was then further assessed in detail using land use maps of two time periods, 1996–97 and 2003–04, obtained from the Institute of Remote Sensing, Anna University, Chennai, Tamil Nadu.

## 3.4 Assessment of water quality

Eco-sensitive sites in Tamil Nadu representing important areas for biodiversity and that were linked and expected to be sensitive to upstream changes in land cover and land use, as well as local changes in the coastal areas, were selected for primary sampling. The sites selected were categorised according to their sensitivity prior to sampling. Figure 3.3 shows the selective eco-sensitive sites chosen for water quality sampling. The sites selected were:

- Mangrove wetland areas: Pichavaram, Muthupet, Punnakayal
- Estuaries:
  - Cauvery estuary at Poompuhar, Nagore and Velanganni (aquaculture)
  - Yedayanthittu estuary (salt pans)
  - Chunnambar estuary
  - Vellar estuary at Parangipettai (Patchy mangrove areas)
  - Vaippar estuary
  - Vaigai estuary at Mimisal and Aatrangarai
  - Area influenced by industries : Roche Park in Tuticorin

The above sites were sampled during May 2008 (pre-monsoon). Five water samples were collected, except for Muthupet (where 10 samples were collected because of the comparatively larger area), and Mimisal and Vaippar (where only three samples were collected because of lesser water).

Sample collection was done between 10.00 a.m. and 12.30 p.m. Surface water samples were collected at each station, in polyethylene bottles and preserved under 40ºC, and sent to the lab for analysis as soon as possible. Water samples for dissolved oxygen (DO) were preserved by adding alkaline iodide (1 ml) and concentrated sulphuric acid (1ml) to a 250 ml sample. Samples for heavy metal analysis were preserved adding 0.25 ml concentrated nitric acid to a 250 ml sample, on site, as soon as the samples were collected.

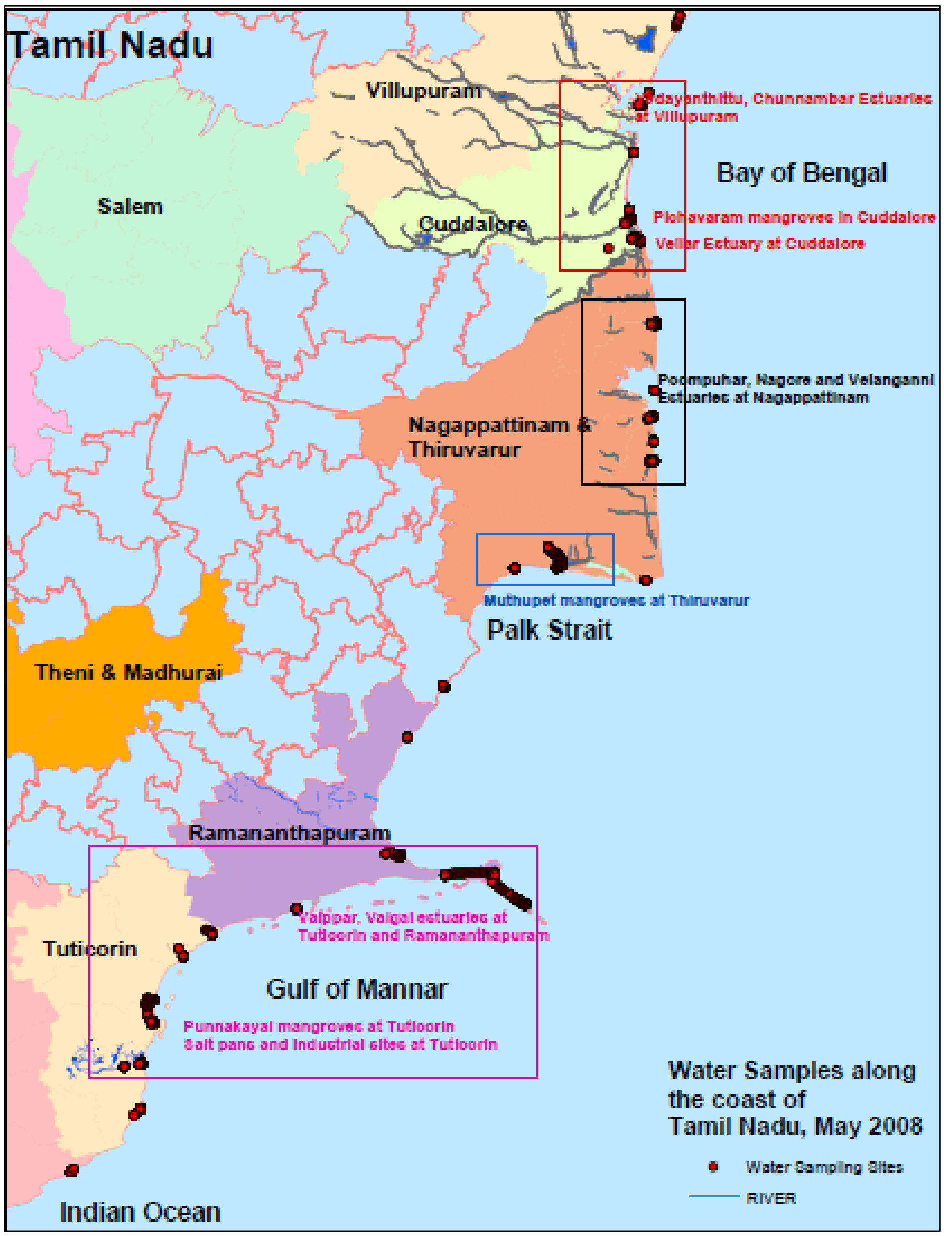



**Figure 3.3:** Selected eco-sensitive sites for water sampling in Tamil Nadu

### 3.4.1 Water quality analysis

Onsite analysis of the water quality as well as laboratory analysis was carried out. The location of each station was marked on the Global Positioning System and the temperature and the salinity were measured on site using a thermometer and a refractometer respectively.

### 3.4.2 Laboratory analysis

All the analyses were carried out according to the Standard Methods for the Examination of Water and Wastewater, 2001 Supplement to the 20$^{th}$ edition: American Public Health Association-American Water Works Association-Water Environment Federation. The standard analytical methods used for the water quality tests are given in Table 3.1.

**Table 3.1:** Standard analytical methods used for the water quality tests

| Sl. no. | Parameter | Method of testing |
|---|---|---|
| 1. | pH | Electrometric method 4500 B |
| 2. | Electrical conductivity (EC) | Laboratory method 2510 B |
| 3. | Total dissolved solids (TDS) | Drying method 2540 B |
| 4. | Total suspended solids (TSS) | Drying method 2540 D |
| 5. | Calcium (Ca) | EDTA Titrimetric method 3500 B |
| 6. | Magnesium (Mg) | Calculation method 3500 B |
| 7. | Chloride (Cl) | Argentometric method 4500 B |
| 8. | Nitrate ($NO_3^-$) | Cadmium reduction method 4500 E and UV Screening method 4500 B |
| 9. | Sulphate ($SO_4^{2-}$) | Turbidimetric method 4500 |
| 10. | Phosphate ($PO_4^{3-}$) | Stannous chloride method 5220 C |
| 11. | Sodium (Na) | Flame photometric method 3500 B |
| 12. | Potassium (K) | Flame photometric method 3500 B |
| 13. | Dissolved oxygen (DO) | Winkler method |
| 14. | Biological oxygen demand-$BOD_3$ at 27°C | IS 3025 (part 44): 1993 |

## 4. River-systems: General profile

There are several rivers passing through the state of Tamil Nadu which eventually fall into Bay of Bengal, Palk Strait and the Gulf of Mannar. Some of the important ones in the state are the River Cauvery, Vaigai, Tambraparani, Ponnaiyar, Vellar and Gingee. Figure 4.1 illustrates the main rivers flowing through the state of Tamil Nadu.

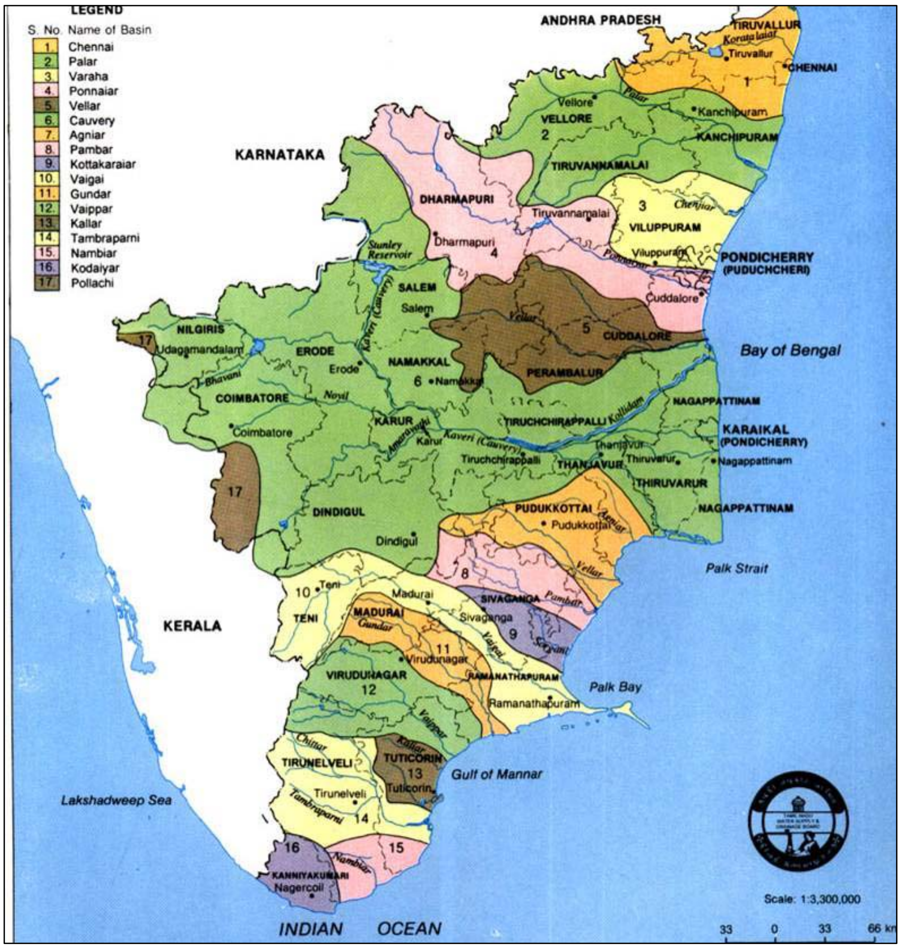



**Figure 4.1:** Rivers in Tamil Nadu

The rivers selected for our study are described in brief in the following section.

## 4.1 Gingee

The River Gingee flows diagonally from northwest to southeast. This river is also known as the Varahanadi or the Sankaraparani. The River Gingee has its source in the hills of Malayanur in the South Arcot (now Villupuram) district of Tamil Nadu. Though the river has a total length of 78.89 km, it has a run of only about 34 km in this region. The river splits into two branches namely the Ariankuppam River in the north and the Chunnambar in the south. The Vikravandi, the Pambayar and the Kuduvaiyar are the tributaries of the Gingee River. The River Gingee is not a perennial river, and it flows only during rainy seasons and floods.

The Gingee River is first intercepted by the Vidur dam which irrigates Villupuram in Tamil Nadu and Puducherry. The Gingee watershed consists of Tindivanam, Villupuram, Gingee, Vannur taluks in Villupuram district and some parts in Puducherry. [DEP n.d. (Villupuram and Puducherry)].

## 4.2 Cauvery

The River Cauvery originates at Talakaveri, Kodagu district, in the Western Ghats in the state of Karnataka. It flows generally south and east through Karnataka and Tamil Nadu and across the southern Deccan Plateau through the southeastern lowlands, emptying into the Bay of Bengal through two principal mouths.

The Cauvery River basin is estimated to be 72,000 sq km with many tributaries including the Rivers Shimsha, the Hemavati, the Arkavathy, the Honnuhole, the Lakshmana Tirtha, the Kabini, the Bhavani, the Lokapavani, the Noyyal and the Amaravati. Rising in southwestern Karnataka, it flows southeast some 765 km to enter the Bay of Bengal. The river is the source for an extensive irrigation system and also for hydro-electric power.

The river enters Tamil Nadu through the Krishnagiri district and along its course forms many gorges and waterfalls, including the famous Hogenakkal falls in Dharmapuri district. The three minor tributaries, the Palar, the Chennar and the Thoppar, enter the Cauvery on her course, above Stanley reservoir in Mettur, where a dam has been constructed. The Mettur dam joins the Sita and the Pala mountains beyond that valley through which the Cauvery flows, up to the Grand Anicut. The dam in Mettur impounds water not only for the improvement of irrigation but also to ensure regular and sufficient supply of water to the important hydro-electric generating station at Mettur.

The river further runs through Erode district where the River Bhavani merges with it. While passing through Erode, two more tributaries merge. The Noyyal and the Amaravati join it before it reaches the Tiruchirappalli district. Here the river becomes wide, with a sandy bed, and flows in an easterly direction until it splits into two at Upper Anicut about 14 km west of Tiruchirappalli. The northern branch of the river is called the Coleroon or the Kollidam while the southern branch retains the name Cauvery, and then goes directly eastwards into Thanjavur district. These two rivers join again and form the Srirangam Island near Tiruchirappalli.

On the border between Tiruchirappalli and Thanjavur is a large historic dam, the Grand Anicut that stands as the head of a great irrigation system in the Thanjavur district. From this point, the Coleroon or the Kollidam runs northeast and discharges itself into the sea at Devakottai, a little south of Parangipettai. From the River Coleroon, the Manniar and the Uppanai branch off at Lower Anicut and irrigate a portion of the Mayiladuthurai and Sirkazhi taluks in Thanjavur district. After the Grand Anicut, the Cauvery divides into numerous branches and covers the whole of the delta with a vast network of irrigation channels and gets lost in the wide expanse of paddy fields. The mighty Cauvery River here is reduced to an insignificant channel and falls into the Bay of Bengal at the historical place of Poompuhar (Kaveripoompatinam) about 13 km north of Tharangampadi. The Cauvery thus flows through the entire districts of Thanjavur, Thiruvarur and Nagapattinam in different names through its tributaries and branches - Grand Anicut canal, Adapparu, Arasalaru, Ayyanaru, Cholasudamani, Harichandranathi, Kaduvaiyar, Kattar, Kirtimanar, Kodamurtiyar, Koraiyar, Mahimalayaru, Manajalaru, Mudikondan Aru, Mullaiyaaru, Nandalaru, Nattaru, Noolaru, Odambogiyaru, Palavaru, Pamaniyaru, Pandavaiyaru, Pannaiyaru, Putharu, Thirumalairajanaru, Vadavaru, Valapparu, Valavaikkal Aru, Vanjiaru, Veerasozhanaru, Vellaiyaru, Vennaru, Vettaru, Vikaraman Aru—and all these branch off into a number of small streams [DEP n.d.(Salem and Erode)].

## 4.3 Vaigai

The Vaigai is a river in Madurai, Tamil Nadu. It originates in the Periyar plateau of the Western Ghats range, and flows northeast through the Kambam valley, which lies between the Palani hills to the north and the Varushanad hills to the south. As it rounds the eastern corner of the Varushanad hills, the river turns southeast, running through the region of Pandya Nadu. Madurai, the largest city in the Pandya Nadu region and its ancient capital, lies on the Vaigai. The river empties into the Palk Strait in Ramanathapuram district. The main tributaries of the Vaigai are the Rivers Suruliyaru, the Mullaiyaaru, the Varahanadi and the Manajalaru. All these rivers join with the great Vaigai close to places around the Vaigai dam which is situated in Theni district.

The Vaigai dam is built across the Vaigai near Andipatti, in the Theni district. It provides water for irrigation to the Madurai and the Dindigul districts as well as drinking water to Madurai and Andipatti. Near the dam the Government of Tamil Nadu has constructed the Agricultural Research Station for studying the growing of a variety of crops, including rice, sorghum, black gram, cowpea and cotton [DEP n.d. (Theni, Madurai and Ramanathapuram)].

## 4.4 Tambraparani

The River Tambraparani originates on the eastern slopes of the Western Ghats in Tirunelveli district of Tamil Nadu. The origins of the Tambraparani and its tributaries are situated at the peaks called the Aduppukkal Mottai, the Agathimalai and the Cherumunji Mottai, at an altitude of about +2,000 m above mean sea level. The Tambraparani basin is situated between latitudes 8.21'N and 9.13'N and at a longitude of 77.10'E. The Vanatheertham waterfall (40 m deep) is located close to the origin of the main river. This river joins the Papanasam reservoir at its $16^{th}$ km. The river has four tributaries—the Peyar, the Ullar, the Karaiar and the Pambayar—upstream of the Papanasam reservoir. The River Servalar, a main tributary of the Tambraparani joins the main river at a running distance of 22 km. Another tributary the Manimuthar originates in the Agathimalai ranges at an altitude of about +2,000 m above mean sea level. It joins the Tambraparani at its $36^{th}$ km near Ambasamudram. The Gadana River joins at its $43^{rd}$ km on the left [DEP n.d. (Tirunelveli and Tuticorin)].

# 5. Analysis

## 5.1 Land use/land cover change

Water is a vulnerable resource, and its quality and quantity changes because of the following factors:

1. Deforestation and poor land use practices in the catchment area, which disturb topsoil and vegetative cover resulting in decreased infiltration rates, increased runoff, sediment transport, and deposition in rivers and storage reservoirs.
2. Over-abstraction of surface water sources upstream reduces the minimum flow required in the downstream sections for the sustenance of ecosystems and mangroves.
3. Over-pumping of ground water induces saline water intrusion into fresh water aquifers resulting in changes in ground water quality with increased total dissolved solids (TDS).
4. Water pollution due to the discharge of untreated/partially treated industrial and municipal waste water into water sources deplete DO and affects fish and other aquatic life.
5. Agricultural runoff and sub-surface drainage, which carry residues of chemical fertilisers and pesticides, affect the water quality, promote weed growth and render the water resources unfit for other uses.
6. Encroachment of agricultural land and watersheds for urbanisation and industrial development has an impact on wetlands and important watershed areas, and affects recharging areas and inflows into reservoirs (DoE-GoTN n.d.).

The land use changes and the selected ground water monitoring sites are described in this section. Few sites presenting noticeable trends in ground water resources were assessed in terms of their changing land use patterns over a certain period of time. The sites selected for this purpose consisted of some inland and some coastal taluks and blocks in the corresponding districts of Tamil Nadu.

### 5.1.1 Gingee watershed

#### Villupuram-Inland

The Gingee watershed consists of the taluks of Tindivanam, Villupuram, Gingee and Vannur in Villupuram district, Tamil Nadu, and the union territory of Puducherry. The upper catchment areas of Vidur dam lie in Villupuram district and the changes in land use patterns were observed between 1993 and 2000. Figure 5.1 shows the changes in land use patterns in 1997 and 2004 in Gingee taluk in Villupuram district.

- Forest land remained relatively unchanged at 71,697 sq km.
- Non-agricultural uses of land increased from 103,987 sq km in 1993 to 135,874 sq km in 2006.
- Significant change was observed in the plantation areas, which decreased from 35, 212 sq km in 1993 to 6,142 sq km in 2006.
- Fallow land increased from 45,306 sq km to 86,725 sq km at present.

## Villupuram and Puducherry - Coastal outlet

The coastal areas of Gingee fall in both Villupuram district and Puducherry with a coastline of about 30 km length, and Villupuram, Marakkanam and Vannur are the major coastal towns. Seven aquaculture units are located within an area of 0.12 sq km in Villupuram district.

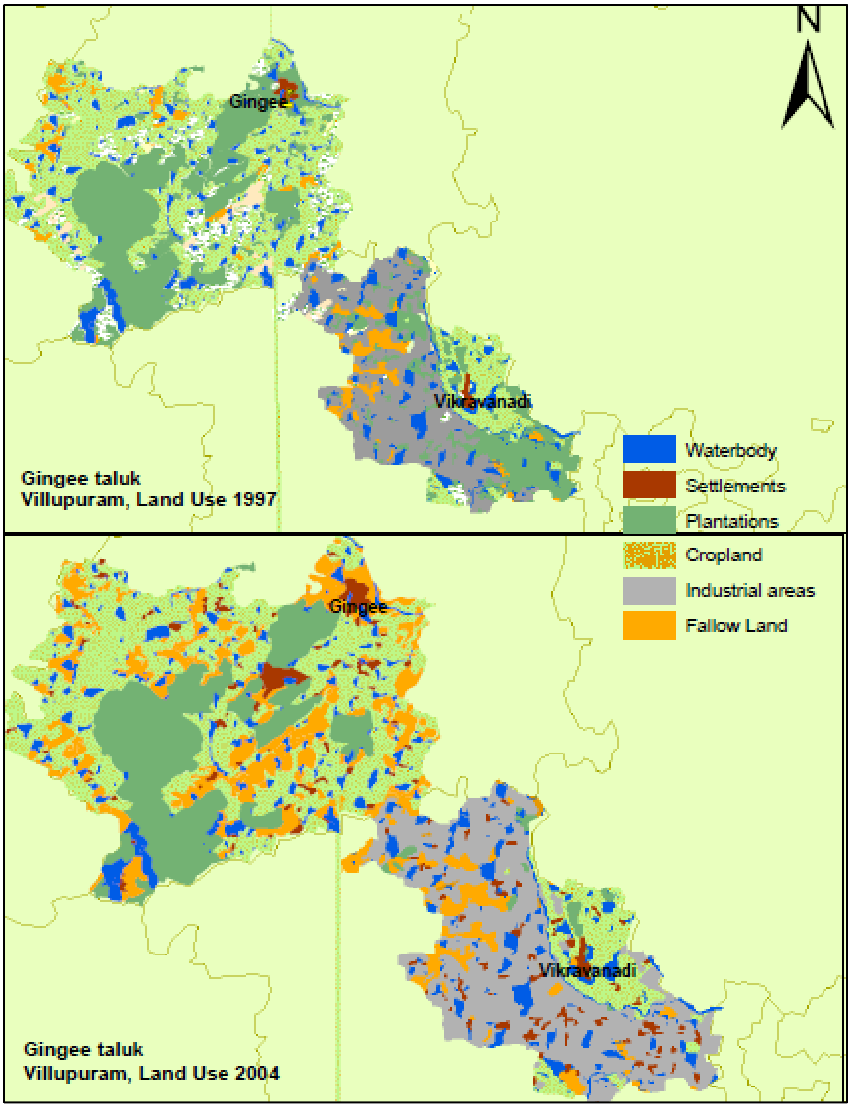



**Figure 5.1:** Land use change of Gingee taluk in Villupuram in 1997 and 2004

### 5.1.2 Cauvery River basin

### Mettur Dam-Inland

The catchment areas of the Mettur/Stanley reservoir constructed on River Cauvery in Tamil Nadu are located in Salem district. The changes in land use patterns observed in this district were between 1970 and 2005. Figure 5.2 shows the land use changes in 1997 and 2004 in Salem district along with the selected ground water sites.

- Significant reduction in the availability of barren land from 88,387 sq km in 1970 to 39,098 sq km in 2005 and open grazing land reduced from 15,689 sq km in 1970 to 4,206 sq km in 2005.
- The gross area sown also reduced from 474,000 sq km to 250,000 sq km at present.
- Between 1995 and 1996, the district had 120 medium- and large-scale industries, 8,250 registered small-scale industries such as chemical, sago processing, mineral pulverising and dyeing units.
- The discharges from major industries such as Chemplast, Madras Aluminium Company Ltd., Mettur Thermal Power Station, etc., are let into Cauvery River. The discharge from sago and dyeing units in Salem, Attur, Valappadi taluks are affecting the water resources to a great extent.
- The urban population has increased from 28.5 percent in 1981 to 32.4 percent in 1991.

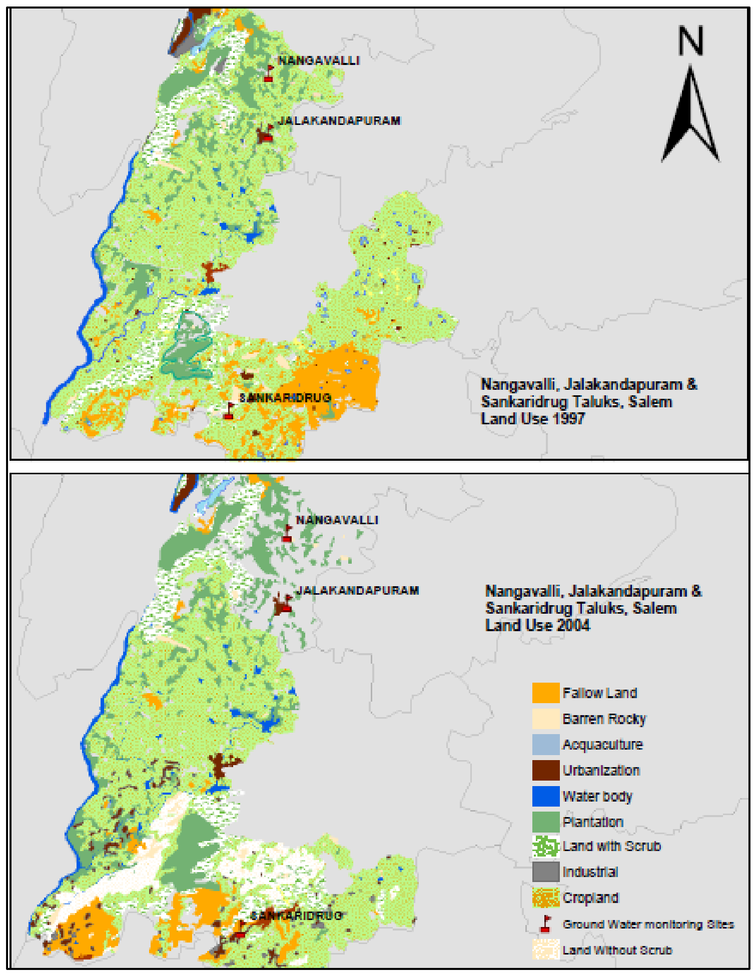



**Figure 5.2:** Land use change of Salem district in Villupuram in 1997 and 2004

## Nagapattinam-Coastal outlet

The River Cauvery forms a deltaic region in this district, criss-crossed by lengthy networks of irrigation canals. The Kollidam or the Coleroon River forms the northern boundary of the district, whereas the Arasalaru, the Thirumalairajanaru, the Vettaru and the Vennaru Rivers drain other parts of it. All these rivers are tributaries and branches of the River Cauvery. Figure 5.3 shows the changes in land use patterns in Velanganni taluk in Nagapattinam district along with the ground water monitoring site. Land use changes in this region were observed from 1992 to 2005.

- Forest area decreased from 7,085 sq km in 1992 to 4,633 sq km in 2005. There is a bird sanctuary at Thalainayar village of Vedaranniyam taluk in the Nagapattinam district that spreads over 17.2881 sq km. This constitutes 14.92 percent of total forest area in the district.
- The available fallow land also decreased from 9,738 sq km to 2,747 sq km.
- The gross area used for agricultural purposes reduced from 443,000 sq km to 241,000 sq km.
- Nagapattinam district has a coastline of 165 km. The inland fresh water area spreads for about 10 sq km. Marine fishing is practiced in 60 coastal villages of the district. The fish production fluctuated in both quantity and value from 1990 to 1996. Aquaculture activities such as prawn culture and shrimp farming are also practiced in a large scale in the coastal areas of this district.

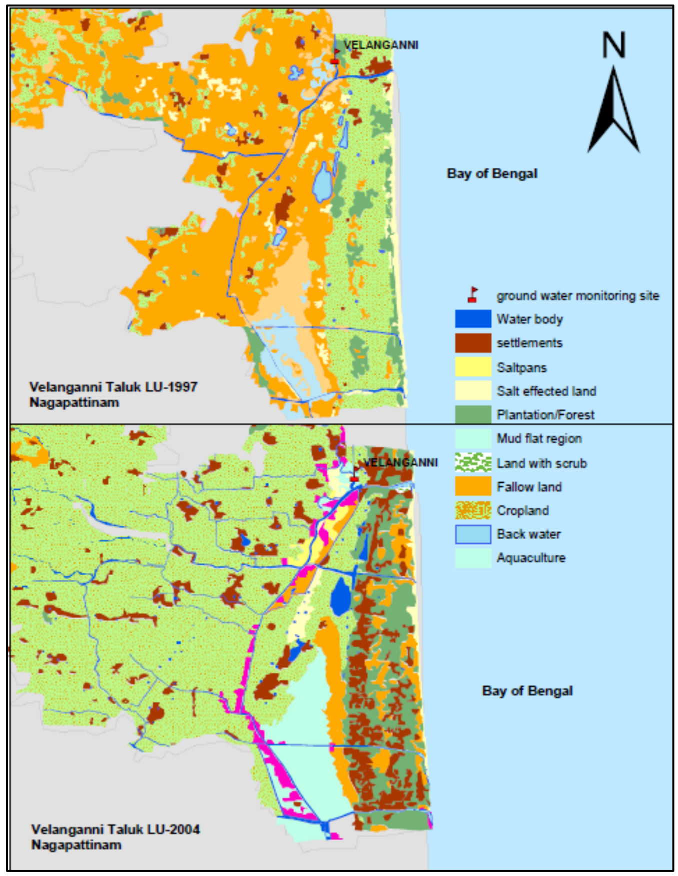



**Figure 5.3:** Land use change of Velanganni in Nagapattinam district in 1997 and 2004

### 5.1.3 Vaigai

#### Theni-Inland

The upstream reservoir identified for this river system in Tamil Nadu is located in the Theni district. The catchment areas fall in the Periyar-Vaigai basin division, which includes parts of Theni and a few areas in Madurai district. Figure 5.4 shows the land use patterns in Andipatti taluk in Theni district which is a catchment area of the Vaigai dam. The land use changes were observed between 1996 and 2005 in Theni.

- Barren land and plantation areas increased from 10,778 sq km in 1996 to 43,322 sq km in 2005 and from 781 sq km in 1996 to 2,334 sq km in 2005 respectively.
- Fallow land decreased from 15,060 sq km in 1996 to 1,636 sq km in 2005.
- There has been inland fresh water area, spreading in 73.95 sq km. The fish production has increased both in quantity (tonnes) and value (lakhs) from 1991 to 1996.
- The proportion of urban population to total population has increased from 33.33 percent in 1981 to 46.71 percent in 1996.

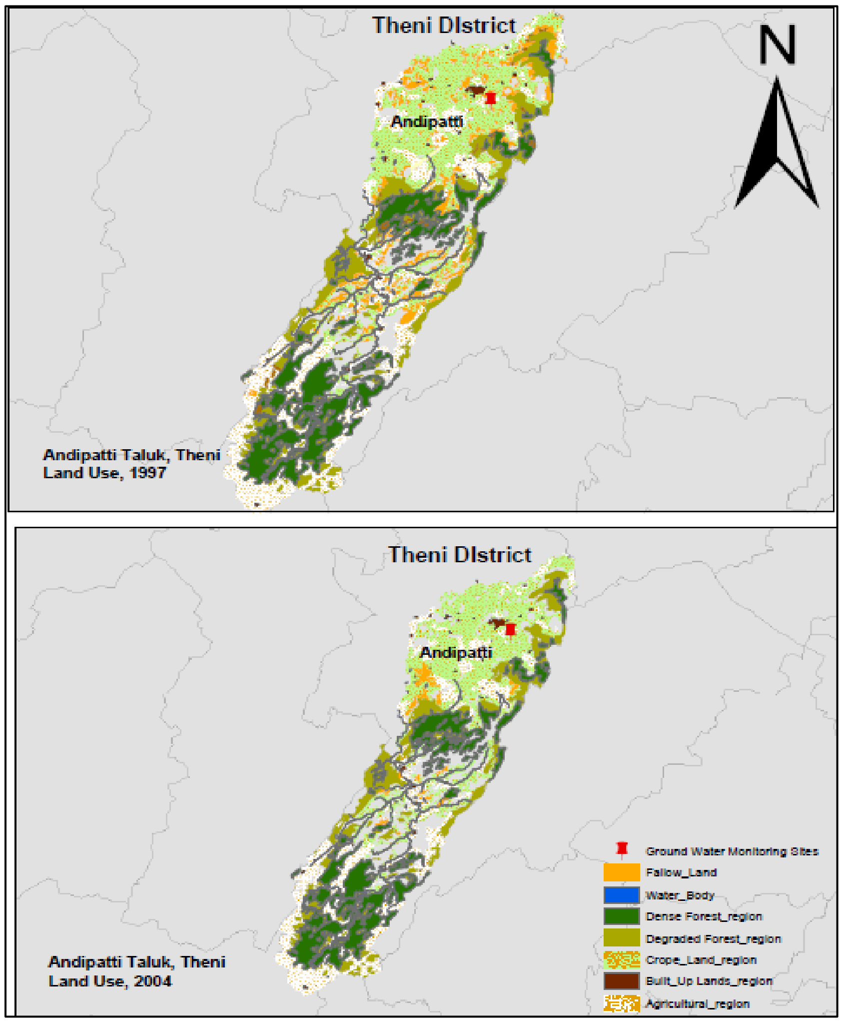



**Figure 5.4:** Land use change of Andipatti in Theni district in 1997 and 2004

## Ramanathapuram-coastal outlet

Pambayar, Kottakaraiyar and Gundar, are the three catchment areas of the Vaigai River basin in the district of Ramanathapuram. Figure 5.5 shows the changes in land use patterns in the Vaigai outlet in Ramanathapuram district along with the ground water monitoring sites. The land use changes were observed between 1970 and 2005.

- A prominent change was observed in the geographical extent of the area, which reduced from 12,00,000 sq km in 1970 to 400,000 sq km in 2005.
- Forest areas decreased tremendously from 45,413 sq km to 4,488 sq km, and barren land decreased from 53,974 sq km to 4,591 sq km.
- The other land use classes also decreased in their areas due to the reduction in the total geographical area of the district.
- The utilisation of chemical fertilisers and bio-fertilisers in the district is high.
- The proportion of urban population to total population increased during the years 1981 to 1996 increased from 21.61 percent to 23.29 percent and it increased at about 15 percent during the period 1991 to 1996.
- Ramanathapuram district has 271 km of coastline covering 99 coastal villages and towns. There are 164 aquaculture units spread over an area of 4.17 sq km.

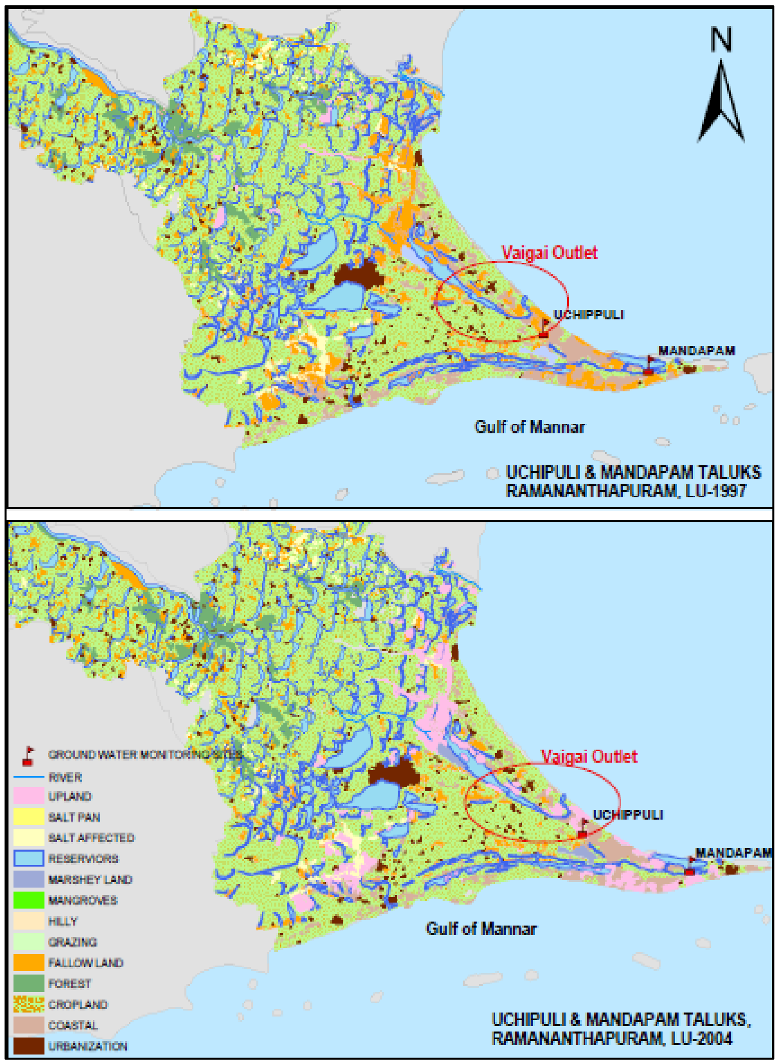



**Figure 5.5:** Land use change of Vaigai outlet in Ramanathapuram district in 1997 and 2004

### 5.1.4 Tambraparani

#### Tirunelveli-Inland

The river has its origin in the district of Tirunelveli. It has been dammed at Papanasam. Tambraparani, Nambiyar and Vaippar are three catchment areas of the river basins in the district. The land use classification in this district was studied between 1970 and 2005. Figure 5.6 shows the land use pattern in Tirunelveli district.

- The total geographical area of the district decreased from 11,42,300 sq km in 1970 to 682,300 sq km in 2005.
- Forest areas remain unchanged during this period.
- Plantation areas decreased from 19,026 sq km to 10,009 sq km.
- Fallow land decreased from 170,000 sq km in 1971 to 32,053 sq km in 2005.
- The total area used for agricultural purposes reduced from 550,000 sq km to 200,000 sq km.
- Another important and interesting phenomenon is that, the district generally comes under the description of 'dry' region; almost all the river water is utilised for irrigation and very little finds its way into the Bay of Bengal. Due to the erratic monsoon and reduction in the density of vegetation in the middle lower reaches of the watershed region, most of the rivers and streams go dry. Seasonal and flash floods have become very common.
- There are five dams/reservoirs in the district, which are used for irrigation and two of them are used for power generation purposes also. Papanasam dam/reservoir has the maximum water spread area as well as designated capacity.

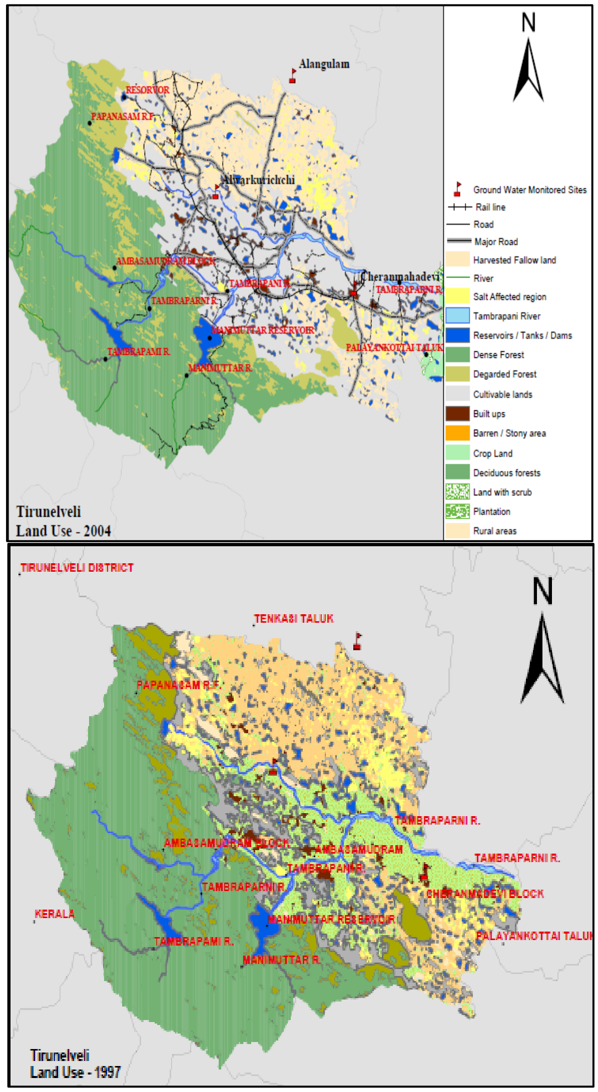



**Figure 5.6:** Land use change of Tirunelveli district in 1997 and 2004

- The proportion of urban population to total population has increased rapidly between 1981 and 1996 from 29.74 percent to 44.91 percent.
- Madura Coats and Sun Paper Mills are the major industries located in the district. Effluents from these mills are drained into the Tambraparani.
- There are two coastal towns in the district. There are about seven aquaculture units functioning in the district occupying areas of about 0.16 sq km.

## Tuticorin -Coastal outlet

The Tambraparani River, which rises in Agathimalai of the Western Ghats, flows through Srivaikundam and Tiruchendur taluks and joins the sea at Punnakayal in Srivaikundam taluks in Tuticorin district. The Pambayar and the Manimuthar are the chief tributaries of the Tambraparani, which passes through the district. Figure 5.7 shows the land use pattern in the Tambraparani outlet in Tuticorin district. The changes in land use patterns were observed between 1986 and 2005.

- Forest areas and barren lands remained unchanged during this period.
- Plantation areas increased from 21,643 sq km in 1986 to 39,256 sq km in 2005.
- Fallow land decreased from 41,152 sq km to 6,693 sq km. The total area used for agricultural activities reduced from 230,000 sq km to 170,000 sq km.
- The utilization of chemical fertilizers and bio-fertilizers in the district is high.
- The dams, Papanasam, Manimutharu (Manimuthar) and Eppodumvernam were built in the district.
- The proportion of urban population to total population has increased from 33.7 percent to 36.07 percent during the years 1981 to 1996 and has increased at about 8.36 percent during the 1991 to 1996 period.
- Salt manufacture is one of the very important industries found in this district. The industrial wastes/effluents allowed into the river cause water pollution in several areas spoiling the marine ecosystem.
- Industries located in the Tambraparani basin such as Paper Mills pollute the Tambraparani River.

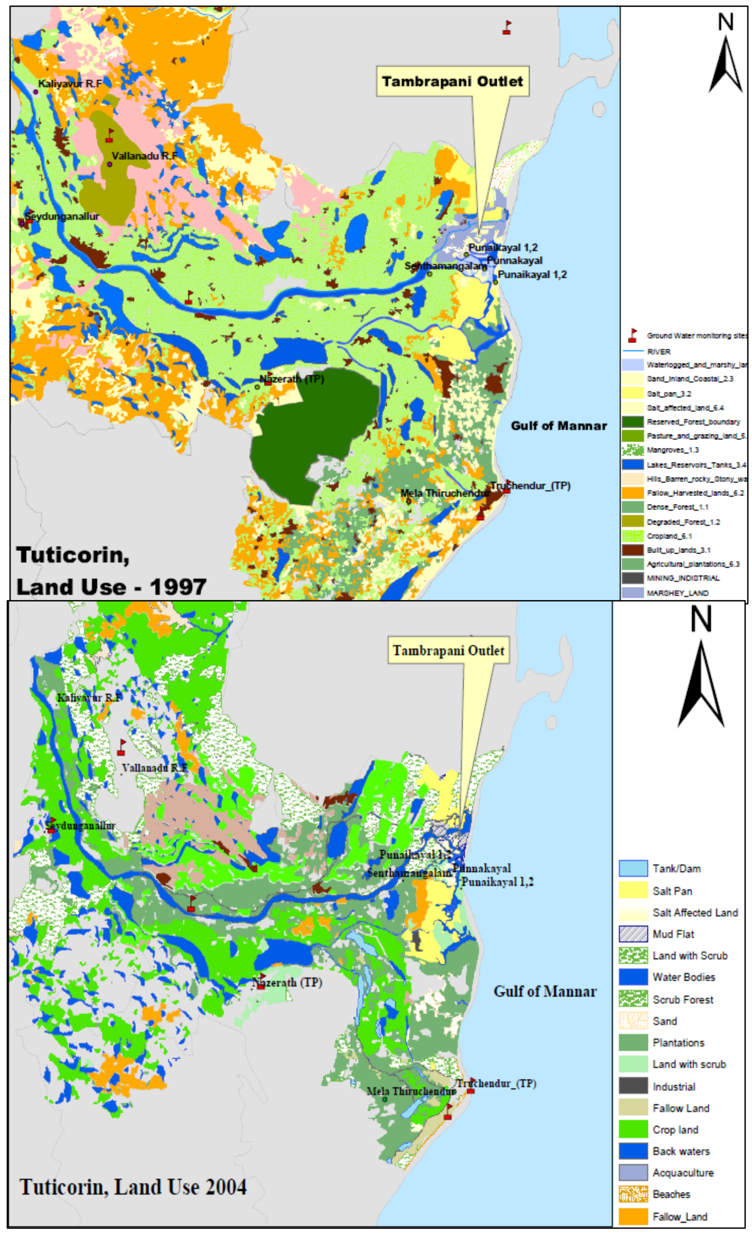



**Figure 5.7:** Land use change in Tambraparani River outlet in Tuticorin district

- Prawn culture and shrimp farming are done in coastal districts of Tuticorin. The effluents from these farms contain non-biodegradable waste which are not properly treated in many cases and hence pollute ground water in adjoining areas, even up to a distance of 6 km and this in turn affects agriculture.
- There are 33 aquaculture units functioning in the district, which occupy 4.06 sq km of coastal area in the Tuticorin district.
- There are 20 islands along the stretch of the Gulf of Mannar and this is declared as a marine national park.

Predominantly observed changes throughout the state are increase in area put to non-agricultural use, increase in other fallow land and decrease in area under cultivation. While most districts followed this trend, districts like Nilgiris and Salem showed increase in area under cultivation over the last three decades. Some districts also recorded reduction in cultivable waste land and this coincides with various watershed development programmes that have been implemented in the recent past. Table 5.1 gives the summary of the land use changes in terms of their increase or decrease in the area of a particular land use category.

**Table 5.1:** Summary of land use change in Tamil Nadu districts (blank spaces indicate non availability of data)

| Categories | Forest | Barren | Non-agricultural use | Culturable waste | Current fallow | Other fallow | Net area sown | Area sown more than once | Gross area sown |
|---|---|---|---|---|---|---|---|---|---|
| Chengleput | | | Increase | | Decrease | Increase | Decrease | Decrease | Decrease |
| South Arcot | | Decrease | Increase | Decrease | Increase | | | Decrease | |
| North Arcot | | | Increase | | Increase | Increase | Decrease | Decrease | Decrease |
| Salem | | | Increase | | Decrease | | | Increase | Increase |
| Dharmapuri | Increase | Decrease | | | Decrease | | Decrease | Increase | Decrease |
| Coimbatore | | | Increase | | | Increase | Decrease | Decrease | Decrease |
| Tiruchirappalli | | | Increase | Increase | Decrease | Increase | Decrease | Decrease | Decrease |
| Thanjavur | | | | | | Increase | Decrease | Decrease | Decrease |
| Madurai | | | Increase | | Decrease | Increase | Decrease | Decrease | Decrease |
| Ramanathapuram | | | Increase | Decrease | Decrease | Increase | Decrease | Decrease | Decrease |
| Tirunelveli | | | Increase | Increase | Decrease | Increase | Decrease | Decrease | Decrease |
| Nilgiris | Increase | Decrease | | Decrease | | | Increase | | Increase |
| Kanniyakumari | | Decrease | Increase | | | | Decrease | Decrease | Decrease |

## 5.2 Trends in hydrology (surface water and ground water resources)

Tamil Nadu has perennial and non-perennial rivers flowing through the state from upstream inland areas to the coastal districts which drain into the Bay of Bengal. Canals, tanks and wells form the sources of irrigation for farmers in the state. There are shallow alluvial phreatic aquifers pumped by private open dug wells and deep sandy alluvial aquifers situated more inland, pumped by tube wells for public water supply. At Puducherry aquifers along the coast are over-pumped and suffer from sea water intrusion. As of 2005-06, the state had 2,395 canals with a length of 9,747 km, 40,319 tanks, 670 ordinary government wells, 16,20,705 ordinary private wells and 290,611 tube wells as shown in Figure 5.8.

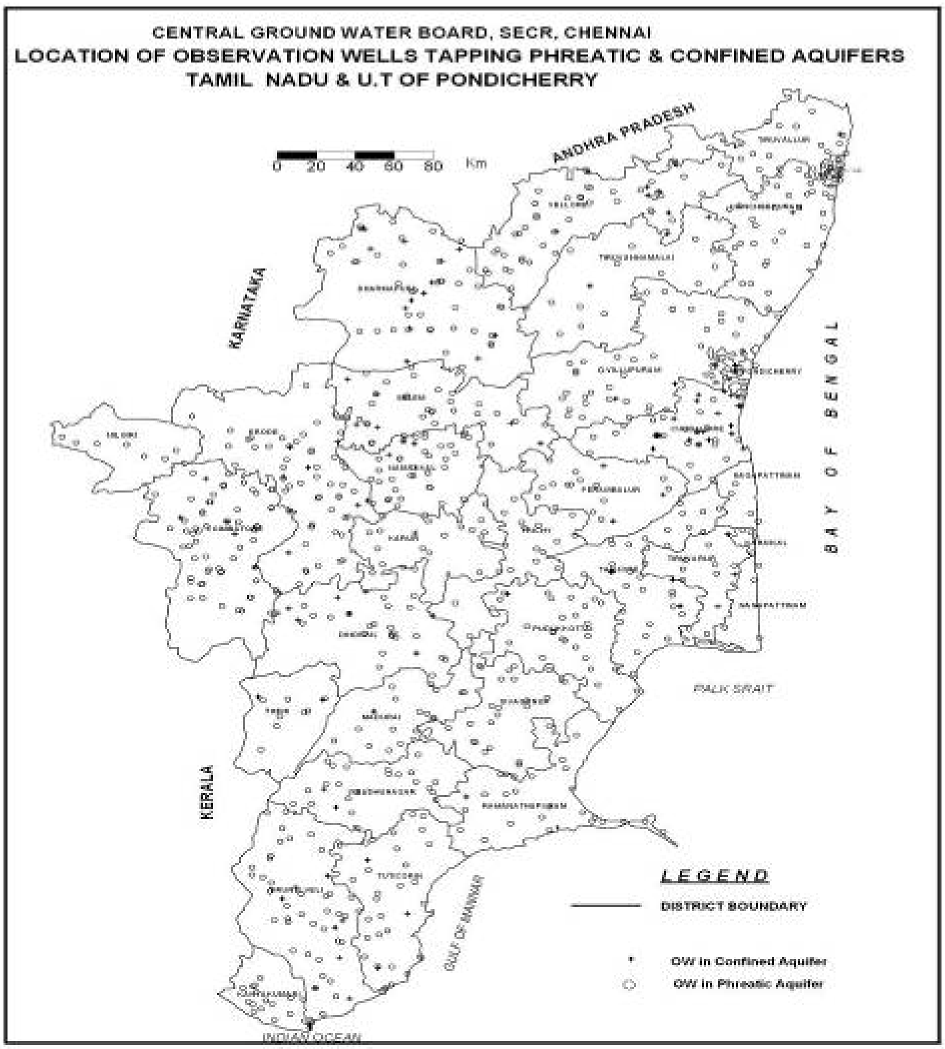



**Figure 5.8:** Location of ground water monitoring wells and aquifers in Tamil Nadu. (Source: Central Ground Water Board)

### *Surface water resources of Tamil Nadu*

The total surface water potential of the state is 36 km or 24,864 cum. There are 17 major river basins in the state with 61 reservoirs and about 41,948 tanks. Of the annual water potential of 46,540 million cum (MCM), surface flow accounts for about half. Most of the surface water has already been tapped, primarily for irrigation, which is the largest user. Twenty-four thousand square kilometres are irrigated by surface water through major, medium and minor schemes. The utilisation of surface water for irrigation is about 90 percent (DoE-GoTN n.d.).

### *Ground water resources of Tamil Nadu*

The utilizable ground water recharge is 22,433 MCM. The current level of utilization expressed as net ground water draft of 13,558 MCM is about 60 percent of the available recharge, while 8,875 MCM (40 percent) is the balance available for use. Over the last 5 years, the percentage of safe blocks has declined from 35.6 percent to 25.2 percent while the semi-critical blocks have gone up by a similar percentage. Over-exploitation has already occurred in more than a third of the blocks (35.8 percent) while eight blocks (2 percent) have turned saline (DoE-GoTN n.d.).

### *Tsunami impacts on ground water resources*

The flooding of the coastal areas with sea water by the tsunami had several effects on the ground water resources such as:

Salinisation of ground water by infiltration of saline water: Infiltration of saline water was evident in areas which remained flooded after the tsunami. The flooding during the tsunami was for a short duration and is expected to have caused infiltration of saline water. The water which remained in pools, lakes, depressions, etc., after the tsunami is expected to have resulted in infiltration of saline or brackish water.

Salinisation of ground water by salts leaching from the unsaturated zone: The flooding during the tsunami has caused a deposition of salts on the soils. Infiltration of the sea water and rainfall after the tsunami may have caused penetration of the salts into the unsaturated zone, which in time will leach into the ground water or which will rise to the surface by capillary action.

Increased sea water intrusion by landward shift of the coastline: The destructive force of the tsunami has removed coastal sediments resulting in a landward shift of the coastline in some areas. The intrusion of sea water in the coastal aquifers is expected to shift landward over a similar distance, which may affect nearby ground water production wells.

Disturbance of the fresh water lens: The tsunami wave caused an underground pressure wave, which may have disturbed the fresh water/salt water equilibrium. The pressure of the wave may have caused mixing of the fresh ground water with saline water from below. This could result both in a reduction of the volume and an increase in the salinity of the fresh water lens. Water abstracted from wells near the shore will have higher salinities. These will only drop during the wet season when the ground water is recharged by infiltration of rainfall.

Table 5.2 shows the key factors contributing to the exhaustion of ground water resources in some of the major river basins in Tamil Nadu.

**Table 5.2:** Key factors contributing to the exhaustion of ground water resources in Tamil Nadu

| Name of River Basin | Catchment Degradation | Siltation in River | Excessive Surface Water Extraction | Sea water intrusion due to excess extraction | Municipal Sewage Pollution | Industrial effluent pollution | Weed Growth | Water Logging and Salinity |
|---|---|---|---|---|---|---|---|---|
| Chennai | * | * | * | * | * | * | * | * |
| Palar | * | 0 | * | 0 | * | * | * | * |
| Gingee / Varahanadi | ~ | ~ | ~ | ~ | * | ~ | * | ~ |
| Ponnaiyar | * | * | * | ~ | * | ~ | 0 | 0 |
| Vellar | * | * | * | ~ | * | ~ | * | ~ |
| Cauvery | * | * | ~ | * | * | * | * | ~ |
| Agniyar | ~ | ~ | ~ | ~ | * | ~ | ~ | ~ |
| PAP | * | 0 | 0 | * | * | ~ | 0 | 0 |
| Pambar | ~ | ~ | ~ | ~ | * | ~ | ~ | ~ |
| Kottakaraiyar | ~ | ~ | ~ | ~ | * | 0 | ~ | ~ |

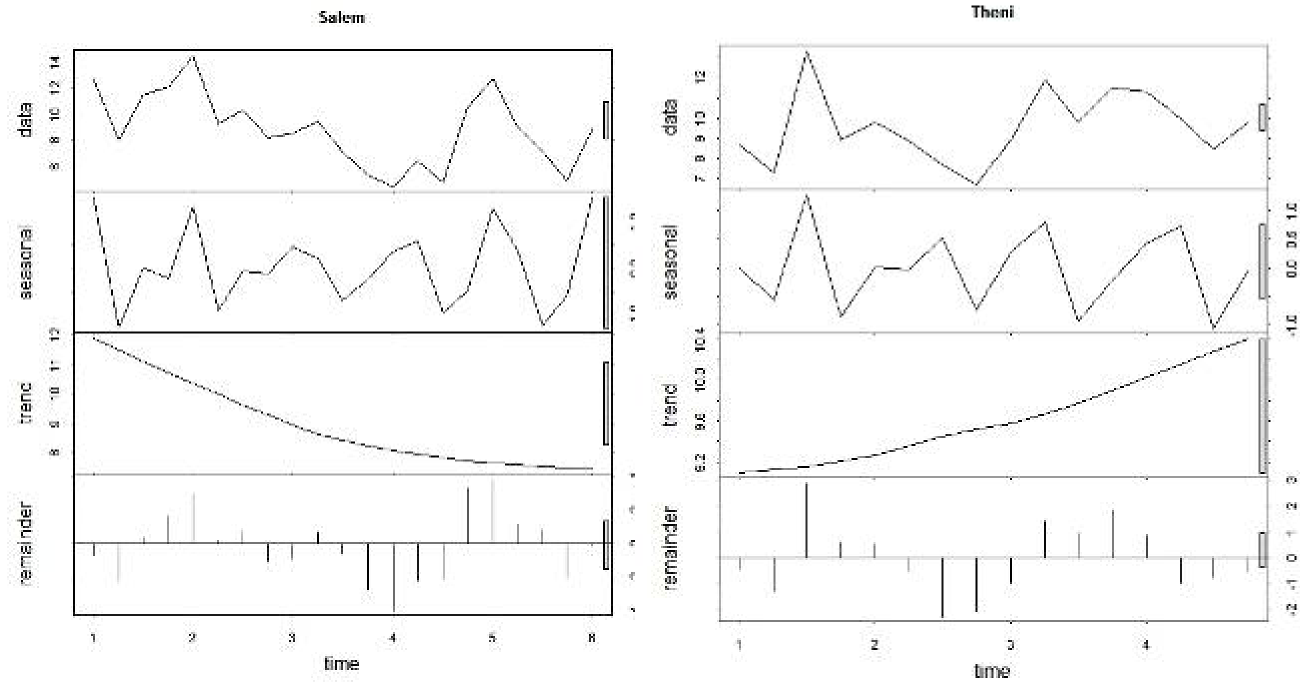
| Name of River Basin | Catchment Degradation | Siltation in River | Excessive Surface Water Extraction | Sea water intrusion due to excess extraction | Municipal Sewage Pollution | Industrial effluent pollution | Weed Growth | Water Logging and Salinity |
|---|---|---|---|---|---|---|---|---|
| **Vaigai** | * | * | * | 0 | * | * | * | 0 |
| **Gundar** | ~ | ~ | ~ | ~ | * | ~ | 0 | ~ |
| **Vaippar** | ~ | ~ | ~ | ~ | * | ~ | 0 | ~ |
| **Kallar** | ~ | ~ | ~ | ~ | 0 | ~ | 0 | ~ |
| **Tambraparani** | * | * | * | ~ | * | ~ | * | 0 |
| **Nambiyar** | ~ | ~ | ~ | ~ | 0 | ~ | 0 | ~ |
| **Valliar** | ~ | ~ | ~ | ~ | 0 | ~ | 0 | ~ |

*** Severe 0 Moderate ~ Insignificant**

(Source: Department of Environment, Government of Tamil Nadu)

### 5.2.1 Evaluation of the ground water trends in the selected sites in Tamil Nadu

The annual time series of pre- and post-monsoon ground water table (depth to ground water in metres) shows high inter-annual variability that can be attributed mainly to corresponding inter-annual variability in rainfall. However, once the quasi-cyclic component is extracted, longer-term trends are detectable and evident. The STL graphs shown in Figure 5.9 show the positive trend in ground water table in Salem and the negative trend in ground water table in Theni districts.




**STL graph of Salem district showing negative trend in depth to ground-water table over time i.e., increase in ground water resources over time**

**STL graph of Theni district showing positive trend in depth to ground-water table over time i.e., decrease in ground water resources over time**

**Figure 5.9:** STL graphs of Salem and Theni Districts showing Positive and Negative Trends respectively

The trend analysis was done using the average pre-monsoon ground water values of each year. We hypothesized that trends in post-monsoon ground water levels would be closely coupled to trends in rainfall, and longer-term changes in recharge characteristics as a result of land use changes, whereas the pre-monsoon (dry season) levels would be relatively more sensitive to trends in extraction of ground water, driven by urbanization, demand for irrigation and industry. Thus comparing pre-monsoon and post-monsoon trends would indicate whether the trends in ground water levels in the dry season could be attributed to non-climatic drivers.

In addition, linear regression models with pre-monsoon depth to ground water as the response variable and corresponding rainfall in the previous year monsoon as the independent variable would tend to have negative slope (i.e., good recharge in previous monsoon if not affected by unsustainable over-extraction should translate into reduced depth to ground water table in the dry season) with high R2 and very low p-values. Figure 5.10 below shows the example of a regression model indicating the trend in ground water level of Thiruchidambalam taluk in Villupuram district.

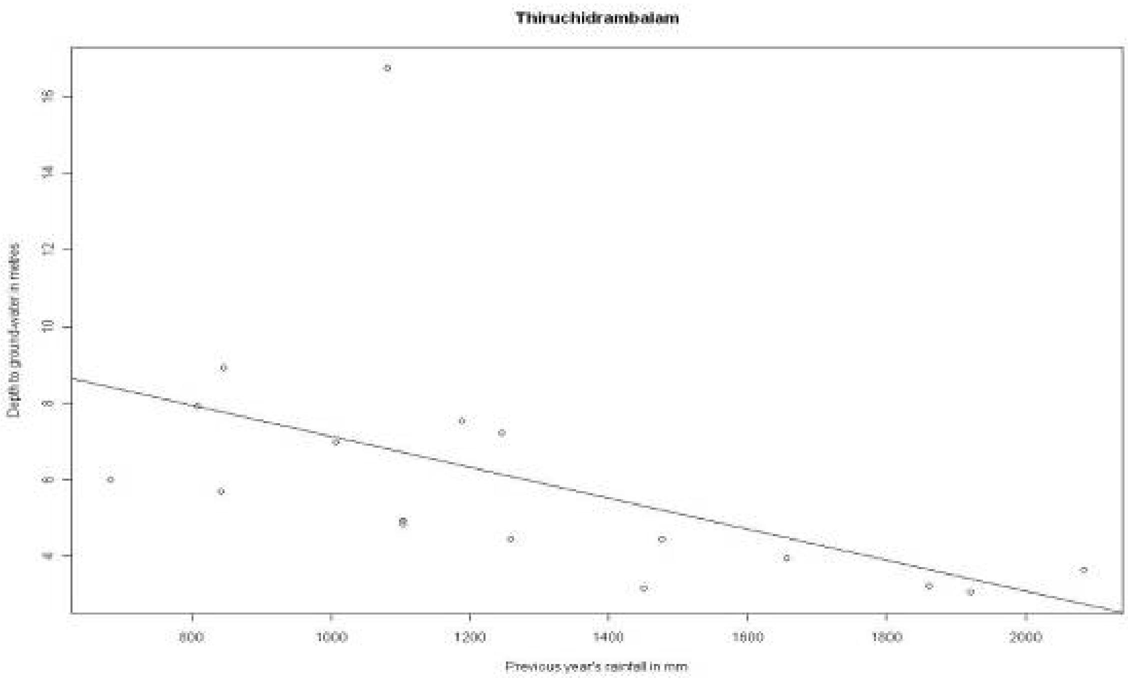



**Figure 5.10:** Graph showing the relationship between the depth to ground water and previous season of rainfall of Thiruchidambalam taluk

However, sites where recharge is exceeded by extraction would show no or very weak relationship between rainfall in previous season and depth to ground water in dry season.

Table 5.3 and Table 5.4 give a comparative study of the ground water tables of the selected sites in both dry and wet seasons using the above mentioned regression model.

**Table 5.3:** Pre-monsoon trend in ground water tables

| **District/block** | **Period** | **Pre-monsoon trend in ground water table** | **Comments** |
|---|---|---|---|
| Madurai | 1993–99 | Decline after 1995-96 | Rainfall increased after 1989 |
| Nagapattinam* | 1992–96 | Decline after 1993 | Rainfall increased after 1993 |
| Tirunelveli | 1978–83 | Increase after 1981 | Rainfall trend is positive after 1985 |
| Villupuram | 1991–96 | Monotonic decline both away and close to the coast | Rainfall decreased |
| Muthupet | 1992–96 | Monotonic decline | Increased in nearby Nagappattinam after 1993 |
| Tuticorin | 1989–93 | Monotonic decline | Rainfall was constant/increased |
| Thanjavur+ | 1993–96 | Increase up to 1995 followed by no trend | Rainfall declined after 1995 |

*Northern and southern areas of Nagapattinam had opposite trends, decline in northern and increase in southern.

+In Thanjavur district, declines observed in Thirivankurichi (1993–96) and Pattukotai after 1994, but increase in Vallam (1993–96).

**Table 5.4:** Post-monsoon trend in ground water tables

| District/block | Period | Post-monsoon trend in ground water table |
|---|---|---|
| Madurai | 1986–92 | Increase |
| Nagapattinam$ | 1990–94 | Increase and no trend |
| Tirunelveli | 1978–84 | Increase |
| Villupuram# | 1090–95 | Increase |
| Muthupet | 1986–91 | Increase |
| Tuticorin& | 1988–93 | Increase |
| Thanjavur* | 1993–97 | Monotonic decrease |

$Opposite trends in southern (decline), northern (increase).

#Consistent both close and away from coast.

&Opposite trends in Srivaikundam (increase) and Tuticorin (decrease).

*Consistent in both Thirivankurichi and Pattukotai blocks, but increase in Vallam.

The comparison of the trends in ground water in the pre- and post-monsoon periods above suggest that recharge during the wet season is unable to cope with increasing demands through extraction through the dry season, although the overall levels are still not very deep. Table 5.5 indicates the comparison of the sites in terms of their strength of recharge from rainfall and sustainability of extraction.

**Table 5.5:** Strength of recharge from rainfall and sustainability of extraction (Basin sub-divisions left blank after no 21)

| Ground water gauging station | District | Basin/sub-basin | Strength of recharge from rainfall and sustainability of extraction | High $R^2$ and low p-value reflects strength of recharge relative to extraction |
|---|---|---|---|---|
| 1.Nazareth | Tuticorin | Tambraparani | Poor | |
| 2.Srivaikundam | Tuticorin | Tambraparani | Good | 0.31, 0.0161 |
| 3.Saidunganallur | Tuticorin | Tambraparani | Very Good | 0.44,0.00252 |
| 4.Papanasam | Tirunelveli | Tambraparani | Poor | |
| 5.Cheranmadevi | Tirunelveli | Tambraparani | Poor | |
| 6.Alwarkurichi | Tirunelveli | Tambraparani | Poor | |
| 7.Kalakaddu | Tirunelveli | Tambraparani | Poor | |
| 8.P.Chatram | Tirunelveli | Tambraparani | Good | 0.30, 0.0329 |
| 9.Mannur | Tirunelveli | Tambraparani | Poor | |
| 10.Madurai | Madurai | Vaigai | Poor | |
| 11.Vadipatti | Madurai | Vaigai | Poor | |
| 12.Mandapam | Ramanathapuram | Vaigai | Poor | |
| 13.Uchipuli | Ramanathapuram | Vaigai | Poor | |
| 14.Alvarupet | Villupuram | Gingee | Poor | |
| 15.Thiruchidrambalam | Villupuram | Gingee | Moderate | 0.26, 0.037 |
| 16.Chittodu | Erode | Cauvery | Poor | |
| 17.Bhavani | Erode | Cauvery | Poor | |
| 18.Attani | Erode | Cauvery | Poor | |
| 19.Elmattur | Erode | Cauvery | Poor | |
| 20.Gopichettipalayam | Erode | Cauvery | Poor | |

| Ground water gauging station | District | Basin/sub-basin | Strength of recharge from rainfall and sustainability of extraction | High $R^2$ and low p-value reflects strength of recharge relative to extraction |
|---|---|---|---|---|
| 21.Velanganni | Nagapattinam | | Poor | |
| 22.Sirkazhi | Nagapattinam | | Poor | |
| 23.Tirukkadaiyur | Nagapattinam | | Poor | |
| 24.Tagattur | Nagapattinam | | Poor | |
| 25.Vedaranniyam | Nagapattinam | | Poor | |
| 26.Sankaridurg | Salem | | Moderate | 0.18, 0.055 |
| 27.Nangavalli | Salem | | Moderate | 0.26, 0.018 |
| 28.Jalakundapuram | Salem | | Moderate | 0.26, 0.018 |
| 29.Mecheri | Salem | | Good | 0.35, 0.0047 |
| 30.Orathanadadu | Thanjavur | | Poor | |
| 31.Thiruvonum | Thanjavur | | Poor | |
| 32.Ayyampet | Thanjavur | | Poor | |
| 33.Papanasam | Thanjavur | | Poor | |

It is apparent from Table 5.5 that recharge is being exceeded by extraction in most areas (25 out of 33 stations), and that ground water use during the period of the record was at unsustainable levels except in parts of Salem and Tuticorin districts, and with a few other sites in Tirunelveli and Villupuram also showing sustainable use.

As mentioned in the above sections, the increase or decrease in the ground water tables through the years depends on both climatic and non-climatic drivers such as ground water extraction. In the beginning of the dry season of each year, the ground water tables would be at their most shallow depth as the ground water resources are recharged from the previous year monsoons. However, throughout the dry season months, the ground water levels will become deeper as ground water is extracted from a finite storage. Thus a good index of the amount of ground water extracted each year is the difference between the maximum depth to ground water and the minimum depth to ground water measured during the pre-monsoon or dry season ground water depths. This index of ground water extraction level was plotted as a time-series graph using the average index for each district. Broad trends and inter-annual variability in demand for ground water can be assessed from these time-series graphs. Figure 5.11 shows the rate of ground water extraction time in the districts of Villupuram, Theni, Nagapattinam, Tuticorin, Tirunelveli, Erode, Madurai and Salem.

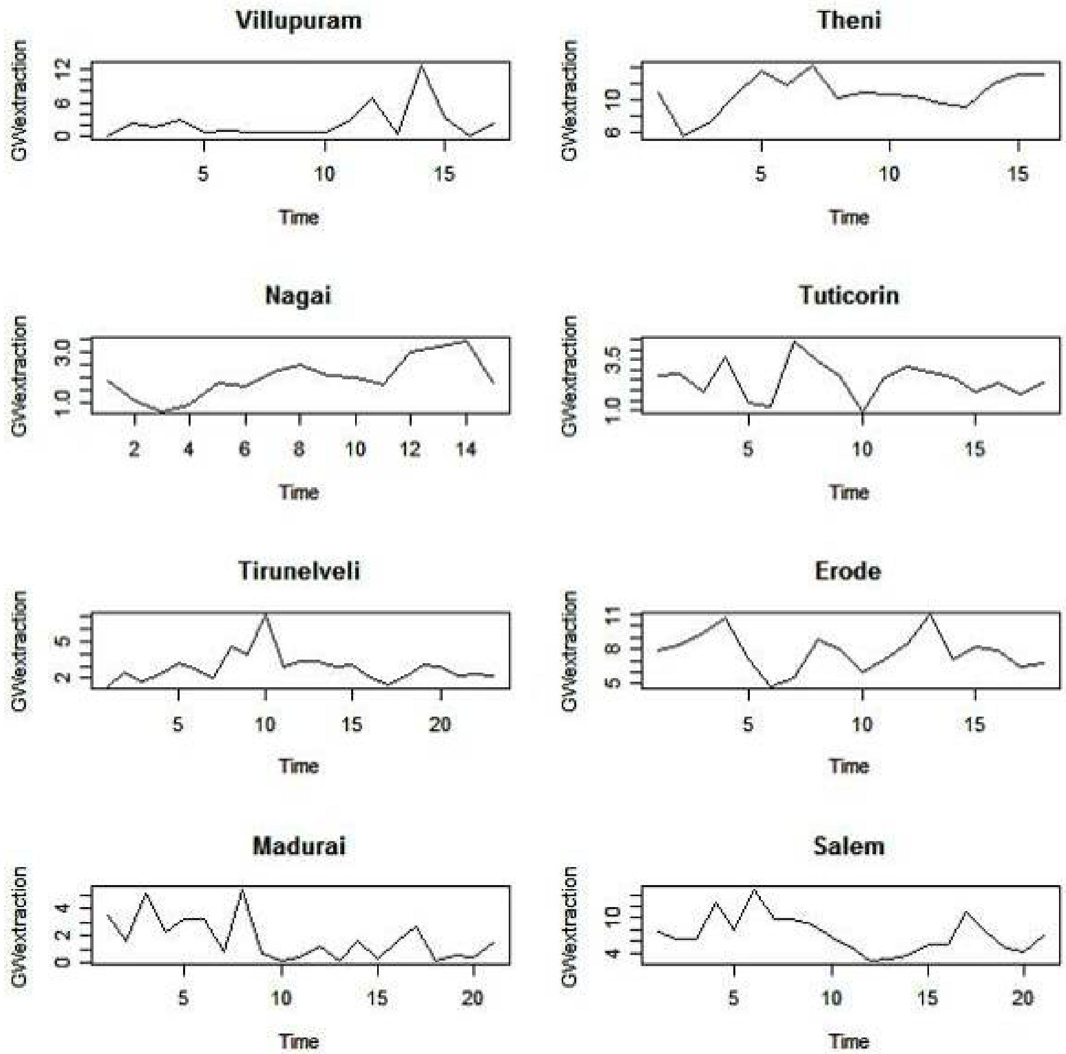



**Figure 5.11:** Graphs indicating the trends in ground water extraction over time

It can be seen from Figure 5.11 that absolute levels of ground water extraction rose over the time period from early 1990s to early months of 2000-07 in Theni and Nagapattinam districts.

## 5.3 Snapshot of water quality at selected coastal sites

India has an extensive coastline of about 7,500 km (Chandramohan *et al.* 2001) and the east coast of India, extending from the international border of India and Bangladesh in the northeast to Kanniyakumari in the south, is 2,545 km long, covering 21 districts in the states of West Bengal, Orissa, Andhra Pradesh and Tamil Nadu (CICFRI 2006).The coastline of Tamil Nadu has a length of 1,076 km, which constitutes about 15 percent of the total coastal length of India, and stretches along the Bay of Bengal, the Indian Ocean and the Arabian Sea. About 46 rivers drain into the Bay of Bengal forming several estuaries adjoining coastal lagoons. The Cauvery River and its tributaries form a large delta supporting extensive agriculture (UNDP-UNTRS 2008).

The coastal zone of Tamil Nadu is very narrow except in the Vedaranniyam-Muthupet stretch of Thiruvarur-Thanjavur districts where extensive mudflats are present. The Cauvery and its tributaries, the Palar and the Tambraparani, are considered the major rivers of Tamil Nadu. The coastal area of Tamil Nadu is considered a rain shadow area because of the low rainfall it receives during the southwest monsoon (June to September). However, during the northeast monsoon season (October to December) most parts of the Tamil Nadu coast receive high rainfall, particularly during the months of November and December (Selvam *et al.* 2005).

The coast is endowed with extensive areas of estuaries, brackish water lagoons, mangroves, coral reefs and sea-grass beds. These coastal habitats are dynamic, high productivity zones, with high species richness and abundance. Hence, they have great ecological, social and economic significance. These areas are important for marine fisheries, serving as nurseries for many species of finfish and shellfish (CICFRI 2006). Along the Gulf of Mannar, the sea-land boundary is almost uniform and regular but for inundation in a few places, where it is intercepted by rivers forming tidal inlets. The Tambraparani, the Vembar and the Vaippar and some other inlets are present in this region (Chandramohan *et al.* 2001). There are a number of coral banks and islands present in the Gulf of Mannar (Krishnamurthy 2001). The River Cauvery is the main supplier of fresh water to the Cauvery delta in which the major mangrove wetlands of Tamil Nadu, namely Pichavaram and Muthupet are located.

The other landforms of the Tamil Nadu coast are rocky outcrops of Kanniyakumari, mudflats, beaches, spits, coastal dunes and strand features. These habitats provide ecological, cultural and economic value and act as critical habitats for thousands of species by providing shelter, spawning grounds and food. Most importantly, they act as buffers by filtering sediment and pollutants from upland drainage improving water quality, recharging aquifers, reducing the effects of floodwaters and storm surges, preventing coastal erosion, and providing cultural values to humans including recreation, scientific knowledge and aesthetics (UNDP-UNTRS 2008). On the other hand, lagoons, estuaries, beaches, sand spits, siltation at harbour channels and formation of marshy lands act as main sinks for the sediments (Chandramohan *et al.* 2001).

The coastal habitats are threatened by domestic, agricultural and industrial pollution as well as deforestation. Industrial activities are the main cause of heavy metal pollution. River runoff is the natural source of metals in ocean waters. Some metals are toxic in nature, for example, cadmium, mercury and arsenic. Increasing transport of goods along the rivers also cause problems in the marine habitats, such as siltation and reduced light penetration. It is evident that many coastal areas need a higher degree of protection than they get today (CICFRI 2006). However, in recent times the changes in land use patterns mainly reservoir construction, industrial pollution have severely stressed these coastal habitats.

### 5.3.1 Tsunami impacts on water quality

The Indian Ocean tsunami of 24 December 2004 has left the Tamil Nadu coastal habitats vulnerable in its water resource potential. The surface water resources meant for irrigation and drinking were affected by the ingress of sea water in all the areas. The massive quantity of sea water that inundated the coastal agricultural lands for nearly 0.5–2 km area inland, and due to reasons of poor drainage stood for few days, affected the quality of ground water.

The surface water stored in ponds got contaminated due to sub-surface seepage of sea water. Direct sea water intrusion into pond/water storage tanks led to deposition of silt and sand as brought in by the tidal wave.

In deep, brown coastal soil zones the quality of shallow ground water has deteriorated. Electrical conductivity (EC) of shallow ground water (25 m below ground level) changed from the pre-tsunami value of 0.5 dS/m (deciSiemens per metre) to the post-tsunami value of 4.8 dS/m.

Deep tube well depth greater than 250 m below ground level were not affected much as the EC of ground water was reasonably good quality (with EC around 0.5 dS/m).

Coastal fresh water aquifers are the major sources of drinking water in coastal areas. The tsunami tidal waves transported large volumes of sea water into inland water bodies and also created large tidal pools of sea water which percolated into coastal fresh water aquifers and salinised them (IGWRAC n.d.).

The present study was carried out to analyse the surface water quality of selected sites along the Tamil Nadu coast, which represented mangrove wetlands, estuaries (influenced by aquaculture and salt pans) and areas influenced by industries. Selection of the sampling sites was subject to the availability of water as it was the pre-monsoon period.

### 5.3.2 Overview of study sites

#### i. Mangrove wetlands

Mangroves have tremendous social and ecological value, and provide livelihoods for many who depend on its fisheries potential (fishes, molluscs, crustaceans, etc.). Mangroves are harvested for fuelwood, charcoal, timber and wood chips. Services include the role of mangroves as nurseries for economically important fisheries, especially for shrimp. Mangroves also provide habitats for a large number of molluscs, crustaceans, birds, insects, monkeys and reptiles. They have received considerable attention as 'bio-shields', protecting the hinterland from the vagaries of the sea.

The main mangrove wetlands of Tamil Nadu are Pichavaram and Muthupet. A large patch of healthy mangroves is present in the Devipattinam area bordered by Palk Strait in the east, in Ramanathapuram district (Figure 5.8). In the islands of Gulf of Mannar Biosphere Reserve, mangroves are present in a few hundred hectares. These mangrove patches consist of a true mangrove species namely, *Phemphis acidula*, which is not present in any other Indian mangrove wetland (Selvam *et al.* 2005). Other mangrove services include the filtering and trapping of pollutants and the stabilisation of coastal land by trapping sediment and protection against storm damage (IUCN 2006).


**Figure 5.12:** Location of mangrove wetlands in Tamil Nadu coast (Source: Atlas of Mangrove Wetlands of India, Part 1 – Tamil Nadu. M.S. Swaminathan Research Foundation, Chennai)

## *Pichavaram mangrove wetland*

The Pichavaram mangrove wetland (latitude 11°22'N to 11°30'N and longitude 79°45'E to 79°52'E), is located in the northernmost end of the Cauvery delta (Ramanathan *et al.* 1999). This is interconnected with the estuaries of the Vellar River in the north, the Coleroon River in the south and the Uppanar River in the west. The large open water body found associated with the Pichavaram mangrove wetlands is the estuarine region of the Uppanar River. Most of the rainfall occurs during the northeast monsoon season (October to December) and nearly 70 percent of the rainfall occurs between November and December. The Pichavaram mangrove wetland receives copious inflow of fresh water during the northeast monsoon season (October to January) through the Coleroon and the Uppanar Rivers. From February to September (including the southwest monsoon period extending from June to September), and particularly in the months of July and August, the fresh water discharge into the mangrove wetland is negligible. This is mainly due to the construction of dams and barrages in the upstream region of the river. Fresh water reaches the Pichavaram mangrove wetland through the backwater. No fresh water is discharged from the Vellar

River into the Pichavaram mangrove wetland (Selvam *et al*. 2003, 2005) but it is the major source of saline water incursion into the mangroves.

The water quality generally reflects the impact of sea water and the Vellar estuary (mixing effect) aided by evaporation and *in situ* biological productivity. Nitrate and phosphate are contributed by fertiliser input from adjoining agricultural fields (Ramanathan *et al*. 1999). This study also showed that the Pichavaram mangrove seems to be relatively unpolluted, since the anthropogenic signal observed is small and acts as a sink for heavy metals contributed from a multitude of sources without an adverse effect.

The 2004 tsunami had an impact on the geo-chemical behaviour of nutrients. An increase in the concentration of various nutrients namely nitrate and phosphate was observed (Ajith Kumar *et al*. 2008). The geo-chemistry of the mangrove forest was observed to be influenced by a number of factors like rapid increase of aquaculture farms, agricultural practices and the anthropogenic discharge from the nearby inhabited areas. Further the sediment column was disturbed due to energetic tsunami waves, which has caused a sheer increase in the DO in water. As a result, the change in the redox potential has resulted in change in the nutrients absorbed/associated with the sediments (Ranjan *et al*. 2008). Figure 5.13 shows the view of Pichavaram mangroves.

**Figure 5.13:** View of the Pichavaram mangrove wetland
(Photos: Terenia Berlie)

### *Muthupet mangrove wetland*

Muthupet is situated 400 km south of Chennai and lies close to Point Calimere on the southeast coast of Peninsular India (latitude 10°25'N and longitude 79°39' E ). It is at the southern end of the Cauvery delta covering an area of approximately 68 sq km of which only 4 percent is occupied by well grown mangroves. Various tributaries of the River Cauvery flow through Muthupet and the adjacent villages. At the tail end, they form a lagoon before meeting the Palk Strait. The northern and western borders of the lagoon are occupied by a sand spit which is devoid of mangrove vegetation (Ajith Kumar *et al*. 1996). The Muthupet mangrove wetland receives inflow of fresh water during the northeast monsoon (October to January) through the drainage arteries of the Cauvery delta. From February to September fresh water discharge into the mangrove is negligible.

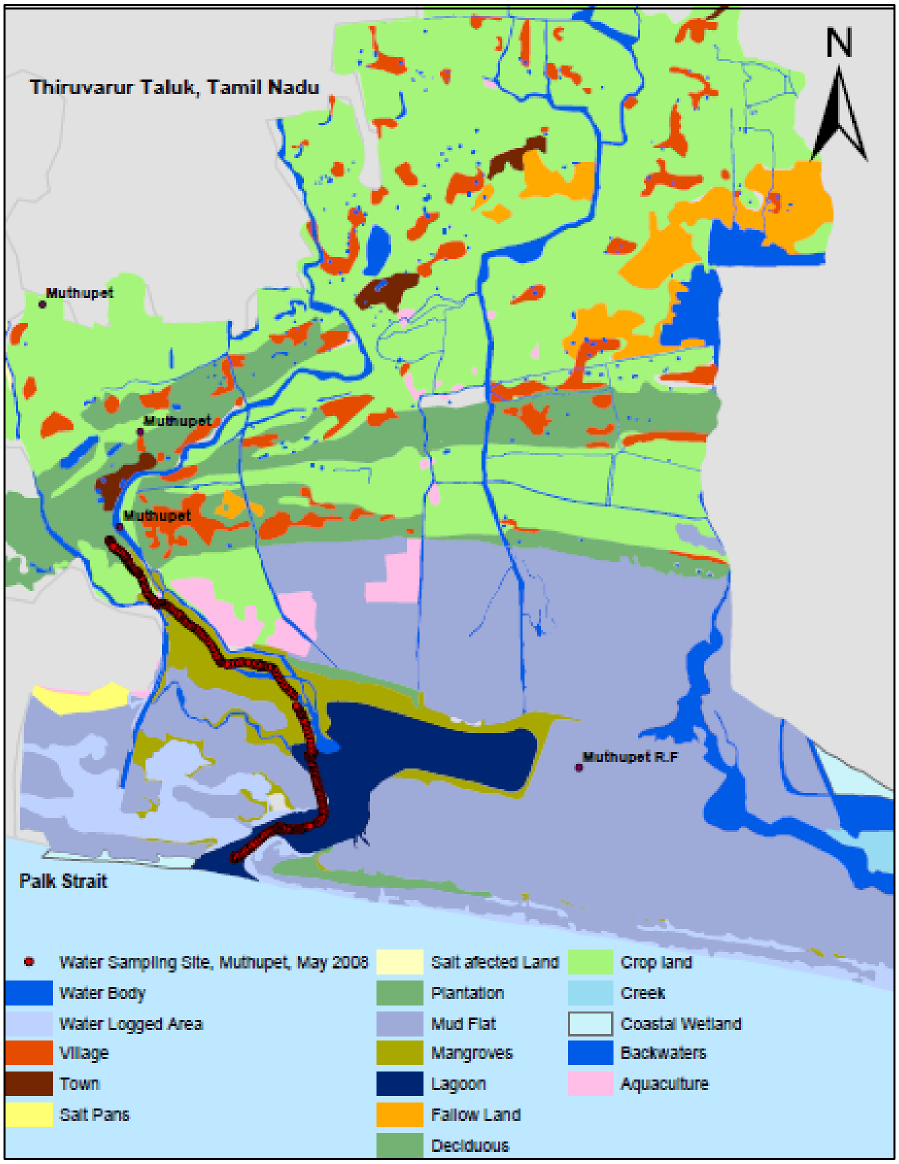



**Figure 5.14:** Muthupet wetland in Thiruvarur taluk

This is mainly due to the construction of dams and barrages in the upstream regions of the Cauvery. However, whenever water from the Mettur dam is discharged into the arteries of the Cauvery during the non-monsoon period, particularly from July to September for paddy cultivation, surplus water if there is any, reaches the Muthupet mangrove wetland through the drainage arteries (Selvam *et al.* 2005).

The developmental activities around these areas are very scanty; among the commercial activities are salt pans, aquaculture ponds, agriculture, etc (Figure 5.14). It has been documented that the upstream waters of the lagoon recorded highest salinity due to aquaculture activities whose impact on water quality is confined only to the near vicinity due to lack of sufficient flushing conditions. Lagoon salinity is controlled largely by seasonal atmospheric temperature (evaporation rates) during dry periods and by monsoonal discharges. The lagoon is totally fresh water dominated during the northeast monsoon when drainage basins bring all terrestrial material, that were accumulated during the dry period, due to which nutrient levels in the lagoon are raised many fold. Oxygen levels of both the lagoon and the Palk Strait appear to accommodate additional loads of organic matter for mineralisation (ICMAM PD n.d.). View of Muthupet mangrove wetland is shown in Figure 5.15.

**Figure 5.15** View of Muthupet mangrove wetland (Photos: Naveen Namboothri)

### *Punnakayal mangroves*

Punnakayal is a coastal fishing village, situated about 26 km southeast of Tuticorin in the Gulf of Mannar (Jayaseeli & Murugan 2002) located at Lat 8º47’ N; Long 78º12’ E and Lat 9º15’ N; Long 79º14’ E (Chellaram *et al.,* 2003).. It is an estuarine region where the River Tambraparani forms riverlets and meanders before entering the sea. Punnakayal is a highly eco-sensitive delta region, including coral reefs and mangroves, along the coast. This delta region is considered as a highly productive area in the Gulf of Mannar. Punnakayal is an important fishing village and has a unique mangrove area. It is said that about half a century ago, the Punnakayal delta region had a dense mangrove forest along the riverlets of the River Tambraparani. But today the mangrove plants are bushy and confined to only a stretch of about 12 km along the shoreline. Even today the salt marshes are found on the dried riverlets. The stunted growth of *Avicennia* sp. is mainly due to the lack of inflow of fresh water from the river except during the monsoon (Jayaseeli & Murugan 2002).

## ii. Estuaries

Estuaries are an important part of the hydrological cycle because they regulate the amount of river borne major and minor elements entering the coastal environment and ultimately the deep ocean. Estuarine structures are complex and dynamic due to strong gradients in chemical composition of water, variable suspended matter concentration and complex hydro-dynamic processes. When river water mixes with sea water, a large number of physical and chemical processes take place that may affect the partitioning of trace metals between particulate and dissolved phases and hence the composition of the deposited sediments (Forstner 1983).

The salt pan industry, the brackish water fish farming and aquaculture industry is being practiced extensively along the Coromandel coast of Tamil Nadu, and in most cases these are associated with the nearby estuaries. Most of the effluents from aquaculture ponds are released to nearby estuaries which may have direct impacts on the water quality of the estuaries.

### *Yedayanthittu estuary-salt pans*

Yedayanthittu estuary is situated about 20 km north of Puducherry along the coast towards Marakkanam in the Villupuram district of Tamil Nadu. It lies about 3 km to the northeast of the Kaliveli tank. The Kaliveli tank is a semi-permanent, fresh to brackish lagoon, which empties into the sea through a narrow channel connecting the tank with the Yedayanthittu estuary to the northeast. The estuary has large areas of inter-tidal mudflats, but only tiny relicts of the once extensive mangrove forests now remain. There are some 5 sq km of salt pans alongside the estuary immediately to the north of the Marakkanam road bridge across the channel from Kaliveli tank (Pieter 1985). This estuary was under mangrove cover earlier, but this is now reduced to a few mudflats with small bushes interspersed among the salt pans. A possible reason for the degradation of mangrove cover is the ever increasing need for firewood and timber, and the conversion of the estuarine part to salt pans. The other major reason for clearing is their swampy nature and the misconception that they play host to a variety of tropical diseases. In the recent past, mangrove restoration programmes have been initiated in and around the Yedayanthittu estuary. But the lack of effective management and protection has resulted in most of the saplings ending up as cattle feed (Srinivas 2004). Some of the local communities in the area depend on the estuary, where fishing has become their main income generation activity.

**Figure 5.16:** View of Yedayanthittu estuary
(Photos: Nelum Wickramasinghe)

### *Chunnambar estuary*

The Gingee River splits into two branches namely the Ariankuppam River to the north and the Chunnambar in the south, where the Chunnambar estuary is formed. The estuary has a recreational value with people enjoying boating in the estuary. However, this may have a considerable impact on the water quality of the estuary. Water of the landward side of the estuary showed signs of eutrophication, which could be a direct impact of the human settlements on the banks of the estuary. Figure 5.17 shows the view of Chunnambar estuary in Villupuram.

**Figure 5.17:** View of Chunnambar estuary
(Photos: Nelum Wickramasinghe)

### *Vellar estuary-Parangipettai*

The Vellar estuary is situated at Porto Novo (latitude 11°29'N and longitude 79°47'E) about 75 km south of Puducherry, where the river opens into the Bay of Bengal (Pritchard 1952). The River Vellar flowing on the southeast coast of India originates in the Shervarayan hills of Salem district. After meandering through a distance of 480 km, it forms the estuarine system at Parangipettai, before it joins the Bay of Bengal (Figure 5.18). The Vellar estuary is always open with the Bay of Bengal and it said to be a 'true estuary' as there is no complete closure of the mouth (Balasubramaniam & Ravichandran 2007) Just inside the mouth, lagoons exist on either side behind a wide sandy beach, the breakpoint bar forming the essential feature of a typical bar-built estuary (Pritchard 1952). The estuary is subjected to semi-diurnal tides with maximum tidal amplitude of about 1 m. The influence of neritic water with estuarine environment promotes perfect exchange of both biotic and abiotic variations and the tidal influence extends over the distance of 16 km upstream of the estuary. Average depth of the estuary is 2.5 m and the maximum depth at high tide is 5.3 m. The estuary is about 600 m wide at its mouth and is prone to both diel- and short-term oscillations, especially during the northeast monsoon (Balasubramaniam & Ravichandran 2007). Ramamoorthy (1954) showed that the estuary is characterised by salinity gradients; on the basis of these preliminary measurements, he demarcated it into four zones. Rangarajan (1958) investigated the hydrological and biological changes over a diurnal tidal cycle and showed that the surface to bottom salinity gradient varied over the tidal cycle and that there were current speeds of almost 0.5 m/set associated with a normal tide range of 70 cm. Jacob and Rangarajan (1959) studied the variation of surface and bottom salinities and temperatures at five stations in the estuary for a year at about two week intervals. During the drought period (May to July), neritic waters occupied almost the entire estuary and tidal influences appeared negligible; during the monsoon period (October to about two week intervals. During the drought period (May to July), neritic waters occupied almost the entire estuary and tidal influences appeared negligible; during the monsoon period (October to November), the estuary was completely scoured out by fresh water. Between these two periods were transitional stages when stratification was intense and tidal fluctuations were large, with some evidence that bottom waters became trapped at low water.

The classical investigation was by Dyer and Ramamoorthy (1969). This typical bar-built estuary is shown, by comparison with dimensionless stratification parameters stratified at low river discharge, to be a salt wedge at high river discharge. During the tidal cycle, the salt wedge near the bottom became isolated in a series of basins during ebb tide; short period diffusion along the intense haloclinc seems to have been an important process in the salt balance of the water column.

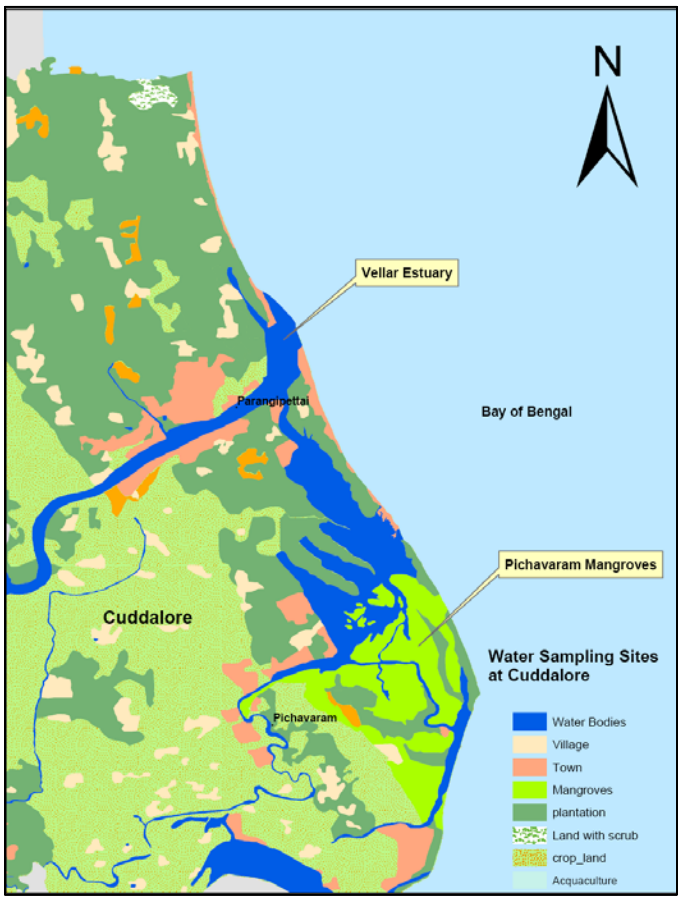



**Figure 5.18:** Vellar estuary at Cuddalore

The water circulation at high river discharge was dominated by a meander system of alternating scour holes, with the high seaward flow in the deepest areas. Superimposed on this was a secondary lateral circulation system that broke down and reversed its sense at low river flows when the saline inflow developed. Rajasegar (2003) studied all the physico-chemical parameters such as temperature, EC, salinity, pH, DO and nutrients like total phosphorus, inorganic phosphate, nitrite and silicate studied in relation to shrimp farming. According to this study, there are as many as 42 shrimp farms situated on the banks of the Vellar estuary. These farms discharge the used water into the estuary, which may influence the biota there. Rajasegar (2003) has also shown that when chemical characteristics due to shrimp farming. Local communities in the area depend on the estuary, where fishing has become their main source of income.

### *Cauvery estuary (at Poompuhar, Nagore and Velanganni)-Aquaculture*

The Cauvery basin extends over an area of 87,900 sq km in the states of Kerala, Karnataka and Tamil Nadu. The total length of the river from the head to its outfall into the sea is 800 km of which about 320 km are in Karnataka 416 km in Tamil Nadu and the remaining length of 64 km forms the common boundary between the states of Karnataka and Tamil Nadu (Central Pollution Control Board n.d.).

The Cauvery estuary, located along the east coast of India, is a part of the Cauvery River basin, encompassing about 800 sq km (Ramanathan *et al.* 1988). The upper reaches of the estuary start from the Grand Anicut (a dam near Tiruchirappalli), where it bifurcates into two large branches, the Coleroon and the Cauvery. Below the Anicut, the river flows almost in a flat plain, having a gentle slope from west to east. The formation of this estuary has taken place over the surface of an area that emerged from the sea. Emergence of this land caused the river to drain further east, resulting in the formation of the estuary (Ramanathan *et al.* 1993).

Ramanathan *et al.* (1993) showed that, EC, TDS, and total suspended matter increased conservatively with increasing chlorinity. In general, sulphate, sodium, potassium, calcium and magnesium showed an increasing trend while silicic acid and phosphate showed a decreasing trend toward the sea. Additional removal mechanisms operating for these ions in the Cauvery estuary have been identified based on observed concentrations. Factor analysis pointed out the sources contributing to the observed trends in estuarine water chemistry. Organic carbon and nitrogen decreased toward the high chlorinity zone.

The parameters identified for the water quality analysis were evaluated by the Box and Whiskers plot graphs which were generated using the R-statistical software. The Box and Whiskers plots were used for the water quality parameters to study their median and variability among different sites. Figures 5.19, 5.20 and 5.21 show the nutrient/mineral contents among the sampled sites along the Tamil Nadu coast.

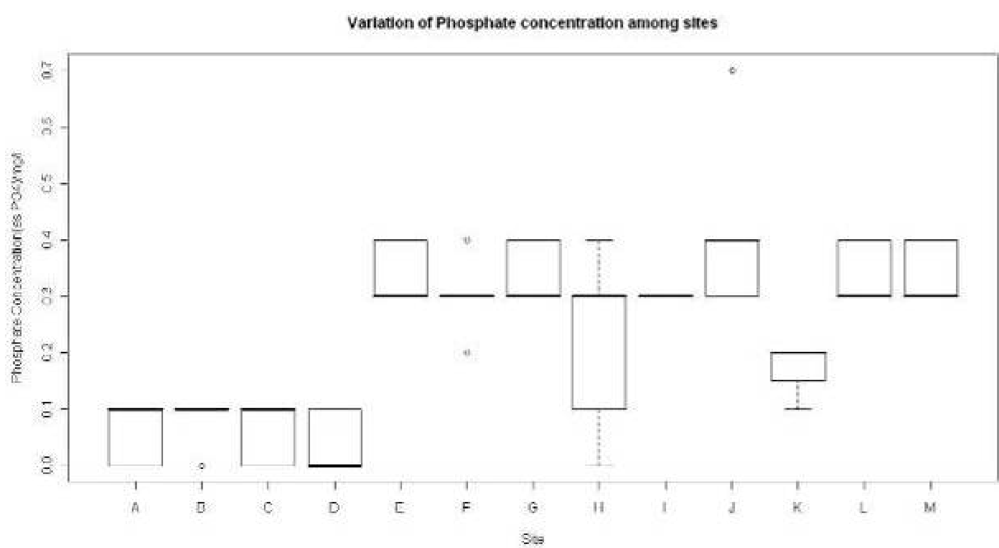



**Figure 5.19:** Box and Whiskers plots for Phosphate concentrations among sites

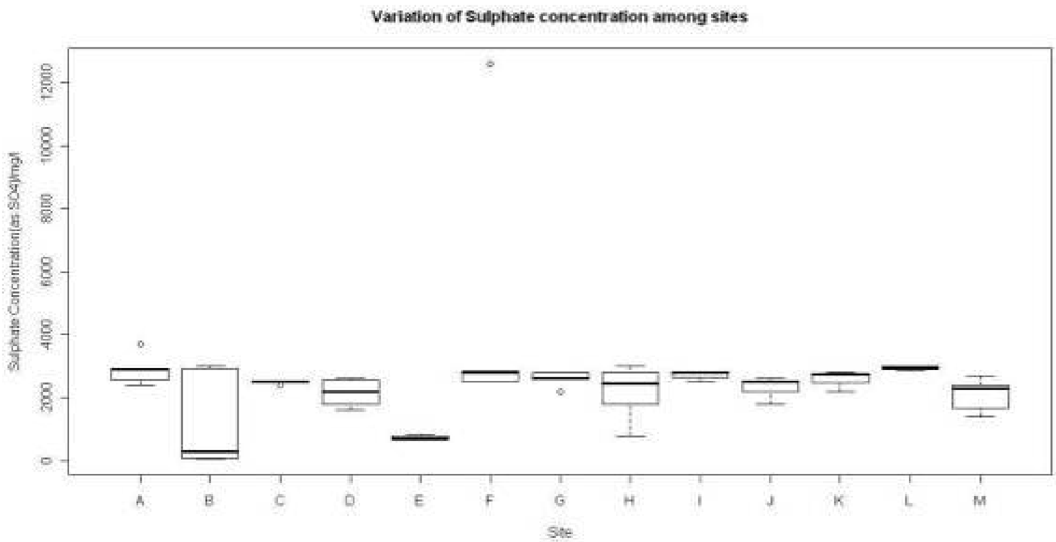



**Figure 5.20:** Box and Whiskers plots for Sulphate concentrations among sites

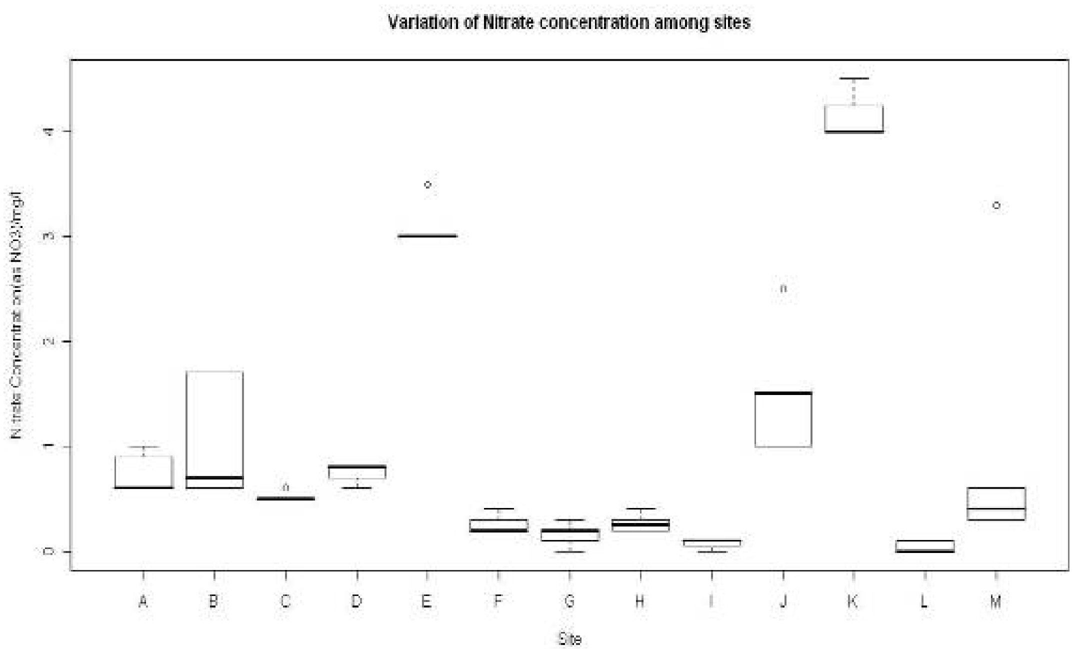



**Figure 5.21:** Box and Whiskers plots for Nitrate concentrations among sites

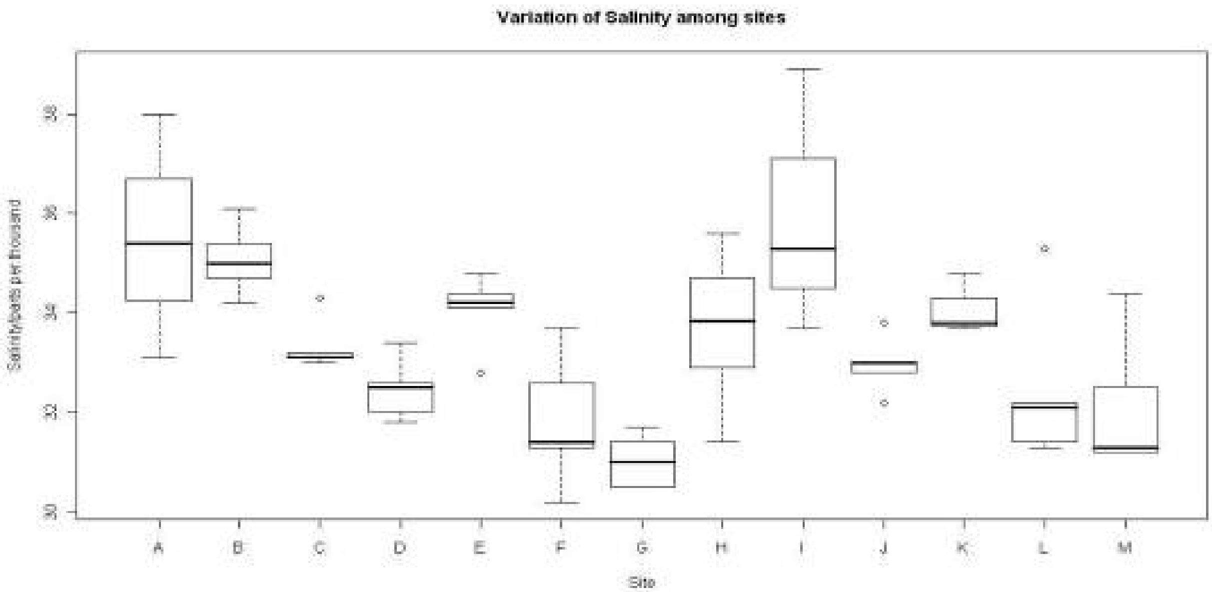



**Figure 5.22:** Box and Whiskers plots for Salinity among sites

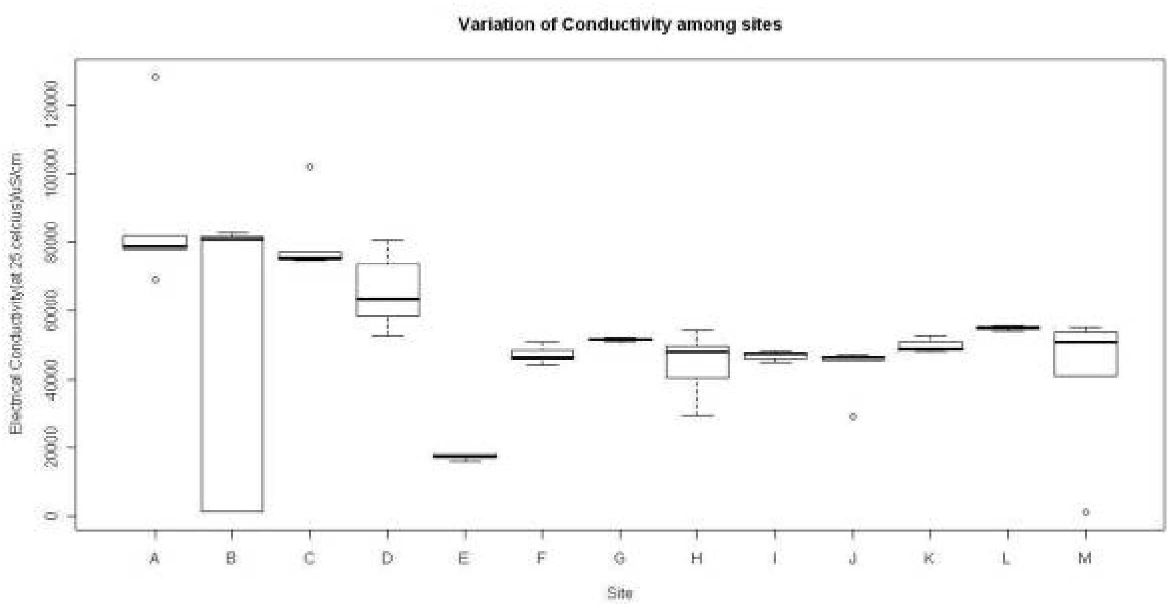



**Figure 5.23:** Box and Whiskers plots for Conductivity among sites

## 5.4 Ground water quality in the coastal sites

The ground water quality remained unchanged in the coastal areas. However, some of the sites showed very high levels of salinity due to the intrusion of saline sea water into the fresh water systems because of the tsunami waves. For example, the districts of Ramanathapuram and Tuticorin showed high levels of EC as the impacts of the tsunami was felt at a greater level in these coastal districts of Tamil Nadu.

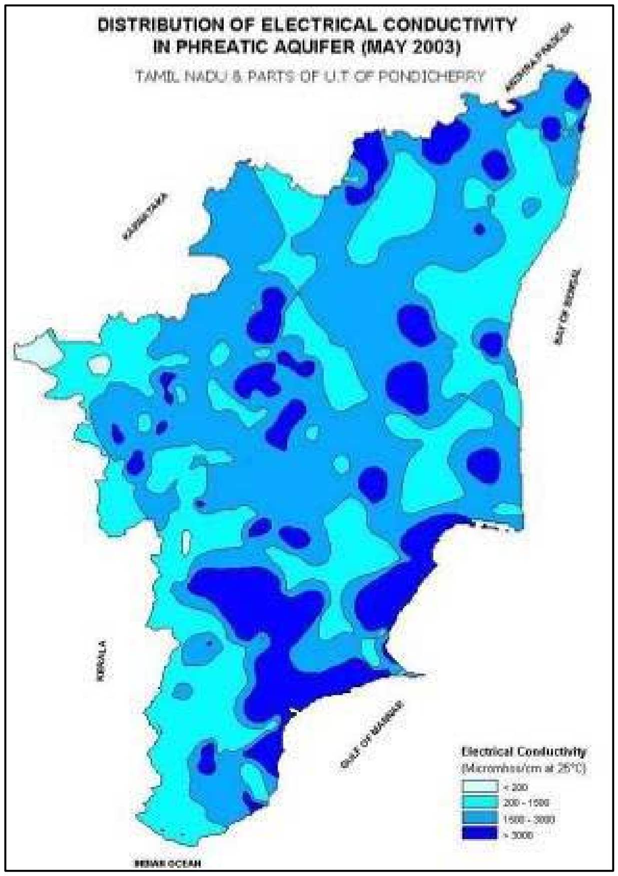



**Figure 5.24:** Electrical conductivity of Tamil Nadu (Source: Central Ground Water Board)

## 5.5 Synthesis-baseline water quality in coastal wetlands and estuaries

Higher biological oxygen demand values in landward areas of Muthupet, Aatrangarai and Tuticorin (Roche Park) were evidence for the water bodies being contaminated by sewage. The possible sources could be: the human settlements along the banks of the Cauvery tributary which forms the Muthupet mangrove wetland; in Aatrangarai, the effluent discharges from the aquaculture ponds operating along the banks of the Vaigai River; and in Tuticorin due to heavy sewage discharges and garbage dumping from human settlement along the bank of Tambraparani River. Garbage dumping by visitors and the frequent boat rides for visitors in Pichavaram and Muthupet may have a considerable effect on the ecosystem stability, which should be limited to a certain extent. Biodiversity of Muthupet was harmed by the garbage dumped by the visitors. Therefore necessary actions should be taken to minimise these stresses.

All the sites showed very high levels of calcium, magnesium, chlorine, sulphate and salinity, which could be a direct result of the salt water intrusions, except for the Cauvery tributary sampled at Poompuhar and branch of the Gingee River at Chunnambar. During the sampling period the sea mouth was closed at Poompuhar and this could be the reason for the lesser concentrations. At Chunnambar, the estuary was almost stagnant towards the landward areas, which could have resulted in lesser concentrations. All the sites had minute levels of nitrates and phosphates; nitrates within the range of 0–4 mg/l and phosphates within the range of 0–0.4 mg/l. This proved for less nutrient pollution among all the sites, further supported by the normal concentrations of sodium and potassium. But the landward side of the Gingee River at Chunnambar showed signs of nutrient pollution, which could be due to the stagnant nature of the water body, human settlements along the bank and cattle rearing. Even thought the mean TDS and total suspended solids value were normal for all the sites, in the areas towards the sea in Muthupet, siltation was evident with the unclear water. Further studies are required to understand sediment loading in those areas. At sites where aquaculture ponds were operating the water was expected to show higher DO and conductivity values, but all the values were normal for brackish water. It could be due to the interferences with the normal brackish water environment that the impact of aquaculture ponds on the estuarine water could not be evaluated. The heavy metal concentrations for most of the sites were very minute and some were even below the detection level. But the landward areas of Pichavaram, Aatrangarai, Muthupet and Roche Park at Tuticorin showed comparatively higher concentrations with regard to the metals. For Pichavaram and Muthupet, the reason could be because of the anchoring of boats at these sites and their releases might have caused the slight increment in the concentrations. For Roche Park it was the industries located around the area and their effluents that may have caused this situation. In the case of Aatrangarai, the source of heavy metal pollution could not be judged and may require further investigation.

The study could come up with several recommendations:

- To get a better picture of the water quality of the study sites, apart form physical and chemical analysis of water, biological analysis should be carried out, which will give accurate and clear results.
- Further studies should be carried out to identify the point and non-point sources for water pollution.
- Steps should be taken to reduce anthropological environmental stresses on Pichavaram and Muthupet mangrove wetlands. The Tambraparani River is in danger due to impacts of human settlements and industries, which should be addressed immediately to protect the ecosystem.

# 6. Synthesis and conclusion

This study has attempted to integrate the changes in land cover/land use and hydrology of upstream coastal ecosystems within the tsunami affected region over the past few decades with the ecological and environmental status of these ecosystems, and their ability to maintain their ecological functions and ecosystem services that they generate for large numbers of people.

## Our major findings are:

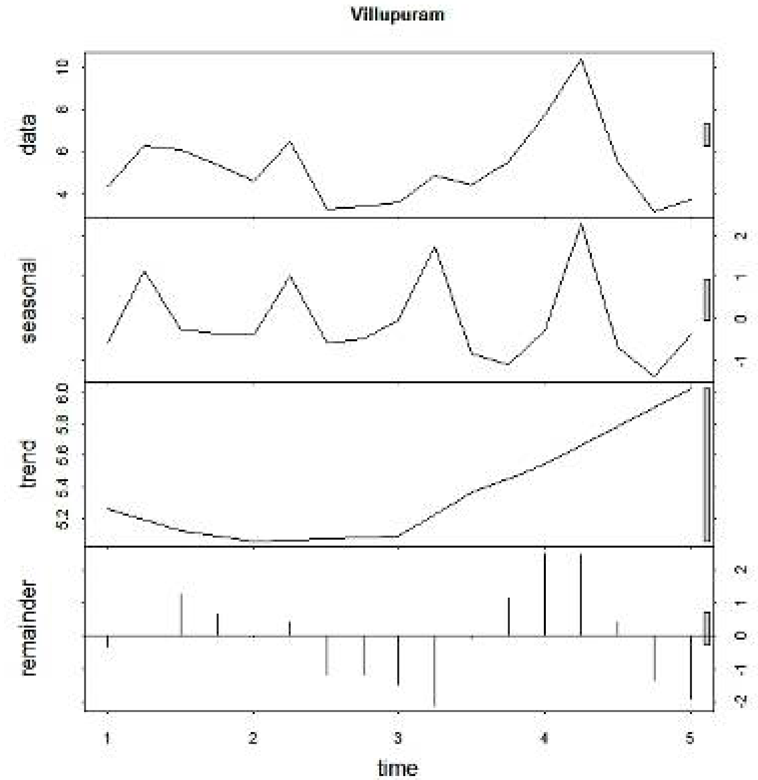
- The major land use and land cover transformations that are evident in the upstream regions of the coastal ecosystems are a major increase in fallow land, decrease in regular cultivation and increases in area under urban category.
- There is a pattern of association between ground water resources and area under cultivation. Areas with high recharge of ground water from rainfall are able to sustain cultivation, whereas in other areas, cultivated land has been left fallow, and this is linked to decrease in recharge and/or over-exploitation of ground water.
- The inflow of fresh water from surface and sub-surface discharges into coastal ecosystems has reduced considerably due to upstream abstraction and diversion, and there is an increasing discharge of untreated sewage, saline effluents from aquaculture, and industrial effluents into these coastal wetlands and estuaries. As a result of reduction in fresh water inflows, coastal wetlands and estuaries are increasingly becoming more marine in their water chemistry through increase in salinity and pH.

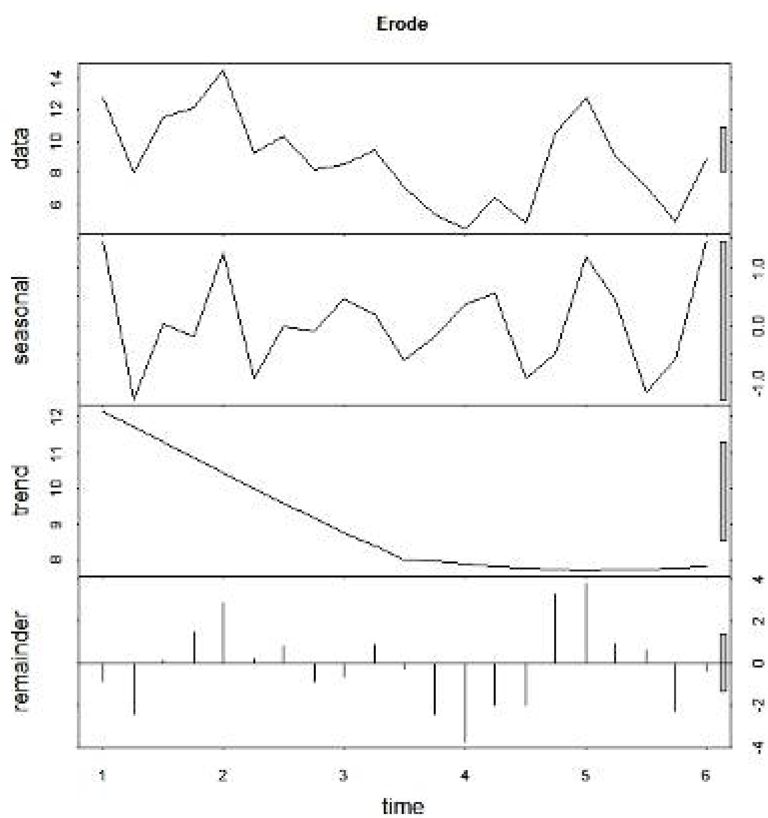
## Our recommendations are:

- Maintenance of minimum ecological and environmental flows in rivers that drain into these coastal ecosystems is essential to sustain their productivity, ecological resilience and ability to generate a diversity and abundance of ecosystem services. This can be achieved only through release of water from reservoirs whenever feasible, and through regulation of ground water extraction and adoption of water efficient crops.
- Ground water use must be regulated in the coastal zone and sand mining from river beds must be prohibited and this must be enforced.
- There must be a major awareness campaign launched amongst coastal scientists, coastal communities, government agencies and political parties about the threat to coastal ecosystems and their ecosystem services from upstream land use and water use. The need to maintain minimum environmental flows in rivers discharging into the coastal wetlands and estuaries must be highlighted.

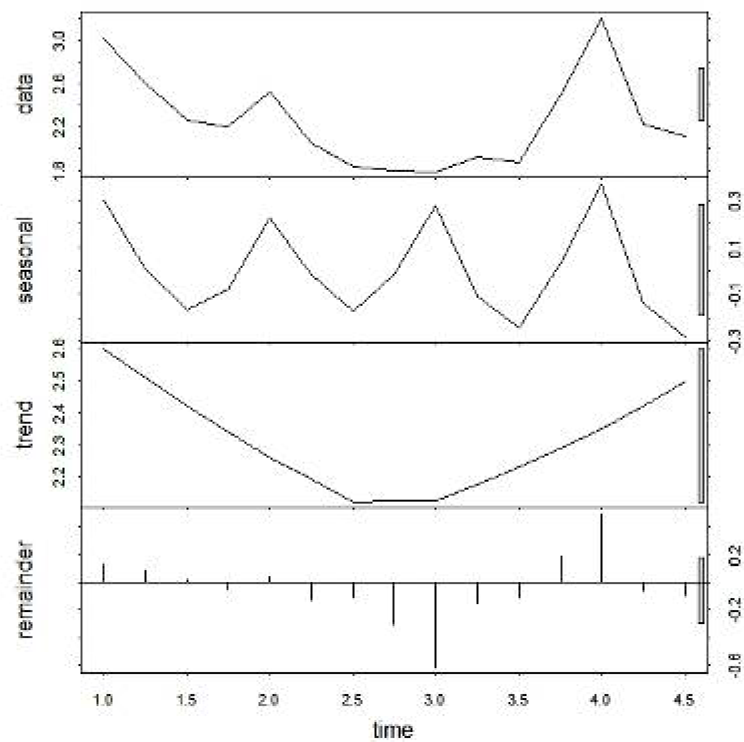
## Appendix 1

## Seasonal Trend Decomposition with Loess Graphs of the Sites

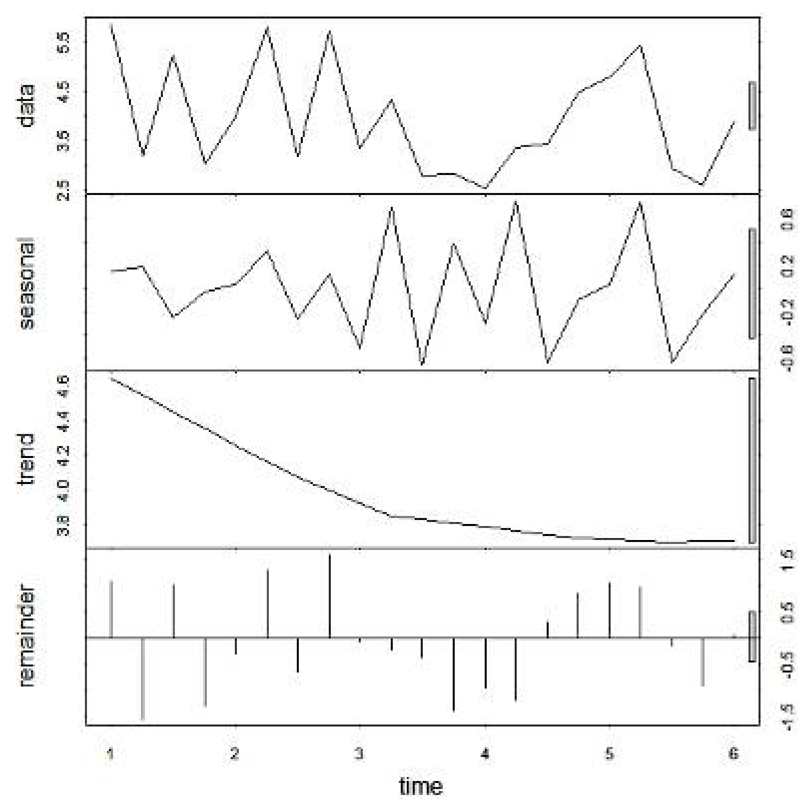


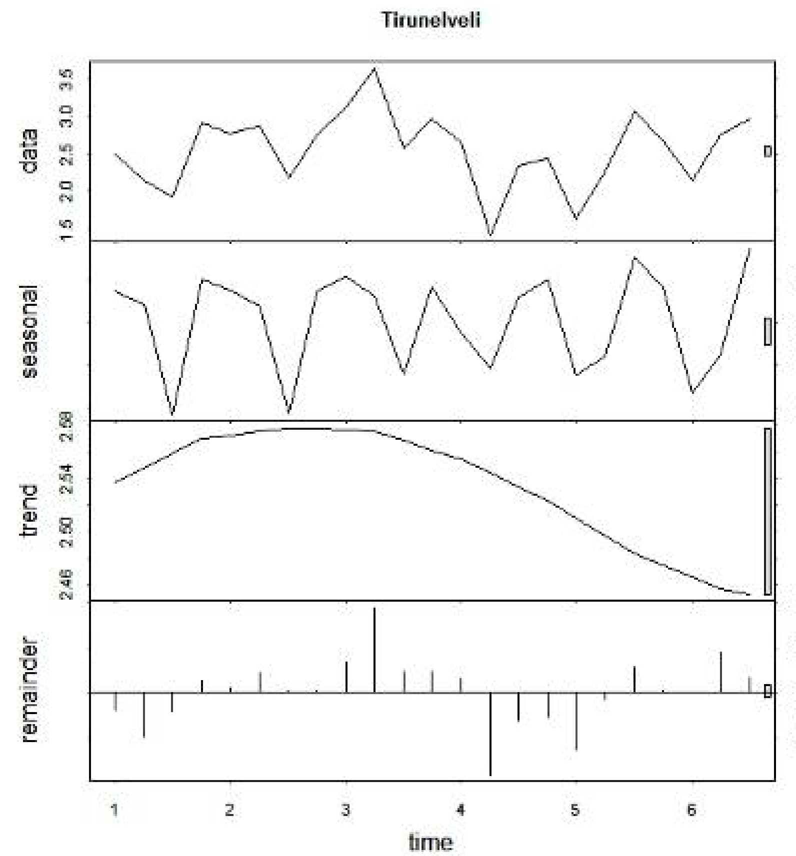



**Nagai**



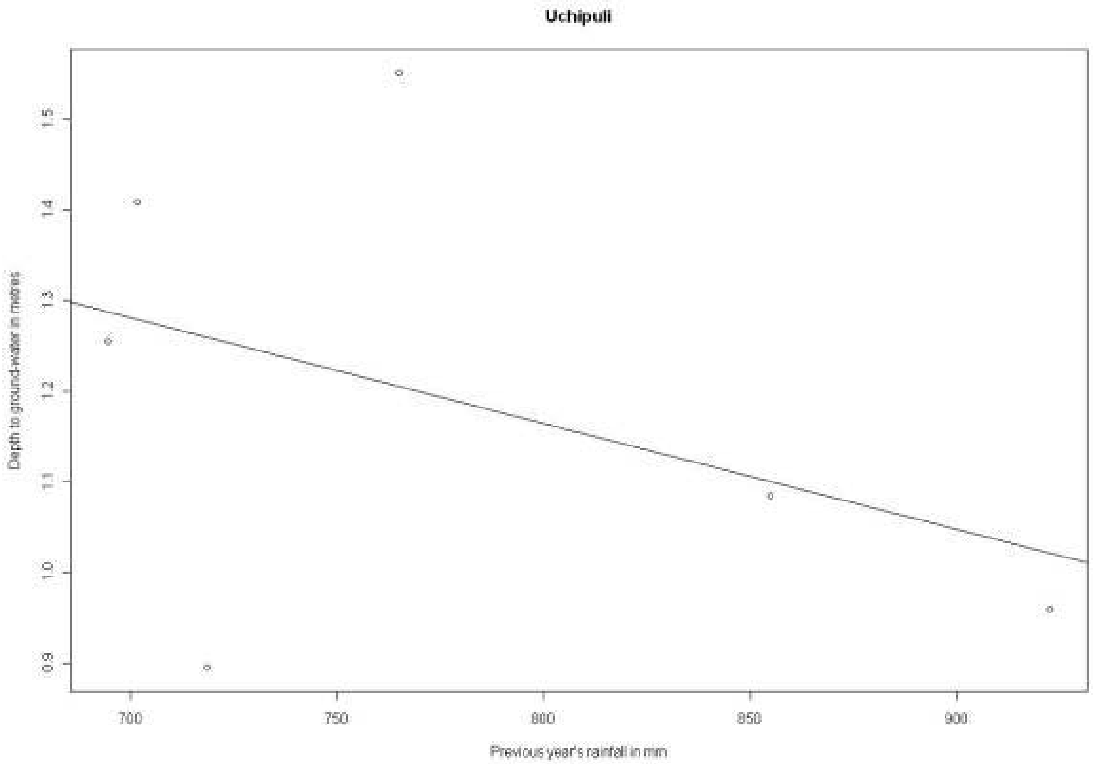

**Madurai**

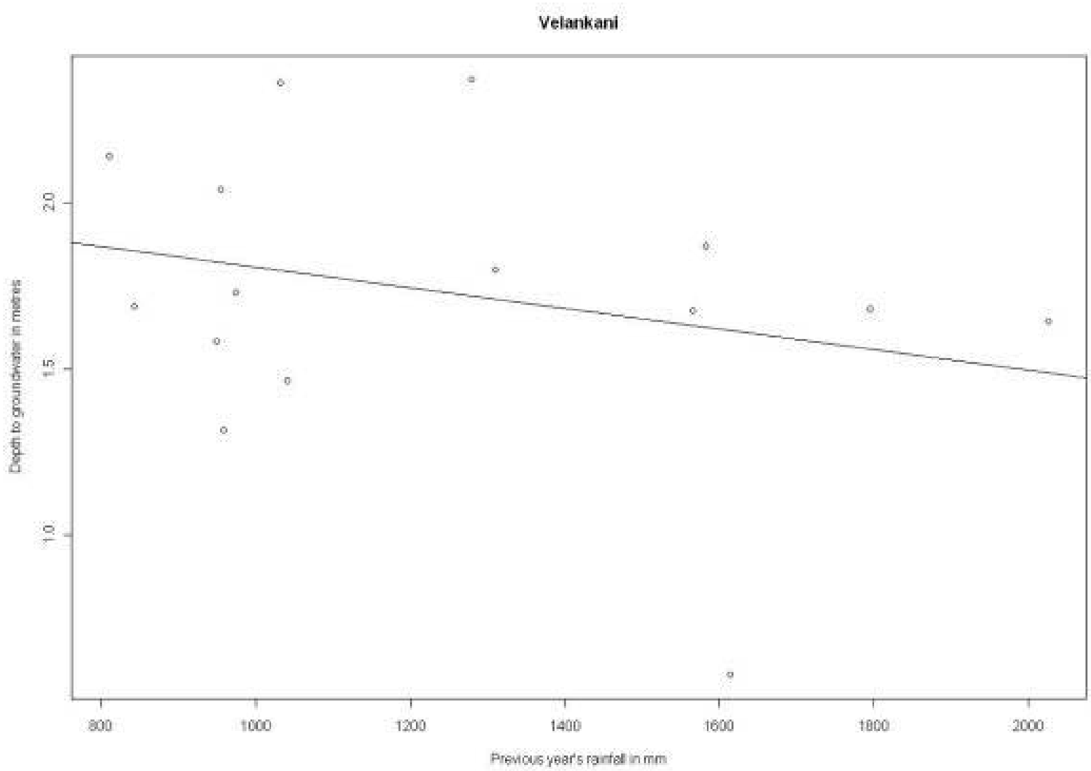


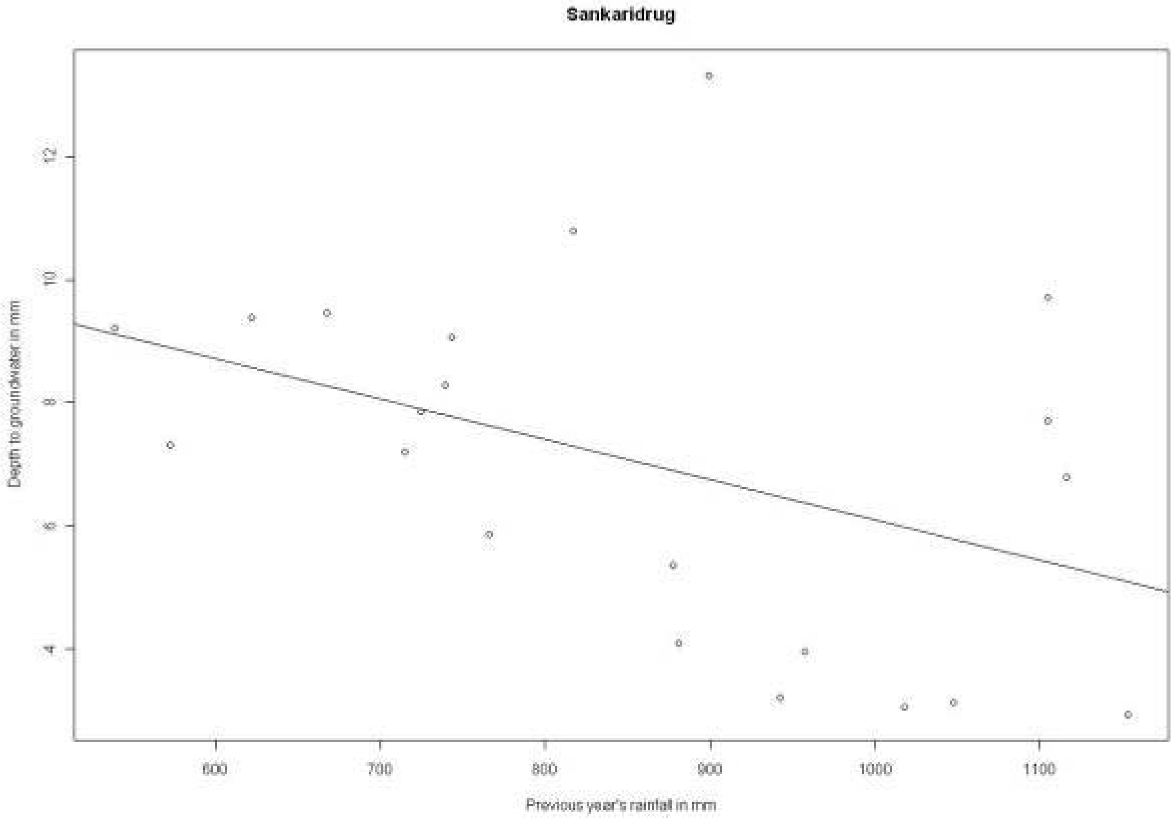

Tirunelveli
data
seasonal
trend
remainder
time
1.5
2.0
2.5
3.0
3.5
-0.4
-0.2
0.0
0.2
2.46
2.50
2.54
2.58
-0.5
0.0
0.5
1.0
1
2
3
4
5
6

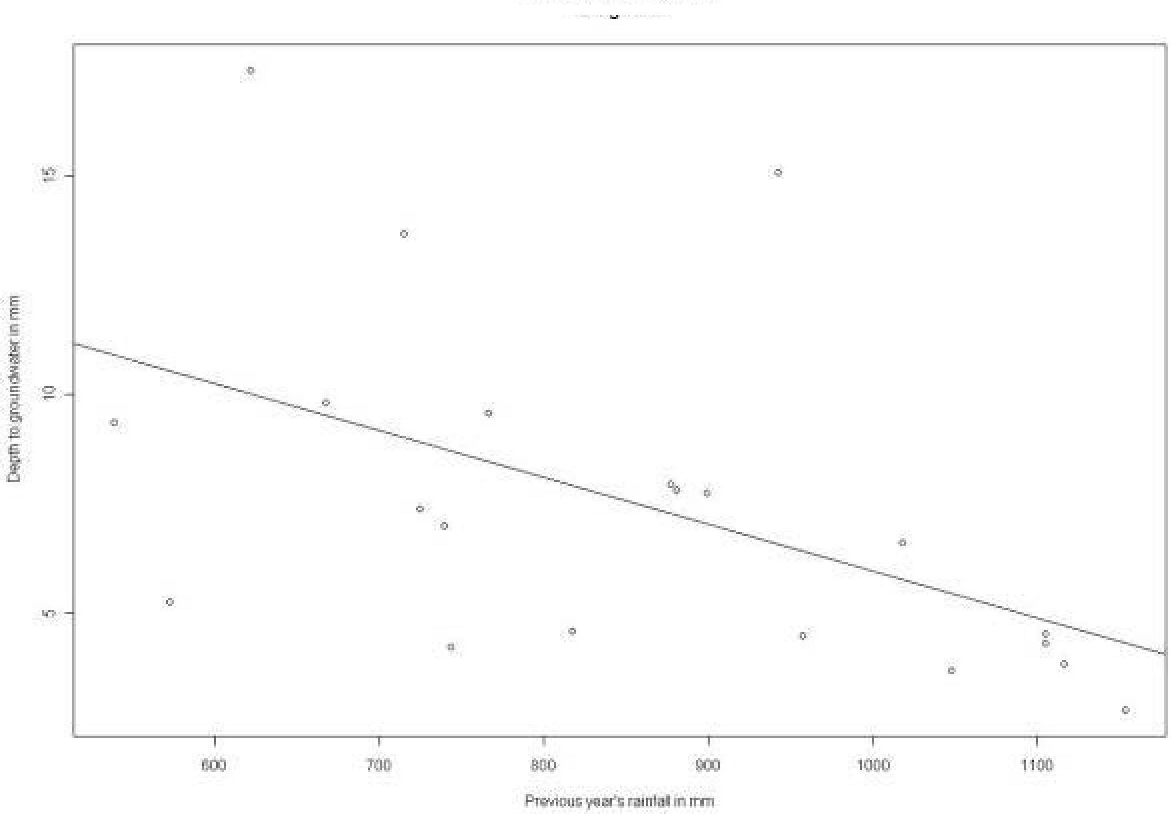
## Appendix 2

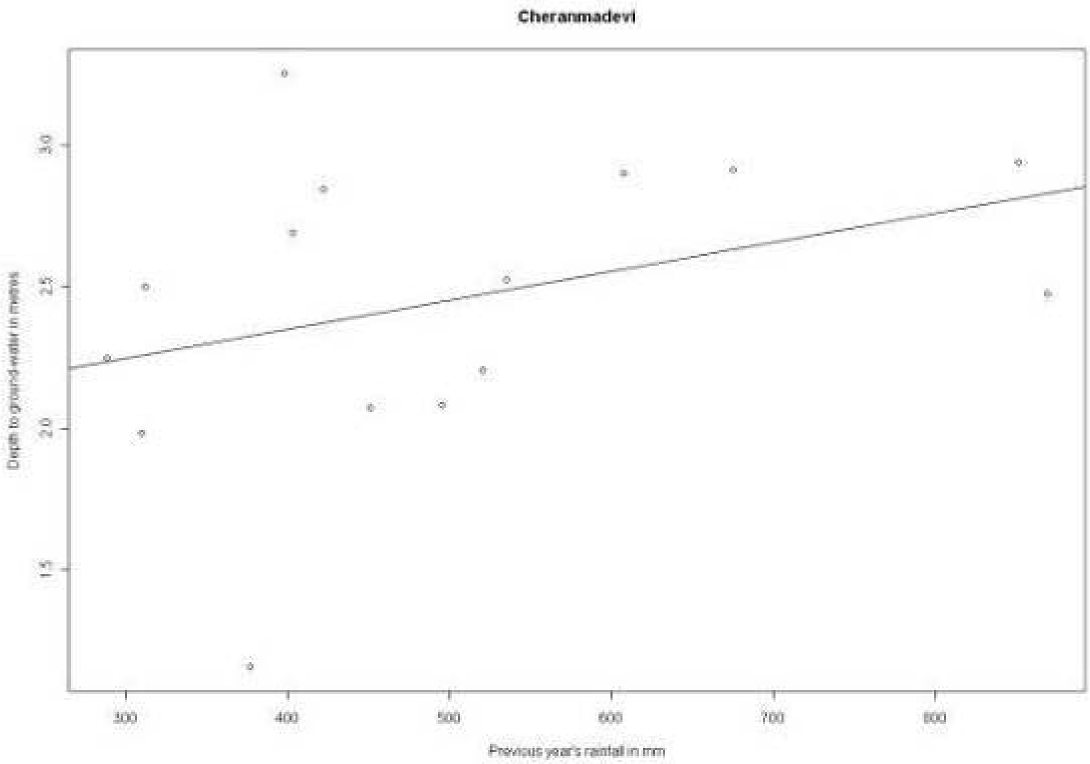
## Pre-monsoon Regression Models

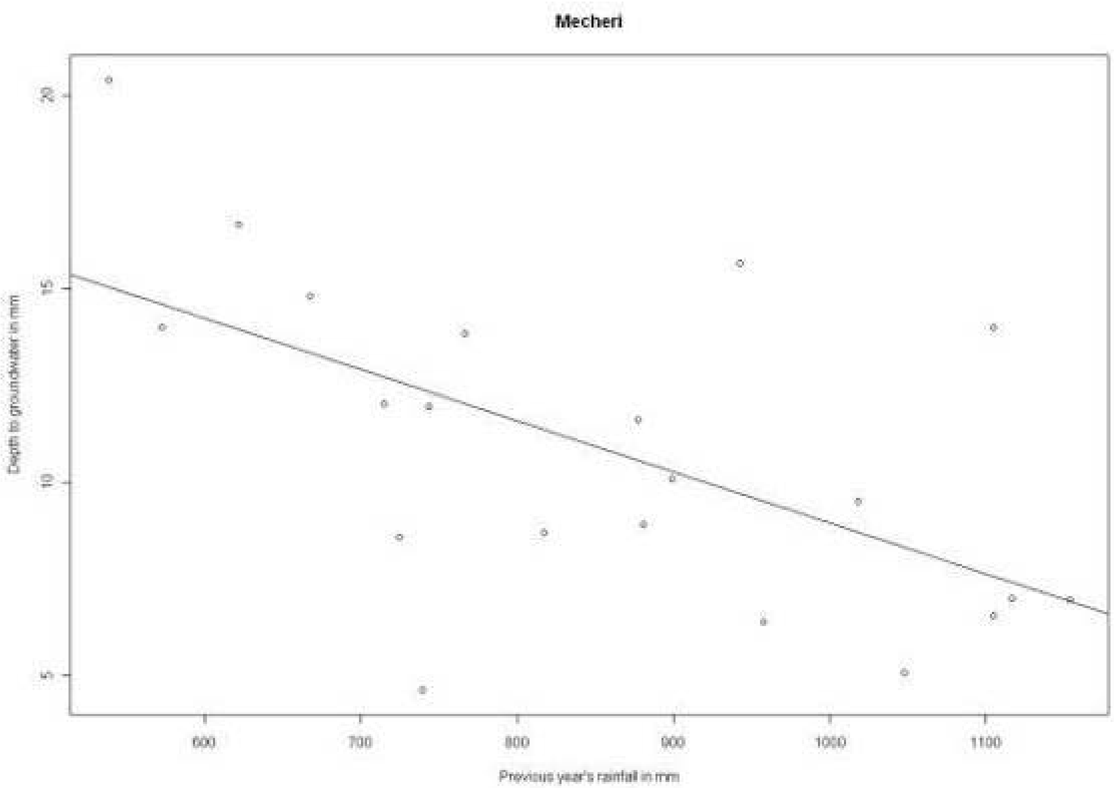


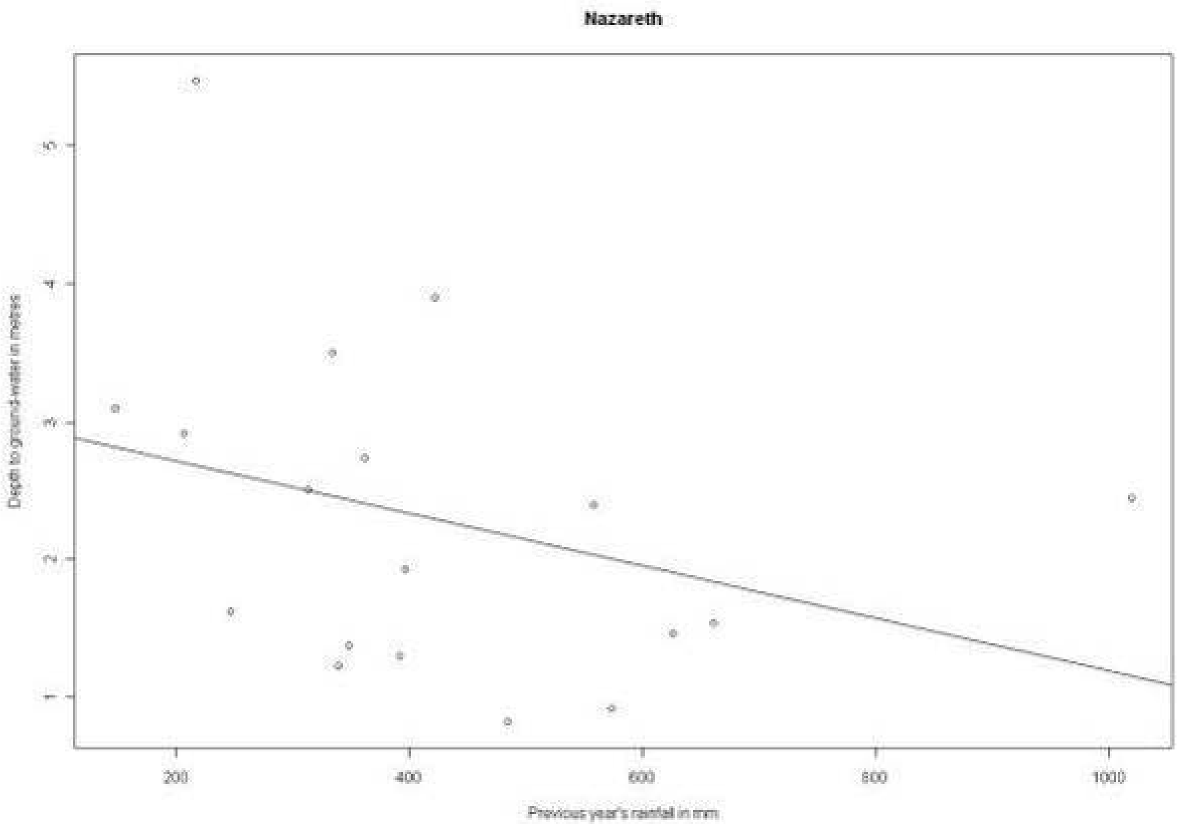



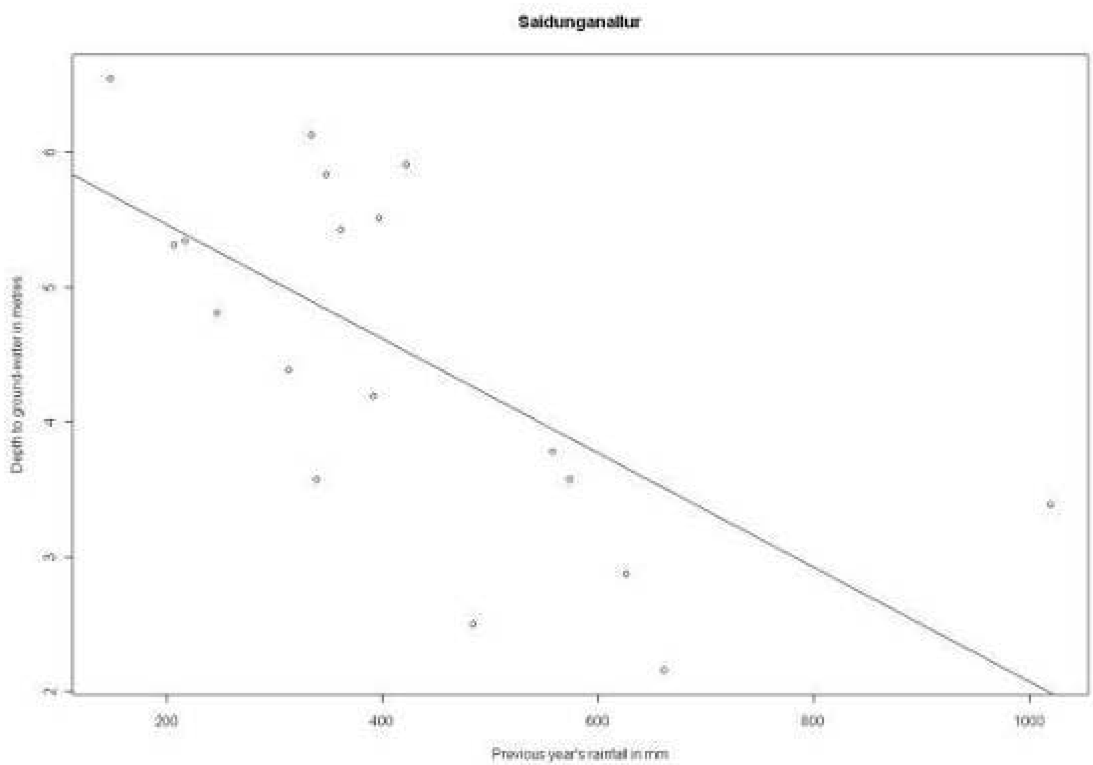

Sankaridrug
Depth to groundwater in mm
4
6
8
10
12
600
700
800
900
1000
1100
Previous year's rainfall in mm

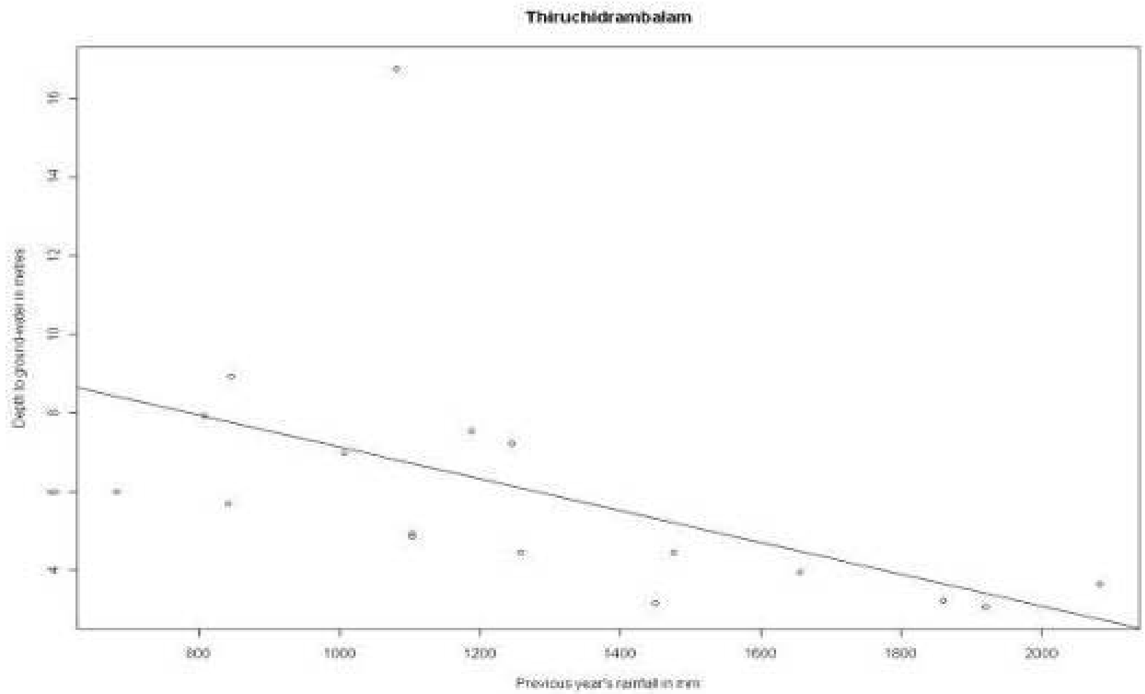

Depth to groundwater in mm
5
10
15
600
700
800
900
1000
1100
Previous year's rainfall in mm

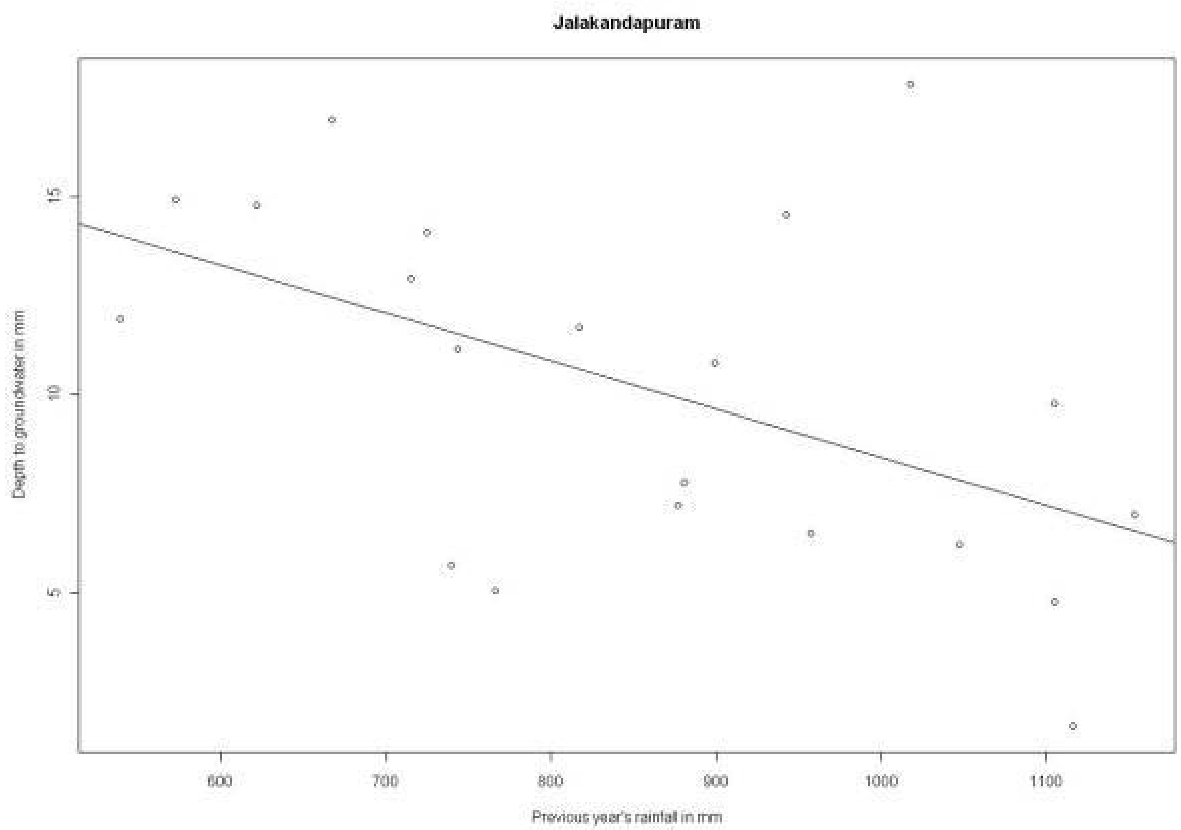

Cheranmadevi
Depth to ground water in metres
Previous year's rainfall in mm

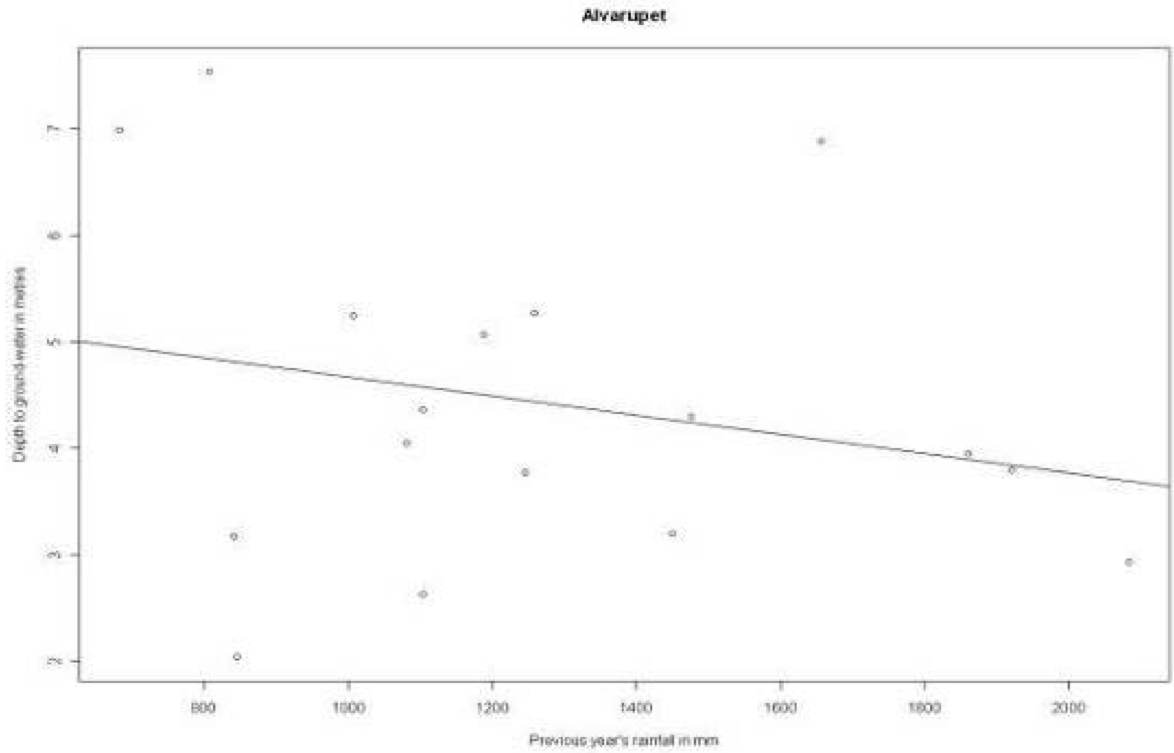

Mecheri
Depth to groundwater in mm
Previous year's rainfall in mm


Nazareth
Depth to ground-water in metres
Previous year's rainfall in mm
1
2
3
4
5
200
400
600
800
1000

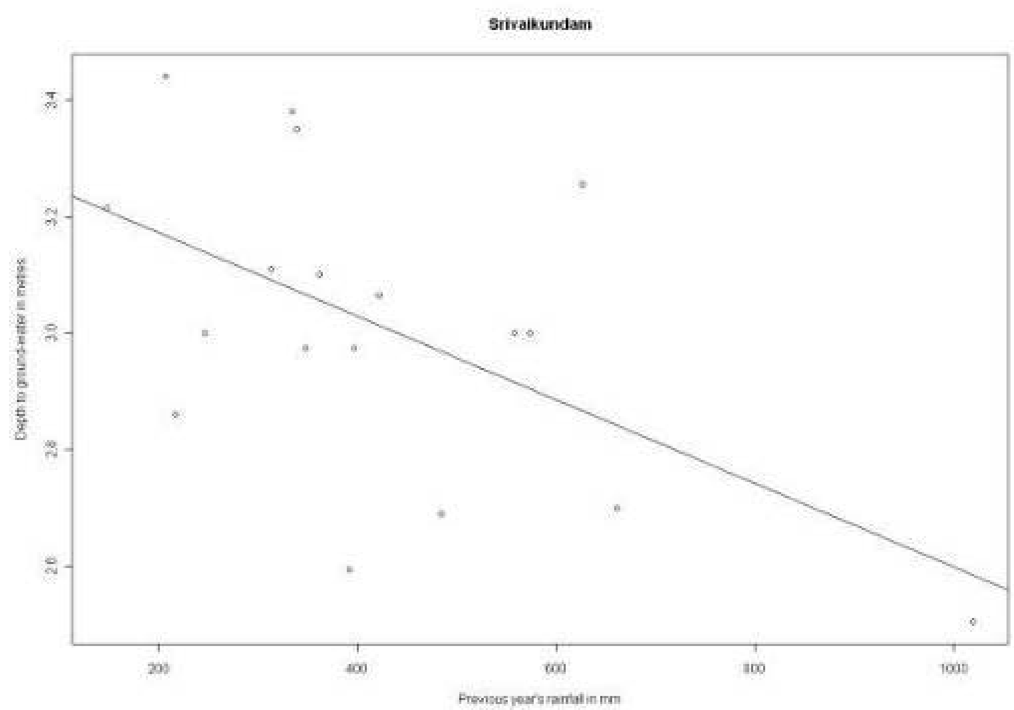

Saidunganallur
Depth to ground-water in metres
Previous year's rainfall in mm
2
3
4
5
6
200
400
600
800
1000


Thiruchidrambalam
Depth to ground-water in metres
Previous year's rainfall in mm


Jalakandapuram
Depth to groundwater in mm
Previous year's rainfall in mm



Alvarupet
Depth to ground-water in metres
Previous year's rainfall in mm
2
3
4
5
6
7
800
1000
1200
1400
1600
1800
2000

Srivaikundam
Depth to ground-water in metres
Previous year's rainfall in mm
2.6
2.8
3.0
3.2
3.4
200
400
600
800
1000

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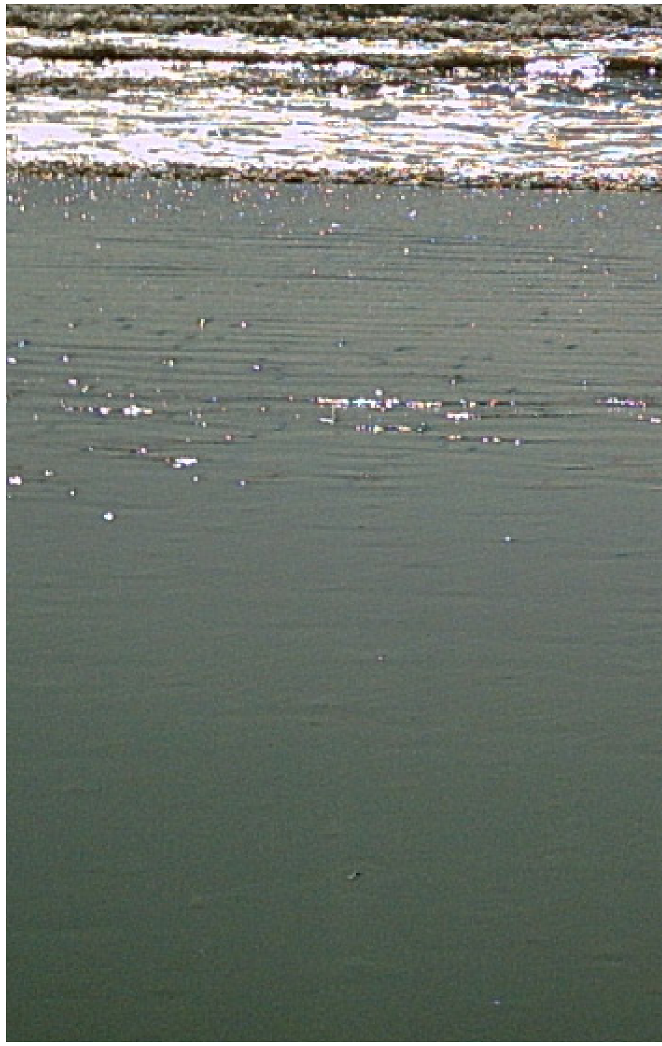
- Sand in my Hands! An Activity Book on Sandy Beaches and Sand Dunes for Children
- Policy Brief: Bioshields
- Policy Brief: Sand Dunes
- Policy Brief: Sea Walls



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