HYDRO-ECOLOGY OF POINT CALIMERE WILDLIFE AND BIRD SANCTUARY, TAMIL NADU

AN ASSESSMENT FOR INTEGRATED MANAGEMENT

IKI INTERNATIONAL CLIMATE INITIATIVE

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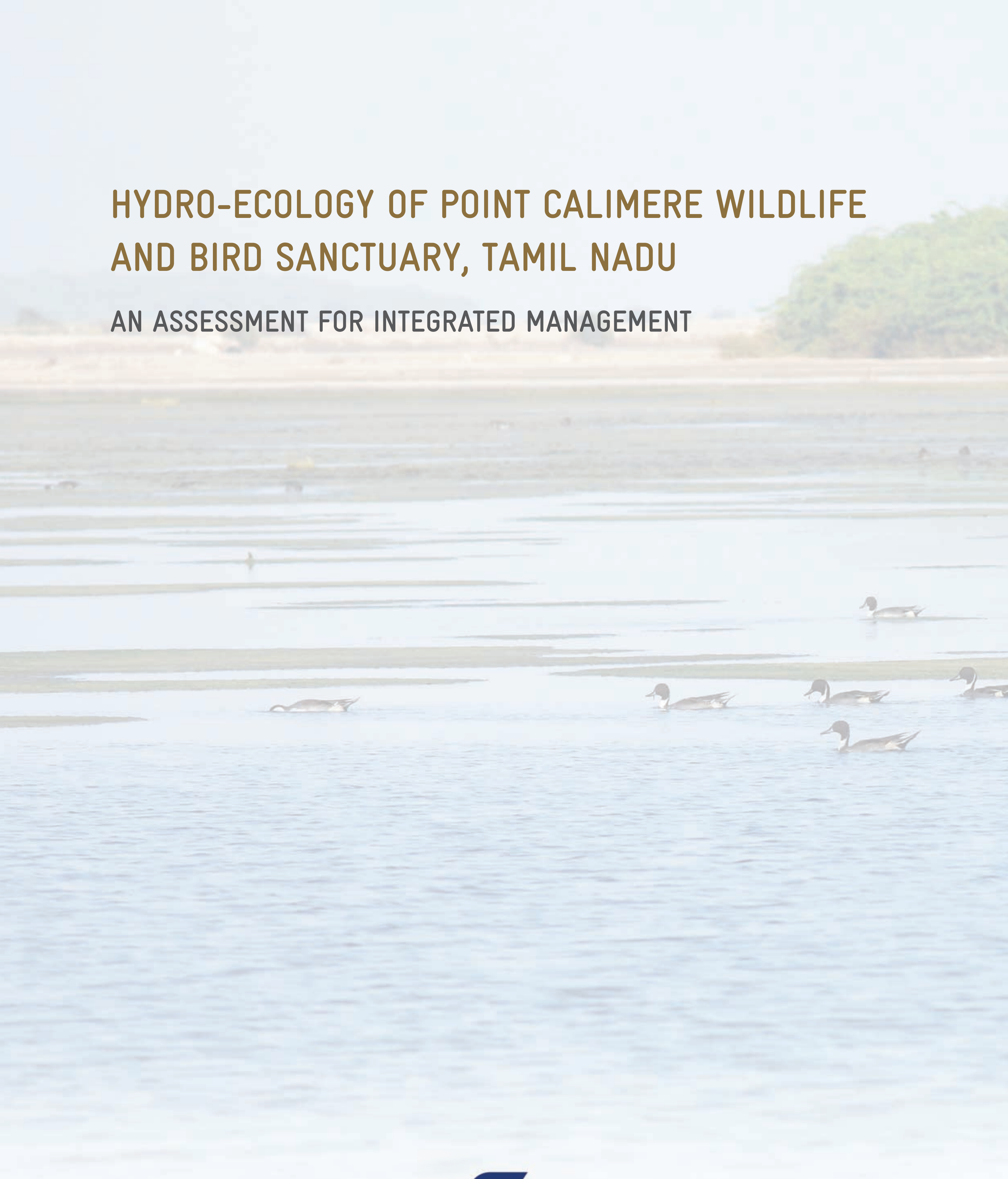

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AN ASSESSMENT FOR INTEGRATED MANAGEMENT

Karunya

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EXECUTIVE SUMMARY

- The key objectives of this investigation are to understand the ecological and hydrological factors, assess the causes of degradation of the Point Calimere Wetland system and to suggest management actions and policies aiming at the wise use of these wetlands. The ecology of coastal wetlands to a great extent depends on the hydrology of the basins draining into these wetlands since water, sediments, nutrients and pollutants are generally brought by the streams and rivers flowing into them. The water balance as well as the hydroperiod of the wetlands also depend on the hydrology and management of the drainage basins. The hydraulic structures in the drainage basins regulate the flows downstream and interfere with the natural flows. Therefore, scientific water allocation policies have to be evolved to cater to not only development demands such as water for drinking, irrigation, hydropower generation and industries but also for environmental purposes, especially to achieve the wise use of wetlands, which are bowls of biodiversity and sources of livelihood for people. Coastal wetlands are also often subjected to salinity intrusion from the sea. Therefore, while considering the hydrology of coastal wetlands, not only the freshwater contribution from inland sources but also the tidal influx and coastal processes may have to be considered since the mixing, circulation and dispersion processes depend on these, and the biodiversity depends on all these factors. The shoreline changes also make coastal wetlands vulnerable. Another major factor to be considered is climate change, which may cause increases in the frequency and intensity of hydrologic extremes and cause sea level rise, which are bound to have their impact on the coastal wetlands. In the present study, an attempt has been made to analyse these factors and processes and to identify the drivers of change and subsequently evolve management action plans and policy recommendations.

- The land use/land cover changes in the Cauvery basin show that there has been an increase in the built-up area by 2.24% and decline in the crop land and forest area by 1.30% and 0.59%, respectively, during the past three decades, which are expected to have an influence on the temporal availability of water downstream. However, these seasonal variations over a year do not generally reflect in the regulated flow downstream, which is mainly intended for irrigating the rice crops in the delta. It is noticed that there has been an increase in the sediment yield, by about 80%, during the last decade, which would cause a reduction in the capacity of the reservoirs upstream and subsequently on the capacity of the stored water to be released during the summer months to the downstream reaches. In the direct catchment of the wetland complex, there is a considerable increase in the area under cultivated land and open scrub, and a decrease in the extent of mudflats, water bodies and forest. Further, the area under settlement, mangroves, saltpans and aquaculture farms have also increased during the past three decades. According to the SWAT model, the soil erosion in the direct catchment of PCWC varies from 100 tonnes/ha/year to 1496 tonnes/ha/year. Higher values of soil erosion are observed at Thagattur, Nallur, Muthupet, Panchanadhikulum (West), Naluvethapathi, Vilangudi, Kadinelvayal, Voimedu, Thalainayar, Madhukkur and Thiruthuraipoondi.

- The rainfall in the wetland complex is mainly from the north-east monsoon (69.33%), followed by that in the south-west monsoon (18%). The rainfall trend analysis showed that during the pre-monsoon and the north-east monsoon seasons, rainfall exhibited statistically significant increasing trend both in the delta and wetland complex. The study area as a whole did not show a significant increase in annual rainfall. The study on extreme rainfall event indices showed an increase in number of heavy precipitation days, which is in line with the regional trends. The precipitation concentration index values suggest strongly irregular trend in the study area. Cyclones generally bring more rainfall and inundate the entire delta. The annual streamflow to the wetland is confined to three months, October–December, according to the data of PWD. The total annual flow to the wetland complex from the Paminiyar, Koraiyar and Marakkakoraiyar is only 3.45 TMC. All the other streams practically remain dry except during the monsoon, when the rainfall in their catchments contributes to their flows. The monthly hydrographs show a marginal increase in flow during August-January in Paminiyar and Koraiyar. There was an increase in the streamflow to the delta immediately after the Interim Award of CWDT, and the temporal distribution of the stream flows has improved in the delta.

- An attempt has been made to delineate the groundwater potential zones. The potential recharge zones in the buffer zone have been identified. The groundwater recharge structures planned and executed for the Point Calimere Wildlife and Bird Sanctuary (PCWBS) and Tropical Dry Evergreen Forest (TDEF) are presented. The structures recommended for groundwater recharge include check dams, earthen bunds, canals, lakes, wells and water troughs, apart from artificial rainwater storage tanks and radial wells. From the spatio-temporal analysis of groundwater quality parameters for the years 2009, 2013 and 2018, it was observed that the water quality parameters such as TDS, EC, chlorides, magnesium, potassium and hardness exceeded the permissible limits as per BIS10500. Though the deterioration in groundwater quality was observed from 2009 onwards, the groundwater remains suitable for irrigation in the post-monsoon season in the areas of Muthupet Estuary, Muthupet mangroves, PCWBS, mudflats and aquaculture farms, which may be due to the lithology and aquifer characteristics of the study area. However, the quality was very poor in the pre-monsoon due to overexploitation, pumping or saltwater intrusion. In the Muthupet Mangroves, mudflats and aquaculture farms and at Siruthalaikadu inlet and saltpans, the major sources of salinity and pollution are salinity intrusion, rock–water interaction, agriculture and domestic activities.

- Freshwater flow is the major factor influencing salinity, formation of salt plugs, movement of estuarine turbidity maximum (ETM) and transport of salt and suspended particulate matter (SPM). The greater the freshwater flow is, the higher is is the salinity gradient and lower is the settling velocity. It is estimated that a minimum flow of 10 m^3/s has to be maintained in Paminiyar and Koraiyar combined all through the year to maintain the salinity level in downstream reaches of the estuary and for the healthy growth of mangroves and to deliver the ecosystem services. Further, flow of 10 m^3/s may be maintained in the Mulliyar, Valavanar and Manakundan rivers combined to sustain the health of mudflats, mangroves and Siruthalaikadu inlet.

- From studies on the geomorphology of a 61.3 km stretch of coast, it is found that 21.41 km shows erosion tendencies. During the past five decades, the area subjected to erosion has been 3.62 km; the erosion rate has been 2.805 m/year. The vulnerability index indicated that a 20.35 km length of coast adjacent to the wetland complex is highly vulnerable and 11.31 km is moderately vulnerable. The mouth of Muthupet estuary comes under the low vulnerability category and the mouth of Siruthalaikadu inlet comes under the moderate vulnerability category. The projected sea level rise of 0.5 m is expected to submerge 2.18 km^2, 2.03 km^2, 2.67 km^2 and 12.37 km^2 of estuary, mangroves, inlets and mudflats, respectively. The sediment deposition from the Kodiakarai and Vedaranyam areas causes accretion at the Point Calimere nose zone. The mouths of Adappar and Harichandranathi, flowing through the wetlands, are heavily silted up. The coastline along the Reserve Forest of Palanjur, Thamarakottai, Maravakadu, Vadakkadu and Thalainayar are vulnerable to erosion. Artificial nourishment and vegetation measures are recommended for protecting the vulnerable stretches of the shoreline.

- The major connectivity among the ecosystems of the wetland complex of Point Calimere are highlighted below:

i) The five rivers draining into the Muthupet Estuary are subjected to upstream regulations before joining the Muthupet Estuary and the mangroves on the fringes of water body.

ii) The water from these five drainages is subjected to pollution due to the application of agro-chemicals in the rice fields and sewage from the thickly populated belts.

iii) There are a few aquaculture ponds on the sides of the Muthupet Estuary that take water from the estuary and discharge their wastewater back to the estuary.

iv) The micro-tidal and shallow Muthupet Estuary enters the Palk Strait through a narrow mouth of 800 m and establishes communication with the sea.

v) The saline water enters the mangroves on the fringes of the estuary through fishbone canals, artificially made for this purpose.

vi) As it is, there is no connectivity between the Muthupet Estuary and the Siruthalaikadu inlet, and there is practically no freshwater flow to the inlet from the upstream; but the inlet is connected to Palk Strait through a deep channel.

vii) The mangroves on the fringes of Siruthalaikadu and in the Panchanadhikulam and Thondiakadu mudflats are practically deprived of freshwater flows.

viii) Most of the saltpans are located on mudflats and divide the mudflats into different grids for activities connected with salt production.

ix) Some of the saltpans pump out saltwater using deep bore wells to produce edible salt.

x) A large number of aquaculture farms are located on the mudflats and near the Thalainayar Reserve Forest, these aquafarms make use of the groundwater and for some of them, brackish water is imported to freshwater zones for shrimp production.

xi) The streams flowing to the Thalainayar Reserve Forest are independent of those draining to the Muthupet estuary and Siruthalaikadu inlet.

xii) The Adappar and Harichandranadhi have been regulated, diverted and silted up so much that their connectivity with Thalainayar Reserve Forest is only marginal.

xiii) The branch of Valavanar flowing into the Siruthalaikadu inlet has silted up and dried; both the Mulliyar and Manakundan rivers are ephemeral and flow only for 3 months in a year.

xiv) The only freshwater stream flowing into PCWBS is the Peralam River, which practically does not contribute to the sanctuary now.

- In spite of the connectivity mentioned in the foregoing, the natural ecosystems of the complex are not connected with each other during most of the year. Therefore, it has been found expedient to consider each of the nine individual ecosystems separately in the context of identifying the direct and indirect drivers of change and in formulating the management action plans.

i) Muthupet Estuary

Direct Drivers:	Indirect Drivers:
1. Overexploitation of water upstream 2. Regulation of downstream flows to the wetland 3. Mushrooming of aquafarms in the periphery, drawing water and discharging wastewater to the estuary 4. Untreated domestic and municipal wastewater discharged from Muthupet town 5. Draining of agro-chemicals from the rice fields	1. Increase in the population in the area 2. Drastic changes in the land use land cover and agricultural practices 3. Economic backwardness of the local population 4. Lack of awareness among stakeholders 5. Lack of policies and regulations to conserve the estuary 6. Non-availability of monitoring mechanisms 7. Absence of inter-sectoral institutional mechanism 8. Natural disasters

Management Action Plan:

1. Maintaining environmental flows for the wise use of the Muthupet Estuary
2. Hydrologic and ecologic monitoring mechanisms
3. Wastewater from Muthupet town to be treated before it is discharged into the estuary
4. Aquafarms to be restricted within a minimum distance of 500 m from the estuary and wastewater to be treated before it is discharged into the estuary
5. Overuse of agro-chemicals in the rice fields to be restricted after a detailed survey and scientific study
6. If the enhancement of flows is not sufficient to bring down the sediment deposition at the salt plug, the possibilities of limited dredging between 5 and 7 km from the mouth are to be probed without causing changes to the habitat.
7. Establishment of a wetland experimental station and wetland museum for education and awareness

ii) Siruthalaikadu Inlet

Direct Drivers:	Indirect Drivers:
1. Drying up of Manakundan River feeding to the erstwhile creek and earlier connecting to the sea 2. Sediment deposition on the western side of the inlet disconnected it from Valavanar. 3. A very shallow and narrow mouth to the sea developed in 1990.	1. Changes in land use land cover 2. Dwindling inflows from the Valavanar, Mulliyar and Manakundan rivers 3. Changes in morphometry due to hydrodynamic and sedimentation processes

Management Action Plan:

1. The possibility of improving the connection of the lagoon with the sea to be probed and the mouth expanded on the basis a model study
2. Allocation of freshwater from upstream through Valavanar to sustain the mangroves planted on the northwest fringes of the lagoon, for which fishbone channels already exist
3. Conversion of the inlet into a bird sanctuary

iii) Mudflats

Direct Drivers:	Indirect Drivers:
1. Construction of grids and sub-division of mudflats for salt production 2. Discharge of effluents into the compartments within the mudflats 3. High coastal berms not permitting tidal water to enter the mudflats 4. Prosopis juliflora spreading in some areas of mudflats 5. Dumping of building waste and other solid waste in the mudflats	1. Non-availability of freshwater from upstream reaches and absence of tidal action 2. Lack of scientific input and awareness in managing the ecosystem 3. Absence of policies for controlling the salt production in these wetlands 4. Deposition of sediments due to natural and anthropogenic causes 5. Area not fully surveyed

Management Action Plan:

1. Channels to be made to connect the mudflats with the existing saltwater channel and the sea and shallow ponds dug to store saltwater and attract more birds on an experimental basis
2. On the basis of the lessons learnt, further planting of mangroves on the mudflats is to be restricted
3. Dividing the mudflats into compartments for salt production to be restricted
4. Regulate the expansion of large-scale salt production by companies
5. The boundaries of the mudflats at Thondiakadu, Panchanathikulam, Kodiakadu, and un-surveyed swamp are to be demarcated on a priority basis
6. The details of the quantum of salt produced and area occupied by the major companies are to be made available to those involved in the wetland management
7. Proper inventory to be made of the area occupied by the saltpans, returns from them, number of people engaged, quantity of salt produced and details of bore wells dug, including their depths and quanta of water extracted, and the data made available to the decision makers

iv) Mangroves

Direct Drivers:	Indirect Drivers:
1. Reduction in freshwater flow into the mangrove areas of Muthupet 2. Absence of freshwater flow and tidal action in the mudflats 3. Lack of tidal action in Thalainayar mangrove area due to the construction of a dyke along the Vedaranyam Main Canal 4. Deficiency of nutrients near the mouth of the Muthupet Estuary 5. Silting up of artificial fishbone channels in mangrove forests	1. Overexploitation of freshwater for irrigation 2. Drying up or blocking of freshwater tributaries, especially in the case of the Siruthalaikadu inlet 3. Exchange processes within the Muthupet Wetland restricted by morphometric characteristics

Management Action Plan:

1. Water distribution for downstream wetland ecosystems after estimating requirements
2. Desilting fishbone channels to ensure tidal water influx to mangrove forest

Management Action Plan:
3. Construction of a few openings in the Vedaranyam Main Canal dyke to permit brackish water to enter the mangrove areas after studying the impact of dyke on the mangroves 4. Establishing a monitoring mechanism for mangrove areas 5. Encouraging local communities, especially fishermen, to plant, monitor and maintain the mangrove forest 6. Participatory planning, management and monitoring system to be developed so as to resolve conflicting interests

v) Point Calimere Wildlife and Bird Sanctuary	
Direct Drivers:	**Indirect Drivers:**
1. Erosion of sand dunes in certain stretches close to the shoreline 2. Large-scale grazing 3. Overexploitation of freshwater from the periphery of sand dunes 4. Collection of firewood from the sanctuary	1. Increase in density of population 2. Speedy draining of rainwater after each storm
Management Action Plan:	
1. Nourishment of areas closer to the shoreline to protect the sand dunes from erosion 2. Prevention of grazing within the sanctuary by assigning alternate areas 3. Creation of small impoundments, recharge pits and radial wells to recharge groundwater and store water for wildlife 4. Removal of exotic trees and planting indigenous species	

vi) Saltpans	
Direct Drivers:	**Indirect Drivers:**
1. Large-scale salt production and spreading of saltwater on ground, especially on mudflats 2. Overextraction of groundwater for salt production and its spreading over the ground, leading to recharging groundwater with saltwater 3. Discharging untreated effluents directly into the mudflats and draining effluents into the channels in mudflats	1. Increase in the number of people involved in salt production and increase in the quantity of salt produced by large companies 2. Lack of proper regulations and policies for controlling the activities 3. Reliable statistics on the units, production and returns from the activity not available for monitoring purposes
Management Action Plan:	
1. Inventory of number of units, area, ownership and economy of saltpans to be prepared 2. An EIA to be conducted to find out the adverse impact of salt production on the mudflats, groundwater quality and ecosystem of the wetland complex 3. Awareness programmes to be conducted for all concerned 4. Alternate projects for livelihoods of people involved in small salt production units to be identified 5. Regulation of expansion of area under saltpans managed by two industries	

vii) Aquaculture farms	
Direct Drivers:	**Indirect Drivers:**
1. Replacing traditional land use pattern by introduction of aquafarms 2. Import of saline water to freshwater zones 3. Excessive application of nutrients and medicines 4. Digging ground for creating ponds 5. Sedimentation caused due to construction and destruction of ponds	1. Large profit margin associated with aquafarm activities 2. Shifting of farmer community from agriculture to aquafarms 3. Availability of land to encroach upon in wetland complex 4. Limitations of existing regulations and their implementation
Management Action Plan:	
1. Further proliferation of aquafarms to be regulated in the area 2. Aquafarms close to the estuary to be shifted to areas at a distance of a minimum of 500 m from the bank 3. Wastewater not to be directly discharged into the water bodies without treatment 4. Excessive use of nutrients and medicines in the pond to be restricted 5. Further construction, re-construction and demolition to be controlled 6. Possibility of lining the ponds to avoid groundwater pollution to be probed 7. Alternate sources of livelihood for people involved in aquafarms to be identified 8. Pumping and channelisation of brackish water to freshwater zones to be banned 9. Structures built for salinity exclusion dykes existing earlier to be repaired and maintained 10. Alternate jobs to be identified for those involved in aquaculture in the areas of animal husbandry, dairying, etc.	

viii) Cauvery Delta	
Direct Drivers:	**Indirect Drivers:**
1. Overexploitation of water for irrigation 2. Application of excessive quantities of agro-chemicals 3. Temporal and spatial regulation of water, only considering the irrigation requirements 4. Connectivity to the sea by artificial channels causing salinity intrusion into the surface and groundwater sources 5. A few farmers shifting to aquaculture 6 Conjunctive use of surface and groundwater not practised in a scientific manner 7. Environmental flows not considered	1. Lack of inter-departmental coordination 2. Principles of Integrated Water Resources Management not put into practice 3. Lack of management of coastal wetland ecosystems by most of the stakeholders 4. Anomalies in the water allocation and distribution system 5. Absence of institutional mechanism to take care of all the water stakeholders in the delta 6. Reservation of decision makers to consider environmental flows as an integral part of water management
Management Action Plan:	
1. Estimation of environmental flows from spatial and temporal viewpoints and release of the estimates according to a scientific operation policy 2. Restriction of overexploitation of water in the delta 3. Control of excessive use of agro-chemicals applied in rice fields by farmers	

Management Action Plan:
4. Regulating conversion of rice fields due to conversion to aquaculture farms 5. Conjunctive use of surface and groundwater sources to be practised scientifically 6. Overexploitation of groundwater in areas prone to salinity intrusion to be avoided 7. Awareness creation to be given priority

ix) Coastal Zone
Direct Drivers:
1. Nose-like promontory of Point Calimere serves as a major sink, and Agasthiyampalli and Kodiakarai stretch as major sources of sediments 2. Geomorphology of the PC coastline attributed to two opposing wave directions, from the north-east and south-east, with one set of waves dominant over the other 3. The projected sea level rise of 0.5 m is expected to submerge 2.18 km^2, 2.03 km^2, 2.67 km^2 and 12.37 km^2 of estuary, mangroves, inlets and mudflats, respectively.
Management Action Plan:
1. Artificial nourishment in vulnerable coastal areas 2. Providing vegetation cover with mangroves and mangrove associate species 3. Areas identified as highly vulnerable at Thethakudi, Maravakadu, and Palanjur RF to be protected properly

- Some of the measures for the wise use of wetlands, which may have a policy implication, are listed below:

i) A mechanism for ensuring environmental flows

ii) Regulating the expansion of area under saltpans and aquaculture farms

iii) Finding alternate livelihood options for aquaculture and saltpan workers

iv) Conjunctive use of surface and groundwater

v) Fixing location-specific optimal pumping from groundwater to prevent salinity intrusion

vi) Coastal zone management plan to include specific wetland conservation components

vii) Creation of wetland management fund by levying a cess on aquafarm and saltpan owners

viii) Declaring the Siruthalaikadu inlet a separate bird sanctuary or a part of the existing bird sanctuary

ix) An integrated IoT-enabled hydro-ecological monitoring system to be established

x) All un-surveyed areas of the wetland complex to be surveyed and demarcated

xi) Establishment of Point Calimere Wetland Authority, similar to the CDA and LDA.

- A network of IoT-enabled monitoring stations is proposed, which is expected to be of use in real-time monitoring, implementation of management action plans and evaluation of the performance of measures implemented. Furthermore the framework of the proposed high-level Point Calimere Wetland Authority, with the representation of stakeholders, in line with the CDA, has been presented in the report.

1. INTRODUCTION

1.1 Cauvery River Basin

The Cauvery River basin is one of the largest river basins in southern India. It benefits Kerala, Karnataka, Tamil Nadu and the Union Territory of Puducherry. In this chapter, the physical characteristics of the river basin have been explained, as also the pressures on its water resources for the requirements of human beings and nature. The general hydrologic features of the basin and the irrigation status, including the details of hydraulic structures, have also been covered. Apart from that, a detailed description of the Cauvery delta, in which the other ecosystems of the Point Calimere Ramsar site are located, has been presented. Thereafter, the characteristics of the Vennar sub-basin specifically, in which the wetland complex is located, are highlighted along with a description of the major structures in this sub-basin. A general description of the wetland complex is provided with details of different ecosystems included in it as also the details of villages in the area and the demographic features. The freshwater sources draining into the wetlands and the details of the reserve forests around it have also been highlighted. A general framework of the indicators, drivers and assessment tools has been given in this chapter, which is expected to help analyse these components with respect to the Point Calimere Ramsar site. The general methodology followed is also briefly described.

The Cauvery basin, in South India, spreads over the states of Tamil Nadu, Karnataka and Kerala as well as the Union Territory of Puducherry, draining an area of 85,626.23 km^2 (MoWR 2014; Table 1.1). The basin is located between longitudes 75° 27′ and 79° 54′ E and latitudes 10° 9′ and 13° 9′ N (figure 1.1). The basin has a maximum length of about 560 km and a maximum width of 245 km (MoWR 2014). The Cauvery basin is bounded by the Eastern Ghats on the eastern, southern and northern sides and by the Western Ghats, on the western side. The Cauvery originates from the Western Ghats and flows in a south-easterly direction. The total length of the main river is estimated as 800 km, of which 320 km lies in Karnataka, 416 km in Tamil Nadu and 64 km along the boundary between the states of Karnataka and Tamil Nadu. The Cauvery has 21 principal tributaries, with an average catchment area of around 250 km^2. The important tributaries are Arakavathy (length 170 km), Harangi (50 km), Hemavathi (234 km), Kabini (238 km), Lakshmana Thirtha (149 km), Shimsha (204 km) and Suvarnavathi (88 km). At the Hogenakal falls, it takes a southerly course and enters Tamil Nadu. Tributaries such as the Bhavani (235 km), Amaravathy (215 km) and Noyyal (182 km) join the river before it enters Tiruchirappalli city. At this stage the river widens into the 'Akhanda Cauvery', with a sandy bed, and flows in an easterly direction. Immediately below Tiruchirappalli city, at Upper Anicut, the Cauvery splits into two branches, the northern branch is known as the Coleroon/Kollidam (flood arm), and the southern branch is the Cauvery (the name of the main river as such). About 16 km below, the Cauvery and Coleroon meet again to form the island of Srirangam. The Grand Anicut is situated at this meeting point below the island and forms the head of the Cauvery delta and the fulcrum of the great irrigation system of the delta. (Mohanakrishnan, 2011). Below the Grand Anicut, the Cauvery branch further divides into two, the Cauvery and the Vennar; further down, it divides and sub-divides into numerous branches, spreading all over the Cauvery Delta (Mohanakrishnan, 2011).

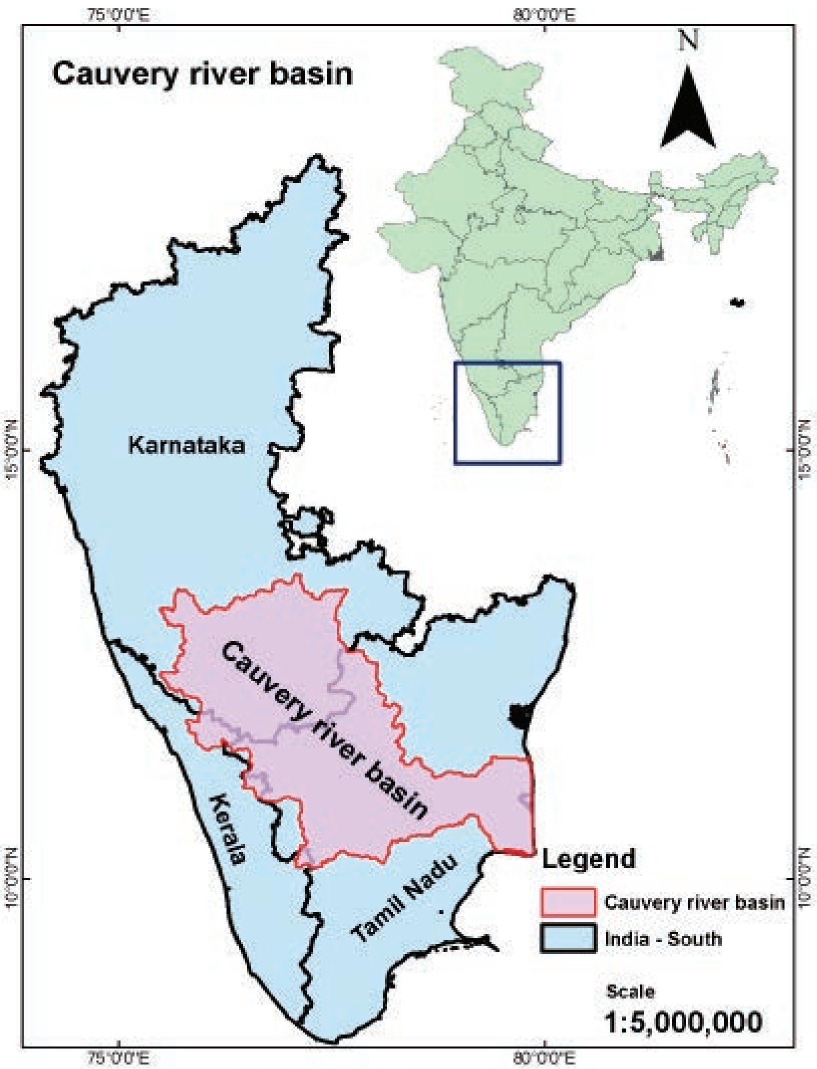


Figure 1.1 *Cauvery basin (Source: Aswin, 2018)*

In the Cauvery basin, 1% of the total geographical area falls between 2000 to 3000 m above main sea level (MSL), 32% falls between 750 to1000 m above MSL, and the rest falls below 750m. The areas under irrigation in the Cauvery basin are given in figure 1.2. The Western Ghats ranges in the Cauvery basin, located in Karnataka and Kerala, receive an annual rainfall between 1700 mm and 3800 mm, mostly during the south-west monsoon (June to September) season. On the other hand, most of the Cauvery basin in Tamil Nadu receives rainfall mainly during the north-east monsoon (October - December), ranging from 500 mm to 1000 mm. According to the agroclimatic zones, the Cauvery basin can be divided into three, hot humid to pre-humid ecoregion, hot semi-arid ecoregion and hot sub-humid to semi-arid ecoregion (MoWR 2014). The Western Ghats region of the basin falls in hot humid ecoregion; the central part in hot semi-arid ecoregion and deltaic part in hot sub-humid to semi-arid ecoregion. As per the Government of India Census (2011), the Cauvery B asin has a total population of 166.86 million, of which 60% live in rural areas and 40% in urban areas. In total, 66.21% of the total river basin is covered by agricultural land, 20.50% by forest area, 4.09% by water bodies and 4.01% by the built-up area.

The Cauvery basin has an average annual runoff of 21.35 billion cubic metres (BCM); the utilisable surface water potential is estimated at 19 BCM (MoWR 2014). There are 43 medium irrigation projects with the Cultural Command Area (CCA, it is the area in which crop is grown) between 20 and 100 km^2 and 16 major irrigation projects with CCA greater than 100 km^2. In the basin, there are 15 hydroelectric projects and 24 power houses. For development of water resources, 96 dams, 10 barrages (a concrete structure that consists of a series of large gates that can be opened or closed to control the amount of water that flows through them),16 weirs/anicuts (weir is simply a concrete or masonry structure that is built through an open channel or river) and nine lift irrigation projects have been constructed in the Cauvery basin (MoWR 2014).

The percentage of water utilised in the Cauvery River basin is the greatest in the county, as a result of which there are water sharing disputes among the riparian states (Raju and Nandagiri 2017). On 2 June 1990, the Cauvery Waters Disputes Tribunal (CWDT) came into existence, and on 25 June 1991, an interim award directed the state of Karnataka to release 205 TMC (5805 MCM) of water to the Mettur reservoir in Tamil Nadu in a 12-month period, from June to May. The Award came to effect in July 1991, and Tamil Nadu was directed to release 6 TMC (170 MCM) of water to Puducherry. In 2007, the Final Award was released, and the riparian state of Puducherry was awarded 7 TMC (198 MCM), Kerala 30 TMC (849 MCM), Karnataka 270 TMC (7641 MCM) and Tamil Nadu 419 TMC (11858 MCM). The award was based on the assessment that total yield of Cauvery River is 740 TMC at 50% dependability and it also sets aside 10 TMC (283 MCM) for environmental protection and 5 TMC (142 MCM) for the inevitable flow into the sea. The parties again approached the Supreme Court and the salient features of the court's verdict (February 2018) are - Karnataka to get 284.75 TMC (8058 MCM); Tamil Nadu 404.25 TMC (11440 MCM); and no change in the allocation to Kerala and Puducherry. The Court also noted that Tamil Nadu could safely make use of 10 TMC (283 MCM) of groundwater available in the Cauvery basin (Khosa and Kanapuram 2005; Javali 2015, SCI 2018).

Table 1.1 *Cauvery basin area and water yield (amount of freshwater derived from a given geographic area over a defined period of time)*

	Karnataka	Tamil Nadu	Kerala	Pondicherry
Basin area, (km2)	35018.11	47502.96	2948.4	154.98
Percentage area (%)	40.9	55.48	3.44	0.18
Yield contribution (MCM*)	12032	7134	3199	-
Percentage contribution (%)	53.8	31.9	14.3	-

**Data on the yield have been provided by the respective states.*

Photo credit: TNFD_Sathish

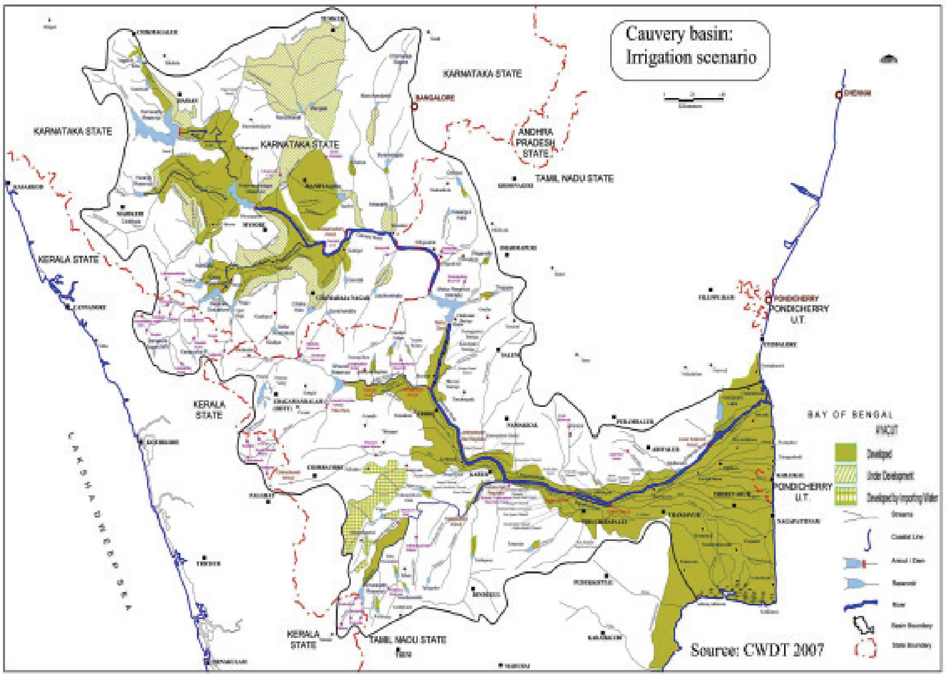


Figure 1.2 Cauvery basin: irrigation scenario

1.2 Cauvery Delta

The Cauvery River has built up a broad arcuate delta (igure 1.3), and Point Calimere Wetland complex is situated in the downstream reach of this fertile delta. The apex of the delta is located near Thanjavur town, from where the river has developed its distributaries, which span from Vedaranyam in the south to Coleroon river in the north. Its major distributaries are the Vennar, Vettar, Arasalar, Kodamurutti, Cauvery and Coleroon, from south to north. Currently, all these distributaries, except the Coleroon, express signatures of abandoned river courses/ palaeochannels, moreover the major fluvial and delta building activity is presently, in general, restricted only to the northern part of the delta along the course of the Coleroon river.

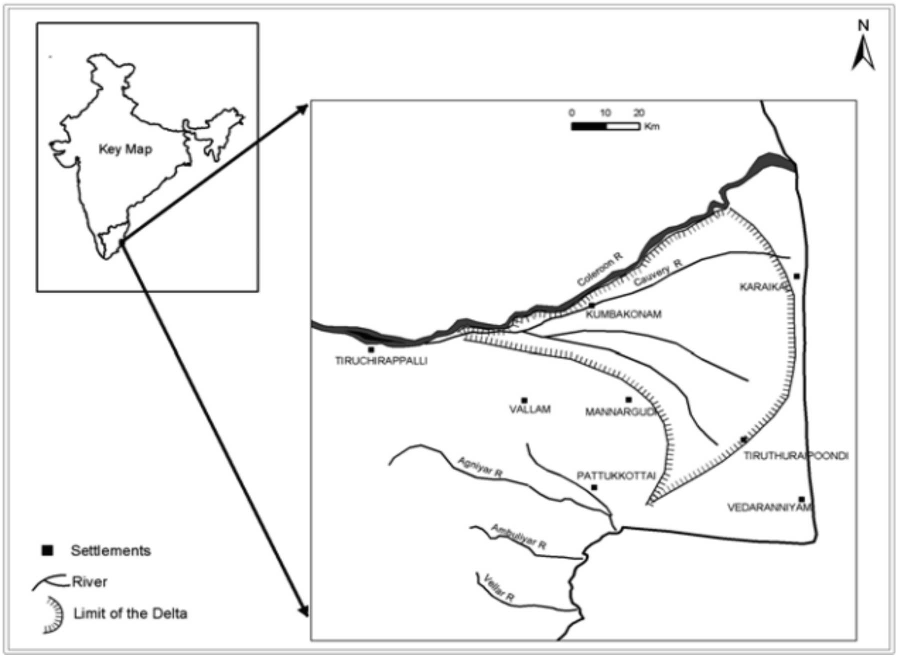


Figure 1.3 Arcuate delta of Cauvery (Source: Ramasamy et al., 2006)

The river Cauvery has developed its numerous branches downstream from Thanjavur onwards (figure 1.4). It is observed that the distributaries located along the southern part of the Vedaranyam nose have dried up and only the northernmost distributary (Coleroon) is showing strong fluvial action. This has made the southern part of the Cauvery delta abandoned and the northern part active. Due to the rapid emergence of the Pattukottai-Mannargudi Tertiary upland, the southern distributaries have dried up, thereby creating an abandoned delta in the south and an active delta in the north. The configuration of the beach ridges in the Tiruthuraipoondi-Kodiyakkarai area, their absolute age dating and integration of the elevation of the beach ridges with their C dates, all show that the sea has regressed nearly 32 km during the last 5000 years (Ramasamy, 2006). This indicates the impact of tectonic action over the fluvial activity.

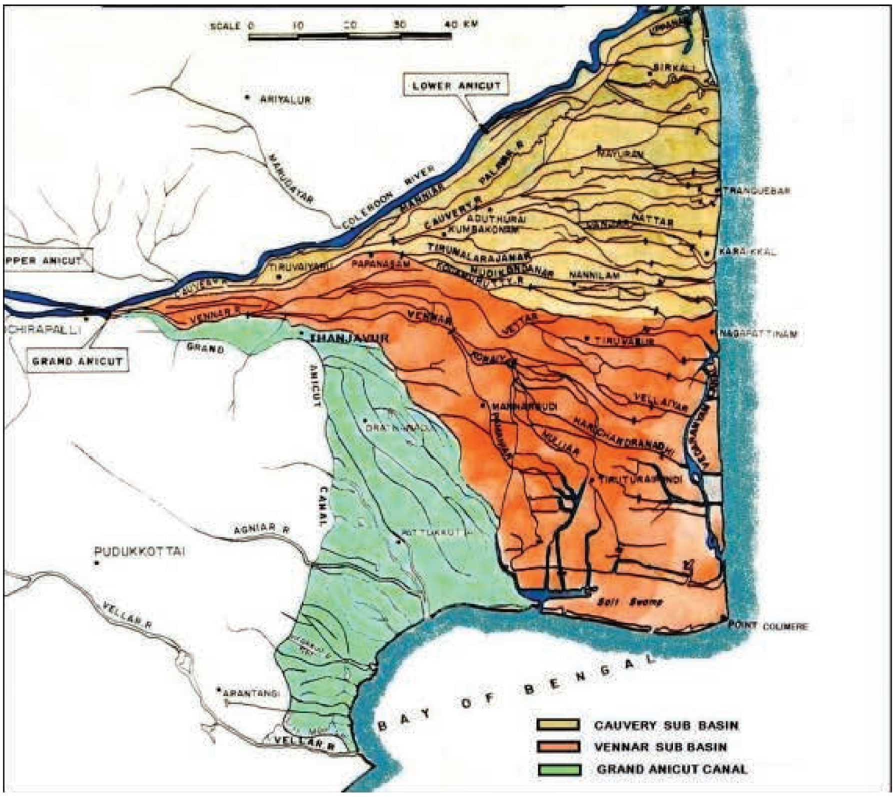


***Figure 1.4** Present Cauvery delta (Source: CWC website)*

The Cauvery delta has two distinct regions, the old natural delta region, irrigated by the Cauvery and Vennar branches, and new delta region, which is irrigated by the man-made Grand Anicut Canal. On the basis of the lithological and hydrogeological conditions, the Cauvery delta is divided into two sub-basins, the Cauvery and Vennar. The Cauvery sub-basin occupies the northern part of the Cauvery delta, enclosed by the Grand Anicut in the west, the Kollidam river in the north, the Bay of Bengal in the east and the Grand Anicut Canal, Vennar and Vettar River in the south. The Cauvery sub-basin has a width of 16 km on the west, and it gradually widens and attains a total width of about 58 km. The natural levee complexes made up of medium to coarse grained deposits are found in the fluvial deposits and natural floodplain deposits. The alluvium deposits in the sub-basin also consist of gravel, coarse sand, sandy clay and brown clay overlaid by a layer of silt deposits. The Vennar sub-basin has the Vettar River in the north, the Pamaniyar river in the west, the Palk Strait in the south and the Bay of Bengal in the east. The sediments in this region were deposited in semi-marine and marine environments, identified as fine sediments with erratic pockets of sand.

1.3 Vennar Sub-basin

The Vennar River originates from the Grand Anicut across the Cauvery River at 27.2 km below the Upper Barrage (figure1.5). It traverses through Thanjavur, Thiruvarur and Nagapattinam districts and empties into the Bay of Bengal by branching off into a number of distributaries. It irrigates an extent of 4.96 lakh acres in the three districts, besides serving as a drainage carrier. The Vennar trifurcates at Thenperambur Village (V.V.R. Head Regulator) into the Vennar, Vettar and Vadavar. The Vennar trifurcates again at Needamangalam Village (LS 96.120 km) into the Vennar, Koraiyar and Pamaniar (Koraiyar Head).

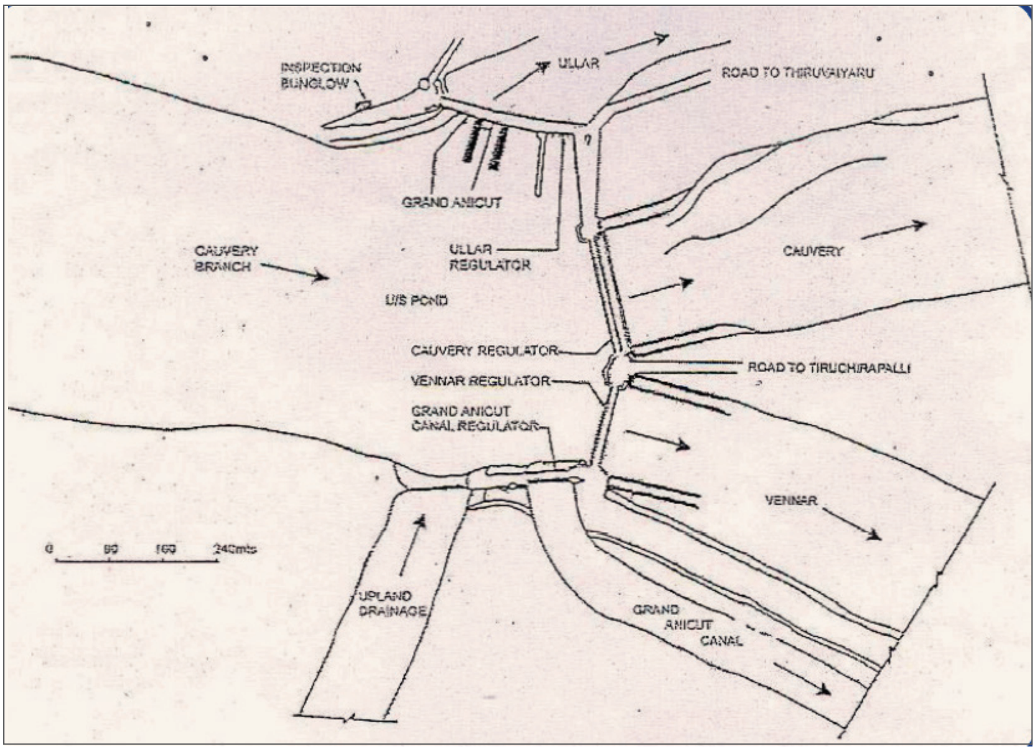


Figure 1.5 *Trifurcation at the Grand Anicut complex (Source: DPR, PWD, 2016)*

The main Vennar River again bifurcates into the Vennar and Pandavayar at LS 108.730 km. At LS 110.54 km, the Vennar again bifurcates into the Vellaiyar and Vennar and then Pandavayar River finally confluences into Vellaiyar River. The Koraiyar River branches into four (river-cum- drainage) at LS 122.150 km: the Koraiyar, Ayyanar, Mulliyar and Harichandranathi. The Mulliyar again bifurcates into the Mulliyar and Adappar at LS 130.236 km at Kottur village. All these branches, namely the Vellaiyar, Harichandranathi, Mulliyar, Adappar and Koraiyar, join the Bay of Bengal.

The river network of the Vennar sub-basin is shown in Fig. 1.6. Normally, floods are generated from the area below the Grand Anicut and a vast area lying south of the Grand Anicut Canal, surrounded by Kulathur, Gandarvakkottai, Vallam, Sengipatti and Thiruverumbur, spreading over four taluks, directly enter the Vennar River after crossing the Grand Anicut Canal. Whenever a heavy downpour occurs in the above-mentioned area, the Vennar S ub-basin experiences a flash flood or a flood caused by overflowing of river courses and channels.

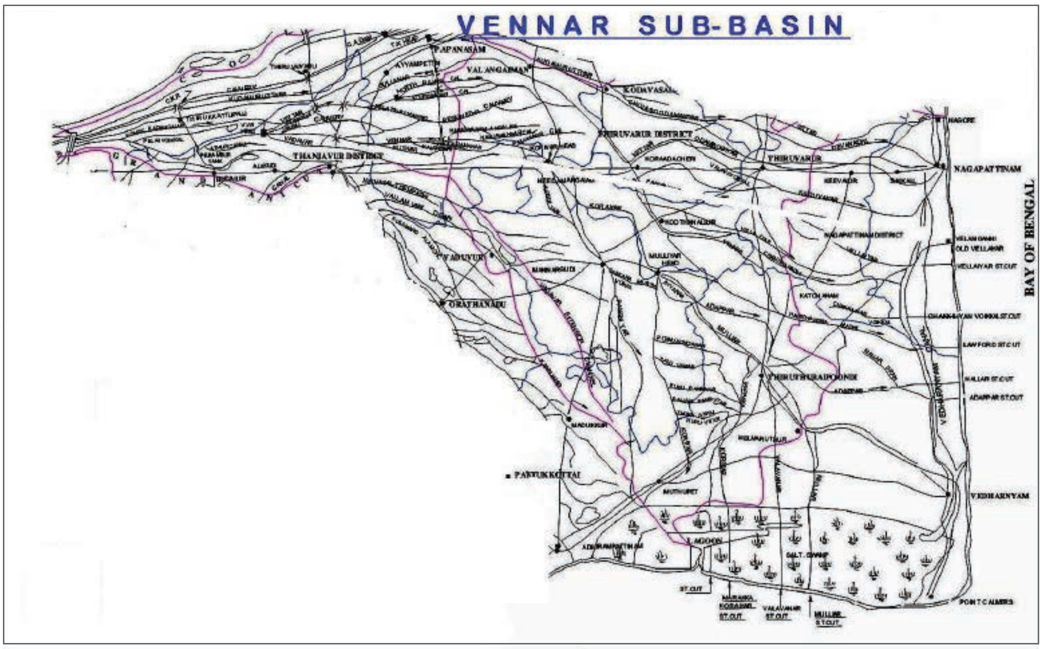


Figure 1.6 *The Vennar sub-basin (Source: DPR, PWD, 2016)*

The system has seven head regulators at major river bifurcation points, 188 intermediate regulators that facilitate the distribution of irrigation flows and 11 tail-end regulators (TERs). The TERs serve the dual purpose of raising water levels to provide irrigation to low-lying command areas near the coast and prevent tidal backwater flows into the system. When heavy rainfall occurs and drainage congestion takes place, the TERs are opened to allow outflows, although high tides and storm surges restrict discharges into the sea.

1.4 Point Calimere Wetland Complex

The Point Calimere Ramsar Site, located in the Vennar Sub-basin, spreads over the districts of Nagapattinam, Thiruvarur and Thanjavur (figure 1.7). The Point Calimere Ramsar Site is a complex wetland composed of lagoons, small bays, creeks, tidal swamps, intertidal mudflats, mangroves, grasslands, sand dunes and dry evergreen forest. The wetland complex also includes agriculture wetland, saltpans and aquaculture farms. The Point Calimere Ramsar Site may be divided into the Point Calimere Wildlife and Bird Sanctuary, and the Great Vedaranyam Swamp (GVS), which includes the mangrove forests of Muthupet and the mangroves of Talaignayar Reserve Forest (TRF). This complex was declared as a Ramsar site in August 2002, owing to the compliance with the criteria - the wetland supports globally threatened ecological communities; the wetland provides refuge during adverse conditions to threatened species; and the wetland regularly supports 20,000 or more water birds.

The Point Calimere Wildlife Sanctuary with an area of about 2,717 ha, forms the eastern boundary of the Ramsar Site and the Muthupet Mangroves, with an area of 11,900 ha, occupy the westernmost part of the site. The Mullipallam lagoon associated with the Muthupet Mangroves is 8 km from the nearby Muthupet town and is accessible only by boat. The entire mangrove forest in the Ramsar Site is presently divided into Palanjur Reserve Forest, Thamarankottai Reserve Forest, Maravakkadu Reserve Forest, Vadakadu Reserve Forest, Thuraikadu Reserve Forest and Muthupet Reserve Forest as shown in figure 1.8. The Muthupet Lagoon and the associated inlets and freshwater drainages to these wetlands are shown in figure 1.9. The distributaries of the Cauvery, viz., the Paminiyar, Koraiyar, Nasuvanniyar, Pattuvanachiayar, Kandakurichan, Kilaithangiyar and Marakkakoraiyar, discharge their waters into the wetlands and form a lagoon and tidal channels before reaching the sea.

The wetland complex receives inflows of freshwater during the north-east monsoon, in the months of November and December, which enrich the agricultural soils, mangrove swamps and aquaculture farms. From February to June, the freshwater discharge into the mangrove wetland is insignificant. The soil in the estuary is clayey silt, and towards the landward side, it is silty clay due to fresh silt deposits. The Survey of India toposheets 58N/7, 58N/11, and 58N/15 (on a 1:50,000 scale) cover this wetland system.

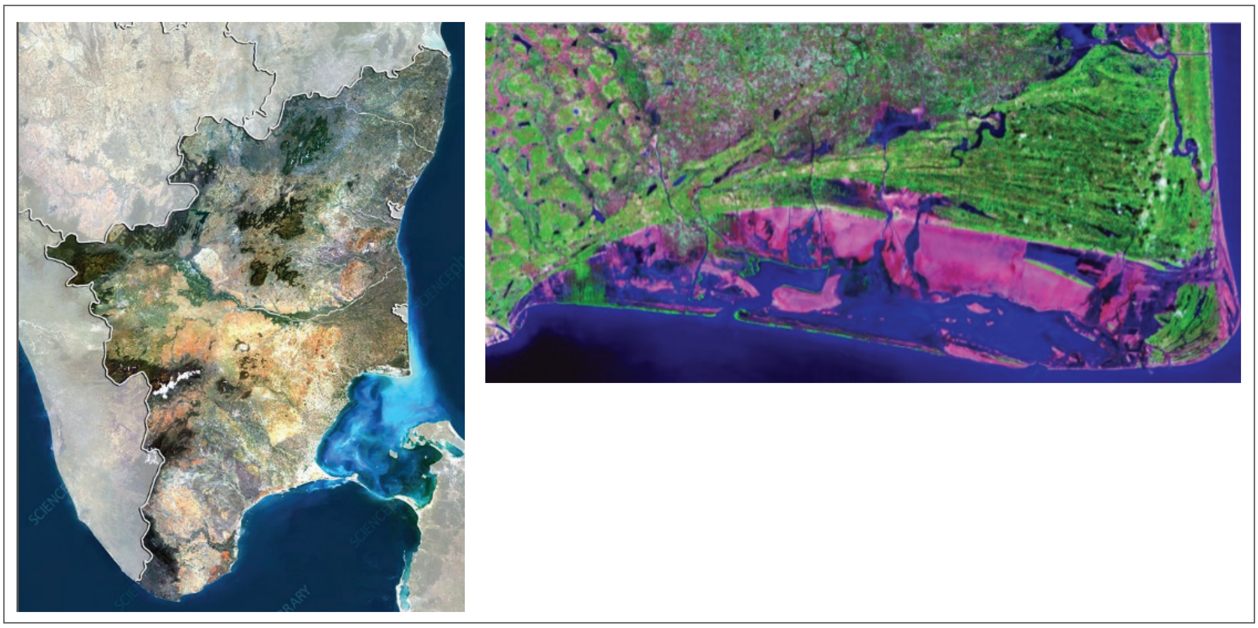


Figure 1.7 *Location map of the wetland system*

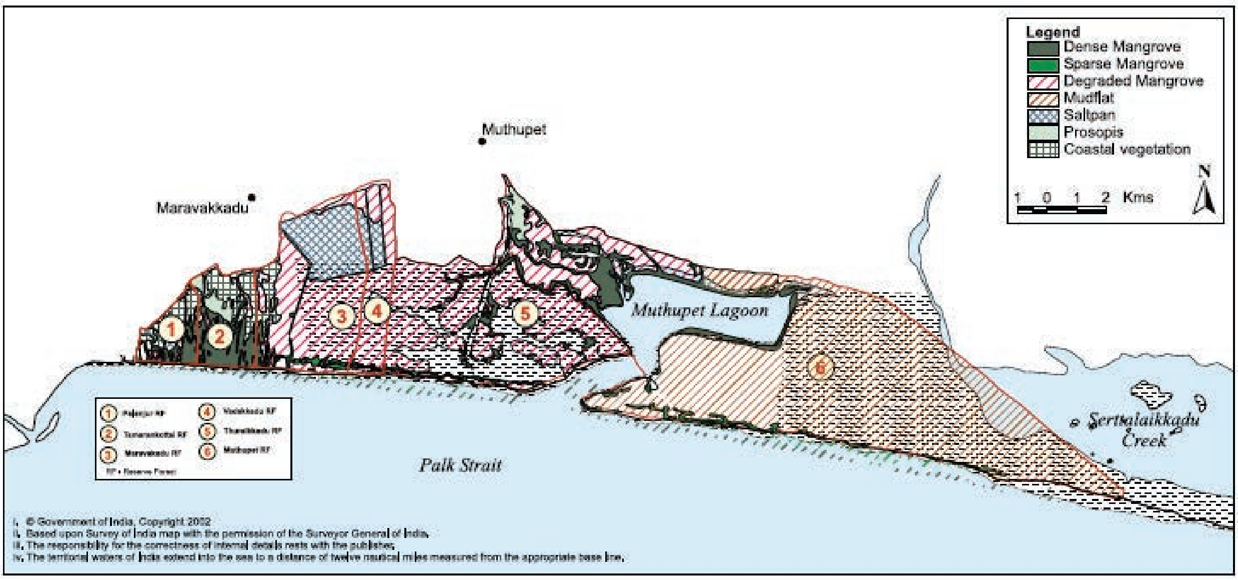


Figure 1.8 *Reserve Forests around the estuary and inlets (MSSRF, 2002)*

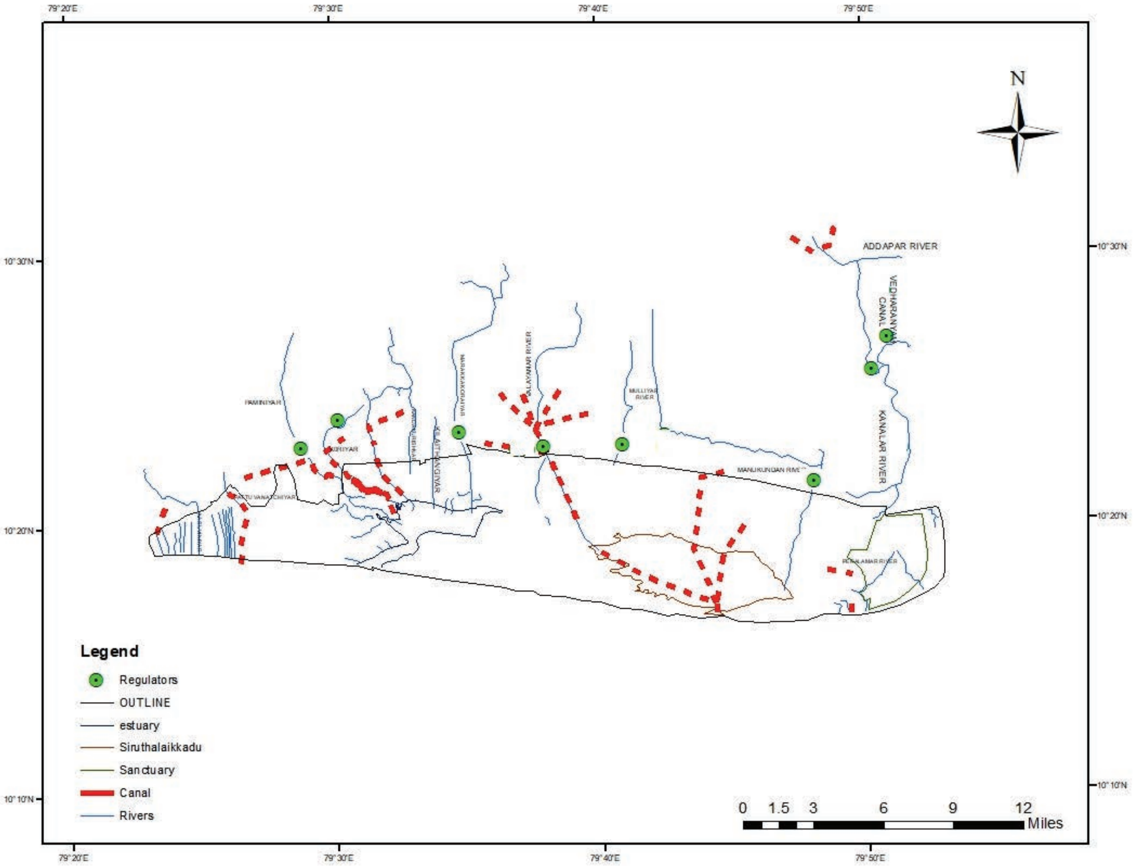


Figure 1.9 *Natural channels and artificial canals in the wetland complex*
(Source: Atlas of Mangrove Wetlands of India, MSSRF, 2002)

The Point Calimere Ramsar site is bordered by a number of farming and fishing villages as shown in Table 1.2. As indicated in the table, one municipality - Vedaranyam - and two town panchayats - Thalainayar and Muthupet - are located along the border.

Table 1.2 *List of districts, taluks and villages in the Point Calimere Wetland Complex*

Sl. No	Districts	Thaluks	Village Name	Area (ha)	Population
1	Nagapattinam	Vedaranyam	Kallimedu		
2			Kodiakarai	694	2118
3			Kodiakkadu	570	3085
4			Pachanathikulam Middle	676	3115
5			Talanayar town panchayat	4905	12798
6			Vedaranyam municipality	3626	34266
7	Thiruvarur	Thiruthuraipoondi	Jambuvanodai	1078	3839
8			Thillaivilagam	2086	6298
9			Muthupet town	1190	24004

Sl. No	Districts	Thaluks	Village Name	Area (ha)	Population
10			Thuraikadu	405	2820
11	Thanjavur	Pattukkottai	Adiramapattinam	1280	31066
12			Eripurakarai	995	4285
13			Narasingapuram	60	1848
14			Palanjur	1476	2070
15			Pudukkottagam	617	35
16			Thamarankottai South	1278	3120
17			Thambikottai Maravakad	2665	2721
18			Thambikottai Melakkadu	653	2613
19			Thambikottai Vadakadu	1292	3338

1.5 Drivers and Assessment Tools

Indicators play an important role by reflecting the overall status, trends of ecosystems and their values, thereby helping to identify the most urgent environmental problems to address, while also helping to set up policy priorities (figure 1.10). In addition, they are the keys to target setting, policy, and instrument design and evaluation, as they can be used to assess the extent of contribution a certain policy has in the achievement of a desired policy objective. It is important, therefore, to identify and use indicators which capture the different dimensions of values of water and wetlands that are useful in practical decision making.

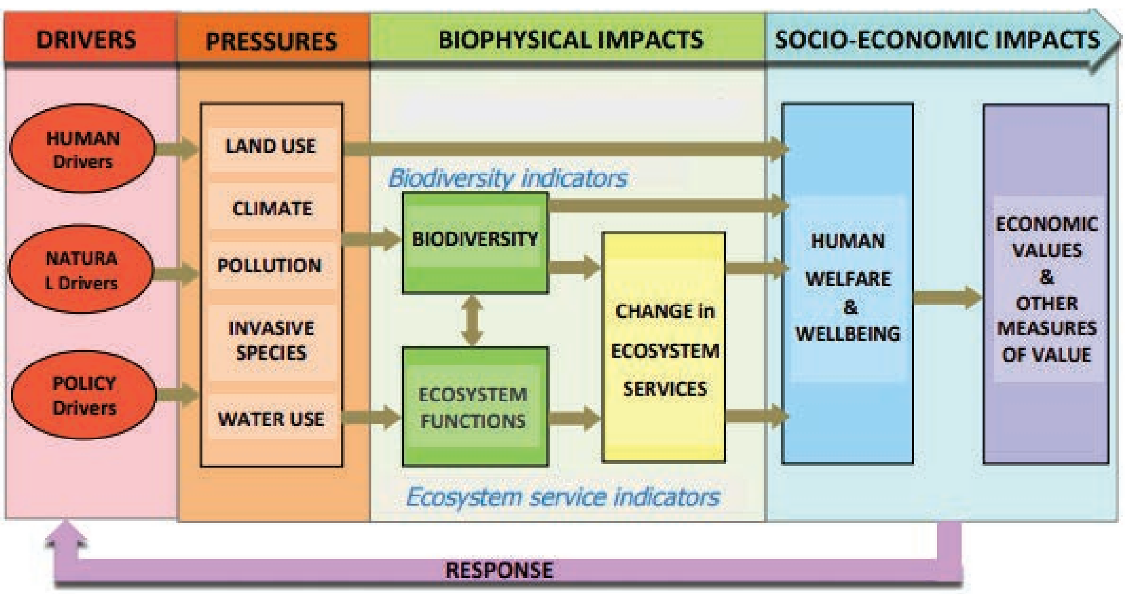


Figure 1.10 *Drivers, indicators and assessment tools*

1.6 Methodology

The general methodology followed in the assignment includes:

- Field visits
- Field data collection
- Field experiments
- Discussions with stakeholders, including government officials
- Collection of secondary data
- Collection of satellite imagery, maps and reports
- Analysis of data and modelling
- Interpretation of data
- Presentation of data on a spatio-temporal platform and identifying the indicators of change and direct and indirect drivers of change and drafting recommendations for management action plans and policy requirements

In order to understand the changes to the land use and land cover with time and space, mainly due to human intervention, an attempt has been made to study the land use and land cover (LULC) of the entire Cauvery Basin and the direct catchments and buffer zone of Point Calimere Wetland complex. These studies have been carried out using the data for the past three to five decades to understand the impact of LULC on the hydrology and sediment yield in the respective basins, sub-basins and buffer zone of Point Calimere Wetland Complex. The changes to the morphometric characteristics of the individual wetland ecosystems were also studied for the period from 1970 to 2020. A detailed study on the rainfall characteristics of Cauvery Delta and the wetland complex was carried out. The data from 35 rain gauge stations for a period of 23 years were made use of in this study. The study deals with the long-term variability, trend analysis, precipitation concentration index, seasonality index, departure analysis, flooding of wetlands during the north-east monsoon and impact of El Nino global parameters. Attempts were also made to estimate the extreme rainfall events as recommended by IPCC for understanding the impact of climate change on the study area. Moreover an attempt has been made to analyse the streamflow data pertaining to the Cauvery and Vennar sub-basins for three decades to find out the variations in flows. The flow characteristics before and after the Interim Award 1991 and Final Award of 2007 of CWDT were analysed. Apart from that, the flow hydrographs of the distributaries flowing into the wetland complex were drawn on the basis of recent data provided by the PWD, Tamil Nadu. All these provide required knowledge on the present status of allocation of water to the delta and the wetlands and help in recommending management action plans with regard to the operation of regulators.

The SWAT model was applied to find out the variations in the water and sediment yield, the streamflow and the changes in temperature and evapotranspiration in the four representative sub-basins of Cauvery, located at different elevations from the mean sea level in areas with a humid tropic and semi-arid climate. The model was applied considering the entire Cauvery Basin as one unit and the results of the SWAT model in the direct catchments of the wetlands are also described. These studies are expected to be useful in appreciating the impact of changes in the catchments on the hydrology during different timeframes.

The hydrodynamics and fluvial hydraulics of Muthupet Estuary were studied to understand the mixing and circulation processes and sediment dynamics. The flows to be maintained to bring down the salinity levels to cater to the ecosystem services were estimated. The findings would help in developing management action plans and policies for the wetland complex. The changes to the morphometry of the coast on the southern and eastern side of the wetland complex were studied to understand the vulnerability of the shoreline to coastal processes. The impact of coastal erosion on the wetland ecosystems was also investigated to come out with management action plans. In addition, the impact of inundation of wetlands and the buffer zone due to the projected sea level rise has been studied to help develop strategies for future management of these wetlands in the context of climate change.

2. ASSESSMENT OF LAND USE AND LAND COVER CHANGES: CAUVERY BASIN AND POINT CALIMERE WETLAND COMPLEX

2.1 Introduction

Land use and land cover (LULC) change generally denotes the conversion of different land use types, which is the result of complex interactions between humans and their physical environment. LULC is a major force in driving global change and has a significant effect on ecosystem processes, biodiversity and biological cycles (Shailesh et al., 1985, Ramasamy et al., 1995, Ramasamy et al., 2006, Nirmal et al., 2018). For identifying land cover, it is necessary to establish a baseline against which changes can be monitored. The most popular and precise methodology to understand LULC change is based on remote sensing techniques, including information gathered by aerial photography and satellites. For interpretation of remote sensing imagery, a wide range of methods exist, which include, fully automated (supervised algorithm), semi-automated and visual interpretation (Francisca et al., 2008, Fetriyuna et al., 2017, Bong et al., 2018). LULC change in due course alters the morphometry of ecosystems – linear, areal and relief aspects (Venugopal and James, 1996). Morphometric analysis is the quantitative description and analysis of landforms that is applied to a particular kind of landscape or a drainage basin. The drainage morphometric characteristics are important to understand the underlain structures, geomorphological formations and hydrological characteristics of the drainage and the wetlands within it. The linkages between LULC changes and morphological parameters enable wetland managers to perceive threats to a wetland ecosystem. This chapter deals with the land use and land cover change studies at four levels, namely, the basin, direct catchment, buffer zone and wetland complex as such. The quantitative geomorphic parameters have also been estimated for the delta, direct catchment and Point Calimere Wetland Complex. The four levels separately considered in the analysis are defined and described in the following sections.

The Basin

A river basin is an area drained by a network of tributaries of different orders. Every stream and tributary in a basin has its own watershed of different orders, which drains to a larger stream or a wetland. The streams, ponds, wetlands, and lakes form part of the river basin.

The Direct Catchment

The distributaries of the Cauvery riverine system, namely, the Paminiyar, Koraiyar, Kandankurichaan channel, Kilaithangiyar, Marakkakoraiyar, Valavanar, Mulliyar and Manakundan, drain into the wetland complex though most of them are regulated upstream. In addition to this, the Nasuvanniyar and Pattuvanachiyar flow into the Palanjur, Maravakkadu, Thamarankottai and Vadakkadu Reserve Forests of the Muthupet mangroves. The direct catchment of the Point Calimere Wetland Complex has been delineated as a combined catchment of all these distributaries and drainage channels. The total area of the direct catchment of the wetland complex is 1957.21 km^2. Around 323 villages are situated within the direct catchment boundary. The names and respective areas of the villages in the direct catchment, indicated in figure 2.1, are given in Table A1 (Annexure A). The direct catchment has been treated separately since it plays an important role in the water balance, water quality and ecosystem services of the wetlands.

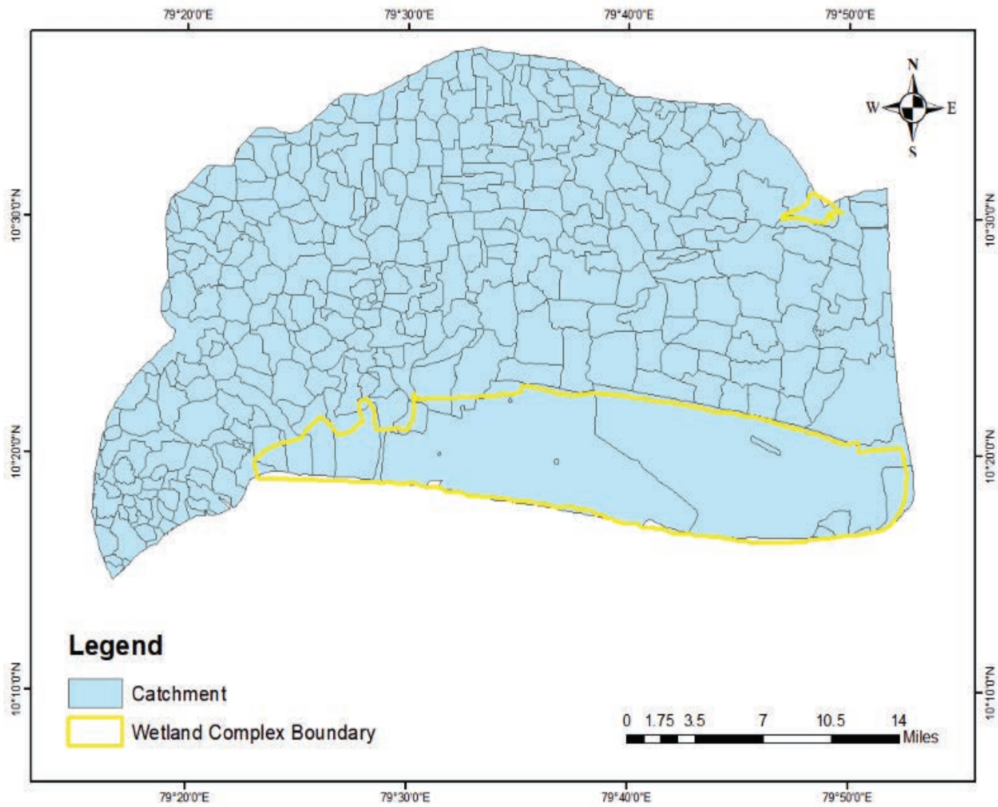


Figure 2.1 *Villages in the direct catchment and the wetland complex*

The Buffer Zone

In the present analysis, a buffer zone up to a distance of 15 km from the boundary of the wetland complex has been considered, which also includes the fringes of Thalainayar Reserve Forest. Physiographically, the slope of the land is from 15 km on the north to the south - upland from the boundary of the Point Calimere Wetland Complex - beyond which the slope is towards the east. The changes in water flow and water quality due to anthropogenic and natural causes to a great degree depend on the slope and finally on the hydraulic gradient. The management of buffer zone is crucial to the water balance, water quality, sediment and pollution transport to the wetland complex and subsequently to the ecosystem services. The total area of the buffer zone of the wetland complex is estimated as 1355 km^2 and around 195 villages are situated within the buffer zone of the Point Calimere Wetland Complex. The names and respective areas of villages in the buffer zone, indicated in figure 2.2, are given in Table A2 (Annexure A).

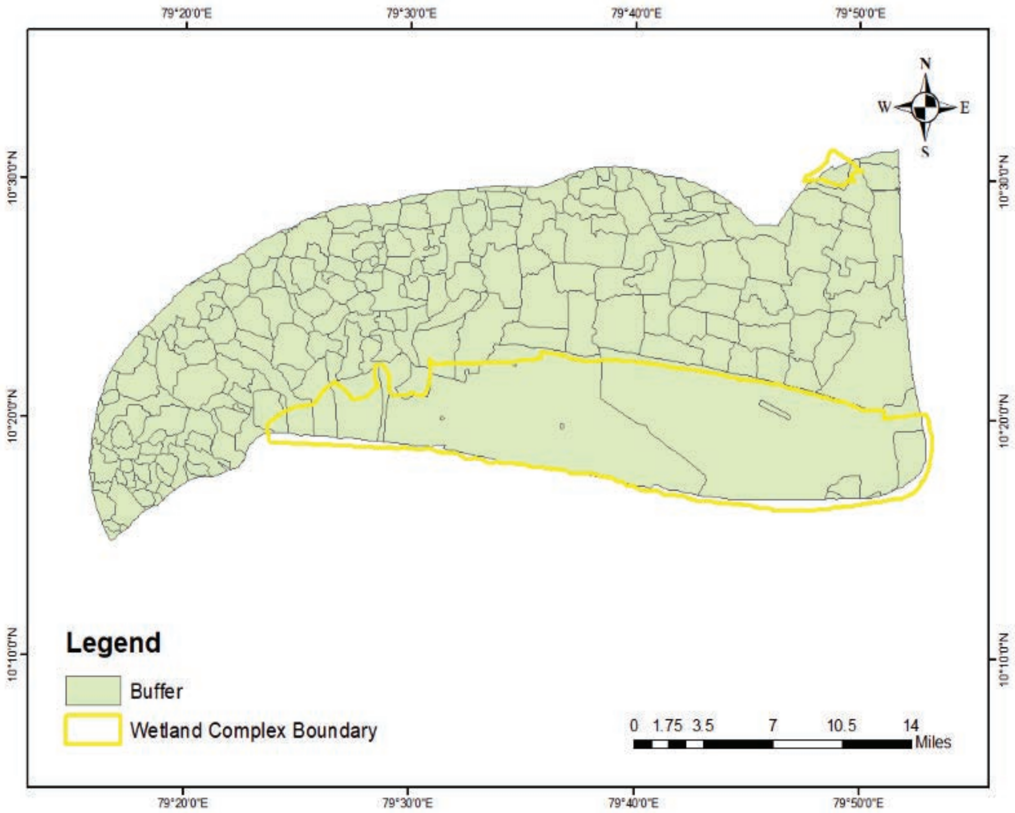


***Figure 2.2** Villages in the wetland complex and its buffer zone*

The Point Calimere Wetland Complex (Ramsar site)

The Point Calimere Wetland Complex comprises of natural and man-made ecosystems that are often inter-connected. The major components identified in the complex are the Point Calimere Wildlife and Bird Sanctuary, the Muthupet lagoon, the Siruthalaikadu lagoon/inlet, mangroves, mudflats, saltpans, aquafarms and the shoreline. This classification is adopted in the present study, considering the morphometry, hydrologic and hydrodynamic processes, sediment dynamics, ecological and biodiversity characteristics and ecosystem services of these specific aquatic and terrestrial ecosystems. The documents available with the Forest Department of Tamil Nadu were also referred to in classifying these ecosystems of the Ramsar Site. The total area of the direct catchment of the wetland complex is 1957 km^2, and the actual area of Point Calimere Wetland Complex per se is 385.40 km^2, encompassing three villages, Kodiakkarai, Kodiakkadu and Siruthalaikadu.

2.2 Database

In the present study, the analysis of LULC changes in the Cauvery basin, direct catchment and buffer zone, Point Calimere Wetland Complex were carried out utilising the satellite imagery corresponding to Landsat 4, 5, 8 and Sentinel 2 images shown in Table 2.1. In the case of the direct catchment and buffer zone, Survey of Indian toposheets (1970) were also used.

Table 2.1 Satellite data used for LULC in Cauvery basin, direct catchment and buffer zone

Year	Period considered	Date	Satellite image/Toposheet
1970			Survey of India Toposheet (direct catchment and buffer zone)
1990	1990–1991	25 October 1990	LANDSAT 5
2000	2000–2001	15 December 2000	LANDSAT 5
2010	2010–2011	16 October 2010	LANDSAT 8
2020	2019–2020	7 October 2020	SENTINEL 2

Sentinel 2 has 13 bands that include aerosol detection bands as well as water vapour and cloud discrimination bands, while bands 2-8 help in vegetation classification. With regard to the resolution, bands 2, 3, 4, and 8 have 10-m resolution while bands 5, 6, 7, and 8A have 20-m resolution. The nearest neighbour resampling was performed on the 20-m bands to obtain an image with uniform 10-m resolution. Landsat images were downloaded from the USGS Earth Explorer platform for the period spanning from 1990 to 2020. Landsat Operational Land Imager multispectral bands 1-7 have 30-m spatial resolution, whereas panchromatic band 8 has a resolution of 15 m. In the Landsat bands, nearest-neighbour resampling was performed on the 15-m band for uniformity. Resampling to a higher and common pixel size for the three sets of imagery introduced a smoothing effect and subsequent loss of spatial accuracy and ability to discriminate features. The visible, near-infrared and short wave infrared bands are identified as optimal bands for wetland mapping due to their spectral signatures. The red and near-infrared regions of the spectrum are suitable for mapping vegetation due to their ability to recognise the plant biochemical properties. Figure 2.3 shows the bands utilised in each of the sensors for the study.

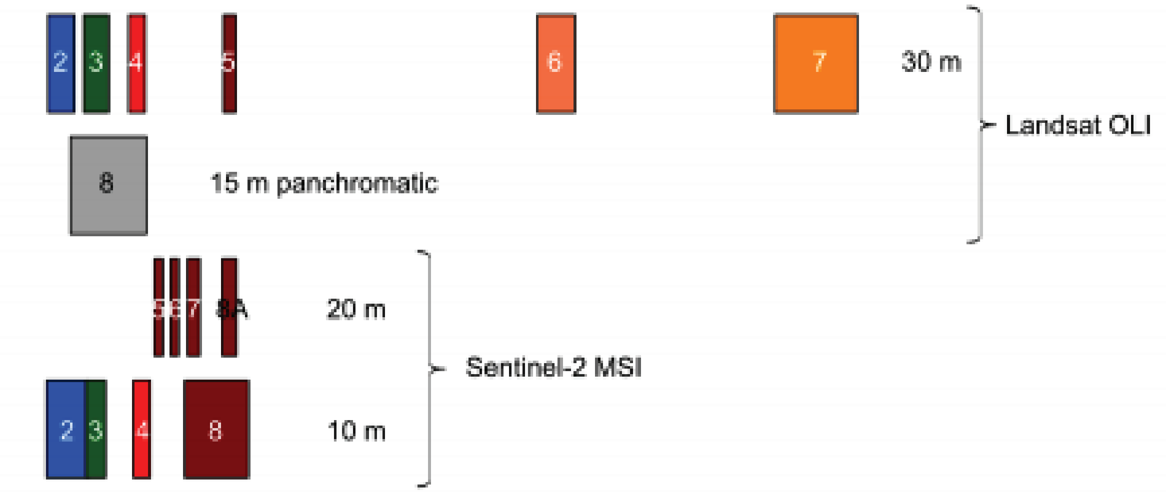


***Figure 2.3** Sensors and bands in the Sentinel-2 and Landsat imagery*

The land cover and land use maps for the Cauvery basin were prepared for estimating the decadal changes from 1990 to 2020.

2.3 Methodology

The land use and land cover classification scheme shown in Table 2.2 was followed for the analysis.

Table 2.2 *Land use/land cover (LULC) classification scheme and description of classes for Cauvery basin*

Land use type	Description
Inlet	The word 'inlet' refers to the shallow body of saltwater or brackish water having communication with the sea with practically no freshwater flow from upstream into it.
Lagoon/estuary	A lagoon is an area where a freshwater river or stream debouches its water before meeting the ocean. In lagoons and estuaries, the sea water mixes with the freshwater, resulting in brackish water. The wider part of the Muthupet Lagoon closer to the mouth can be considered as a complex lagoon with more than one stream/river joining it. The Muthupet Lagoon is surrounded by mudflats.
Water Bodies	All other surface water bodies other than the Muthupet Lagoon and inlets are designated as just 'Water Bodies'
Muthupet mangroves	Muthupet mangrove forest is located at the southern end of the Cauvery Delta, which has extended close to the Siruthalaikadu Lagoon
Cultivated land	Cultivated land is those lands subjected to ploughing and sowing and raising crops
Open scrub	Vegetation that is grown at low altitude areas; it is located close to Point Calimere Wildlife Sanctuary
Aqua farm	Aquaculture, also known as aquafarming, is the farming of fish, crustaceans, molluscs, aquatic plants, algae, and other organisms. Aquaculture involves cultivating freshwater and saltwater populations under controlled conditions and can be contrasted with capture fishery, which is the harvesting of wild fish.
Barren land	'Barren land' denotes an area of land where plant growth may be sparse or stunted or contains limited biodiversity: barren lands include deserts, dry salt flats, beaches, sand dunes, exposed rock, strip mines, quarries and gravel pits
Settlement	Land covered by buildings and other man-made structures
Mudflats	Mudflats or mud flats, also known as tidal flats, are coastal wetlands that form in intertidal areas where sediments have been deposited by tidal or riverine action.
Saltpan	Natural saltpans or salt flats are flat expanses of ground covered with salt and other minerals, usually shining white under the sun.

Image classification is performed to segregate the LULC classes in the study area. The satellite imagery is pre-processed using ortho-rectification, co-registration, atmospheric correction, cloud and shadow removal and selection of training and validation sets. Ortho-rectification is the process of removing the effects of image perspective (tilt) and relief (terrain) for the purpose of creating a planimetrically correct image. Atmospheric correction is the process of removing the effects of the atmosphere on the reflectance values of images taken by satellite or airborne sensors (figure 2.4). On the other hand, cloud and shadow removal is done to reduce the effects of noise due to clouds. In this study, supervised classification (maximum likelihood algorithm) and a human-guided approach is considered. In this classification, the user selects a few pixels that represent a specific class referred to as training samples (figure 2.4). These training samples are used to classify the other pixels having similar values into specific classes. The knowledge of the study area, false colour composition (FCC) and NDVI images generated from the optical images form the basis for training and validation of data.

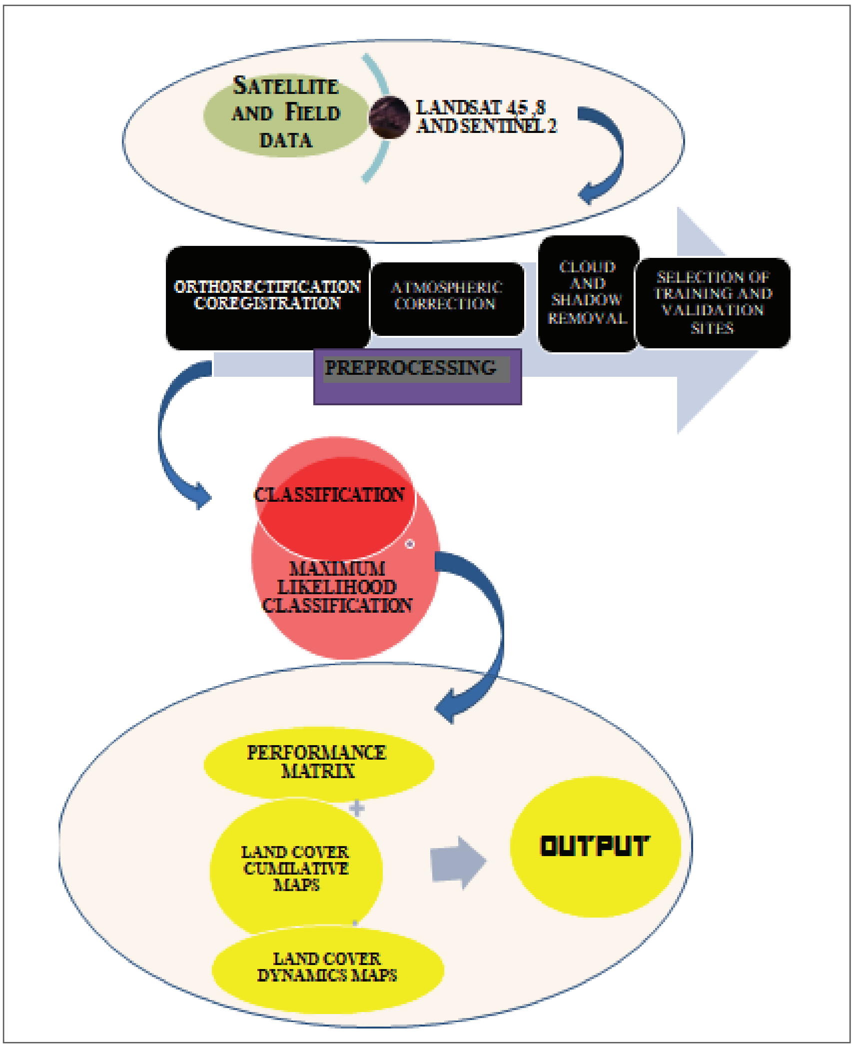


Figure 2.4 *Schematic representation of LULC mapping*

In the morphometric analysis, there are basically three aspects, namely, linear, areal and relief parameters. Linear aspects provide information on one-dimensional parameters such as stream order, stream number and bifurcation ratio, while areal aspects deal with two- dimensional parameters, namely, drainage density, stream length, stream length ratio, drainage texture, stream frequency, circularity ratio and form factor, and relief aspects represent three-dimensional parameters, including relief, relief ratio, slope and gradient ratio. The Shuttle Radar Topography Mission (SRTM) digital elevation model, with a resolution of 90 m, was downloaded from USGS Earth Explorer. Using the DEM of the sub-basins, the slope and aspect maps were generated. The methodology followed for morphometric analysis of the Cauvery delta, direct catchment of Point Calimere Wetland Complex and Point Calimere Wetland Complex as such is given in figure. 2.5.

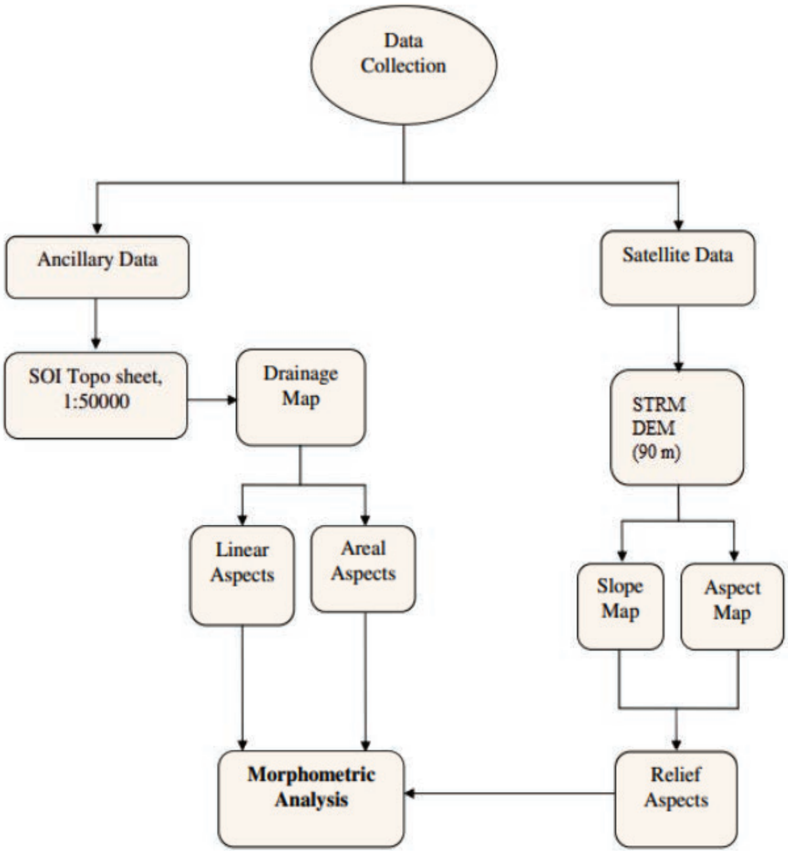


Figure 2.5 *Methodology for morphometric analysis*

2.4 Results and Discussion

2.4.1 Land Use Land Cover Changes: Cauvery Basin

The changes in various land use categories in the Cauvery basin during the years 1990, 2000, 2010 and 2020 are given in table 2.3 and figure 2.6. The largest portion of the basin is composed of crop land and fallow land, which together account for nearly 60% of the basin. This is followed by plantations and deciduous forests. Other classes such as scrubland, mixed forest, grassland and permanent wetland cover less than 2% to 3% each. Futhermore waste land and barren land occupy the minimum area.

Table 2.3 *Distributional percentages of classes in Cauvery basin from 1990 to 2020*

Class	1990	2000	2010	2020
Deciduous forest	11.39%	11.12%	10.77%	10.41%
Crop land	33.22%	32.63%	32.31%	31.91%
Built-up area	1.78%	2.14%	2.97%	4.02%
Mixed forest	2.29%	2.08%	1.91%	1.71%
Scrubland	3.23%	2.84%	2.34%	1.84%
Barren land	0.26%	0.22%	0.18%	0.13%

Class	1990	2000	2010	2020
Fallow land	20.25%	22.48%	24.78%	27.35%
Waste land	0.69%	0.56%	0.41%	0.12%
Plantations	17.36%	16.87%	16.03%	15.11%
Grassland	1.96%	1.85%	1.49%	1.11%
Evergreen forest	4.44%	4.17%	3.88%	3.39%
Water	2.72%	2.71%	2.68%	2.66%
Permanent wetland	0.41%	0.32%	0.26%	0.23%

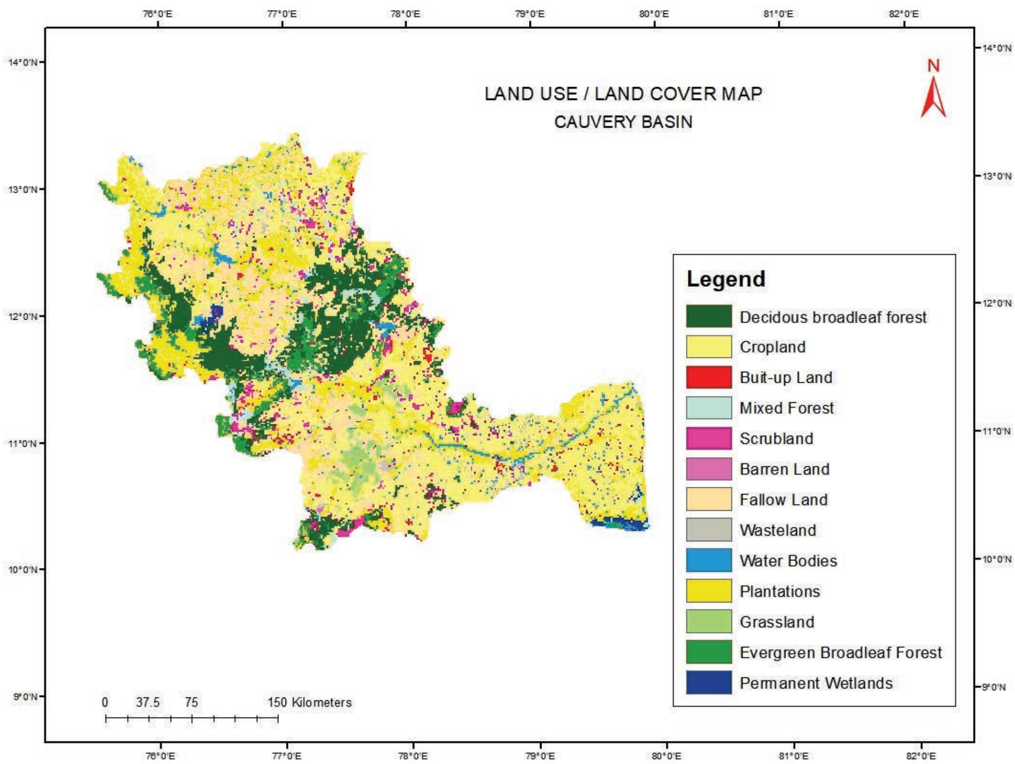


Figure 2.6 *Land use map of the Cauvery basin for 2020*

Regarding changes in the LULC between 1990 and 2020, the highest variation is seen in fallow land, with an increase of 7.09% in the total area followed by area under plantations, which shows a 2.25% decrease. Another class that shows an increasing trend is built-up land, with a 2.23% increase (Table 2.2). There is a considerable decrease in scrubland, crop land, evergreen forest, deciduous forest, grassland, mixed forest and waste land, at a rate of 1.38%, 1.3%, 1.04%, 0.98%, 0.85%, 0.58% and 0.57%, respectively. Permanent wetland, barren land and water bodies remain almost constant with less-than-0.2% changes. Both evergreen and deciduous forest areas are also on the decline since 1990, along with other forms of vegetation such as grasslands, scrub jungle, mixed forests and plantations.

Table 2.2 Changes in areas under different land use categories

Sl. no.	Land use category	Area (km^2) (1990)	Area, km^2) (2020)	% Change	Trend
1.	Crop land	26942.91	25898.59	1.30	Decreasing
2.	Built-up area	1446.22	3262.06	2.24	Increasing
3.	Mixed forests	1858.91	1383.02	0.59	Decreasing
4.	Barren land	207.98	104.61	0.13	Decreasing
5.	Plantations	14079.09	12261.99	2.25	Decreasing
6.	Permanent wetland	330.94	190.22	0.17	Decreasing

The projected changes in LULC in the Cauvery basin in 2030 is given in Table 2.3. The same trend of the past decades is assumed because the scope for drastic changes is limited, the conservation of forests has been streamlined and the water and land available for irrigated agriculture have come to a saturation level. However, urbanisation is expected to escalate, and the associated built-up areas, industrial clusters and infrastructural facilities are also expected to increase.

***Table 2.3** Projected LULC in Cauvery basin for the year 2030 (percentage shown in parentheses shows the trend compared with 2020; -, decrease; +, increase)*

Class	2030	Class	2030
Deciduous forest	10.21% (-0.20)	Waste land	0.089% (-0.03)
Crop land	30.25% (-0.66)	Plantations	14.32% (-0.79)
Built up area	5.12% (+1.10)	Grassland	0.86% (-0.25)
Mixed forest	1.58% (-0.13)	Evergreen forest	2.67% (-0.72)
Shrub land	1.26% (-0.58)	Water	2.64 (0.02%)
Fallow land	30.12% (+2.77)	Permanent land	0.17% (-0.06)

The major concern of the present investigation is how the land use changes are impacting the streamflow pattern in the Cauvery B asin, which can be taken as an indicator of the impact of land use change on hydrology. Moreover it was observed that the seasonal flows had a definite correlation with rainfall.(figure 2.7, figure 2.8 & figure 2.9)

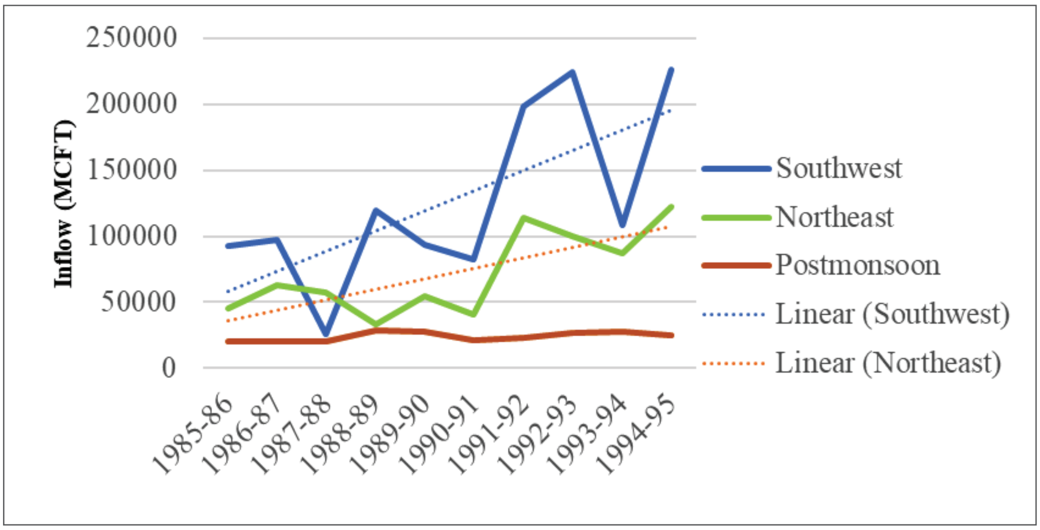


Figure 2.7 *Flows to Mettur reservoir (Tamil Nadu) during 1985 - 1995*

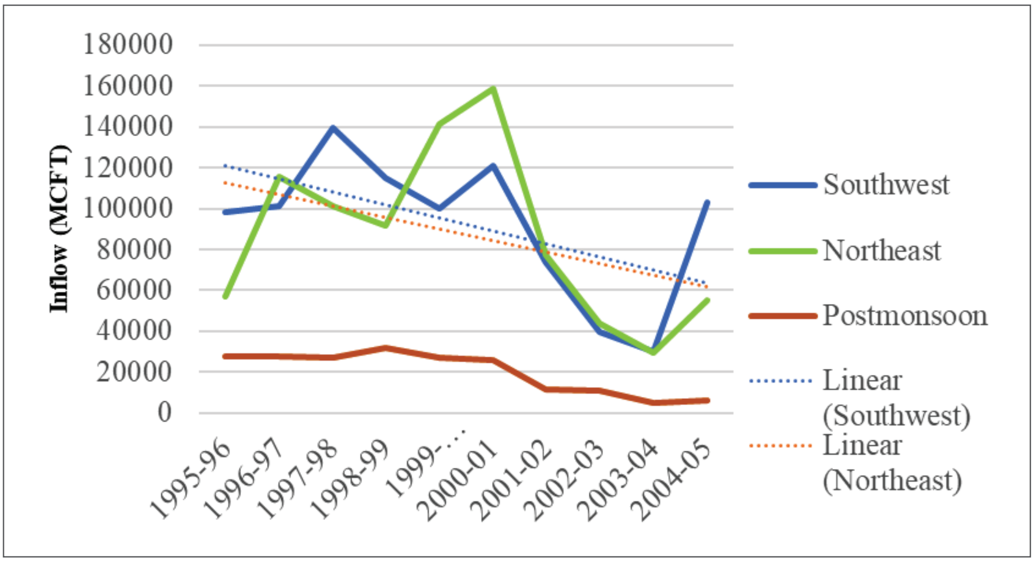


Figure 2.8 *Flows to Mettur reservoir (Tamil Nadu) during 1995 - 2005*

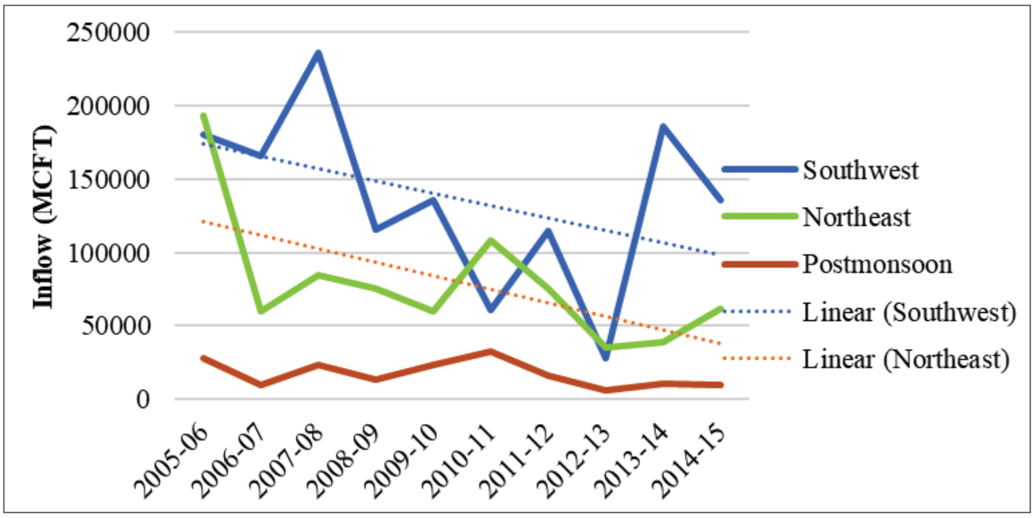


Figure 2.9 *Flows to Mettur reservoir (Tamil Nadu) during 2005 - 2015*

An earlier study carried out by KITS for the Meenachil river basin, in Kerala, had shown that the monocrop rubber plantations in the basin and large built-up areas had contributed to increases in peak flows and reductions in flows during the summer months, possibly due to large-scale deforestation and rubber cultivation (Celine 2015). Even such a trend of increase in peak flows during the monsoon and reduction in summer flows is experienced in Cauvery, it may not affect the water distribution due to the large capacity reservoirs in the basin and the regulated flows to cater to the irrigation requirements in the delta. The variation in seasonal flows due to land use land cover changes may not affect the releases for the wetland complex from the impoundments and regulators. Therefore, seasonal variations if any, in streamflows due to land use land cover changes may not have a direct impact on the wetland ecosystem. It is also worthwhile to note that the regulated flows now do not take into account the requirements of wetlands.

2.4.2 Land Use Land Cover Changes: Direct Catchment of Point Calimere Wetland Complex

Details of the various land use categories and the LULC matrix in the direct catchment and wetland complex corresponding to 2000 and 2020 are given in Table 2.4. The land use maps of the wetland complex and the direct catchment corresponding to 2020 and 2000 are given in figures 2.10, 2.11, respectively. There is an increase in the area under cultivated land, open scrub, mangroves and plantation 2000-2020. The area under settlement increased from 62 km^2 to 124.19 km^2. The largest portion of the direct catchment was composed of open scrub, followed by water bodies, plantation and mudflats in 2020. The cyclone Gaja has destroyed the mangrove canopy. The spread of aquaculture farms in the direct catchment causes water quality deterioration (both surface water and groundwater). The effluents from settlements, for example Muthupet town, degrade the water quality of Muthupet Estuary. The saltpans encroach upon the mudflats and are harmful for the wetland ecosystem.

Table 2.4 *Area under various categories of land use and land cover in the direct catchment from 2000 to 2020*

	Area km^2	
Land use category	**2000**	**2020**
Aquaculture	8.28	8.28
TDEF	90.23	90.23
Open Mangrove	4.72	4.72
Dense Mangrove	4.15	4.15
Mudflat	260.37	260.37
Scrub forest	32.22	32.22
Open scrub	439.37	439.37
Plantation	475.81	475.81
Saltpan	9.76	9.76
Settlement	62.53	62.53
Water bodies	318.88	318.88
Cultivated land	159.97	159.97

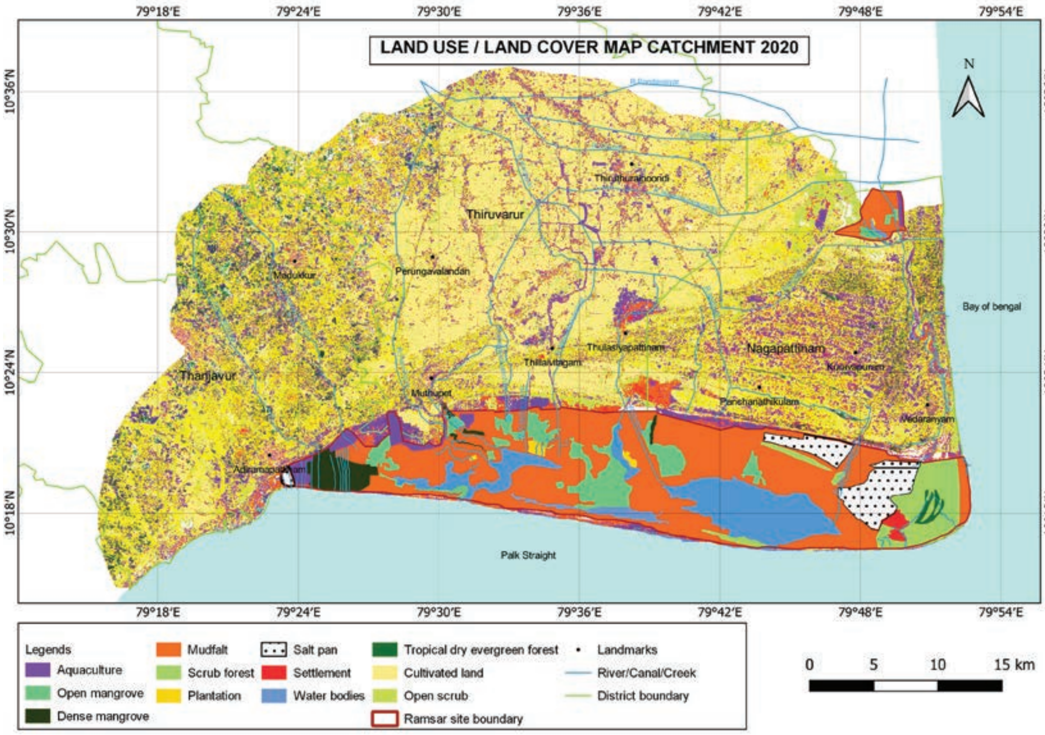


Figure 2.10 *Land use map of direct catchment of PCWC for 2020*

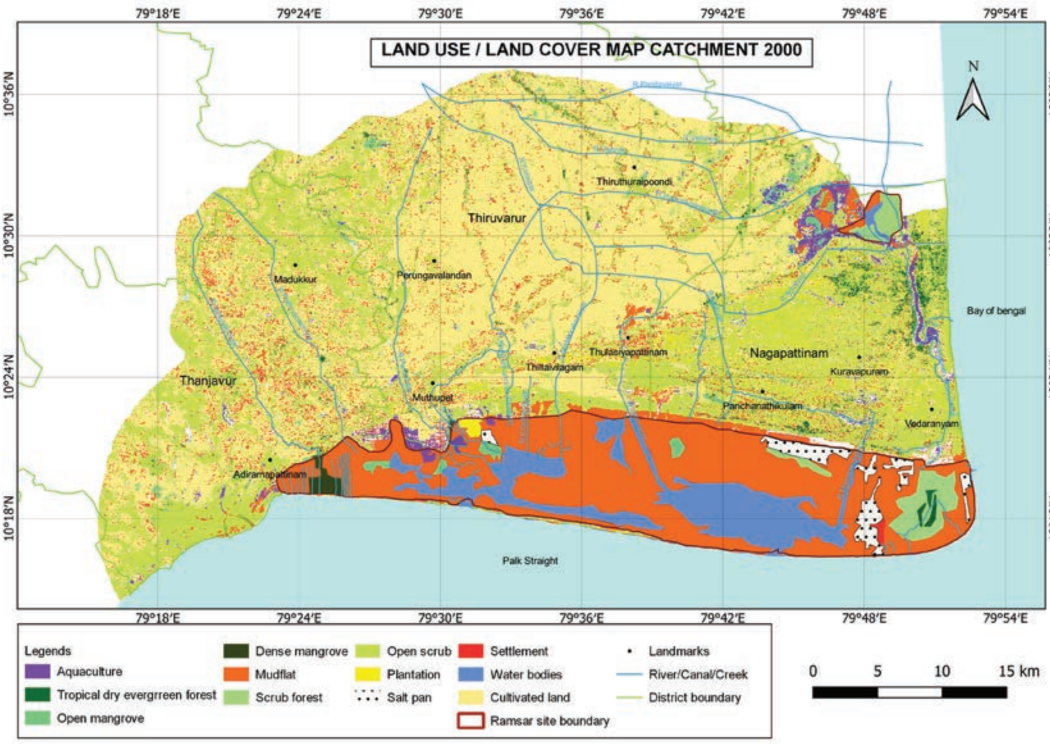


Figure 2.11 *Land use map of direct catchment of PCWC for 2000*

2.4.3 Land Use Land Cover Changes: Buffer Zone of Point Calimere Wetland Complex

The conservation practices in the buffer zone will have a direct impact on the wetland complex since the water from upstream is impounded and controlled at various locations upstream and utilised for different purposes right up to the buffer zone and to some extent within the buffer zone. Therefore, the management of LULC within the buffer zone will have a great impact on the conservation of wetlands and enhancing the ecosystem services. The sediment load from upstream is also affected by the upstream impoundments, controls and development activities. The details on the various land use categories in the Point Calimere Wetland Complex and buffer zone corresponding to 2020 and 2000 and 1990 are given in Table 2.5. The land use map of the wetland complex and buffer zone corresponding to 2020 and 2000 are given in Figs 2.12 and 2.13. The largest portion of the buffer zone is composed of plantations (about 18.5%), followed by open scrub (17.92%), water bodies (15.11%) and mudflats (15.12%) in 2020. The area under remaining categories, namely, cultivated land, mixed forest, evergreen forest, mangroves, settlements, aquafarms and saltpans are 8.81%, 12.27%, 6.23%, 1.28%, 2.76%, 0.92% and 0.95%, respectively.

Table 2.5 Area under various categories in the buffer zone, including the wetland complex

Class	Area (km^2) 1990	Area, km^2) 2000	Area, km^2) 2010	Area (km^2) (2020)	Change in area (km^2)	% Change
Cultivated land	95.28	103.51	118.52	119.46	24.18	25.38
Open scrub	176.8	185.26	202.17	242.95	66.15	37.42
Water	215.84	208.97	198.52	204.85	-10.99	-5.09
Settlement	5.3	28.38	35.4	37.46	32.16	606.79
Mangrove	12.97	8.61	10.2	17.42	4.45	34.31
Mudflat	272.96	260.37	253.48	204.95	-68.01	-24.92
Plantations	238.83	254.86	249.45	251.89	13.06	5.47
Mixed forest	201.98	198.56	188.09	166.4	-35.58	-17.62
TDEF	127.2	88.92	78.37	84.55	-42.65	-33.53
Salt pan	8.06	9.76	10.97	12.97	4.91	60.92
Aquafarm	0.56	8.28	10.77	12.55	11.99	2141.07
Total area	**1355.78**	**1355.48**	**1355.94**	**1355.45**		

During the period 1990-2020, the changes are high with regard to the area under the categories of settlement, aquafarm and saltpan, the increase being 32.16 km^2, 11.99 km^2 and 4.91 km^2, respectively. Similar changes are also observed during the same period in the areas under open scrub, mangroves and plantations (with an increase of 37.42%, 34.31% and 5.47%, respectively). Decrease in the areas of water bodies, mudflats, mixed forest and evergreen forest are observed (5.09%, 24.92%, 17.62% and 33.53%, respectively).

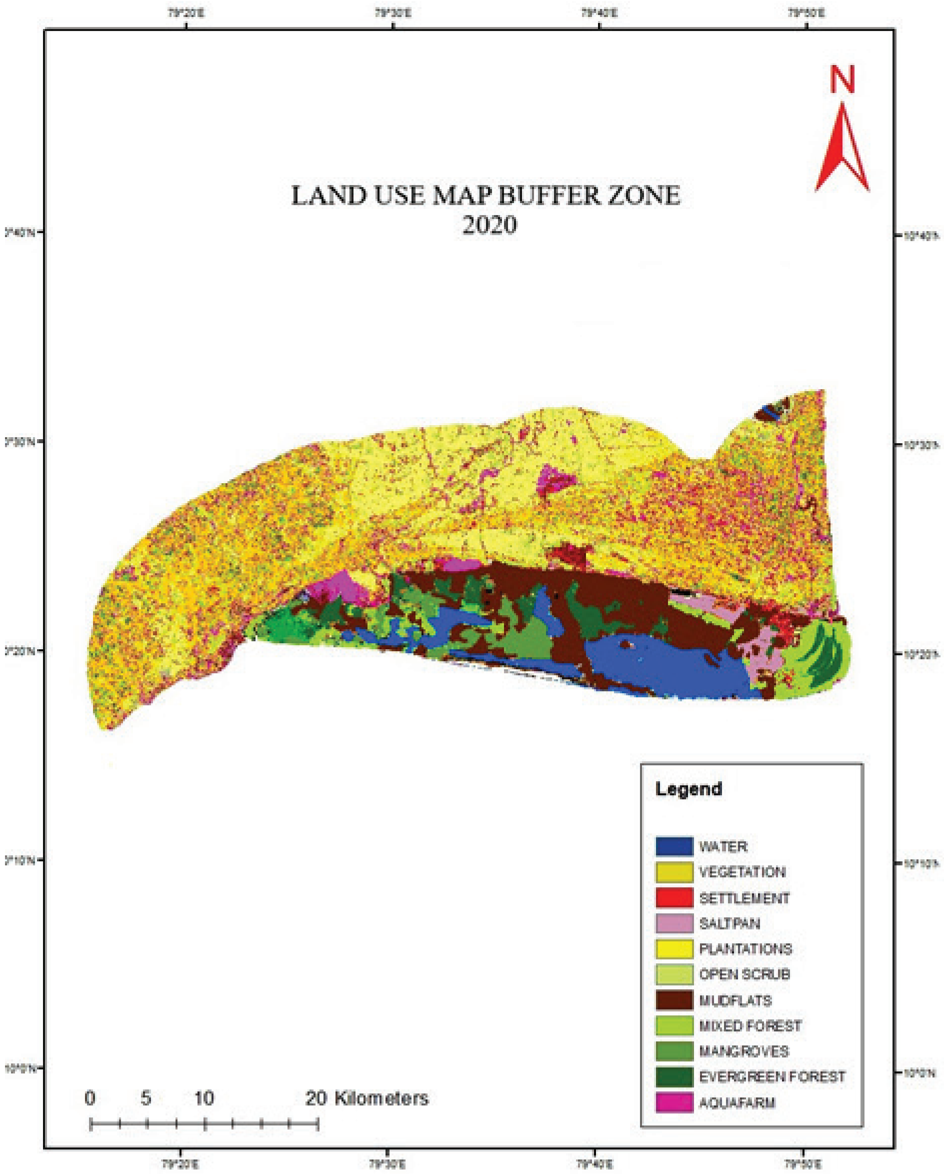


Figure 2.12 *Land use map of PCWC and its buffer zone for 2020*

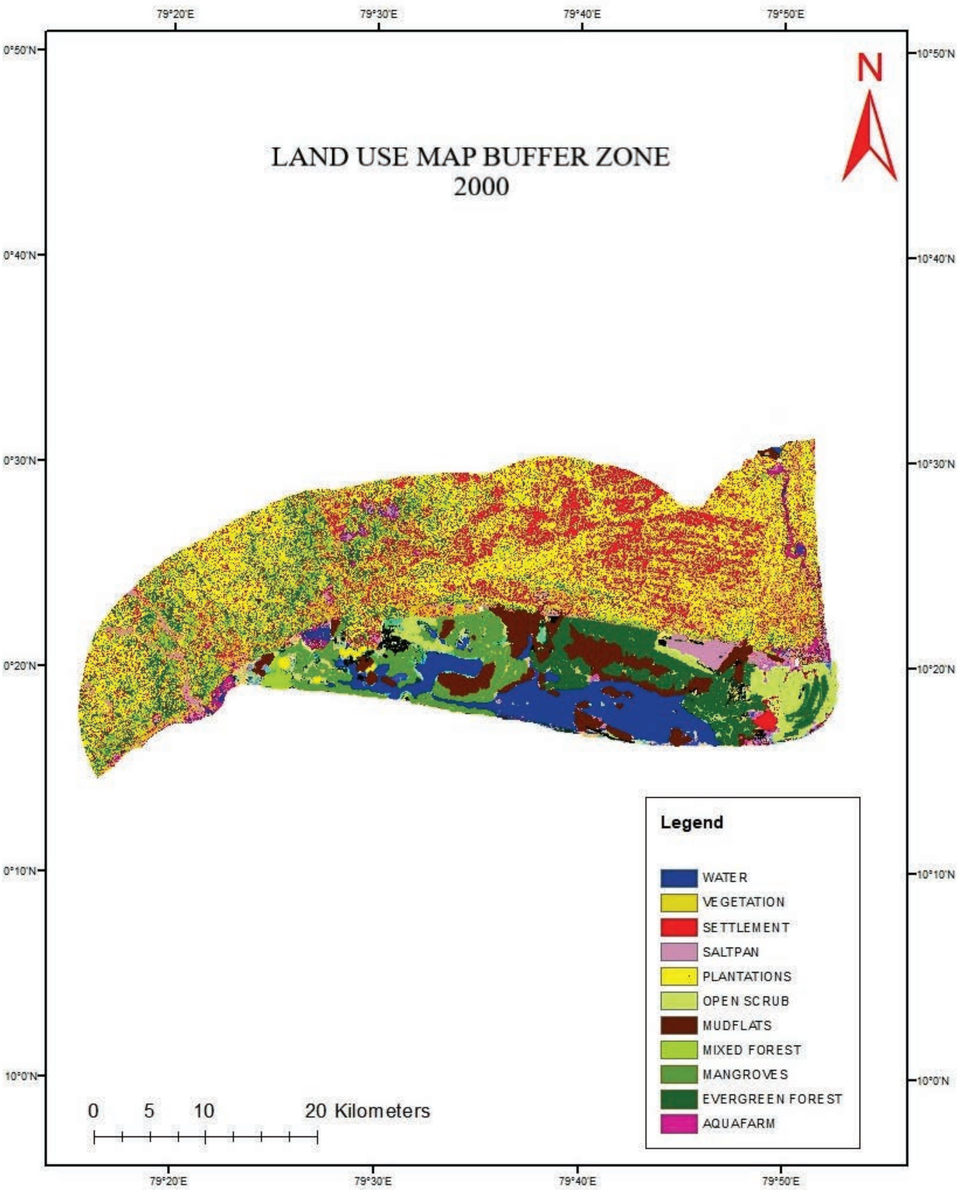


Figure 2.13 *Land use map of PCWC and its buffer zone for 2000*

It is to be noted that there is a considerable increase in the area under settlements in the buffer zone of the wetland complex, which is expected to have an adverse impact on the water availability, water quality and sediment deposition status in the wetlands. The townships are discharging the sewage to the wetlands without treatment and therefore, settlements in the buffer zone have to be discouraged. The increase in aquaculture farms is at the cost of existing land use, both farmland or mudflats. The brackish water, nutrients and medicines from the aquaculture farms are finally discharged into the surface water bodies or join the groundwater table, by polluting these sources. The expansion of saltpan areas over mudflats is harmful to the wetlands. Extraction of saltwater from groundwater sources or pumping it from the sea and spreading it on the mudflats adversely impacts the aquatic ecosystems of the wetland complex. The increase found in the mangrove area is a healthy sign.

2.4.4 Land Use and Land Cover Changes: Point Calimere Wetland Complex

A base map with all physical and cultural details has been prepared from the topographic maps published by the Survey of India (SoI) on a 1:50,000 scale. The LULC maps for the Point Calimere Wetland Complex were prepared to estimate the changes, from 2000 to 2020. The preliminary information and secondary data were collected from the Forest Department (Nagapattinam and Thiruvarur) and Fisheries and Public Works departments of Tamil Nadu, while other details are based on field observations. The land use maps of Point Calimere Wetland Complex for the years 2020 and 2000 are given in figure 2.14 & 2.15. In 2020, the largest portion of the Point Calimere Wetland Complex is occupied by mudflats, followed by water bodies, open scrub and saltpans.

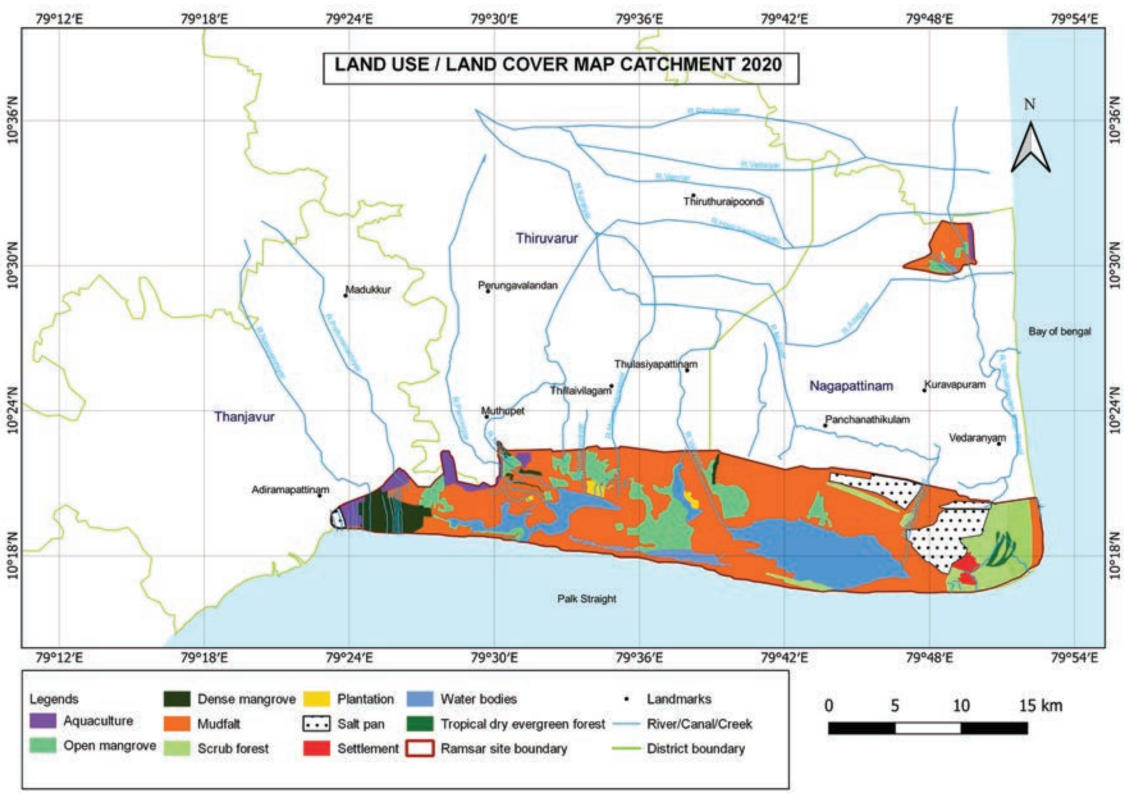


Figure 2.14 Land use map of PCWC for 2020

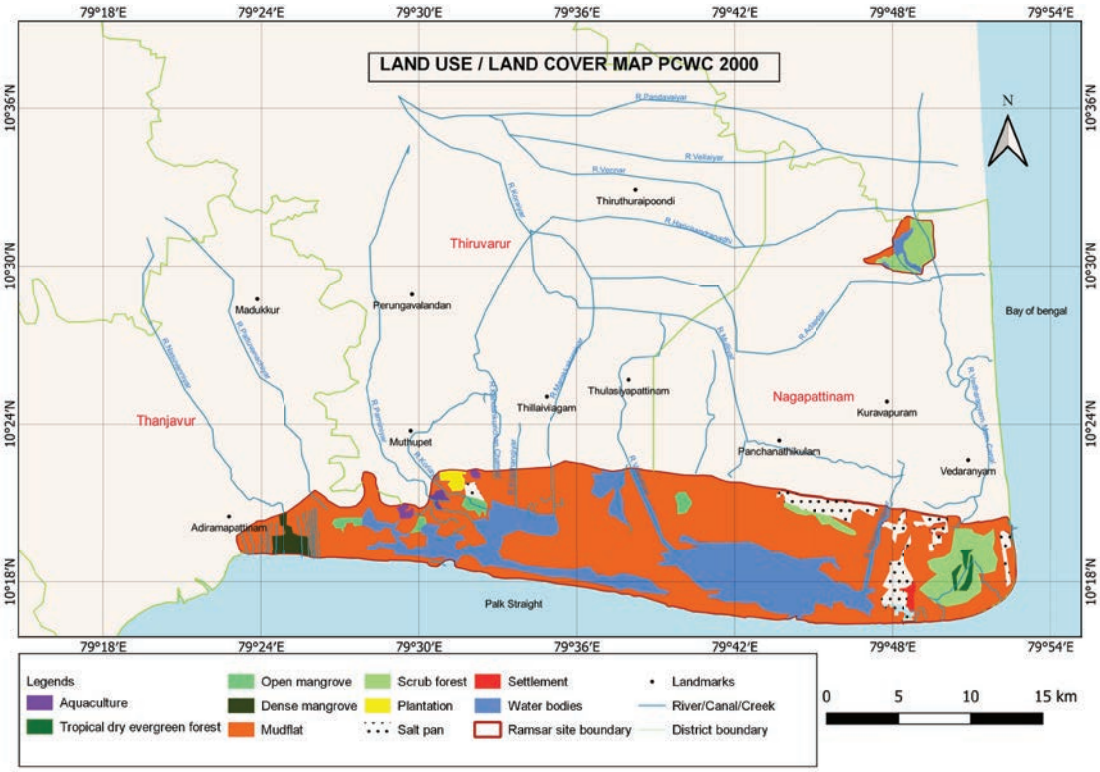


Fig. 2.15 Land use map of PCWC for 2000

The land use conversion map and LULC matrix pertaining to Point Calimere Wetland Complex are given in Table 2.6. During the past five decades, there has been an increase in the area of open scrub, water bodies, area under settlement, mangroves, mixed forest and saltpans. It is also observed that there has been a drastic decrease in the area of mudflats in the wetland complex during 2000-2020, which has to be taken into cognisance. The area under mangroves has increased in the wetland complex due to the efforts of the Forest Department, NGOs such as M S Swaminathan Research Foundation and the fishing community. The increase in saltpans is at the expense of mudflats, as also part of the increase in the area of open scrub.

***Table 2.6** Land use change for the wetland complex*

	2000 (sq.km)	2020 (sq.km)
Class		
Aquaculture	1.93	9.37
Open mangrove	4.72	38.38
Mudflat	235	193.27
Water Bodies	88.89	64.33
Salt pan	19.89	29.31
Plantation	1.91	2.32
Dense mangrove	4.15	14.06
Scrub forest	25.88	29.36
Settlement	1.07	2.94
Tropical Dry Evergreen Forest	2.01	2.23
Total	**385.45**	**385.57**

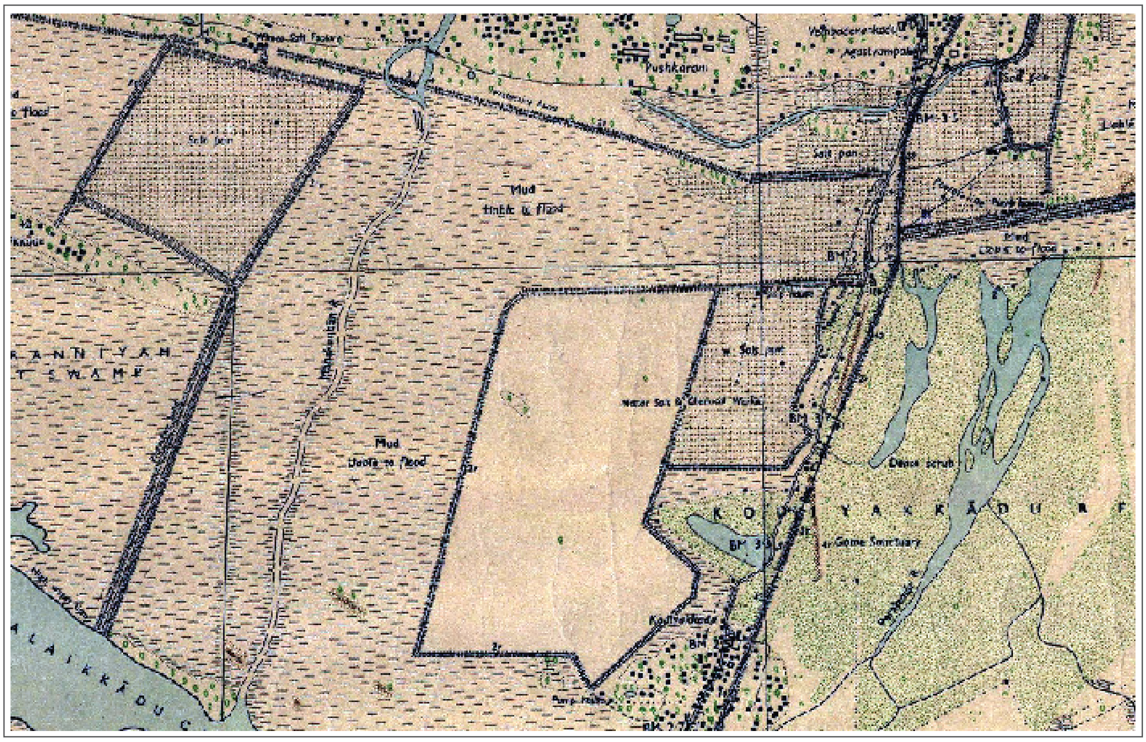
2.4.5 Variations in Land Use Categories within the Point Calimere Wetland Complex

The analysis of the remote sensing data shows that the area under mangroves has increased from 5.4 km^2 to 17.42 km^2 from 1990 to 2018. Cyclone Gaja destroyed the canopy of the mangroves in certain pockets, which is in the process of regeneration. The imagery of February 2019 shows a reduction in the area ofmangroves, presumably due to the impact of the Gaja cyclone. This estimation is based on the satellite data, and the ground truth for 2019 was not available for comparison. Around 4.035 km^2 of mudflats and 1.48 km^2 of lagoon areas in the western side of the Pamini river has been transformed into mangroves during the past five decades. The changes in the extent of area of mangroves are observed more in the northern and western sides of the estuary, especially on the mudflats. However, some pockets of mangroves have emerged in the eastern part between the lagoon and the inlet. There is a decline in the mangrove in certain pockets. The entry of seawater has stopped due to siltation at the mouth of the straight cut of Adappar and Harichandra rivers. The mangroves in the Thalainayar Reserve Forest can be revived by releasing more freshwater through the Umbalacheri regulator in the Adappar River and the Brinjimoolai regulator in the Harichandra River and desilting the Adappar and Lawford straight cuts, which will allow the movement of sea water into the Thalainayar Reserve Forest. Fishermen engaged in channelisation and planting of mangroves have reported better fish catches from the area, especially in and around Muthupet Estuary, Siruthalaikadu inlet and Thalainayar Forest area.

The waterspread area of Muthupet lagoon has increased by 39.5% over a period of five decades, from 15.62 km^2 in 1970 to 25.83 km^2 in 2020, due to the changes in flows and sediment dynamics and proliferation of mangroves in the eastern and western sides of the ecosystem (near the confluence of the Pamini River with the wetland). The increase in the water spread area 3.508 km^2 in the eastern side of the Muthupet Lagoon is mainly due to the collapse of the eastern bank of the Valavanar drain.In 1970, the water spread area of Siruthalaikadu Lagoon was 43.12 km^2. Fluctuations in the water spread area of Siruthalaikadu Lagoon (shown as Siruthalaikadu Creek in the Survey of India maps) for the last five decades it was found that in 2000 it was 40.92 km^2, in 2010 it was 46.35 km^2 followed by a significant decrease in 2020 with a value equal to 38.42 km^2, mainly attributed to the reduction in freshwater availability and continuous deposition of sediment transported by tidal currents. The Manakundan River flowing through the Siruthalaikadu Lagoon has become ephemeral due to the newly formed saltpan in the north of PCWBS (figures. 2.16 and 2.17). The absence of freshwater drainage and reduction in depth due to continuous siltation have practically deprived the lagoon of vegetation on its fringes.

Photo credit: GIZ_ Prasanth

Figures 2.16 *Emergence of salt pan closing the flow from the Manakundan river*



Figures 2.17 *Mudflats close to the drainage point of the Manakundan river*

The extent of the mudflats has reduced from 297.84 km^2 in 1970 to 200.92 km^2 in 2020 decreased by 32.53% due to its conversion to cultivated lands, saltpans, aquafarms, mangroves, human settlements and due to other anthropogenic activities. The fishbone channels dug within the mangrove forest for enabling new plantations by permitting tidal waters are not properly desilted and maintained. It is also observed that *Prosopis juliflora* covers an area of 3.75 km^2 on the mudflats of Point Calimere. In the Panchandikulam wetland, mudflats are getting converted into pits and puddles. The unsurveyed salt swamp and mudflats are getting converted to open scrubs and saltpans. The land use changes in the direct catchment/buffer zone are comparatively less when compared with the wetland system as such. As per the morphometric analysis, the drainage density is comparatively higher in the Cauvery Delta, followed by the direct catchment and wetland complex. The drainage density in the wetland complex has decreased due to the interventions such as digging fishbone channels in the eastern and western sides of the estuary and expansion of saltpan area in the Point Calimere Wildlife and Bird Sanctuary (PCWBS), and loss of connectivity between Valavanar drain and Muthupet estuary. In the Point Calimere Wildlife and Bird Sanctuary, it is observed that the connectivity between the mudflats in the PCWBS, Peralam River and backwaters near the sea in the sanctuary has been lost. Since there is no flow in the Peralam River in the sanctuary, the Muniappan Lake, which has been serving as a source of water for the village community in Kodikkarai, has dried up. The flow to the Peralam River from the mudflats ceased due to the construction of saltpans in the mudflats near the seacoast. There is a proliferation of *Prosopis juliflora,* an exotic plant species introduced in 1961 as a wind barrier and fuelwood; it has doubled its extent from 3.03 km^2 in 1990 to 6.16 km^2 in 2019.

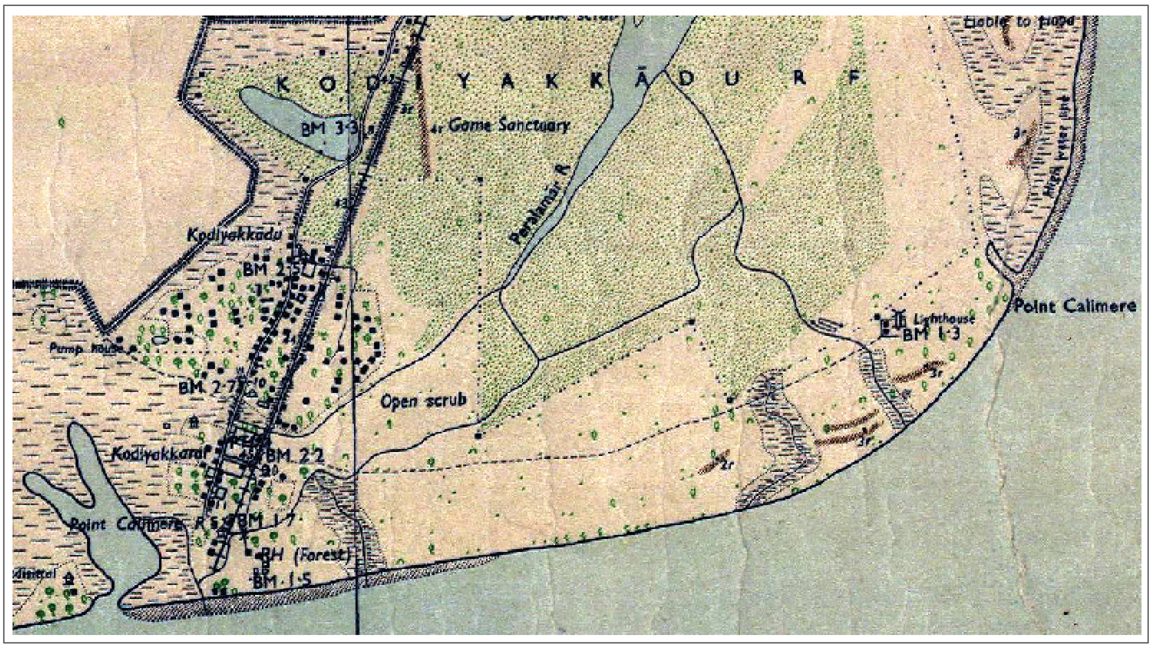


Figure 2.18 *Stream connecting the Peralam river and the sea*

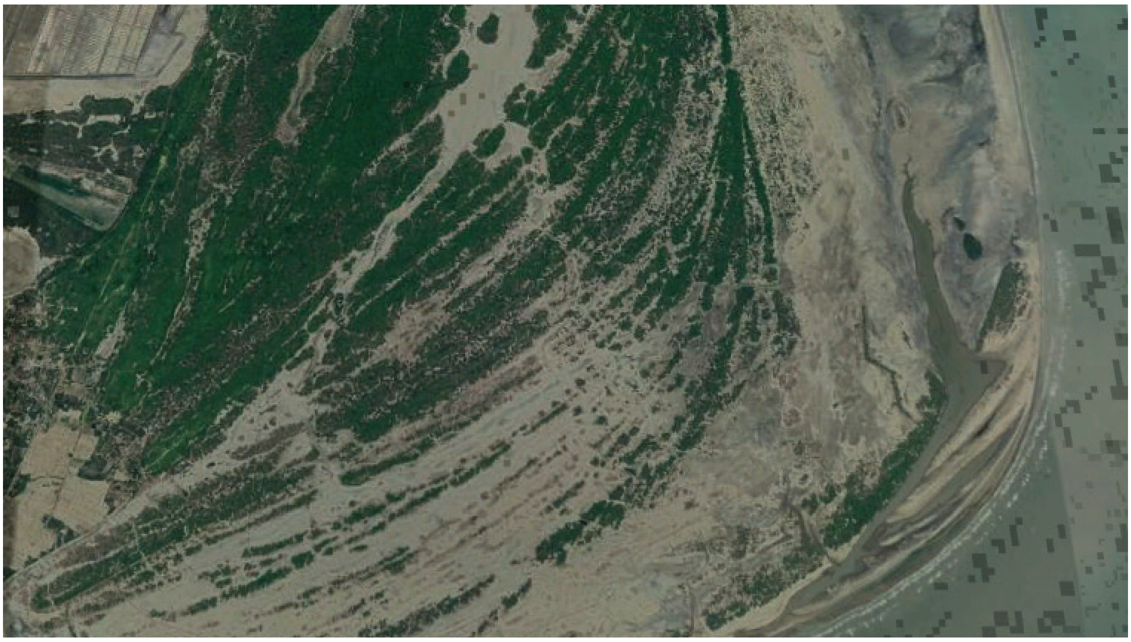


Figure. 2.19 *Disconnected stream*

2.4.6 Studies on Quantitative Geomorphology

The results of the quantitative geomorphologic study of the Cauvery Basin, direct catchment and Point Calimere Wetland Complex are given in figures 2.20 to 2.22 and Table 2.7.

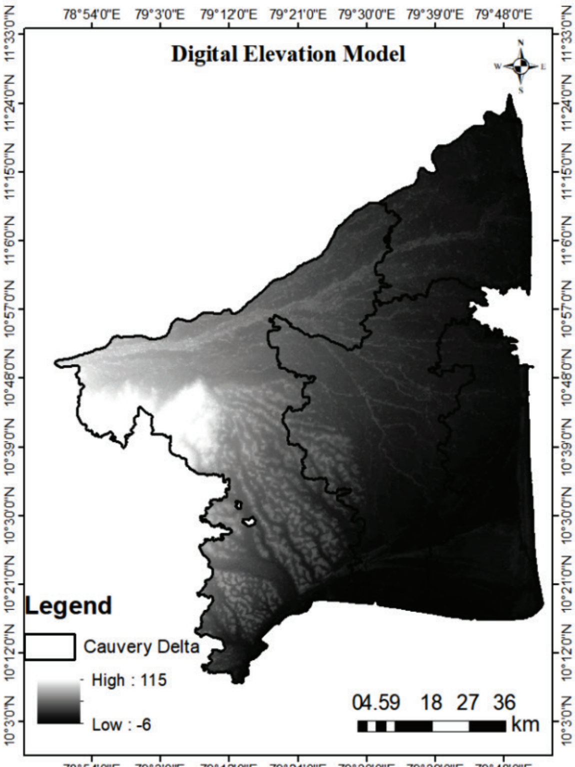


Figure 2.20 *Digital elevation model of the Cauvery Delta*

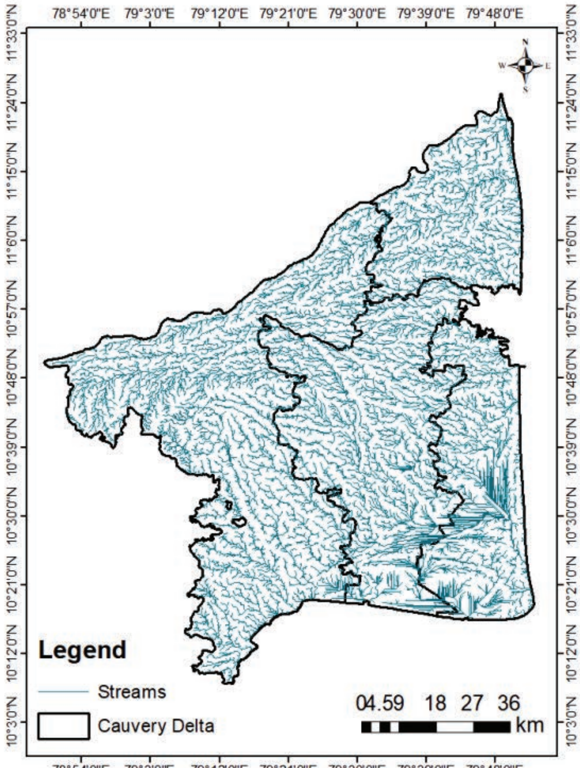


Figure 2.21 *Flow lines in the Cauvery Delta*

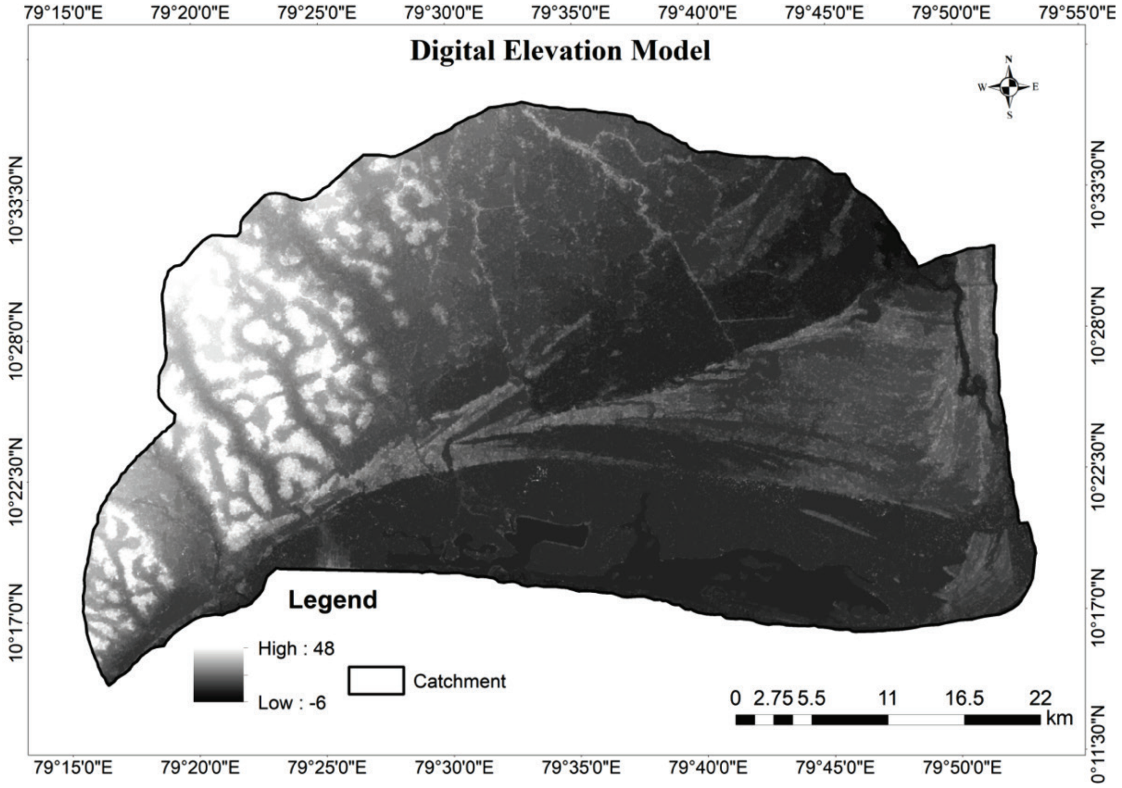


Figure 2.22 *Digital elevation model of the direct catchment of the wetland complex*

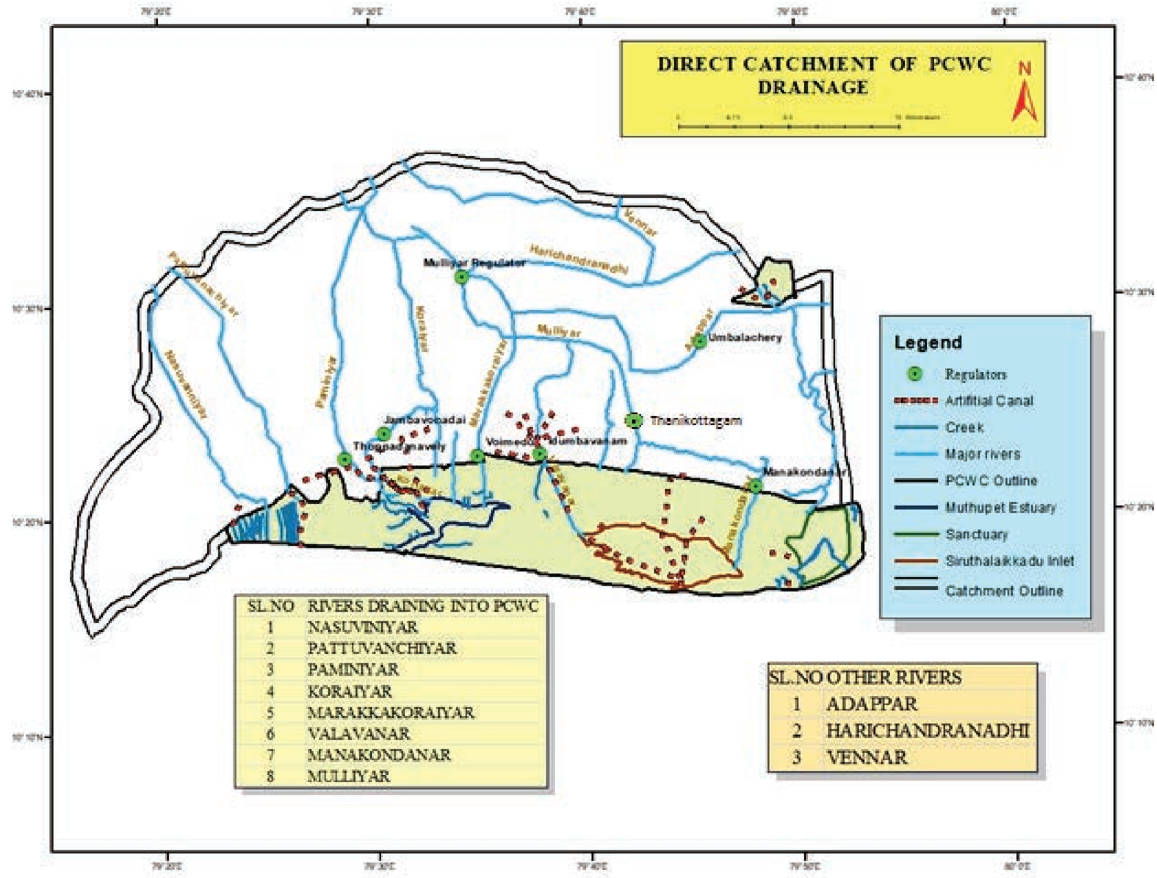


Figure 2.23 *Rivers and streams in the direct catchment of the wetland complex*

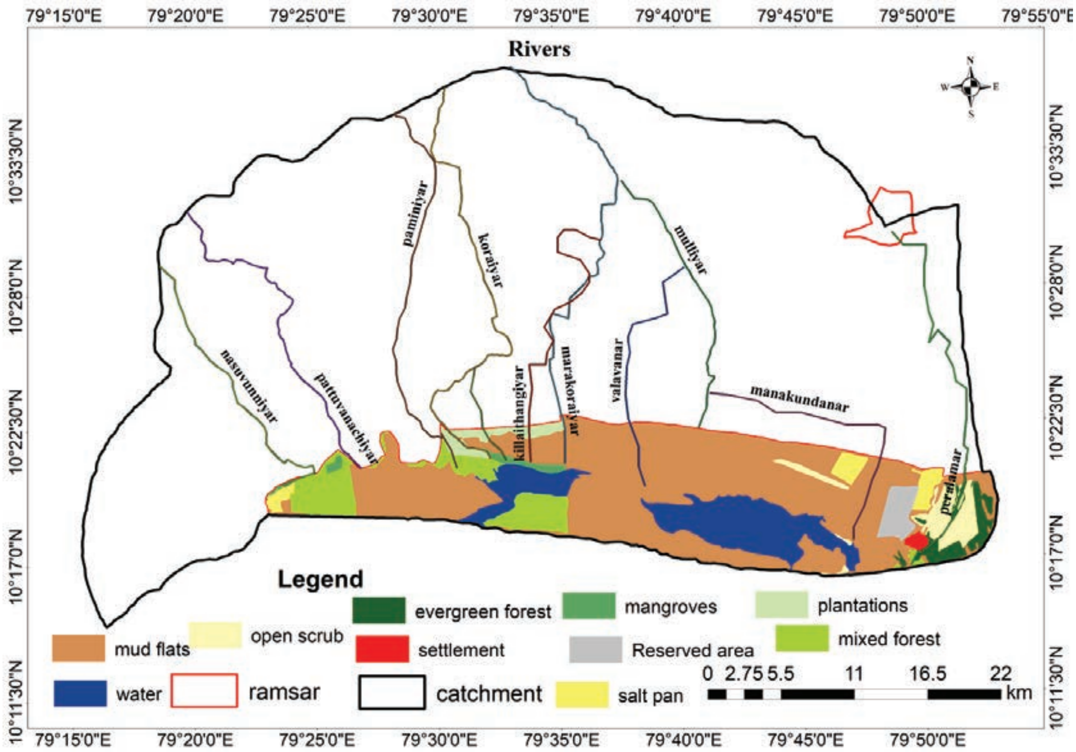


Figure 2.24 Rivers draining into the wetland complex

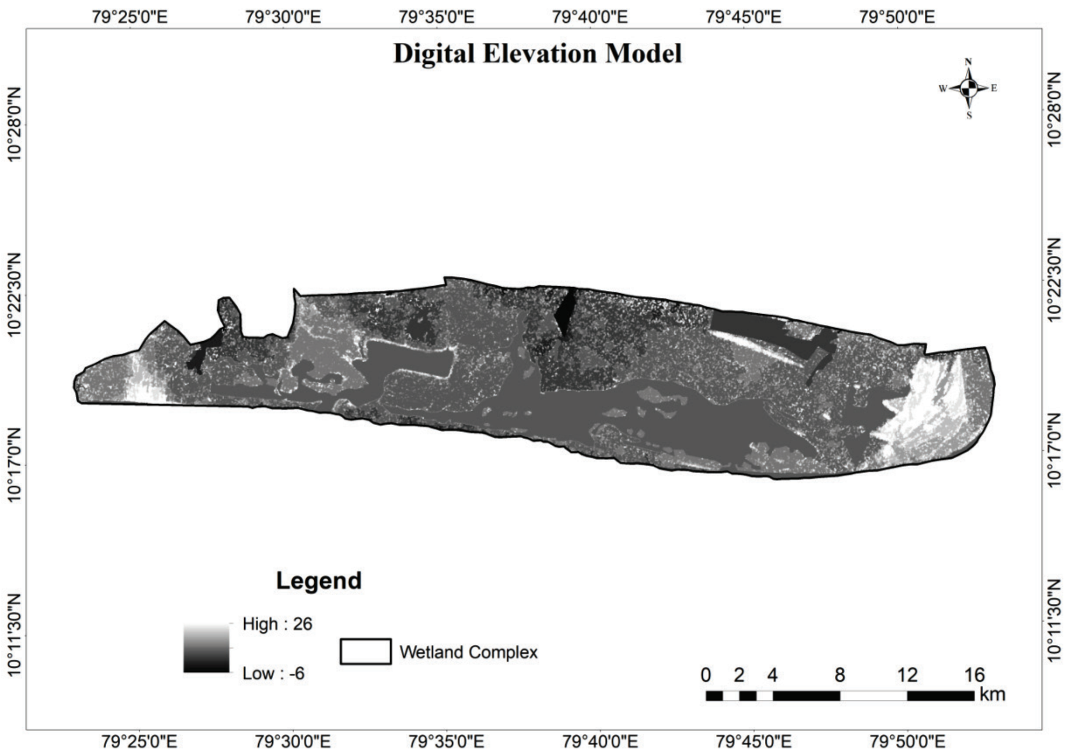


Figure 2.25 Digital elevation model of the wetland complex

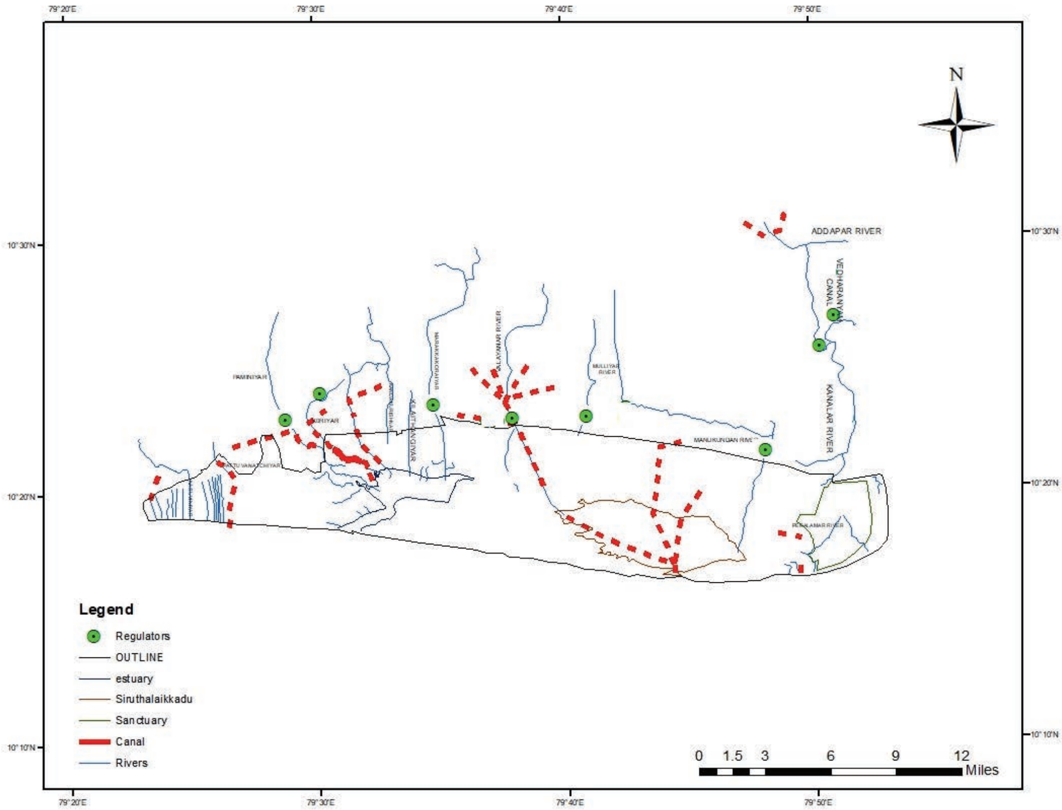


Figure 2.26 *Streams and major regulatory structures in the wetland complex*

Figure 2.26 shows the major streams, rivulets, man-made canals and regulators in and around the Point Calimere Wetland Complex. The names of the regulators are Thoppadanavely, Jambavanodai, Idumbavanam, Voimedu, Thanikottagam, Manakondanar and Umbalacherry. These regulators are positioned across the Paminiyar, Koraiyar, Marakakoraiyar, Valavanar, Mulliyar, Manakundanar and Adappar, respectively.

Table 2.7. *Morphometric parameters of the Cauvery Delta, direct catchment and PCWC*

Sl. no.	Aspect	Cauvery delta	Direct catchment	PCWC
1.	Area (km^2)	8280	1957.38	406.85
2.	Perimeter (km)	1538.53	199.01	127.28
3.	Length of basin (km)	155.1	70.28	54.92
4.	Total length of streams (km)	9915.35	1839.98	205.49
5.	Drainage density (km-1)	1.19	0.94	0.51
6.	Form factor	0.34	0.39	0.14
7.	Elongation ratio	0.66	0.71	0.414
8.	Circularity ratio	0.04	0.62	0.32
9.	Length of overland flow (km)	0.042	0.53	0.98
10.	Ruggedness number (km-1)	143.99	50.76	17.34
11.	Melton's ruggedness number	1.33	1.22	1.69
12.	Relief ratio	0.78	0.77	0.62

On the basis of the value of elongation ratio, the time for peak flow is less in the catchment and delta area compared with the wetland complex. The circularity ratio is high in the catchment compared with the delta and wetland complex, indicating the structural interventions are high in the catchment area. Further introduction of new structural measures may further reduce the flow to the Point Calimere Wetland Complex. The ruggedness number points to the structural complexity of the terrain in association with the relief and drainage density. The high value of Melton's ruggedness number of the delta shows that the suspended sediment transport is higher than the bed load, pointing to the possibility of high soil erosion and silt deposition in the wetlands.

The changes in the waterspread area of different wetland types between the pre-monsoon season and the post-monsoon season were mapped using the satellite imagery available for the past 20 years. The maps prepared are for the two seasons of 2000, 2010 and 2020.

Figs. 2.27 to 2.32 show the extent of the water spread area in the Point Calimere Wetland Complex complex before and after the north-east monsoon during the years 2000, 2010 and 2020, respectively. The maps have been obtained from Normalised Differential Water Index (NDWI) technique using Landsat 8 and Sentinel 2 Imageries. In the post-monsoon season the water spread area increases in the eastern and northern directions of the Siruthalaikadu inlet, submerging the mudflats. More changes are observed in and around Siruthalaikadu inlet compared with the Muthupet Estuary. However, in the Muthupet Estuary, there is a heavy flow from the estuary towards the mudflats on the eastern side, near the seashore.

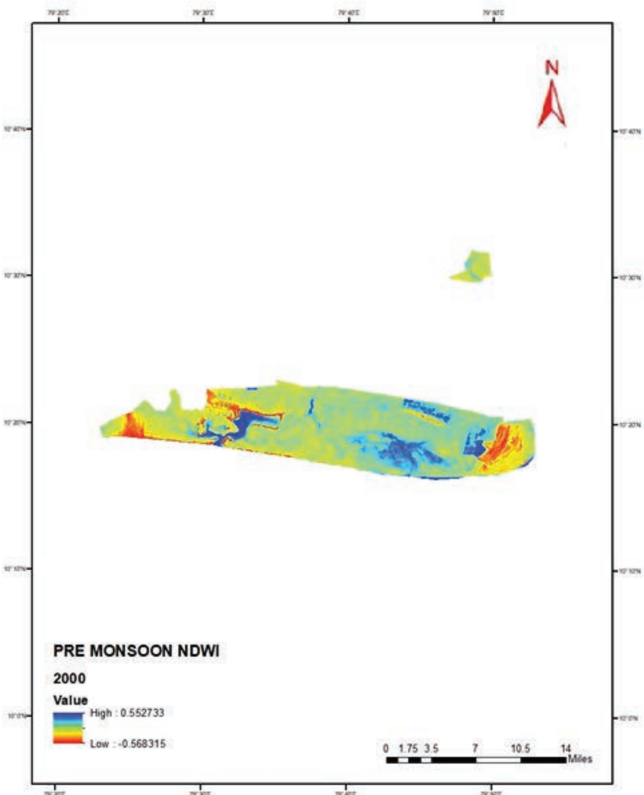


Figure 2.27 *NDWI during the pre-monsoon – 2000*

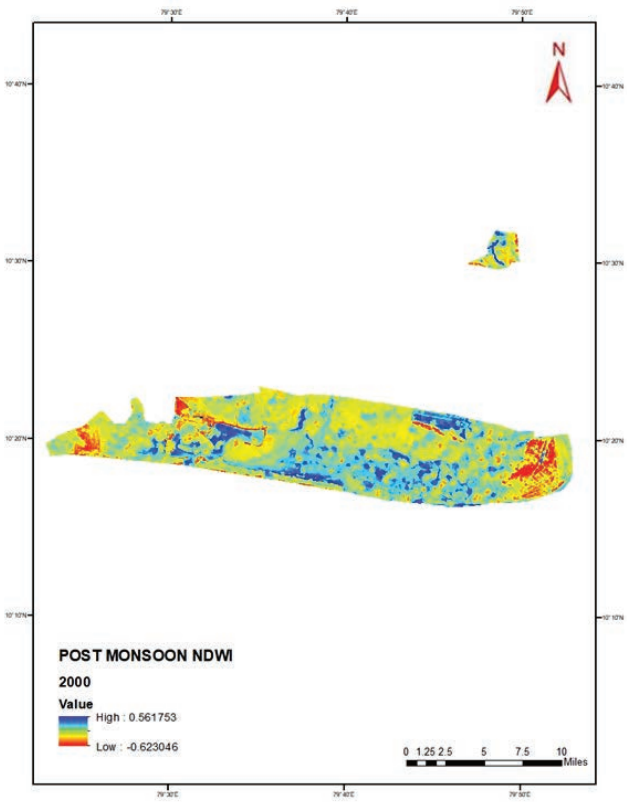


Figure 2.28 *NDWI during the post-monsoon – 2000*

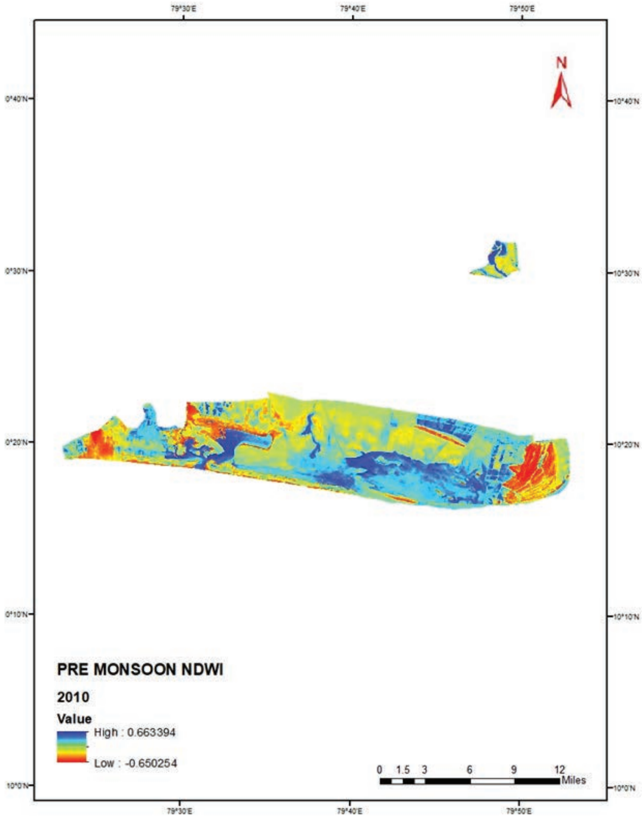


Figure 2.29 *NDWI during the pre-monsoon – 2010*

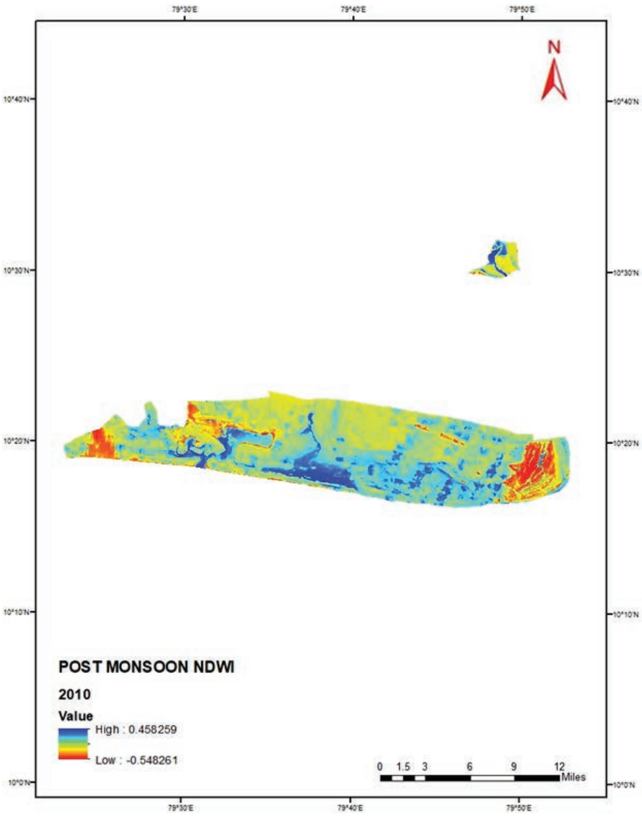


Figure 2.30 *NDWI during the post-monsoon – 2010*

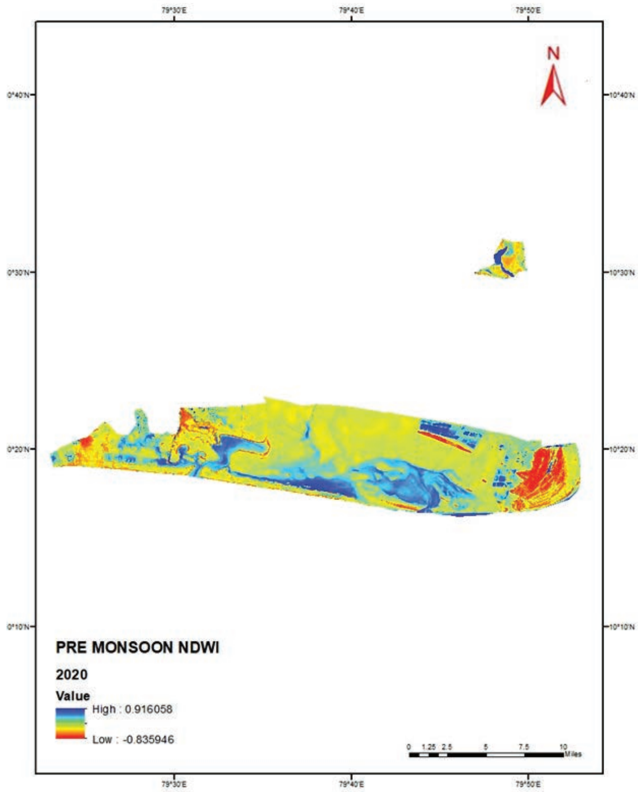


Figure 2.31 *NDWI during the pre-monsoon – 2020*

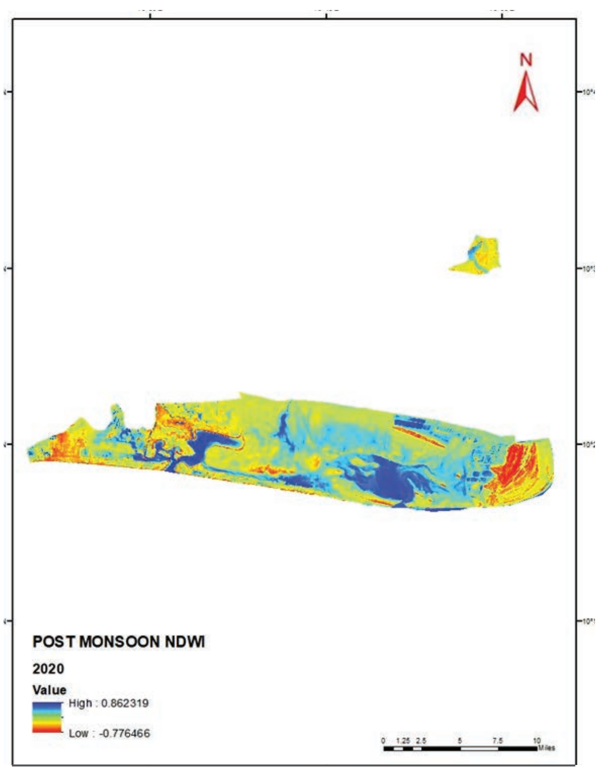


Figure 2.32 *NDWI during the post-monsoon – 2020*

__Table 2.8__ shows the variations in the waterspread area estimated from NDWI maps for the years 2000, 2010 and 2020 in the PCWC complex

Year	Waterspread Area (km²)	
	Pre-monsoon	Post-monsoon
2000	69.31 (18%)	131.87 (34%)
2010	94.49 (25.5%)	129.90 (33.7%
2020	89.96 (23%)	160.97 (41.5%)

2.4.7 Major industries in the buffer zone

The major industries in the buffer zone and wetland per se have been identified as the sources of industrial pollution. Figure 2.3.3

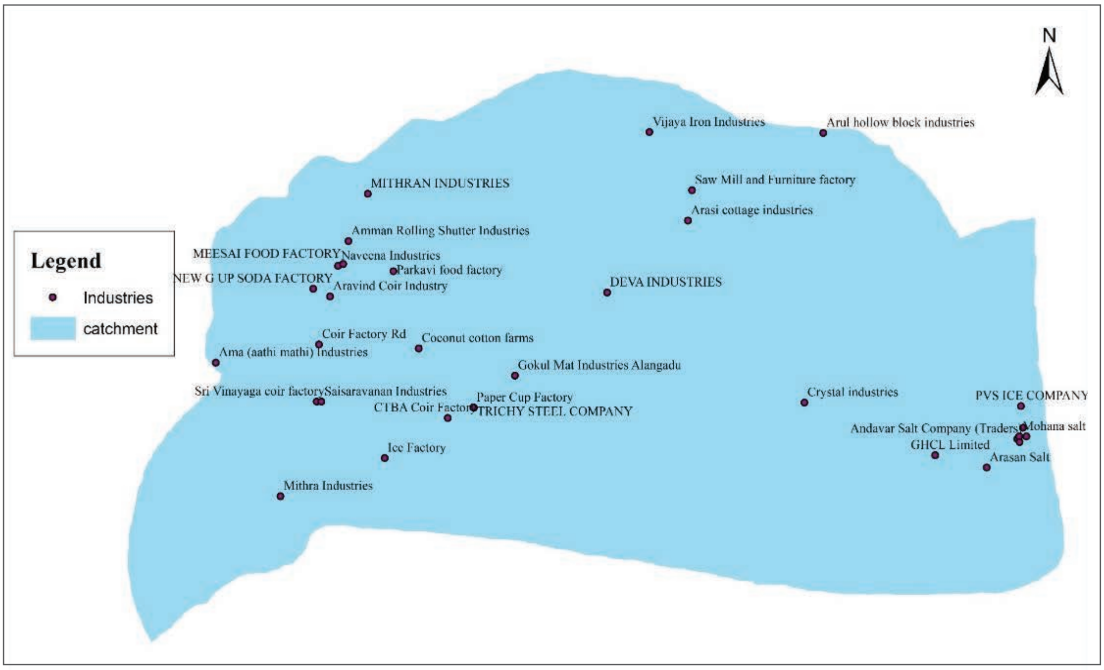


***Figure 2.33** Major Sources of pollution (industries)*

***Table 2.9** Major Sources of Industrial Pollution and Nature of Pollutants*

Sl. no.	Name of the Industry	Latitude (°E)	Longitude (°N)	Waste generated
1.	Ama Industries	10.4252282	79.3161462	Scrap
2.	Soda Factory	10.473724	79.380642	Inorganic waste
3.	Coir Factory	10.4371491	79.3844407	Coir compost
4.	Aravind Coir Industry	10.468669	79.3917453	Coir compost
5.	Naveena Industries	10.4886779	79.3969797	Scrap

Table 2.9 Major Sources of Industrial Pollution and Nature of Pollutants

Sl. no.	Name of the Industry	Latitude (°E)	Longitude (°N)	Waste generated
6.	Mithra Industries	10.3375743	79.3589967	Diethyl phthalate (DEP)
7.	Amman Rolling Shutter Industries	10.505000	79.4039056	Scrap
8.	Messai Food Factory	10.4899179	79.4005538	Organic waste
9.	Mithran Industries	10.536015	79.416795	Scrap
10.	Sri Vinayaga Coir factory	10.3996578	79.3829396	Coir compost
11.	Saisaravanan Industries	10.3996107	79.3860171	Scrap
12.	Parkavi Food Factory	10.4851494	79.4337095	Organic waste
13	Ice factory	10.3626395	79.4279682	Organic waste
14	Coconut cotton farms	10.4345698	79.4504525	Organic waste
15	CTBA Coir Factory	10.3888914	79.4697855	Coir waste
16	Gokul Mat Industries	10.4167601	79.5142254	Cotton waste
17	DEVA Industries	10.4712297	79.5752867	Slag, dust
18	Vijaya Iron Industries	10.5764886	79.603328	Scrap
19	Arasi Cottage Industries	10.5184886	79.62874	Slag, dust
20	Arul Hollow Block Industries	10.5759456	79.7184772	Debris
21	Crystal Industries	10.3990415	79.7060462	Scrap
22	Lonestar Industries	12.585026	79.5699235	Scrap
23	Gujarat Heavy Chemicals Ltd.	10.3644824	79.7925646	Brine
24	Arasan Salt	10.3563832	79.8266394	Brine
25	PVS Ice Company	10.3967644	79.8493811	Organic waste
26	Andavar Salt Company	10.3751491	79.847004	Brine
27	Mohana Salt	10.376811	79.8482868	Brine
28	Sri Thanalakshmi Fireworks Factory	10.3824771	79.8506535	Inorganic chemicals
29	Swasthik Tobacco Factory	10.37314	79.8484566	Organic waste
30	Jeeva Salt Works & Allied Industries Pvt. Ltd,	10.3768095	79.8529943	Brine
31	Trichy Steel Company	10.3956696	79.4871265	Scrap
32	Paper cup factory	10.3957799	79.4867278	Organic waste
33	Saw Mill and Furniture Factory	10.538338	79.6314745	Scrap and dust

2.5 Summary

- The LULC analysis of the Cauvery Basin shows that there has been an increase in the area under fallow land to an extent 7.09% during the past three decades and there is a decrease in area under plantations by 2.25%. The built-up area has increased by 2.23% during the past three decades.
- The annual flows from the catchment in Karnataka and Tamil Nadu did not show much variation during the period 1995–2015. However, the peak flows increased during the south-west and north-east monsoon periods, and there has been a decreasing trend in the low flows during summer. This can be attributed to the changes in the LULC. Since the flows are stored and regulated upstream, they may not have an impact on the downstream flows to the delta and the wetlands.
- The sediment yield has considerably increased during the last decade, which has brought down the storage capacity of the reservoirs in the Cauvery Basin and subsequently the availability of water in the delta.
- The studies in the direct catchment show that the area under open scrub, mangroves and plantations have increased by during the past three decades. The area under mudflats and water bodies has come down.
- The area under settlement, aquafarms and saltpans in the buffer zone has gone up by during the past three decades. The area under mangroves has gone up by 37.42% and the area under mudflats has come down by 24.92% during the past three decades.
- There is an increase in the area under *Prosopis juliflora:* it has doubled from 3.03 km^2 in 1990 to 6.16 km^2 in 2019.
- The quantitative geomorphic studies show that the drainage density is comparatively higher in the Cauvery Delta, followed by the catchment and wetland complex. The lower drainage density in the wetland complex is due to the low elevation difference and interventions for irrigation. The high value of Melton's ruggedness number of the delta shows that the suspended sediment transport is higher than the bed load, pointing to the possibility of high soil erosion and silt deposition in the wetlands. Soil erosion has also been high in Muthupet, Thethakudi, Vilangudi, Naluvethapathi, Thiruthuraipoondi and Voimedu in the direct catchment.

Photo credit: GIZ_ Neha

3. RAINFALL CHARACTERISTICS: CAUVERY DELTA AND POINT CALIMERE WETLAND COMPLEX

3.1 Introduction

Weather extremes and fluctuations in the monsoon pattern are considered a part of the climatic system, their intensity and occurrence often being unpredictable. Global warming might bring about changes in the frequency and magnitude of extreme rainfall events. According to the report of the Intergovernmental Panel on Climate Change (IPCC 2007), wet extremes are projected to become more severe in many areas where the mean precipitation is expected to increase, and dry extremes are projected to become more severe in areas where the mean precipitation is projected to decrease. Timely availability of freshwater is important for maintaining the energy balance, water balance, sediment balance and related physical, chemical and biological processes in the wetland ecosystems downstream. Analysis of historical rainfall trend helps in the planning and management of water resources of a particular region. Such studies gain more importance since global warming is expected to have its impact on the hydrologic cycle and subsequently on the spatial and temporal availability of surface and groundwater (Jain and Kumar, 2012). To recognise the magnitude and direction of trends in time series observations, several statistical techniques are in vogue. The Mann-Kendall test is a non-parametric approach, which is simple and widely used for detecting the trends in different fields of research including hydrology and climatology (Partal and Kahya, 2006). Sen's non-parametric estimator of the slope has also been used to estimate the magnitude of trends (Jain and Kumar, 2012). These approaches are found to be useful in understanding the basic trends in rainfall of a particular region.

The basic understanding of the hydrology of the Cauvery Delta is useful in estimating the surface and groundwater potential and water quality. The recharge of shallow aquifers is due to infiltration of surface irrigation water and precipitation in the Cauvery Delta (UNDP, 1973). Preliminary analysis of rainfall data of the delta showed conspicuous variations in annual rainfall values. Therefore, the need for studying the long-term variability in rainfall has been recognised since it is the major input of freshwater to the delta and especially to the wetland complex. These studies in the Cauvery Delta and the direct catchments of Point Calimere Wetland Complex are of great help in understanding the availability of freshwater for the wetlands of the Point Calimere Ramsar Site. A trend analysis of the rainfall was carried out apart from estimation of Precipitation Concentration Index (PCI) Seasonality Index (SI) and Departure Analysis (DA).

3.2 Relevance

The Indian climate is dominated by the monsoons. About 80% of the rainfall in India occurs during the four monsoon months, with large spatial and temporal variations over the country in the south-west monsoon (June–September). Tamil Nadu state has three distinct periods of rainfall: (i) the south-west monsoon, from June to September, with strong south-west winds; (ii) the north-east monsoon, from October to December, with dominant north-east winds; and (iii) the dry season, from January to May. Since the state is entirely dependent on rains for recharging its water resources, monsoon failures lead to acute water scarcity and severe drought. The present study provides the long-term trend in rainfall and identifies the Seasonality Index, Departure Analysis value and Precipitation Concentration Index corresponding to the Cauvery Delta region. Extreme rainfall events have been using the recommendations of IPCC (2014) to understand the climate change trends, if any. The impact of El Nino on the rainfall characteristics of the delta has been investigated and the inundation in the wetland complex, especially the mudflats, has been investigated considering the daily rainfall data.

3.3. Database

3.3.1 Primary Data

Rainfall data from 35 rain gauge stations over a period of 22 years (1997–2018) were obtained from the State Ground and Surface Water Resources Data Centre, Public Works Department (PWD), Taramani, Chennai for analysis. Data available for 2019 were also used in the present study. The locations of the rain gauge stations are given in figure 3.1.

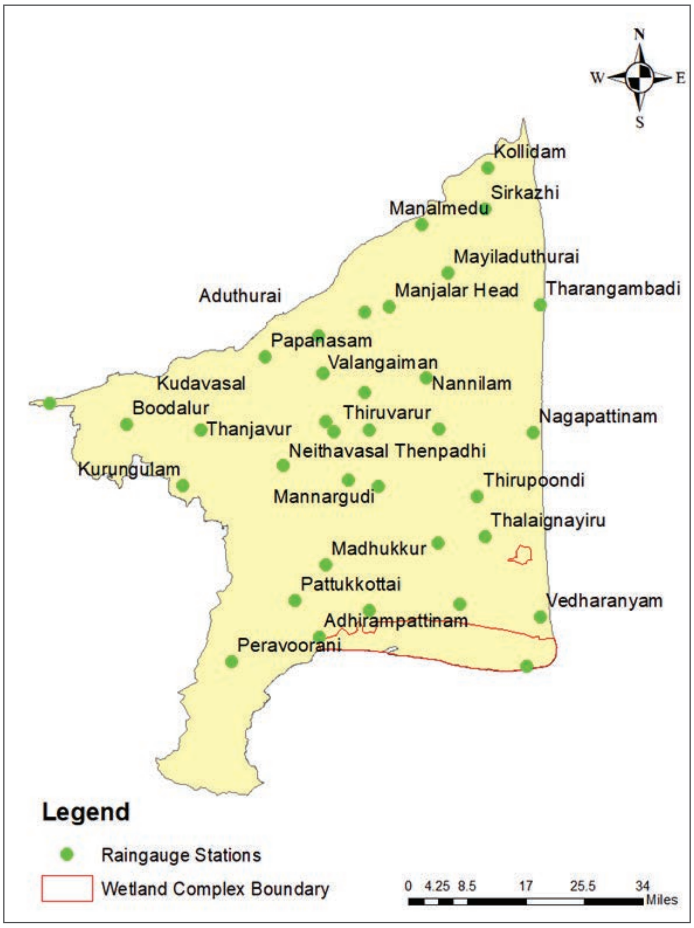


Fig. 3.1 Locations of rain gauge stations in the study area

3.4 Methodology

3.4.1 Long-term Variability

The long-term variability of rainfall was initially studied using the coefficient of variation (CV), which is a measure of relative dispersion. The variation in series, which differ in the magnitude of their averages, is defined as the ratio of the standard deviation to the mean (Simpson and Kafka, 1977).

3.4.2 Trend Analysis

The Mann-Kendall non-parametric test was carried out to understand the rainfall trend. The trend is estimated considering the slope of the linear regression line. The slope of the linear regression line is examined using the Sen's slope estimator. An excel template known as MAKESENS was used for the trend analysis (Salmi 2002). For the Mann-Kendall test, the test statistics are given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign\,(xj - xk)$$

----------- (3.1)

where xj and xk are the sequential data values, n is the dataset record length, and

$$sign\,(xj - xk) = \begin{cases} +1 if\ (xj - xk) > 0 \\ 0\ if\ (xj - xk) \ = 0 \\ -1\ if\ (xj - xk) < 0 \end{cases}$$

----------- (3.2)

The normal approximation test is resorted to if the sample size (n) is at least 10. However, if there are several tied values (i.e., equal values) in the time series, the validity of the normal approximation reduces when the number of data values is close to 10. The variance of S is computed by equation (3.3), which takes care of the ties which are present:

$$V\,AR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p - 5)\right]$$

----------- (3.3)

where, q is the number of tied groups and tp the number of data values in the pth group. The value of S and VAR(S) are used to compute the test statistics (Z) given by

$$Z = \begin{cases} \dfrac{s-1}{\sqrt{VAR(S)}} & if\ s > 0 \\ 0 & if\ s = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if\ s < 0 \end{cases}$$

---------- (3.4)

The Mann-Kendall test has the following two parameters that are important for trend detection: (i) the parameters of significance level that indicate the strength of trend; and (ii) the slope magnitude estimate that indicates the direction as well as the magnitude of the trend. Using MAKESENS, the tested significance levels are 0.001, 0.01, 0.05, and 0.1. For the four tested significance levels, symbols used in the trend statistics are:

*** if trend at α = 0.001 level of significance,

**if trend at α = 0.010 level of significance,

*if trend at α = 0.050 level of significance, and

+ if trend at α = 0.100 level of significance

If the cell is blank, the significance level is greater than 0.1; the presence of statistically significant trend is evaluated using the Z value. A positive value of Z indicates an upward trend and a negative value indicates a downward trend.

3.4.3 Precipitation Concentration Index (PCI)

The PCI, an indicator of rainfall concentration (De Luis et al., 2011), was estimated for the study area as a whole and for the northern Cauvery sub-basin and southern Vennar sub-basin separately. The index is given by

$$PCI = \frac{\sum_{i=1}^{12} p2i}{\left(\sum_{i=1}^{12} pi\right)} \times 12$$

---------- (3.5)

where Pi is the monthly rainfall for the month i. The lowest theoretical value of PCI<10 implies a perfect uniformity in rainfall distribution, i.e., the same amount of rainfall occurs in every month. A PCI value of 11-15 indicates moderate precipitation, and a value of 16–20 indicates irregular rainfall. A value >20 denotes a strongly irregular rainfall distribution.

3.4.4 Seasonality Index (SI)

The SI is used to quantify the degree of variability in the monthly rainfall through the year. The index identifies the rainfall regimes on the monthly distribution; this is based on the monthly distribution of rainfall and is estimated as the sum of the absolute deviations of the mean monthly rainfall from the overall monthly mean, divided by the mean annual rainfall (Thomas and Prasannakumar, 2016). It is given by

$$SI = \frac{1}{\bar{R}} \sum_{i}^{12} \left| X_n \frac{\bar{R}}{12} \right|$$

--------- (3.6)

where Xn is the mean rainfall of month n, and R is the mean annual rainfall. Theoretically, SI can vary from zero to 1.83; zero indicates that all the months have equal rainfall and a value of 1.83 denotes that the rainfall had occurred in one month (Kanellopoulou 2002). A classification of seasonality based on the study of Kanellopoulou (2002) is given in Table 3.1.

Table 3.1 *Classification of seasonality*

Index	Classification
≤0.19	Very equable
0.40–0.59	Rather seasonal with a short drier season
0.60–0.79	Seasonal
0.80–0.99	Markedly seasonal with a long drier season
1.00–1.19	Most rain in 3 months
≥ 1.20	Extreme, almost all rain in 1–2 months or less

3.4.5 Departure Analysis

The percentage of departure (D%) of the annual rainfall is estimated as

$$D\% = \frac{x_i - x_m}{x_i} \times 100$$

----------- (3.7)

where xm is the mean annual rainfall from annual rainfall series xi. It gives a better representation of drought years. India Meteorological Department (IMD) has classified the distribution of rainfall in a region according to the percentage departure as given in Table 3.2.

Table 3.2 *IMD classification of rainfall departure*

Terminology	Definition
Excess	Percentage departure of realised rainfall from normal rainfall is +20% or more
Normal	Percentage departure of realised rainfall from normal rainfall is between -19% and +19%
Deficit	Percentage departure of realised rainfall from normal rainfall is between -19% and -59%
Scanty	Percentage departure of realised rainfall from normal rainfall is between -60% and -99%
No rain	Percentage departure of realised rainfall from normal rainfall is -100%

3.4.6 Extreme Rainfall Events

- Extreme precipitation events have produced more rain and become more normal since the 1950s in many regions of the world.
- Scientists expect these trends to continue as the planet continues to warm. Warmer air can hold more water vapour. For each degree of warming, the air's capacity for water vapour goes up by about 7%. An atmosphere with more moisture can produce more intense precipitation events.
- Increases in heavy precipitation may not always lead to an increase in total precipitation over a season or over the year. Some climate models project a decrease in moderate rainfall, and an increase in the length of dry periods, which offsets the increased precipitation falling during the heavy events.

- The most immediate impact of heavy precipitation is the prospect of flooding. In addition to flooding, heavy precipitation also increases the risk of landslides.
- Excessive precipitation can also degrade water quality, harming human health and ecosystems. Storm water runoff, which often includes pollutants such as heavy metals, pesticides, nitrogen, and phosphorus, can end up in lakes, streams and bays, damaging aquatic ecosystems and lowering water quality for human use.
- The R statistical package is based on the RClimDex 1:1 software, used for studying extreme rainfall events.

The definitions of extreme rainfall indices are given table 3.3.

Table 3.3 *Extreme rainfall indices*

ID	Index Name	Definitions	Units
Rx1day	Max 1 day Precipitation	Monthly maximum 1-day precipitation	mm
Rx5day	Max 5-day Precipitation	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number wet days (defined as PRCP> =1.0 mm)	mm/day
R10mm	Number of heavy precipitation days	Annual count of days when PRCP>=10 mm	day
R20mm	Number of very heavy precipitation days	Annual count of days when PRCP>=20 mm	days
R2.5mm	Number of wet days	Annual count of days when PRCP>=2.5mm	days
CDD	Consecutive dry days	Maximum number of consecutive days when R>=1 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days when R>= 1mm	days
R95P	Very wet days	PRCP when RR > 95th percentile annual total	mm
R90P	Extremely wet days	PRCP when RR > 99th percentile annual total	mm
PRCPTOT	Annual total wet-day precipitation	PRCP in wet days (RR>=m1mm)	mm

3.4.7 Impact of El Nino and Indian Ocean Dipole

An attempt was made to understand the impact of El Nino and the Indian Ocean Dipole on the rainfall of the delta.

3.4.8 Rainfall and Flooding of Wetland Complex

Considering the daily rainfall data, the inundation or submergence trends in the wetland complex were analysed.

3.5 Results and Discussion

3.5.1 Rainfall Analysis

The average annual rainfall of the Cauvery delta region was found to be 1348.5 mm. The study area consists of districts of Nagapattinam, Thiruvarur and Thanjavur. RIt receives most of its rainfall from October to December (69.33%), during the north-east monsoon season. During the south-west monsoon season, the study area receives only 18% of annual rainfall. This is a major contrast between the Cauvery Delta and most other parts of the country, including the upper catchment of Cauvery Basin, which is located in Karnataka and Kerala.

The average annual rainfall is 1353 mm, 1199 mm, and 1103 mm for the period from 1997 to 2019 (Tables 3.4, 3.5 and 3.6) in Nagapattinam, Thanjavur and Thiruvarur districts, respectively. The average monthly rainfall values of the rain gauge stations are given in Tables 3.4 to 3.7 and Figs. 3.2, 3.3 and 3.4 for Nagapattinam, Thanjavur and Thiruvarur districts, respectively. The rainfall occurs due to the north-east and south-west monsoons. But the percentage of rainfall occurring due to the north-east monsoon is more compared with the south-west monsoon.

Table 3.4 *Annual rainfall of Nagapattinam district (1997–2019)*

Year	1997	1998	1999	2000	2001	2002	2003	2004
Rainfall (mm)	1782.7	1272.9	1179.5	1308.28	1148.8	1090.7	1070.33	1808.91
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Rainfall (mm)	1642.4	1250.1	1432.3	1761.63	1847.2	1699.9	1109.42	992.21
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**ARR***
Rainfall (mm)	1027.8	1368.0	1613.0	648.1	1597.81	1110.3	1333.2	1352.01

Average annual rainfall

Table 3.5 *Annual rainfall of Thiruvarur district (1997–2019)*

Year	1997	1998	1999	2000	2001	2002	2003	2004
Rainfall (mm)	1630.81	1318.45	978.63	1186.66	968.84	1081.15	1018.34	1631.09
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Rainfall (mm)	1354.62	1020.63	1276.23	1536.89	1363.12	1723.09	1140.43	918.27
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**ARR***
Rainfall (mm)	852.07	1171.49	1452.50	633.17	1303.02	963.90	1072.09	1199.80

Table 3.6 *Annual rainfall of Thanjavur district (1997–2019)*

Year	1997	1998	1999	2000	2001	2002	2003	2004
Rainfall (mm)	1369.02	1272.4	910.48	1202.83	934.28	1046.39	1041.8	1442.40
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Rainfall (mm)	1351.42	908.21	1200.3	1445.64	1158.0	1459.91	1069.2	818.91
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**ARR***
Rainfall (mm)	733.98	1057.5	1287.3	636.32	1154.3	831.05	1038.9	1103.09

Table 3.7. *Average monthly rainfall of all three districts (1997–2019)*

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Nagapattinam District												
Rainfall (mm)	32.86	27.33	28.08	28.21	58.80	31.87	35.83	87.67	88.63	267.79	443.43	225.39
Thiruvarur District												
Rainfall (mm)	23.38	25.40	20.16	34.61	71.35	31.45	49.25	99.35	106.79	219.70	342.19	182.75
Thanjavur District												
Rainfall (mm)	17.50	22.15	16.32	38.0	75.45	29.83	45.19	112.93	108.51	202.29	290.02	144.87

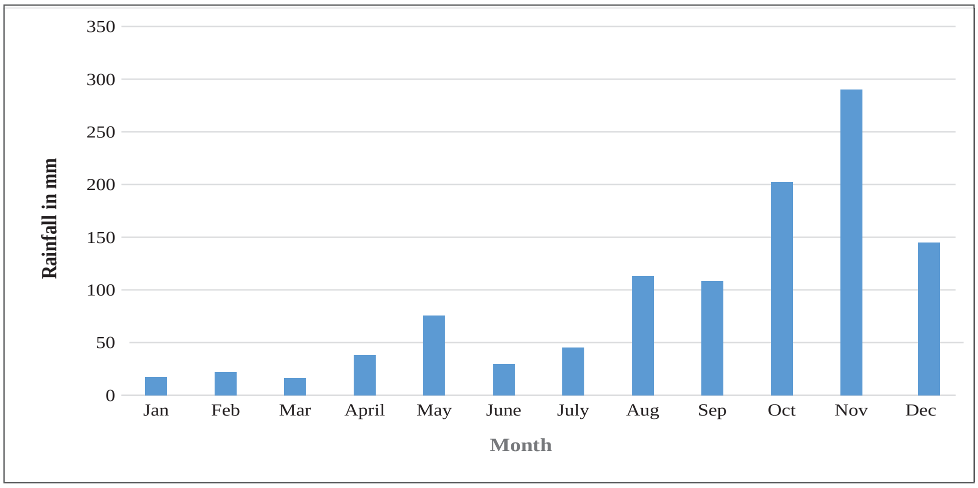


Figure 3.2 *Average monthly rainfall of Nagapattinam district (1997 –2019)*

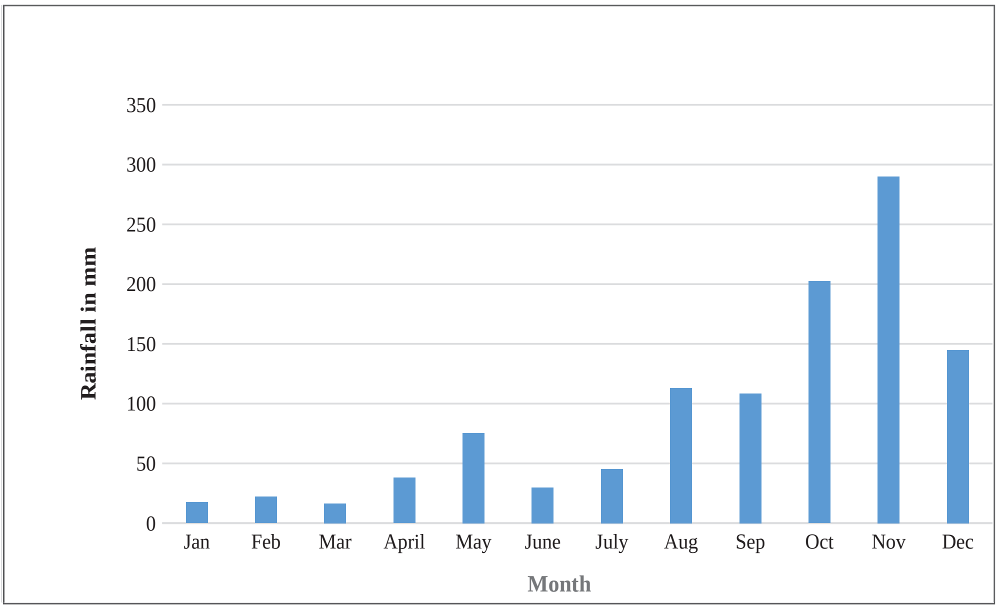


Figure 3.3 *Average monthly rainfall of Thiruvarur district (1997 –2019)*

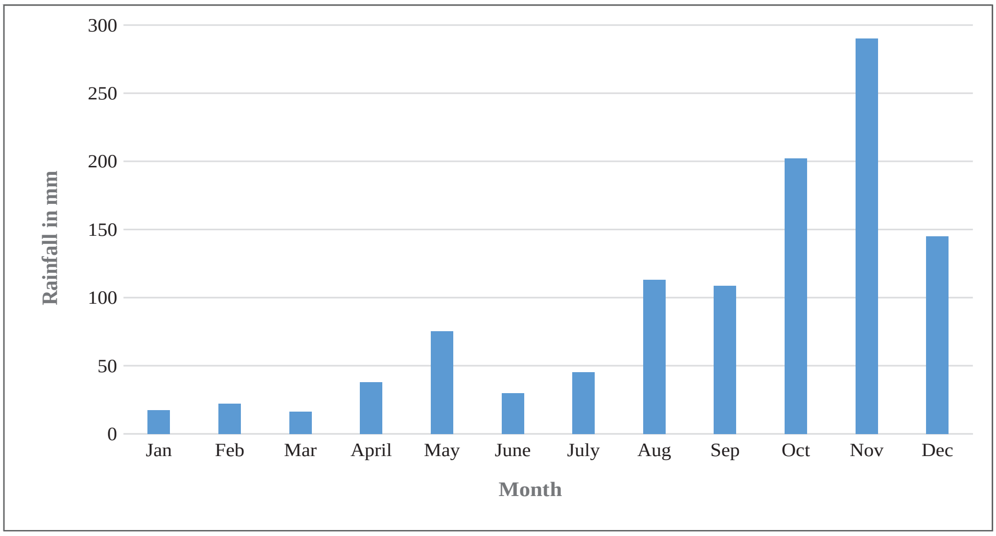


Figure 3.4 *Average monthly rainfall of Thanjavur district (1997–2019)*

3.5.1.1 EXTREME RAINFALL EVENTS

The annual total wet precipitation days and indices of very wet days, simple daily intensity index, max 5-day precipitation, number of heavy precipitation days and number of very heavy precipitation days showed increasing trends at most of the stations. A decreasing trend of consecutive dry days was observed. Consecutive wet days showed an increasing trend. The extreme rainfall events in the delta can impact agriculture adversely and can cause crop damage. The Cauvery deltaic region will experience a 20% increase in the 5-day rainfall (PWD 2016). Alexander et al., (2006) observed a widespread significant increase in the number of heavy precipitation events or days during the latter half of the twentieth century. The increasing trend of extreme rainfall events in India during the past five decades could be associated with the increasing trend in sea surface temperatures and surface latent heat flux over tropical Indian Ocean (Rajeevan et al., 2008). The increase in rainfall and extreme rainfall events in the delta may further aggravate the drainage congestion faced by the coastal deltaic regions and increase the risk of inundation.

The results in general are consistent with the results of similar studies conducted on regional and global scales. Globally, there is a trend towards wetter conditions, and the study area also shows a similar trend.

Table 3.8 *Annual rainfall of Nagapattinam district (1997–2019)*

Year	1997	1998	1999	2000	2001	2002	2003	2004
Rainfall (mm)	1782.7	1272.9	1179.5	1308.28	1148.8	1090.7	1070.33	1808.91
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Rainfall (mm)	1642.4	1250.1	1432.3	1761.63	1847.2	1699.9	1109.42	992.21
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**ARR***
Rainfall (mm)	1027.8	1368.0	1613.0	648.1	1597.81	1110.3	1333.2	1352.01

**Average annual rainfall*

3.5.1.2 LONG-TERM TREND ANALYSIS

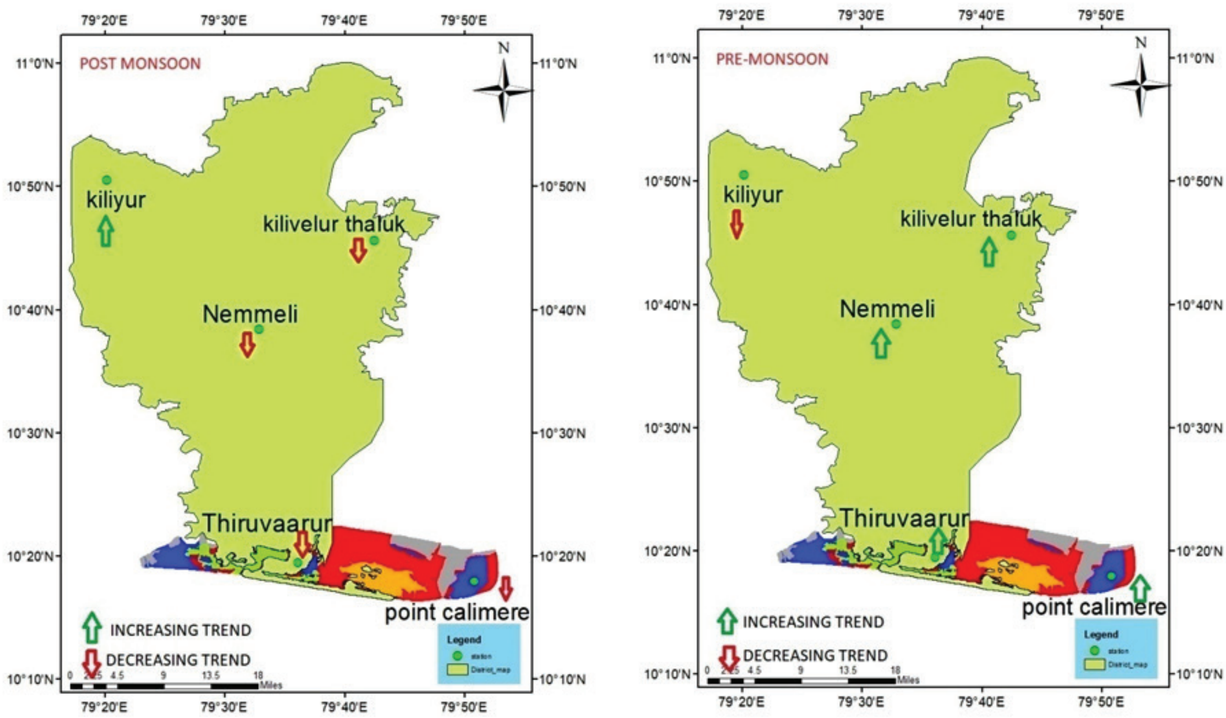
The study mainly concentrated on Nagapattinam and Thiruvarur districts, where most of these wetlands are located. The trend analysis shows that the rainfall decreases during the months of February, April, November and December and increases during the months of May, July and September. The rain gauge data at Nagapattinam station showed a decreasing trend in January (-0.58 mm/year), June (-0.82 mm/year) and December (-1.01 mm/year) and an increasing trend in May (0.72 mm/year) at a significance level of 0.1. At Thalainayar, there was an increasing trend in May (1 mm/year) and October (5.41 mm/year) at a statistically significant level of 0.1. In Voimedu, an increasing rainfall trend was observed in October (7 mm/year) at a statistically significant level of 0.01. In Vedaranyam station, a decreasing trend was observed in July (-0.74 mm/year) and September (-1.70 mm/year) at a statistically significant level of 0.05. At 0.5 significance level, Manalmedu and Thalainayar showed increasing trends of 2.78 mm/year and 2.43 mm/year, respectively. The pre-monsoon rainfall of Vedaranyam showed an increase of 2.37 mm/year at 0.1 significance level. There was a decreasing trend at Vedaranyam (-2.97 mm/year) at 0.1 significant level. The north-east monsoon was observed to be increasing in all stations. Stations such as Manalmedu (12.34 mm/year) showed an increasing trend during the north-east monsoon.

In the southern part, Thiruthuraipoondi station showed an increasing trend of 11.82 mm/year at a significance level of 0.1. The rainfall trend decreases in the coastal area during the pre-monsoon and vice versa during the post-monsoon season (figure 3.5). There is an increasing trend in all the stations during the north-east monsoon, and two stations in the coastal area showed a decreasing trend during the south-west monsoon (figure 3.6). The trend analysis shows that there is a decreasing trend in rainfall during the months of February, April, November and December.

Table 3.9 ***Trend and significance of extreme rainfall events in the study area, the regional and global scenario***

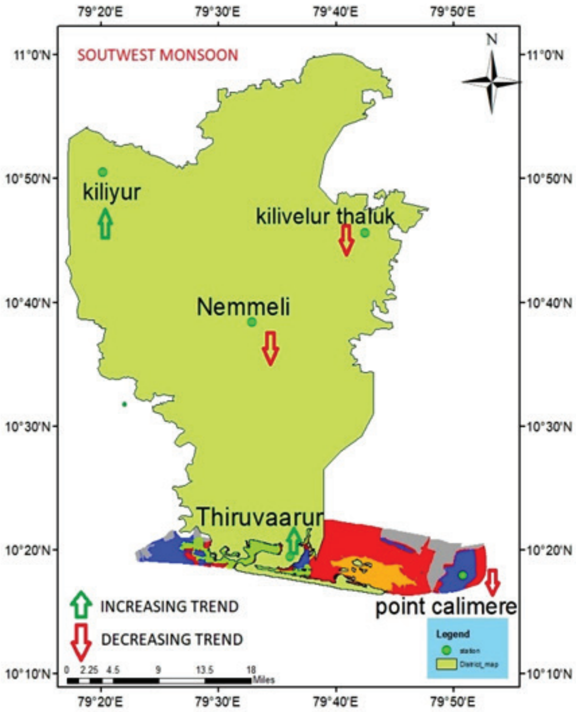
Indices	Kollid-am 1989 - 2015	Myladu durai 1981-2015	Nagap-attinam 1981-2015	Tha-ranga-mpadi 1997-2015	Thalain ayar 1980-2015	Sirkali 1985-2015	Thiru-thuraip oondi 1981-2015	Ve-daran-yam 1986-2015	Indo-Pacific 1971-2005	Equato-rial sector 1971-2005	Global 1971-2005
rx1day	-1.729	0.028	-0.488	3.004	-0.864	-0.118	-1.101	1.115	-1.12	-0.33	0.26
rx5day	-3.702	0.749	2.305	9.849+	-1.051	2.728	-0.142	4.516#	0.90	-0.67	0.73#
Sdii	-0.325#	0.105	0.034	0.585#	-0.099	0.14	0.228	0.275#	0.25#	-0.89	0.05
r10mm	0.179	0.246#	0.038	0.651+	-0.055	0.117	-0.108	-0.009	-0.14	-0.28	0.03#
r20mm	0.104	0.128	0.003	0.598#	-0.068	0.151	-0.047	0.134	-0.04	-0.04	0.06
R2.5mm	0.163	0.118	0.041	0.759	-0.028	0.1	-0.245	-0.239	-	-	-
Cdd	-2.472#	-0.472	-1.546	-1.163	-0.175	-0.367	0.332	0.891	-1.01	0.32	-1.19#
Cwd	-0.135	0.055	-0.037	0.31#	-0.002	-0.021	-0.017	-0.001	-0.13	0.50	-0.07#
r95p	-4.199	3.592	3.353	19.655#	-2.464	5.701	1.327	7.166+	12.24	-0.50	4.68#
r99p	-1.769	-0.07	-0.846	7.256+	-2.657	-1.003	-1.157	2.277	4.98	-2.30	3.38#
Prcptot	-0.367	9.65	3.335	35.711#	-2.54	10.256	1.439	7.994	-2.86	-0.85	5.91

 # = 5% significance level, + = 10% significance level.

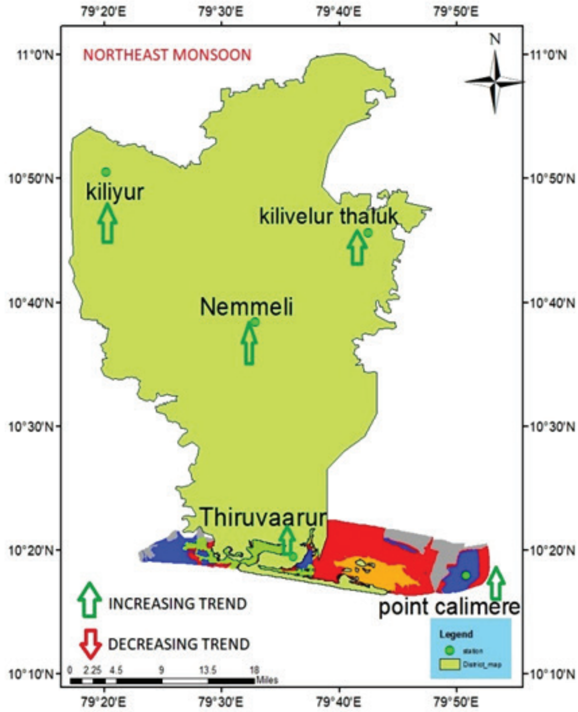


(a) Pre-monsoon *(b) Post-monsoon*

Figure 3.5 *Long-term rainfall trend in the Point Calimere Wetland Complex region during the pre-monsoon and post-monsoon periods*



(a) South-west monsoon



(b) North-east monsoon

Figure 3.6 *Long-term rainfall trends in the Point Calimere Wetland Complex region during the south-west and north-east monsoons*

3.5.1.3 Precipitation Concentration Index (PCI)

The concentration of the rainfall in a year is an important aspect. An unbalanced distribution of rainfall leads to periods of excess rainfall and periods of drought, which make plant growth difficult. Rainfall concentration is also important parameter in the assessment and the prediction of soil losses by water erosion during flooding periods. The time series of PCI on the annual scale was calculated for the entire Cauvery Delta and Vennar and Cauvery sub basins. The PCI mean value for the entire study area is 23.48. This indicates that the study area has marginal variations in monthly rainfall over a period of 35 years. The Mann-Kendall trend analysis for each station shows a declining trend for the stations in Thalainayar and Vedaranyam. The results of the analysis for the delta are given in figure 3.7, and the PCI for the Point Calimere Wetland Complex is given in figure 3.8.

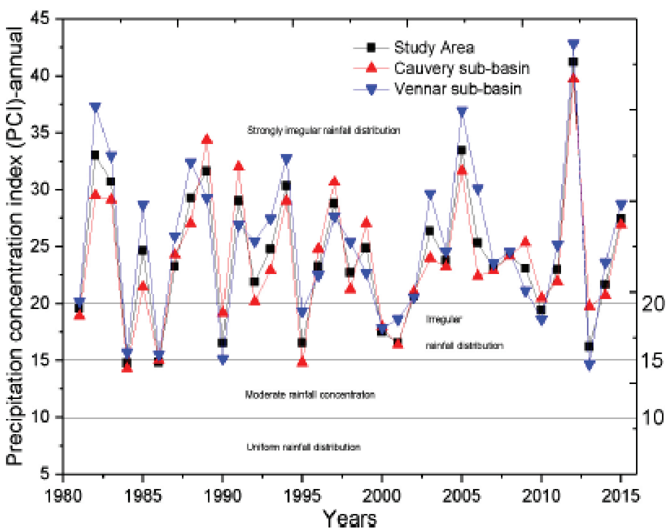


Figure 3.7 *PCI for Cauvery delta and for the Cauvery and Vennar sub-basins*

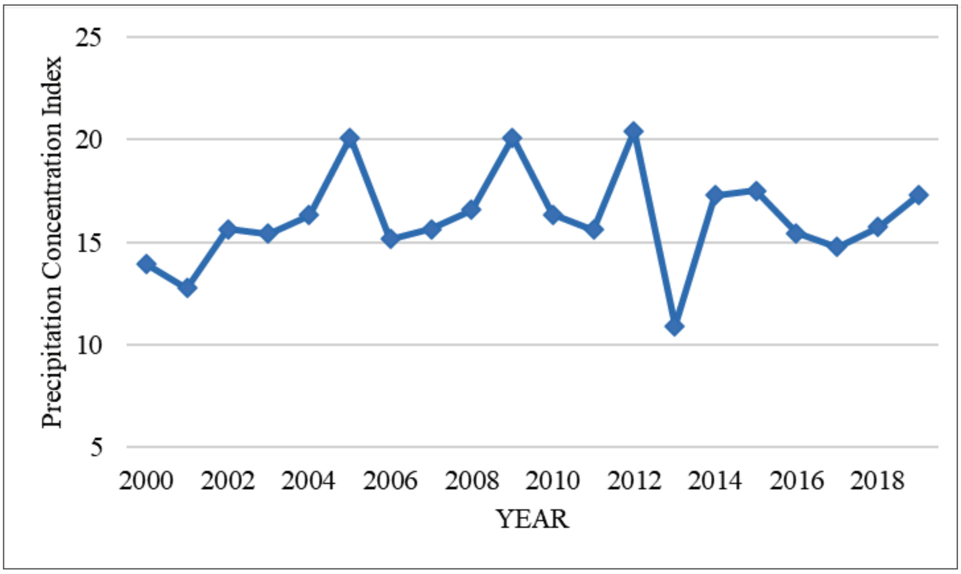


Figure 3.8 *PCI for the Point Calimere Wetland Complex*

3.5.1.4 Seasonality Index (SI)

The Seasonality Index is used to analyse the intra-annual monthly distribution of precipitation. The SI is used to understand rainfall regimes of monthly distribution. The variation in the SI value is estimated from the monthly rainfall data. The results are given in Table 3.10. The average seasonality during the period considered showed that the station at Manalmedu was markedly seasonal with long drier period and the rest of the stations experienced more rain in 3 months or less. Manalmedu station showed insignificant decreasing trend for SI value and other stations an insignificant increasing trend. Most rain in 3 months or less was observed for 71% of the years considered; 20% of the years showed markedly seasonal rainfall with a long drier season. Seasonal rainfall was observed in 1984 and 1995. The year 2012 showed extreme rainfall, with almost all the rain received in 1-2 months, with an SI value of 1.20.

Table 3.10 *Seasonality Index values*

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989
Thalainayar	1.11	1.41	1.08	0.66	0.88	0.93	0.96	0.87	1.04
Vedaranyam	0.90	1.23	1.14	0.85	0.95	0.74	1.19	1.00	1.04
Point Calimere	0.93	1.13	1.24	0.95	1.02	0.88	1.06	1.03	1.15
Year	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**
Thalainayar	0.84	1.05	1.19	1.23	1.07	0.88	1.06	1.20	1.06
Vedaranyam	0.78	0.97	1.06	1.22	1.00	0.72	1.04	1.23	1.07
Point Calimere	0.89	0.99	0.98	1.18	1.05	0.85	1.05	1.21	1.13
Year	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Thalainayar	0.99	0.96	0.91	0.89	0.96	1.09	1.18	1.25	1.14
Vedaranyam	0.85	0.95	0.97	1.20	1.14	1.18	1.00	1.22	1.09
Point Calimere	0.95	0.88	0.92	1.06	1.12	1.23	1.15	1.10	1.03

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Thalainayar	1.16	1.10	0.84	1.27	1.27	0.77	1.03	1.04	1.12
Vedaranyam	0.95	0.95	0.85	1.04	1.15	0.68	1.07	1.22	1.17
Point Calimere	0.84	0.87	0.92	0.98	1.21	0.75	1.08	1.25	1.12
Year	**2017**	**2018**	**2019**						
Thalainayar	1.12	1.09	1.12						
Vedaranyam	1.17	0.98	0.92						
Point Calimere	1.12	1.37	1.06						

3.5.1.5 Departure Analysis

The rainfall departure analysis of the study area reveals that between 1981 and 2015 (35 years), the departure varied from year to year according to the IMD classification. The rainfall was deficit in 22% of the years considered; excess rainfall was recorded in 25% of the years, and the rest of the years were normal. Figures 3.9 and 3.10 show rainfall departures based on the IMD classification of rainfall departure for the Cauvery Delta and Point Calimere Wetland Complex, respectively.

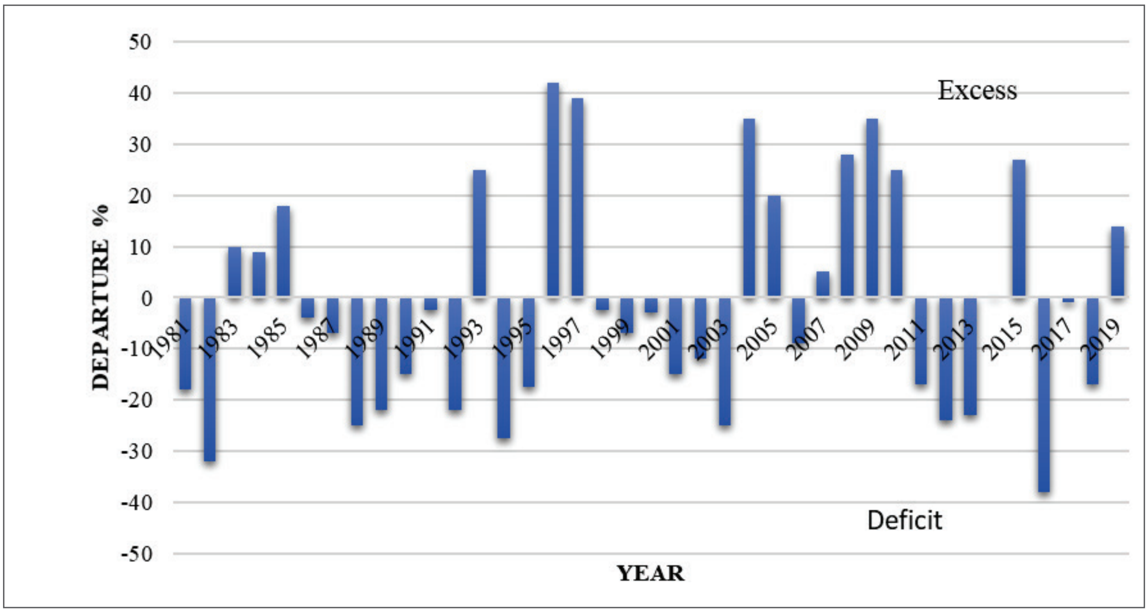


Figure 3.9 *Rainfall departure for Cauvery Delta based on IMD classification of departure*

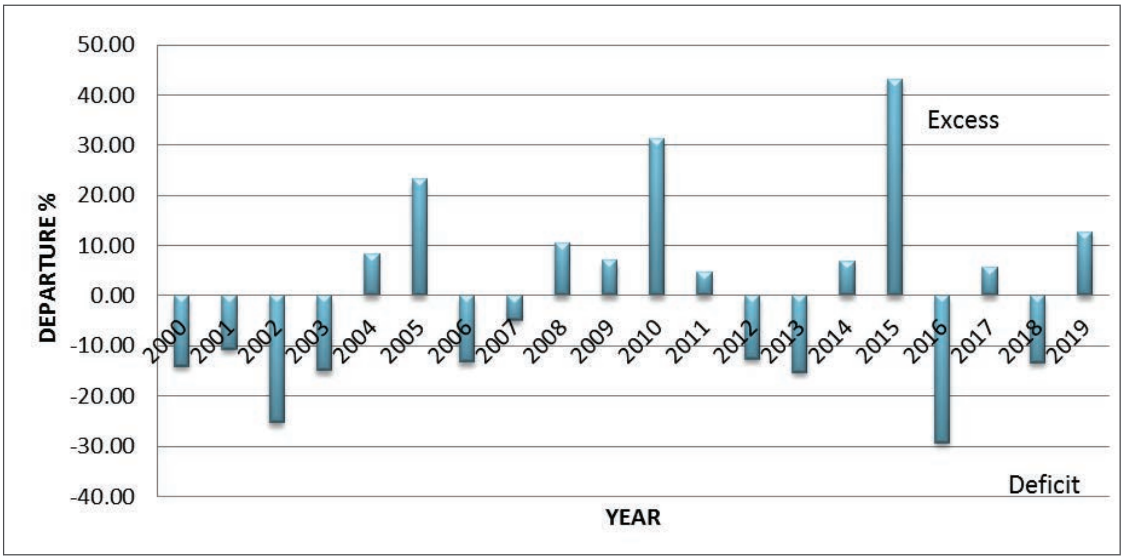


Figure 3.10 *Rainfall departure of PCWC based on IMD classification of departure*

3.5.1.6 Impact of El Nino and Indian Ocean Dipole

The El Nino-Southern Oscillation and Indian Ocean Dipole events are reported to have a marked influence on the rainfall. Out of the eight El Nino years considered, six years had more than average rainfall during the north-east monsoon in the study area (Table 3.11). During five La Nina years, there was above average rainfall during the south-west monsoon. This indicates linkages between the rainfall and global events in the study area. However, no clear trend was observed between the rainfall and IOD events.

Table 3.11 *Seasonal and annual rainfall and their relationship with ENSO and IOD events*

Year	El Nino	La Nina	Pos IOD	Neg IOD	NEMR	SWMR	Annual
1981				■	-15.31	-98.72	-18.98
1982	■		■		-22.82	-54.45	-36.00
1983			■		14.03	63.46	11.26
1987	■				3.75	-0.80	-1.48
1988		■			-32.22	22.12	-28.11
1989				■	-17.26	-6.24	-21.26
1991	■				4.96	24.02	-0.69
1992				■	-19.41	-15.80	-23.61
1994			■		-17.73	-63.96	-25.06
1995		■			-36.31	15.83	-16.51
1996				■	46.73	107.12	42.14
1997	■		■		67.86	0.88	37.97
1998		■		■	1.53	-0.99	-4.95
1999		■			-3.85	-54.71	-12.74
2000		■			-15.24	-28.80	0.52
2002	■				-31.10	-42.38	-17.69
2004	■				24.45	42.87	24.69
2006			■		1.94	-31.15	-10.42
2007		■			12.87	48.75	6.47
2009	■				44.50	-34.15	35.85
2010		■		■	18.55	81.72	22.08
2011		■			-11.47	-20.69	-12.06
2012			■		-17.41	-9.83	-25.69
2015	■				42.28	-22.46	29.93

3.5.1.7 Rainfall and Inundation Trends in Wetland Complex

It was observed that when the one-day rainfall is 150 mm or more, the rice fields and the mudflats downstream experience an average inundation of 40 cm. When the combined rainfall of two days is 150 mm, the lower part of the delta and the mudflats experience inundation ranging from 20 cm to 30 cm. It is estimated that the entire mudflats are flooded annually during an average of 15 days in different phases of the north-east monsoon season. The cyclones bringing daily rainfall of more than 150 mm cause inundation of the mudflats. During these times the entire wetland complex is connected as one water body. The estuary and channels drain away the flood water to the sea, especially during the low tide periods.

3.5.1.8 Isohyetal Map of the Delta and Annual Rainfall in the Direct Catchment

The isohyetal map of the delta is given in figure.3.11. The annual rainfall increases from 950 mm to 1500 mm from Thanjavur district to the coastal belts in Nagapattinam and Tiruvarur districts. The annual rainfall in the direct catchment is given in figure 3.14.

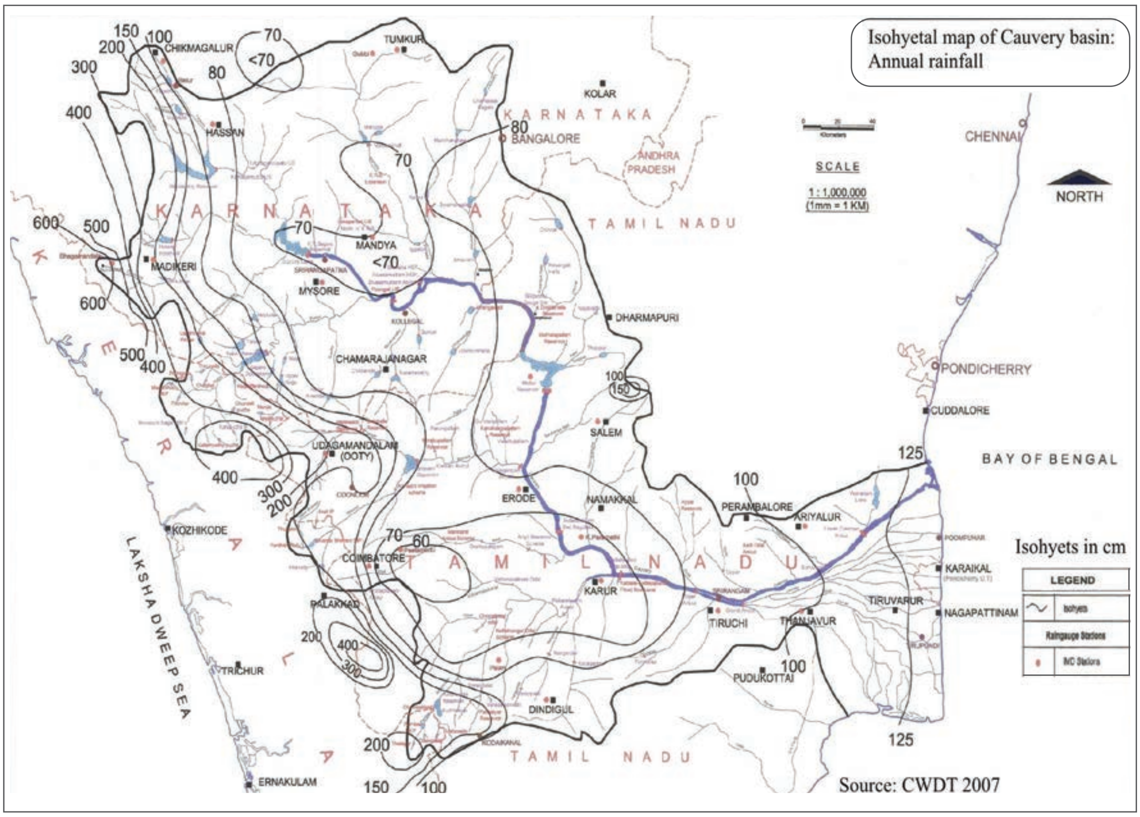


Figure 3.11 *Isohyetal map of Cauvery basin: Annual rainfall*

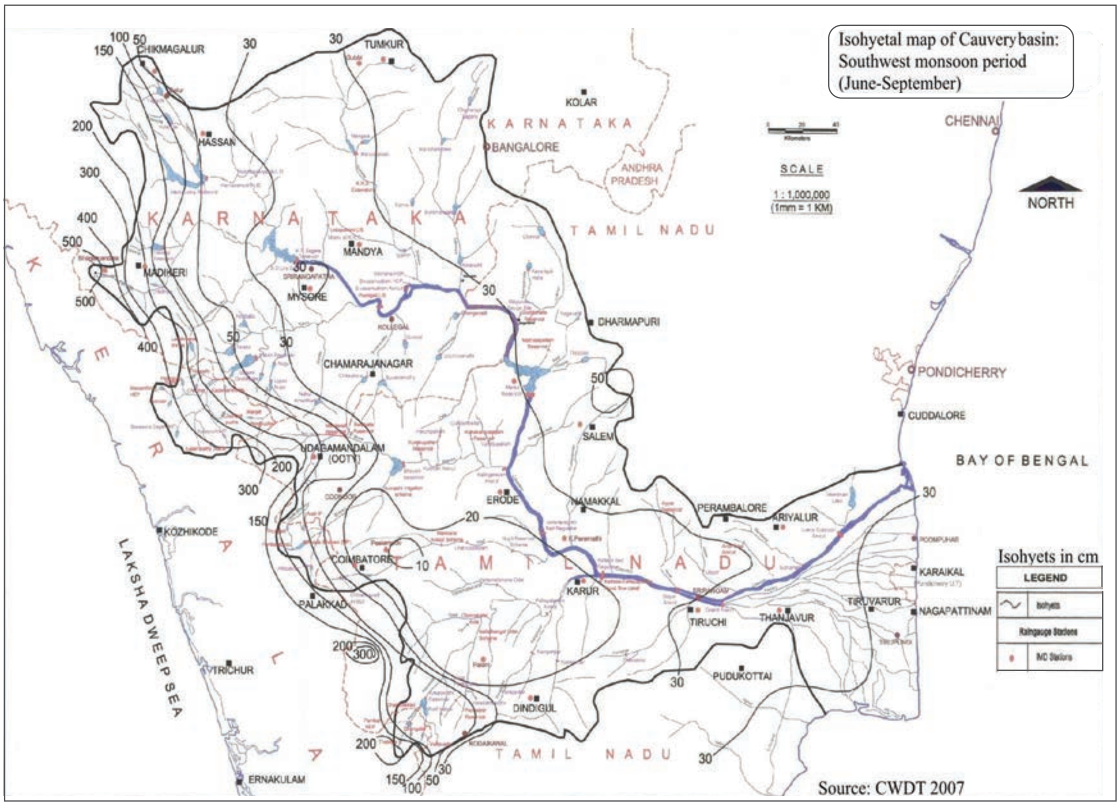


__Figure 3.12__ Isohyetal map of Cauvery basin: South-west monsoon (JJAS)

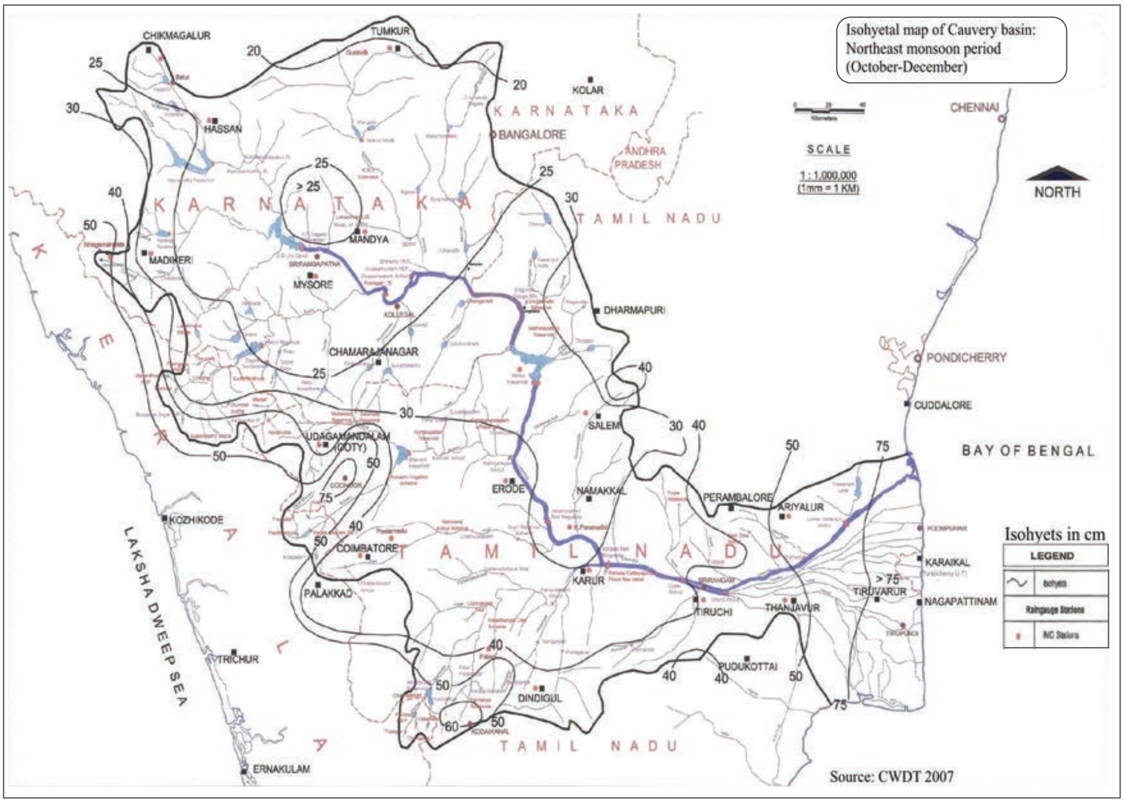


__Figure 3.13__ Isohyetal map of Cauvery basin: North-east monsoon (OND)

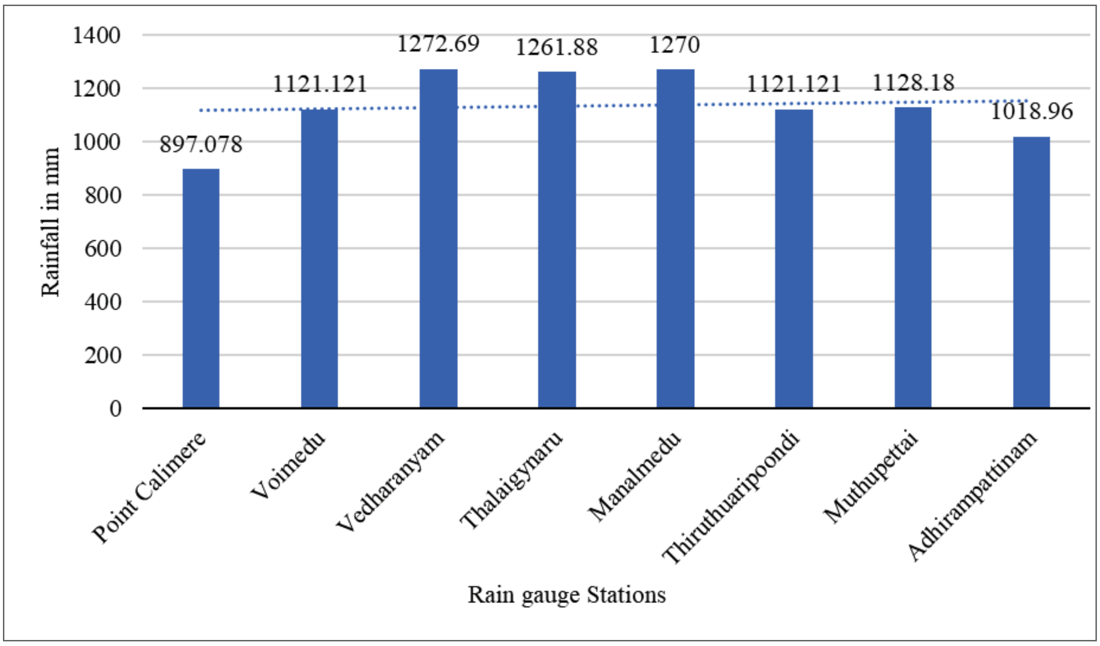


Figure 3.14 *Average annual rainfall of direct catchment of PCWC*

3.6 Summary

- From the study, it is concluded that on an average 11 out of 19 years negative departure of the Standardised Precipitation Index (SPI) was recorded in Thiruvarur district and the wetland complex as such, which means the precipitation was less than the median precipitation.
- The Seasonality Index shows that there was excess rainfall during 2005, 2010 and 2015.
- The study area as a whole shows an insignificant increase in rainfall. The Thalainayar and Vedaranyam stations, which are close to the wetland complex, showed a declining rainfall trend.
- The rainfall is received mainly in the north-east and the south-west monsoon seasons but the percentage of rainfall received during the north-east monsoon is much more than that received during the south-west monsoon period.
- The rainfall trend analysis showed that during the pre-monsoon and north-east monsoon seasons, the rainfall exhibited a statistically significant increasing trend both in the whole delta and wetland.
- The Cauvery sub-basin in the lower reaches showed an increasing rainfall trend compared with the Vennar sub-basin, in which most of these wetlands are located.
- The extreme rainfall event indices show that the total annual precipitation days, indices of very wet days, max 5-day precipitation, number of heavy precipitation days have an increasing trend at most of the stations, which finding is in line with the regional trends.
- The PCI values suggest strongly irregular rainfall in the study area.
- The Seasonality Index showed that most rain in three months or less was observed for 71% of the years considered.
- The rainfall showed a positive correlation to global indicators such as the El Nino-Southern Oscillation.
- When the daily rainfall exceeds 150 mm, the mudflats are inundated to an average of 40 cm and when two-day rainfall exceeds 150 mm, the mudflats are inundated between 20 cm and 30 cm.
- In a year, all the mudflats remain inundated for only about 15 days, during which period the downstream reaches of the delta become a single water body. However, during each of these events, water is drained away generally within 3 days.

4. SURFACE WATER AVAILABILITY IN CAUVERY DELTA AND DIRECT CATCHMENT OF POINT CALIMERE WETLAND COMPLEX

4.1 Introduction

The flow of a stream is directly related to the amount of water moving off the watershed into the stream channels, wetland or sea. It is affected by weather, increasing during the rainstorms and decreasing during the dry periods. It also changes during different seasons of the year, decreasing during the summer months when evaporation rates are high, and vegetation is actively growing and removing water from the ground. Streamflow, or discharge, is the volume of water that moves over a designated point over a fixed period of time. It is often expressed in cubic feet per second (f^{t3}/sec) or cubic meter/sec (cumec). The variations in streamflow have an impact on the water quality and on the living organisms and habitats within the stream and associated water bodies. The Point Calimere Wetland Complex , situated at the tail-end of the Cauvery Delta, has more dwindling freshwater flows, as a result of which the availability of water in the wetland complex has been affected. For a better understanding of the hydro-environment of the Cauvery delta, an attempt has been made to carry out an analysis of the streamflow data. This hydrological analysis will lead to an understanding on the fluctuations of flow into the delta and the wetland complex, especially to the Muthupet and Siruthalaikadu lagoons in the wetland complex, and the consequences thereof.

4.2 General description of distributaries and channels

A general description of the distributaries and channels in the delta, especially in the direct catchment, has been furnished since the stream gauging stations are located in these distributaries and channels. There are several regulators at the tail-end of the distributaries and channels which regulate the flows to the wetland complex and downstream reaches. The details of the regulators have also been highlighted.

The Vennar River traverses through Thanjavur, Thiruvarur and Nagapattinam districts and empties into the Bay of Bengal by branching off into a number of streams and channels. It irrigates an extent of 1,65,762 ha in the three districts, besides serving as a drainage carrier.

At Thenperambur Village (V.V.R. Head), the Vennar trifurcates into the Vennar, Vettar and Vadavar. Further, at Needamangalam the Vennar trifurcates into the Vennar, Koraiyar and Pamaniyar and the main Vennar River again bifurcates into the Vennar and Pandavayar. The Koraiyar river branches into four river-cum-drainages, namely, the Koraiyar, Ayyanar, Mulliyar and Harichandranathi. Moreover the Mulliyar again bifurcates into the Mulliyar and Adappar at Kottur Village. All these branches, namely, the Vellaiyar, Harichandranathi, Mulliyar, Adappar and Koraiyar, fall into the Bay of Bengal. The Valavanar, Marakkakoraiyar and Kilaithangiyar are the drainage channels diverted from the Mulliyar, and the Kandankurichan channel is diverted from the Koraiyar River. The Adappar and Harichandranadhi are distributary channels of the Koraiyar. The river network of Vennar sub-basin is given in figure. 4.1.

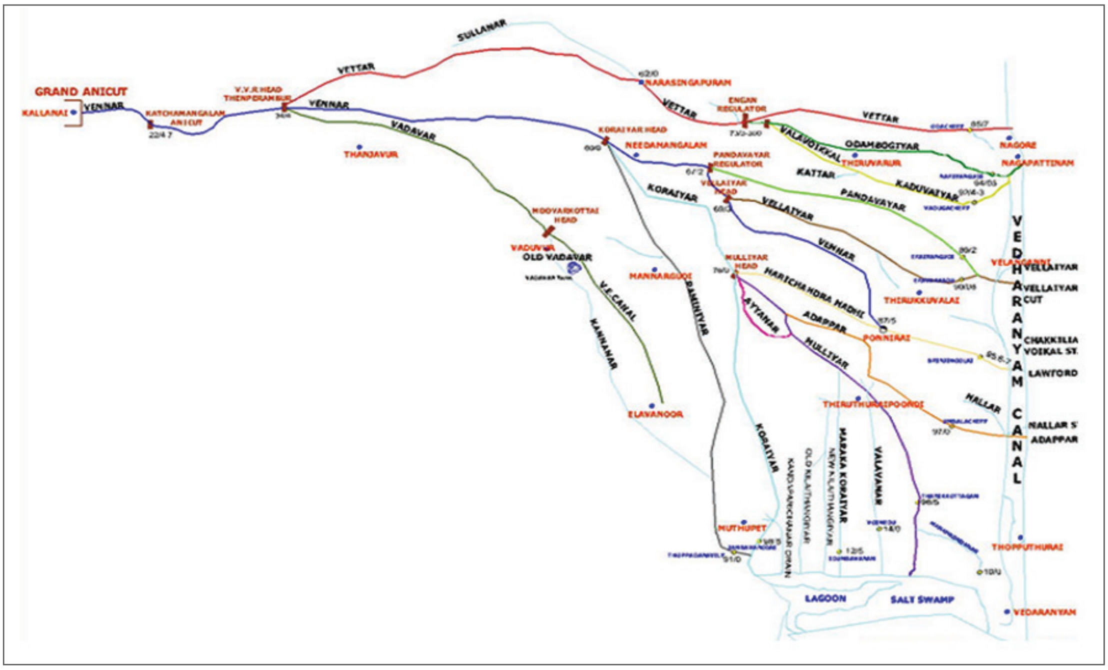


Figure 4.1 *Vennar sub-basin drainage network (cavscdptnwrd.in)*

4.2.1 Tail-end Regulators

The total number of tail-end regulators present in the Cauvery Delta is 26, of which 15 are on the rivers of the Cauvery arm and its distributaries, and 11 are on the rivers of the Vennar arm and its distributaries. Of the 15 regulators in the Cauvery arm, nine are in Tamil Nadu and six are in the Karaikal area of the Union Territory of Puducherry. In the Vennar arm, all the tail-end regulators are in Tamil Nadu.

These regulators serve the dual purpose of heading up the irrigation waters for commanding the ayacut and at the same time holding up the saline backwaters of the sea. From the data, it can be inferred that the Koraiayar carries maximum flow under normal as well as flood conditions. During the flood period, flow is diverted only into Koraiyar and Paminiyar rivers. The flood flow is not diverted into the Mulliyar and Harichandra rivers, which act as feeding channels for the Siruthalaikkadu Lagoon and Thalainayar Reserve Forest. In contrast, the Koraiyar and the Paminiyar discharge into the Muthupet Lagoon and associated water bodies only.

The stream flow data for the Cauvery delta and Vennar Sub-basin were obtained from the Public Works Department of Thanjavur and Thiruvarur districts for the period from 1983-2019 (36 years).

4.3 Methodology

4. 3.1 Streamflow Analysis

The Indicators of Hydrologic Alteration (IHA) programme, originally developed by the Nature Conservancy in the 1990s to analyse the daily flow data, was used to characterise the natural water flow conditions and to understand the changes induced by anthropogenic activities (Mathews and Richter, 2007; Yang et al., 2008). The monthly flow duration curves were developed for the streams/rivers flowing into the wetland complex. The flows at the tail-end regulators were also estimated. All these analysis and modelling are expected to throw light on the quantum of flows to be maintained at the tail-end for the wise use of wetlands.

4.4 Stream flow in Cauvery and Vennar Basin

The data from two streamflow measuring stations at the entry point of the delta (figure 4.2) were analysed to gain a preliminary understanding of the flows from the upstream reaches of the delta - both natural and regulated. An attempt was also made to assess the flow conditions before and after the Interim and Final Awards of the Cauvery Water Dispute Tribunal (CWDT) in 1991 and 2007, respectively.

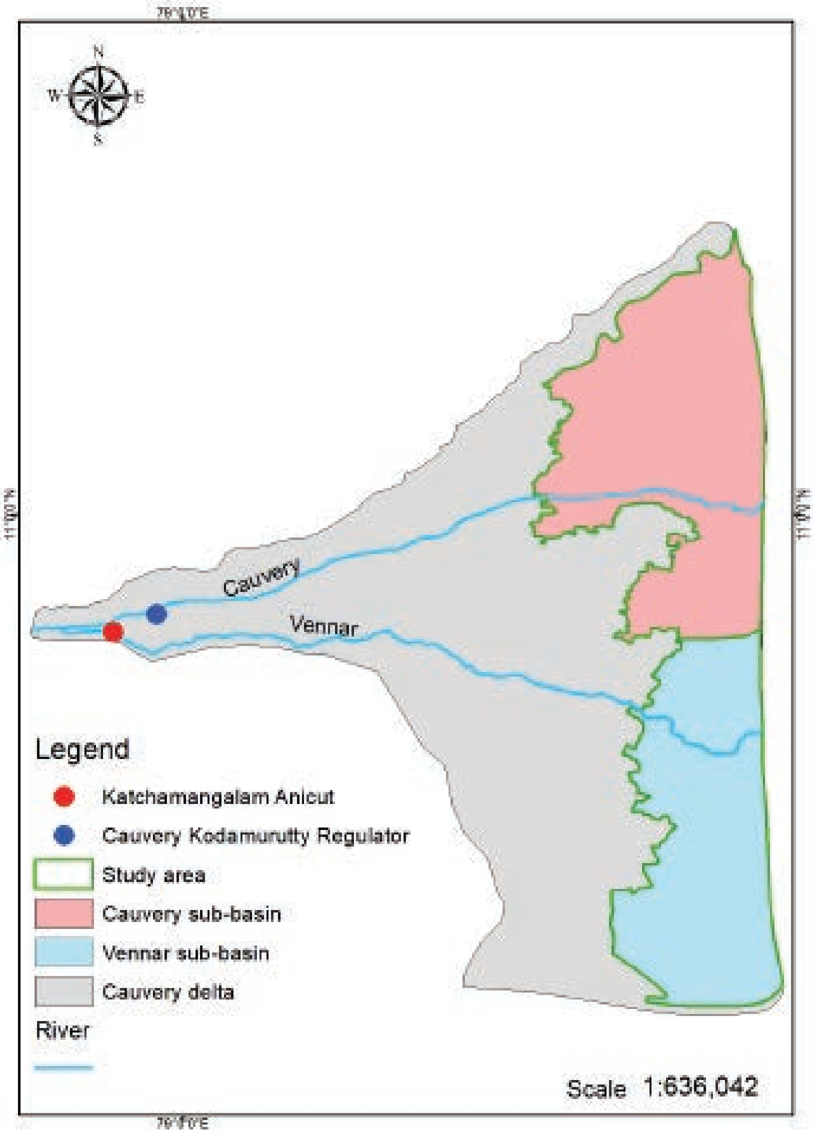


Figure 4.2 *Location of streamflow gauging stations in the Vennar Sub-basin*

4.4.1 Cauvery Delta

The monthly hydrographs for the Cauvery delta for the years 1983 to 2014 are given in figures. 4.3 to 4.5, and the results of the flows to the delta are provided in Table 4.1 The monthly flow hydrographs show that the flows to the delta are confined to the period from July to January in a water year. The monthly hydrograph for each year indicates that there is a decreasing trend in the flows to the delta in all the months considered, except August and September. In the Cauvery Sub-basin, within the delta, the monthly hydrograph for each year indicates that there is a decreasing trend of flows in all the months.

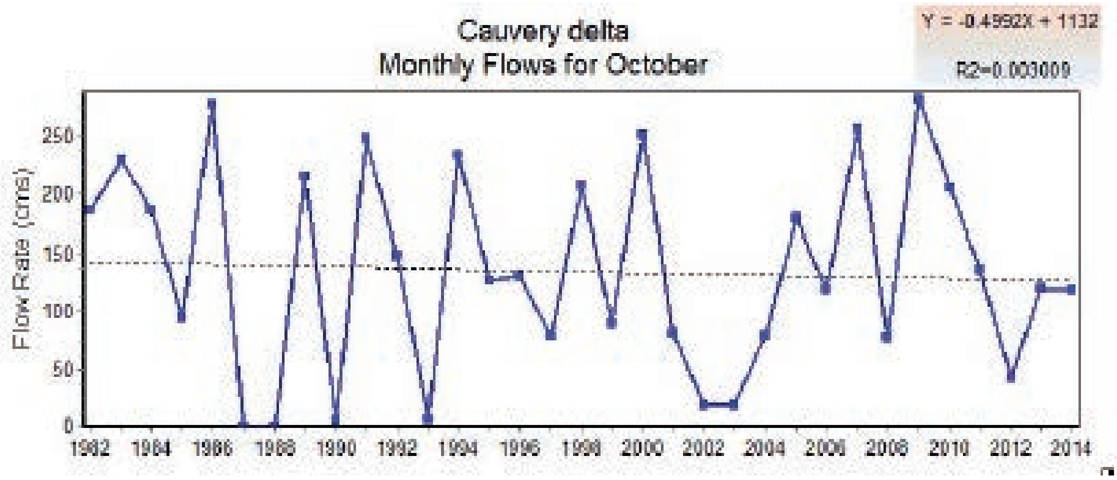


Figure 4.3 *Streamflow trends in October – Cauvery delta*

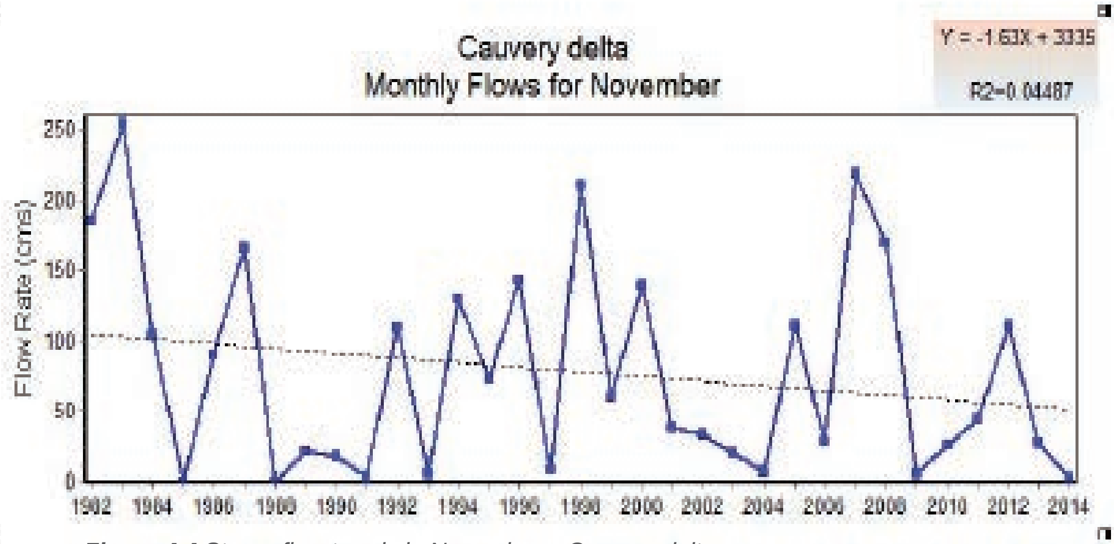


Figure 4.4 *Streamflow trends in November – Cauvery delta*

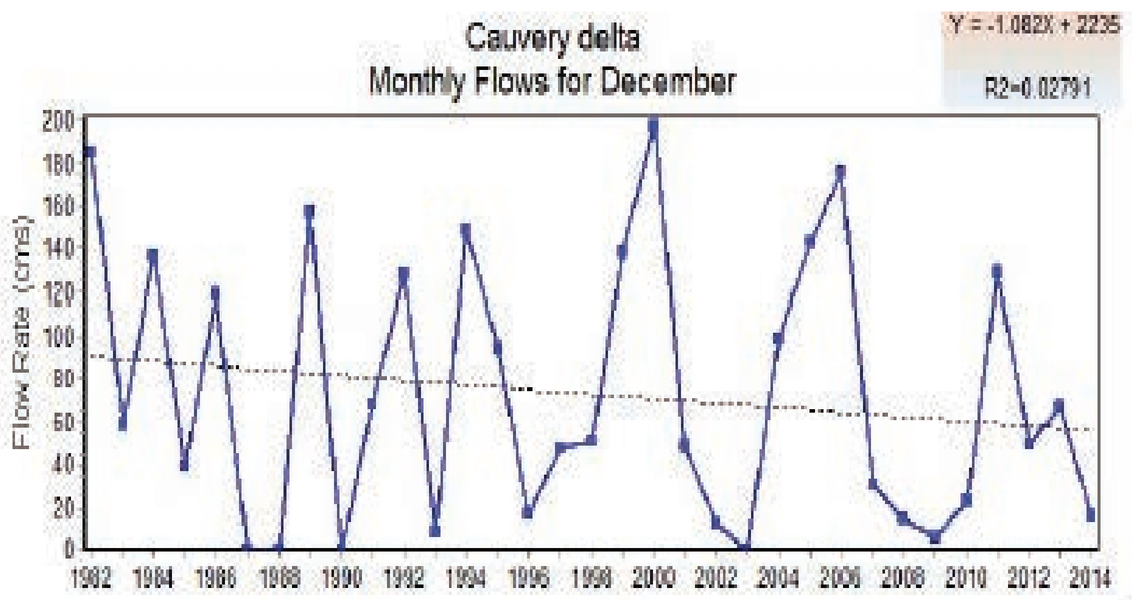


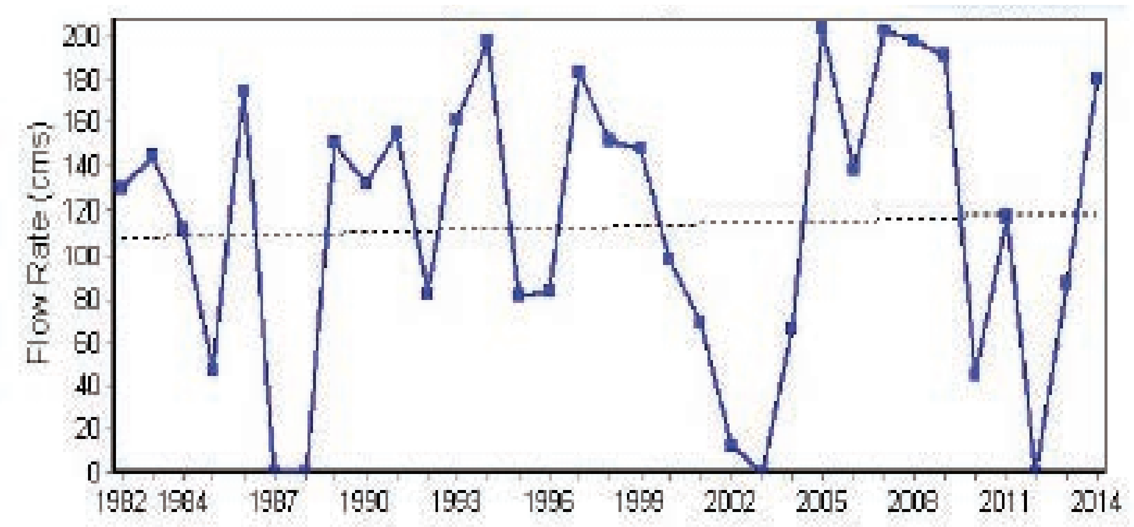
Figure 4.5 *Streamflow trends in December – Cauvery delta*

Table 4.1 Trend of monthly flows to the Cauvery delta: 1983–2014

Environmental Flow Components (EFC) Parameters	Cauvery Delta	
	Slope	R^2
July	-0.892	0.005
August	0.181	0
September	0.758	0.005
October	-0.499	0.003
November	-1.63	0.045
December	-1.082	0.028
January	-0.87	0.026
Number of Zero days	-1.166	0.03

4.4.2 Vennar Sub-basin

The monthly hydrographs for the Vennar sub-basin are given in figures 4.6 to 4.9, respectively, and the results of the flows to the sub-basins are given in Table 4.2. In the Vennar Sub-basin, within the delta, the flows show a decreasing trend in all months considered, except September.



***Figures 4.6** Streamflow trends in October – Vennar sub-basin*

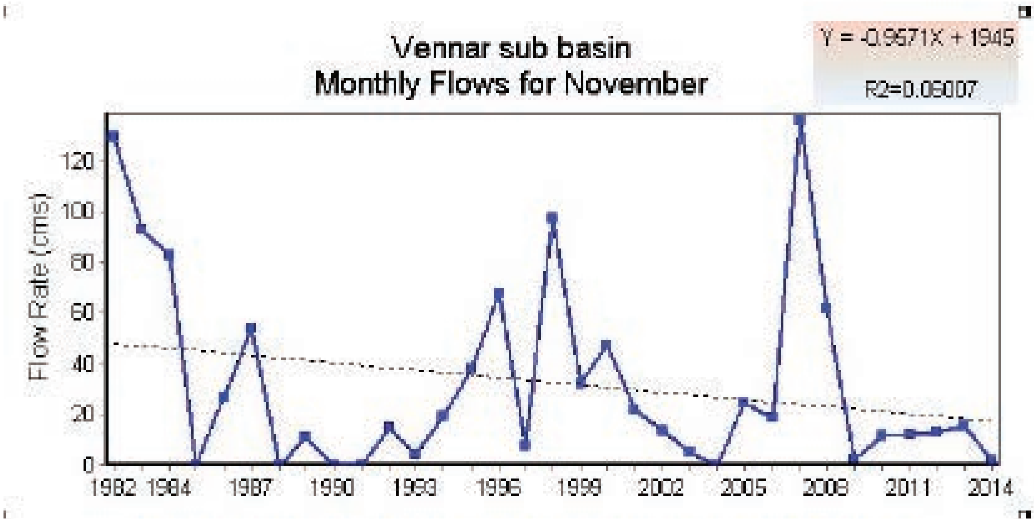


Figure 4.7 *Streamflow trends in November – Vennar sub-basin*

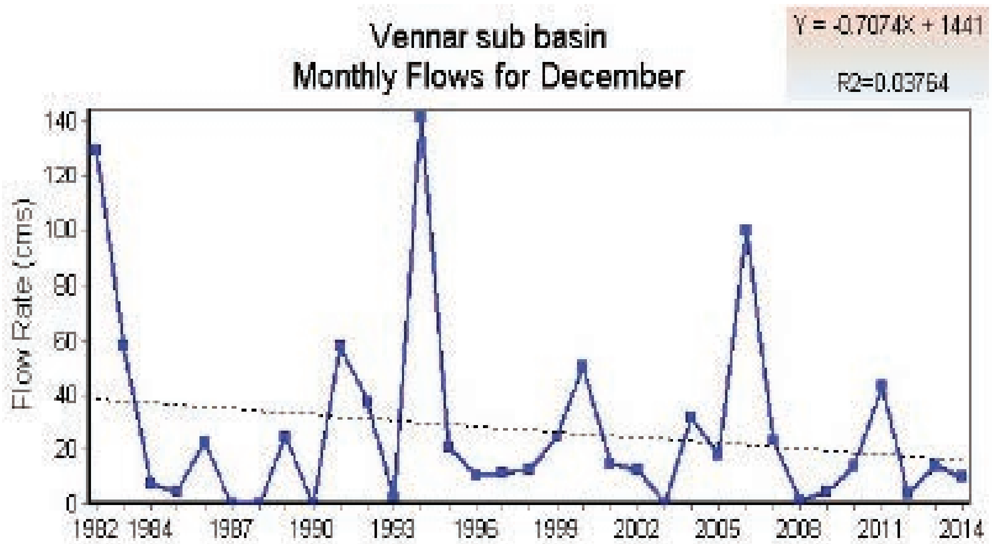


Figure 4.8 *Streamflow trends in December – Vennar sub-basin*

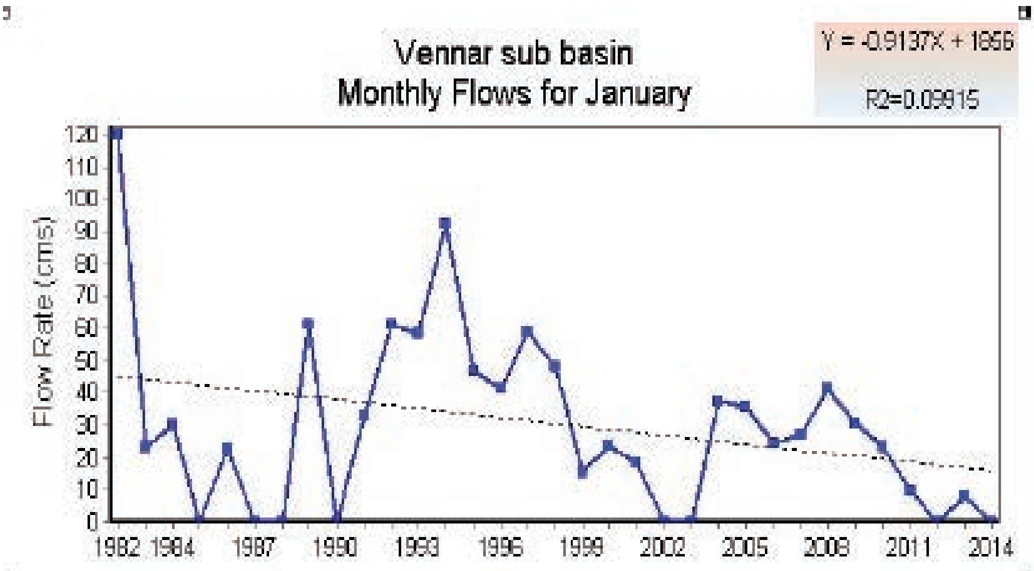


Figure 4.9 *Streamflow trends in January – Vennar sub-basin*

__Table 4.2__ Trend of monthly flows to the Vennar sub-basin of the Cauvery delta: 1983–2014

Environmental Flow Components (EFC) Parameters	Vennar sub-basin	
	Slope	R^2
July	-0.44	0
August	-0.12	0
September	0.33	0
October	-0.09	0
November	-0.96	0.06
December	-0.71	0.04
January	-0.91	0.1
Number of Zero days	-0.7	0.01

The trends in the flows of the Cauvery delta and Vennar sub-basin may be either due to a decrease in rainfall in the upper catchment or reduction in the regulated flow from the upstream reservoir or both. The trend analysis of monthly flows to the delta shows that the number of zero-days are decreasing, indicating a tendency towards an increase in the number of days with streamflow. In other words, the temporal distribution of streamflow has improved. A similar trend of decreasing zero-days can also be observed in the Vennar Sub-basin within the delta. Even marginal changes in the stream flow pattern are expected to have an impact on the flora and fauna and farming activities of the delta.

The annual and monthly flow duration curves generated using the average of 32 years of data for the flows to the Cauvery Delta and to the Vennar Sub-basin, within the delta, in which the wetland complex is located, are given in figures 4.10 and 4.11, respectively.

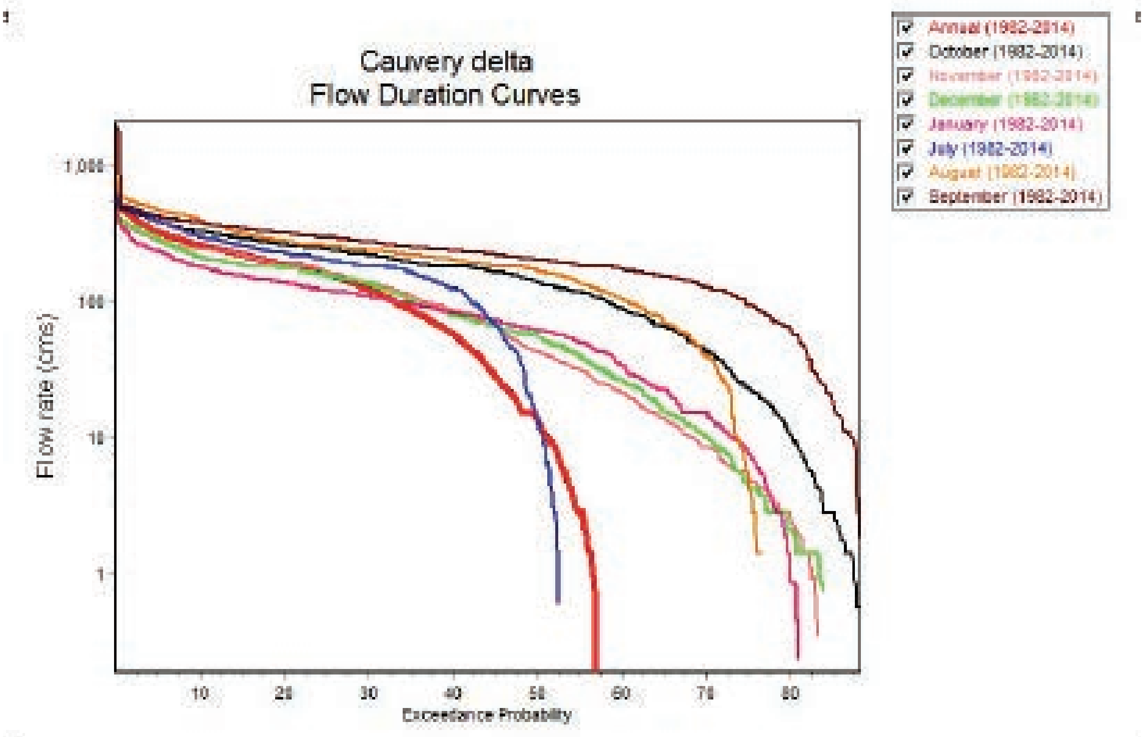


__Figure 4.10__ Annual and monthly flow duration curves – Cauvery Delta

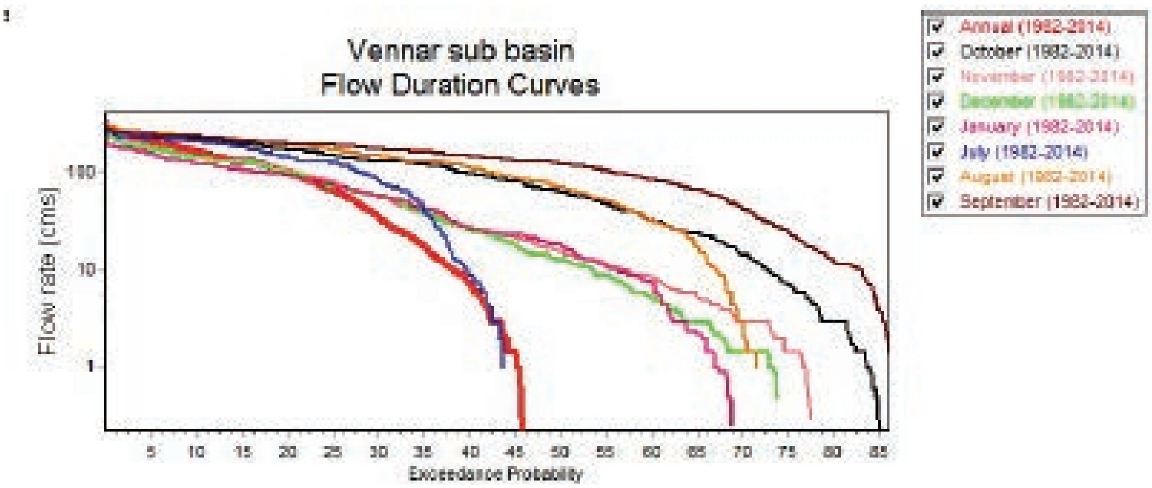


***Figure 4.11** Annual and monthly flow duration curves – Vennar sub-basin*

The curves shows that there are flows to the delta during 57% of the time in a year. The monthly flow duration curves show that the flows are there all through September and October. The flows are there for 84%, 83%, 81%, 76% and 52.5% of the time in December, November, January, August and July, respectively. The flow duration curves for the Vennar sub-basin show that flows are there all through the month of September and only 64%, 60%, 58% and 56% of the time in October, August, January and November, respectively. The month of December has flows for 56% of the time and July only for 45% of the time.

It may be noted that all the three crops, namely, Kuruvai, Thaladi and Samba are at different growth stages in the delta in September and part of October. In November and December, only two crops are grown in the delta, while the Samba is harvested during this period. During the winter, the population of migratory birds to the wetlands is at the peak, during which period there is a reduction in flows to the delta. The month of July is mainly the initial period of growth for Kuruvai and the second half of July for that of Samba. The flow duration curve reflects the availability of streamflow in different months during the different crop periods in the delta. The monthly flow duration curve for the Vennar Sub-basin show more or less the same pattern, except that each of the months has flows for more time than in the Cauvery Sub-basin; however, in the month of July, the flow available in the Vennar sub-basin is marginal and for less time than the Cauvery Sub-basin. The results obtained from the flow duration curves highlight the fact that the stream flows are regulated so as to meet the irrigation requirements of the delta as much as possible. However, the requirements for the wise use of the wetlands have not been considered in regulating the flows to the delta. There is an imminent need to reconsider the regulation of flows taking into account the sustainability of the wetlands and their ecosystem services, especially biodiversity. The flow requirements of the wetland complex have been estimated and are presented in Chapter 8.

In the Vennar sub-basin, the annual and seasonal river flows vary from year to year. The irrigated area in the Cauvery Delta is approximately 6,94,000 ha, with mainly rice being cultivated. Approximately 5,84,000 ha of this area is in the Cauvery Delta of Thanjavur, Thiruvarur and Nagapattinam districts, of which about 1,88,000 ha is in the Vennar system. During normal operations, the distribution of water within the Vennar system reflects the demand. The data of Water Resources Department shows a broadly consistent distribution from the head regulators. During the floods, however, the system is operated in flood management mode, wherein the head regulators are fully opened in all the rivers except the Vadavar, Mulliyar, Ayyanar and Harichandrinadi, which are effectively isolated. The results of analysis carried out using the streamflow data to find out the possible impact of 2007 Final Award of CWDT are given in Table 4.3

__Table 4.3__ Statistics for 16 hydrologic alteration factors before and after 2007 Final Award

Indicators of Hydrologic Alterations (IHA*) parameters	Pre-impact period 1982-2007		Post-impact period 2008-2014		RVA** Boundaries		HA†
	Mean	CV	Mean	CV	Low	High	(MC)
July	47.17	4.82	0.00	0.00	0.00	211.20	23.81
August	184.30	1.44	137.30	0.92	96.56	233.20	85.71
September	231.30	0.55	223.60	0.55	168.80	254.30	48.57
October	128.80	1.21	120.00	1.07	80.86	187.70	11.43
November	66.71	1.88	27.79	3.78	21.40	112.20	48.57
December	63.50	1.94	23.36	2.23	38.64	129.30	11.43
January	72.52	1.30	15.57	5.93	60.46	111.90	11.43
1-day maximum	507.70	0.27	430.00	0.26	470.10	527.50	-25.71
3-day maximum	463.60	0.42	342.30	0.31	381.90	508.20	-25.71
7-day maximum	401.80	0.52	305.10	0.46	298.10	474.90	48.57
30-day maximum	287.70	0.57	233.70	0.49	199.90	319.20	48.57
90-day maximum	229.50	0.69	193.40	0.35	183.40	259.90	48.57
Number of zero days	129.50	0.59	142.00	0.40	113.00	169.90	35.06
Rise rate	38.43	0.42	22.97	0.41	33.93	42.34	-62.86
Fall rate	-31.90	-0.50	-21.46	-0.20	-35.40	-26.69	-62.86
Number of reversals	110.00	0.40	105.00	0.57	100.90	126.20	11.43

* IHA = Indicators of Hydrologic Alterations
** RVA = Range Variability Approach
HA † = Hydrologic Alteration

4.4.3 Point Calimere Wetland Complex

The monthly flow hydrographs (figures 4.12 to 4.14) corresponding to the Paminiyar river show that the flows to the delta are confined to the period from July to January in a water year. Generally, there seems to be an increasing trend in flow during the months of September, October and November from the year 2004 onwards. The monthly hydrograph for each year indicates that there is an increasing trend in flows during the months from August to January in a water year. The hydrographs indicate that there is a drainage problem in this region during the north-east monsoon because by the time the upland catchment forces the flood waters down the Vennar, the flow in the lower reaches is already fully congested with the flood generated. Far from being able to receive any part of the vast quantities of waters that the rivers bring down, the fields that drain into these rivers are themselves in need of adequate drainage during this period of intense north-east monsoon, more because of its vast extent. The flow duration curves as shown in figure 4.15 reflect the availability of streamflow in different months during the different crop periods in the Paminiyar River. However, in July, the flow available in the Vennar is marginal and for a shorter period compared with the Cauvery Delta.

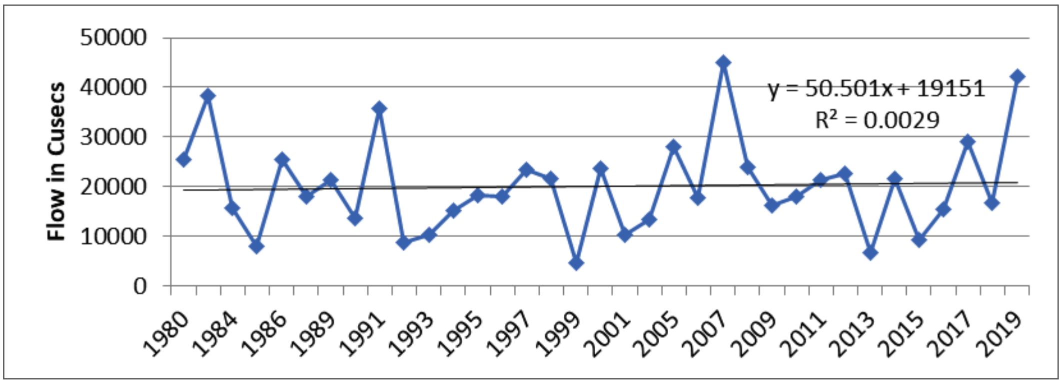


Figure 4.12 *Streamflow trends in October – Paminiyar river*

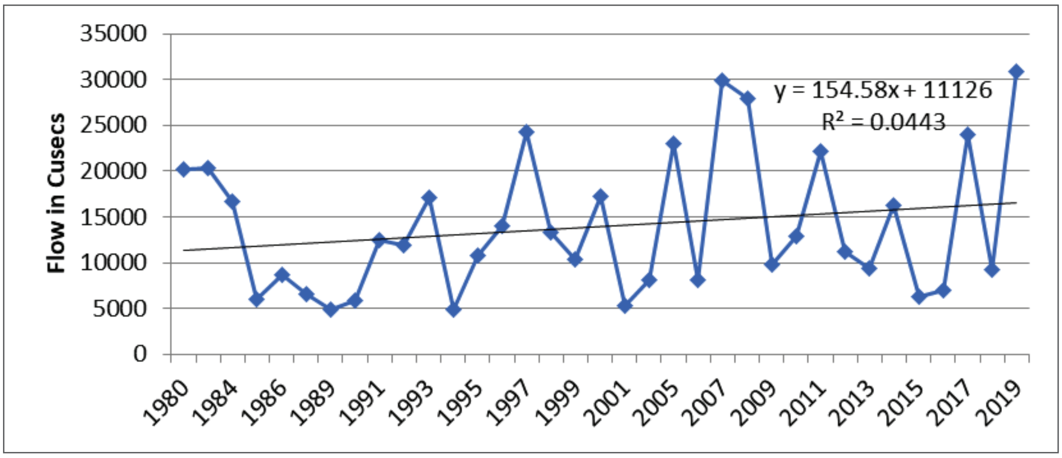


Figure 4.13 *Streamflow trends in November – Paminiyar river*

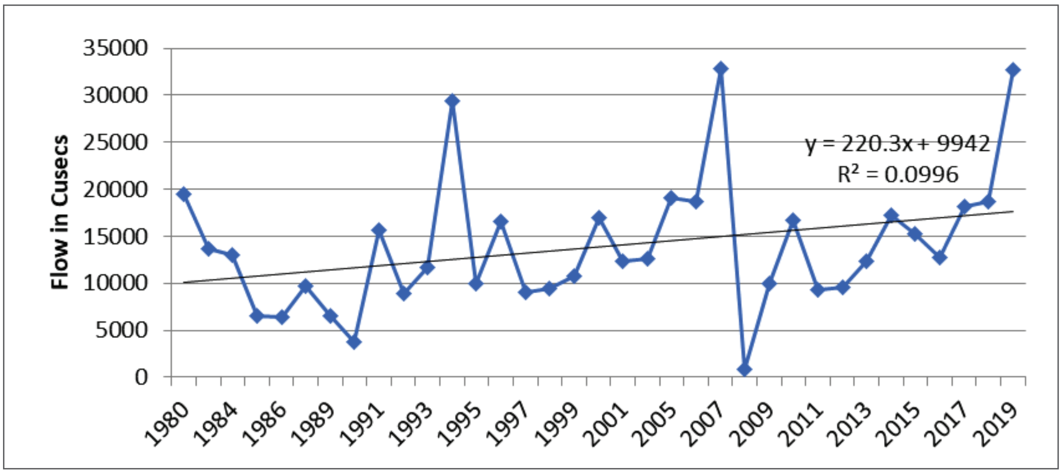


Figure 4.14 *Streamflow trends in December – Paminiyar river*

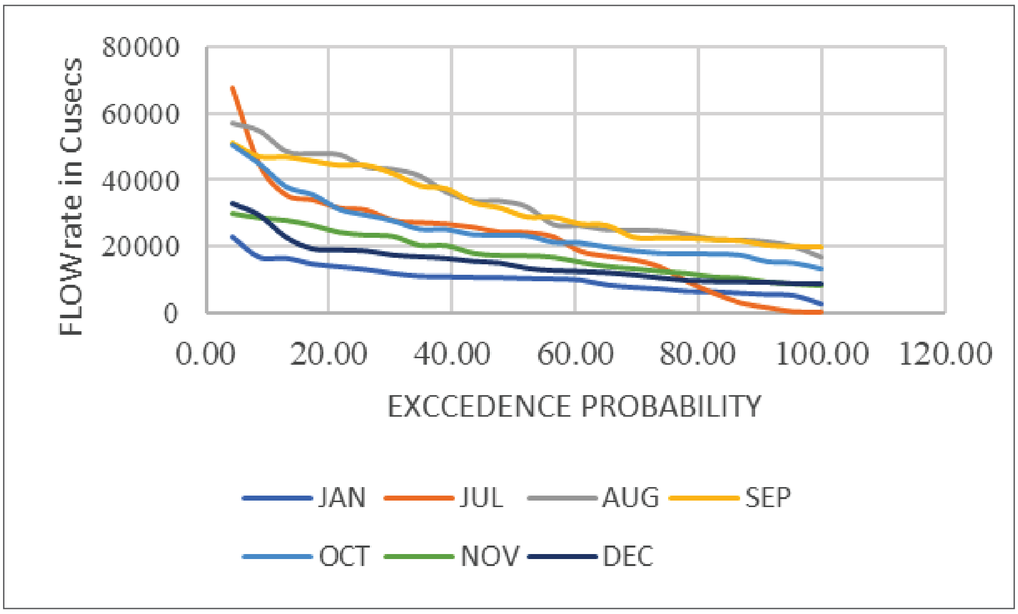


Figure 4.15 *Monthly flow duration curves - Paminiyar River*

4.4.3.2 Koraiyar River

The monthly flow hydrographs (figures 4.16 to 4.18) corresponding to the Koraiyar River show that flows to the delta are confined to the period from July to January in a water year. The monthly hydrograph for each year indicates that there is an increasing trend in flows during the months from August to December in a water year. The hydrographs, figures 4.16 and 4.17, show that high flows occur in the river during the months of October and November.

The flow duration curves as shown in figure 4.19 reflects the availability of streamflow in different months during the different crop periods in the river. However, in the month of July, the flow available in the Vennar Sub-basin is marginally less than that in the Cauvery Delta when compared to other months. The flow requirements of the wetland have not been taken into account by the PWD in arriving at this water-releasing policy.

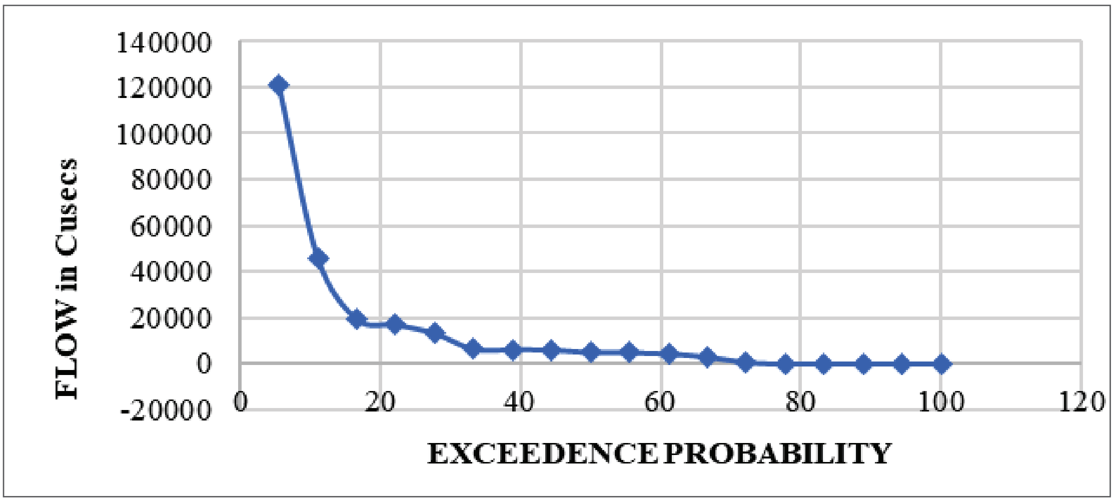


Figure 4.16 *Streamflow trends in October - Koraiyar river*

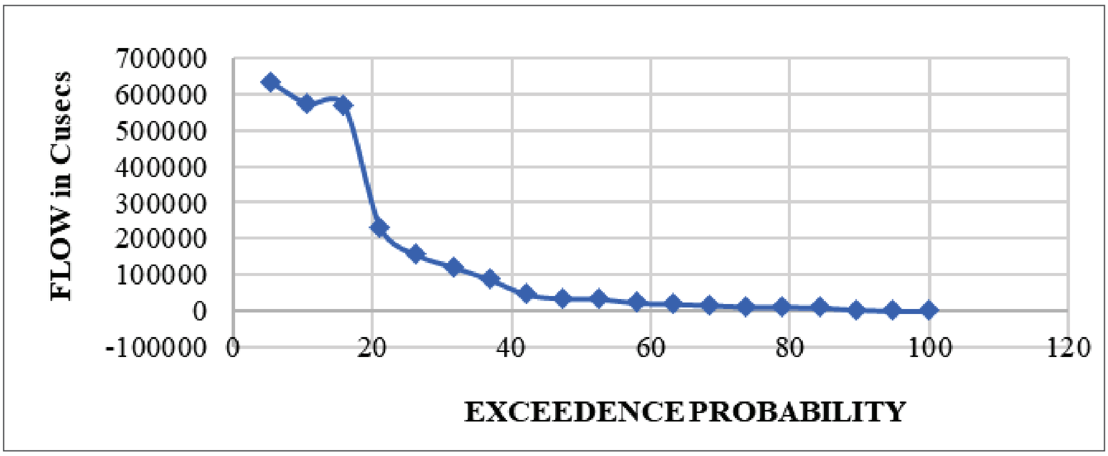


Figure 4.17 Streamflow trends in November – Koraiyar River

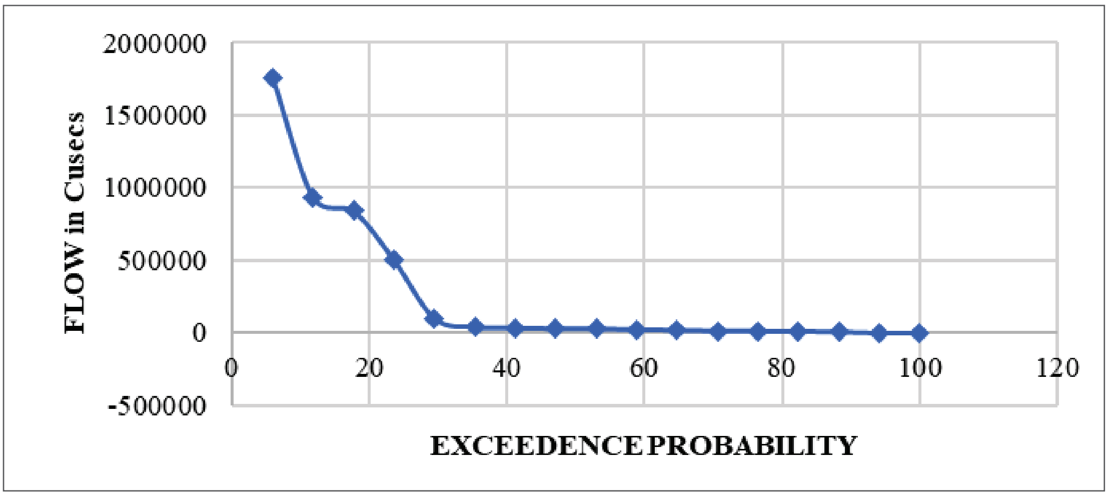


Figure 4.18 Streamflow trends in December – Koraiyar River

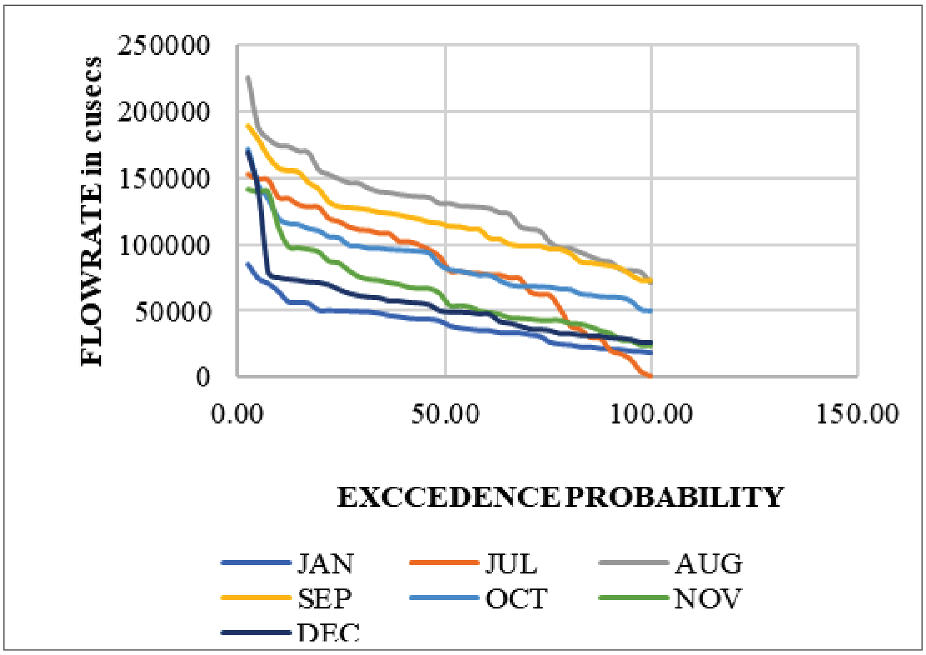


Figure 4.19 Monthly flow duration curves – Koraiyar River

A poor south-west monsoon in Kerala and Karnataka limits the flows in the Cauvery River and the quantity of water stored in the Stanley reservoir, thereby bringing down the amount of surface water available for irrigation during the rice-growing season (June-January) in the delta. The potential annual irrigation demand for two rice crops in the Vennar system is approximately 2407 MCM (85 TMC) but average annual flow in the Vennar River at the VVR head regulator is only 1260 MCM (44.5 TMC) (figure 4.20), which is less by 850 MCM (30 TMC) in 2 out of 10 years. Therefore, it is necessary for the north-east monsoon to contribute an average of 1147 MCM (40.5 TMC) and as much as 1557 MCM (55 TMC) in 2 out of 10 years.

However, the north-east monsoon in Tamil Nadu is notably erratic. The analysis of rainfall data in the Vennar system for the period October to December indicates an average rainfall of 750 mm with a standard deviation of 241 mm. When the flow from 1980 to 2019 was analysed, the total flows during the months of November and December have doubled during the past decade. Previously, the highest flow at the regulators occurred during September, whereas the highest flow occurs during the month of November in the present decade (figures 4.21 and 4.22).

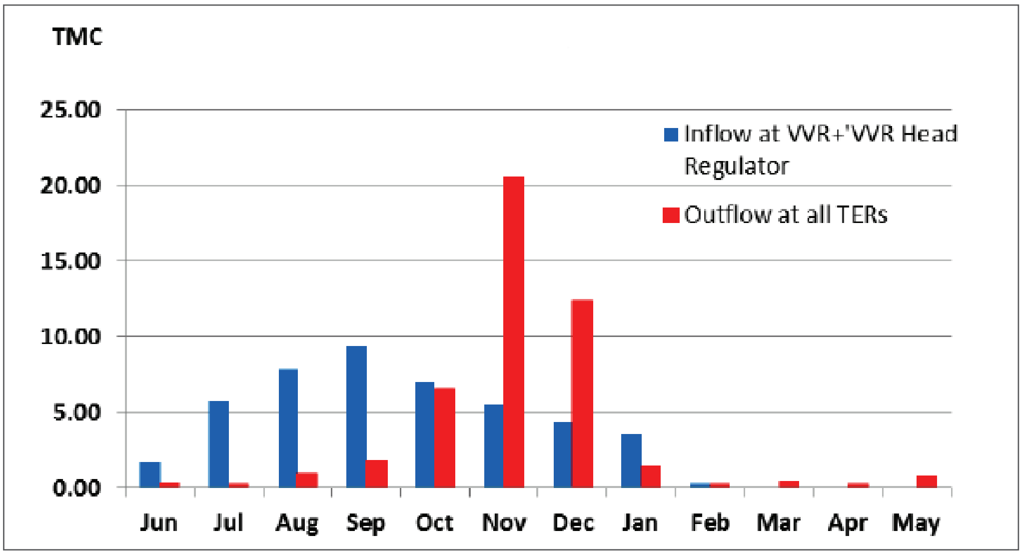


Figure 4.20 *Flow at the VVR regulator and Tail-end regulators*

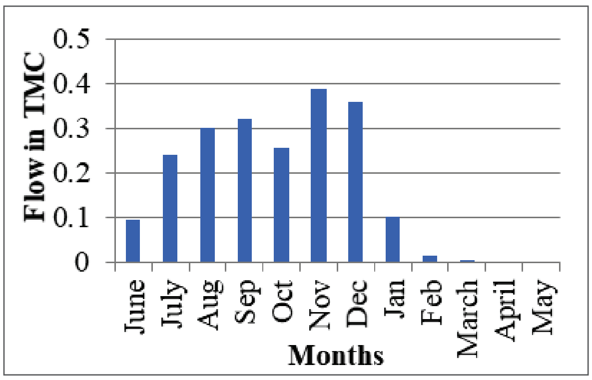


Figure 4.21 *Flow at the tail-end regulators: during 1990-2010*

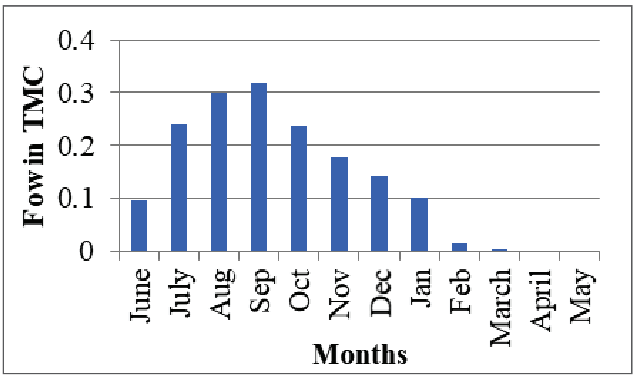


Figure 4.22 *Flow at the tail-end regulators: during 2011-2020*

4.5 Water Balance

A water balance study for the Muthupet Lagoon has been made making use of available rainfall data and by estimating the stream flows, evapotranspiration and groundwater recharge using a water balance equation. The proposed monitoring mechanisms would take care of the data requirements for water balance studies in future. As per the data obtained from PWD, there are no inflows into the complex during the months from January to September. Since no data are available related to groundwater recharge, 5% of rainfall has been assumed as recharge. Based on the areal extent of vegetation, mangroves and water bodies, the estimation of the other parameters in the water balance equation has been carried out and are presented in Table 4.4.

***Table 4.4** Water balance in the PCWC complex*

Month	Precipitation (m^3)	Groundwater recharge (m^3)	Evaporation (m^3)	Evapotranspi-ration (m^3)	Streamflow (m^3)	Increase/ decrease in surface water n the complex (mm^3)
January	8435350	421767.5	5441128	7339750	-	-4.767
February	8008000	400400	5479672	5612750	-	-3.484
March	13682900	684145	8524648	5181000	-	-0.706
April	24401300	1220065	11749496	4317500	-	7.114
May	29645000	1482250	12873696	7167050	-	8.122
June	14229600	711480	1183301	2935900	-	9.398
July	20482000	1024100	11486112	2935900	-	5.035
August	25367650	1268382.5	11132792	5526400	-	7.440
September	33687500	1684375	12012880	7512450	-	12.477
October	61530700	3076535	10227008	12089000	19538624.15	55.676
November	165561550	8278077.5	5852264	9498500	30299025.85	172.231
December	96423250	4821162.5	6687384	8203250	180661481.3	257.372

4.6 Water Abstraction in Direct Catchment

The Cauvery Delta has a geographical area of 6,900 km^2 and a gross irrigation extent of 5220 km^2, which is about 48% of the total area irrigated by canals in Tamil Nadu. Irrigation water to the delta is supplied from the Cauvery River at the Grand Anicut via the Cauvery and Vennar rivers and their 36 natural branches and a distribution network of 29,881 distribution canals with a total length in excess of 22,400 km. Table 4.5 shows the list of villages located in the direct catchment that are benefitted by the pumping stations. The water demand in the Vennar system is summarised in Table 4.6.

Total geographical area of Cauvery delta	= 6900 km^2
Gross irrigation extent	= 5220 km^2
Total area of the direct catchment	= 1957 km^2
Unutilised extent	= 1680 km^2
Gross irrigation extent in the direct catchment	= 277 km^2 = 27700 ha = 69,250 acres

Table 4.5 *The list of villages located in the direct catchment benefitted by the pumping schemes*

Sl. No.	Village	Area (km^2)
1	Ayakkarambulam	18.33
2	Ayemoor	7.82
3	Karppaganatherkulam	10.93
4	Korukkai	14.41
5	Mangal	2.07
6	Segal	11.15
7	Thennadar	8.26
8	Thillaivilagam	18.24
9	Umbalacheri	5.94
10	Vanduvancheri	8.51
11	Vilangady	7.36
	Total area	113.02

Table 4.6 *Annual water demand in Vennar sub-basin*

Demand (mm^3)					
Status	Irrigation	Aquaculture	Industrial and domestic	Power	**Total**
Present	5007	66	75	18	5166
Future	4740*	241	83	18	5082

4.7 Water quality analysis – Point Calimere Ramsar Site

Table 4.7 *Analysis of physico-chemical water quality parameters in Point Calimere Wetland Complex*

Location	Latitude	Longitude	Elevation (m)	Date	pH	EC (mS)	TDS (g/l)	Total Hardness (ppm)	Fluorides	Sulphate (ppm)	Nitrate (ppm)	Phosphate (ppm)	Sodium (ppm)	Potassium (ppm)	Calcium (ppm)	Magnesium (ppm)	Chlorides (mg/l) (Titration)
Palankallupathi-1	10° 29' 56.4"	79° 49' 37.41"	4	10.02.2020	7.8	1.022	0.49	325	0	22.949	0	0	87.465	9.494	118.293	24.446	152.435
Chemplast front side	10° 17' 39.7"	79° 48' 55.8"	18	10.02.2020	8	55.7	34.49	5945	8.131	2552.095	0	0	11284.74	404.839	427.588	1365.821	58421.6
Sempodai	10° 27' 56.0"	79° 50' 00.9"	4	10.02.2020	8.8	6.42	3.2	800	0	290.335	0	0	1110.043	120.228	76.12	133.582	3545
Wildlife sanctuary	10° 17' 18.9"	79° 52' 11.6"	13	10.02.2020	8.5	57.5	35.6	6700	0	2604.158	42.39	0	11903.9	416.214	435.39	1472.124	37896.05
Saltpan outside	10° 20' 27.7"	79° 50' 39.3"	11	10.02.2020	7.1	283	165	38500	0	13737.12	0	0		1853.719	1176.417		199229
SITE-2	10° 20' 45.9"	79° 36' 44"	12	10.02.2020	8.7	15.44	8.38	1850	0	611.972	9.254	0	2768.266	94.762	172.031	367.912	12762
Pallankallupathi-2	10° 26' 09.8"	79° 50' 16.2"	5	10.02.2020	7.8	40.4	24.2	4600	0	2159.267	28.973	0	7964.756	238.168	399.349	1007.883	35450
Ramasamy house	10° 22' 49.8"	79° 50' 54.7"	8	10.02.2020	7.6	2.47	1.19	550	0	101.196	32.237	0	340.738	58.84	128.676	49.287	5672
Vadaranyam ThalainayarRF	10° 31' 48.7"	79° 49' 32.1"	9	10.02.2020	8	9.25	4.73	1100	0	755.59	5.039	14.953	1681.578	43.985	156.218	231.396	11344
Adaparu Palam	10° 29' 38.5"	79° 49' 31"	6	10.02.2020	8.3	16.94	9.12	1950	2.15	1271.886	13.107	22.499	3144.871	76.768	196.128	385.593	14180
Pallankallupatti SW	10° 22' 50.2"	79° 50' 53.8"	8	10.02.2020	9	0.78	0.36	200	0	137.267	0	30.457	110.299	10.991	35.851	22.95	1418
Thalainayar area – surface water	10° 48' 0"	79° 49' 41.7"	5	10.02.2020	8	13.1	7.22	950	2.362	418.188	0	29.098	1522.715	26.638	71.613	206.17	7090
Wild life sw-1	10° 17' 19.0"	79° 52' 08.6"	10	10.02.2020	8.1	57.5	34.6	6250	13.173	3456.258	17.45	18.014	11739.48	414.768	476.074	1479.784	48212
Bank right	10° 20' 54"	79° 37' 06.0"	10	10.02.2020	8.1	32	18.4	3800	16.125	1744.349	51.077	136.489	6301.097	171.066	256.108	855.058	24106
Chemplast pumping area	10° 17' 38.7"	79° 48' 55.9"	17	10.02.2020	8.1	57.5	34.5	6400	0	3660.164	79.496	28.313	11757.08	414.038	669.329	1462.179	41831
Wildlife sanctuary	10° 17' 18.9"	79° 52' 11.6"	13	10.02.2020	8.1	63.6	39.2	7200	0	4247.201	91.144	0	13493.7	481.867	534.353	1674.055	48921

Location	Latitude	Longitude	Elev-ation (m)	Date	pH	EC (mS)	TDS (g/l)	Total Hardness (ppm)	Fluo-rides	Sul-phate (ppm)	Nitrate (ppm)	Phos-phate (ppm)	Sodium (ppm)	Potassi-um (ppm)	Calcium (ppm)	Magnesi-um (ppm)	Chlorides (mg/l) (Titration)
S2 I	10° 21' 23.5"	79° 31' 28.9"	0.2	11.02.2020	7.8	34.3	19.65	3850	3.034	2174.056	41.983	72.927	6709.98	229.223	303.244	849.942	29069
S2 II	10° 21' 23.5"	79° 31' 28.9"	0.8	11.02.2020	7.8	32.9	19.13	3750	0	2054.733	47.946	91.574	6526.598	225.688	279.33	820.038	25524
S3 I	10° 21' 24.2"	79° 31' 59.7"	0.2	11.02.2020	7.8	37.3	21.84	4250	0	2377.921	54.024	0	7457.655	256.011	323.976	941.535	29069
S3 II	10° 21' 24.2"	79° 31' 57.7"	0.8	11.02.2020	7.8	34.1	19.9	3800	0	2112.171	0	55.897	6710.934	233.911	286.33	840.244	27651
S4 I	10° 20' 41.1"	79° 32' 21.7"	0.2	11.02.2020	7.8	45.3	27.1	5250	0	2826.792	64.114	50.422	9041.212	311.404	436.309	1135.769	34032
S4 II	10° 20' 41.1"	79° 32' 21.7"	0.8	11.02.2020	7.8	44.8	26.9	5150	0	2789.034	63.713	31.009	8880.235	308.881	596.048	1128.239	34032
S6 I	10° 20' 5.4"	79° 32' 28.7"	0.2	11.02.2020	7.8	48.8	29.3	5500	0	2928.595	62.539	0	9349.227	365.847	380.187	1158.947	38995
S6 II	10° 20' 5.4"	79° 32' 28.7"	0.8	11.02.2020	7.6	48.7	29.3	5050	0	2996.509	56.164	0	9663.159	413.436	467.709	1211.749	37577
S9 I	10° 19' 9.3"	79° 33' 10"	2	11.02.2020	7.9	42.3	25.1	4900	2.178	2624.911	53.5	35.891	8243.815	282.891	392.773	1071.398	31905
S9 II	10° 19' 9.3"	79° 33' 0"	0.8	11.02.2020	8.1	32.1	18.65	3700	3.339	1752.131	44.138	0	6313.831	176.638	240.456	865.231	26942
S10 I	10° 18' 59"	79° 32' 11"	0.2	11.02.2020	8	53.2	32.3	6200	0	3278.176	71.243	27.003	10636.77	375.949	437.038	1319.959	40413
S10 II	10° 18' 59"	79° 32' 11"	0.8	11.02.2020	7.8	33.1	19.2	3900	0	1947.969	44.176	26.221	6317.56	215.91	276.083	814.43	29069
S11	10° 18' 41"	79° 21' 22"	0.2	11.02.2020	7.8	53.6	32.5	6000	0	3376.832	13.72	16.215	10840.91	380.631	453.069	1325.371	43958
S12 I	10° 19' 17.5"	79° 31' 84"	0.2	11.02.2020	7.9	49.5	29.8	3400	0	3090.942	65.372	0	9933.995	347.983	417.432	1224.206	41122
S12 II	10° 19' 17.5"	79° 31' 84"	0.8	11.02.2020	7.6	30.5	17.5	3500	0	1809.905	32.171	7.441	5598.217	190.477	265.848	706.99	22688
Starting point 1	10° 21' 57.0"	79° 30' 54.0"	0.2	11.02.2020	7.8	30.5	17.5	3650	0	1820.092	44.487	0	5841.248	195.658	254.186	738.453	24106
Starting point 2	10° 21' 57.0"	79° 30' 54.0"	0.8	11.02.2020	7.7	32.8	19	3600	0	2077.326	32.817	10.593	6505.533	222.276	280.145	815.777	26233
Mullipalam	10° 19' 34.8"	79° 31' 41.6"	0.4	11.02.2020	7.9	52.4	31.7	5950	0	3118.567	7.317	14.752	10130.58	359.807	395.871	1233.467	43958
Marakoraiyar	10° 20' 21.9"	79° 32' 54.9"		11.02.2020	8	49.6	29.8	5550	0	3079.824	66.544	14.634	9868.468	343.043	397.201	1224.826	38286

Location	Latitude	Longitude	Date	pH	EC (mS)	TDS (g/l)	Cl (mg/l)	Total Hardness (mg/l)	Calcium Hardness (mg/l)	Magnesium Hardness (mg/l)	Sodium (ppm)	Potassium (ppm)	Fluorides (mg/l)	Sulphates (mg/l)
Vedaranyam hand pump water	10° 25.4' 59"	79° 50' 9"	16-10-2020	7.78	0.587	0.291	44.98	120	40	80	83.3	89.4	0.4867	19.106
Chemplast left	10° 17' 38"	79° 48' 56"	16-10-2020	7.6	59	29.4	5528.28	500	16	484	126.6	244.5	0.1623	140.63
Chemplast sump	10° 17' 38"	79° 48' 56"	16-10-2020	7.32	65.3	32.4	6577.96	170	48	484	88.2	273.5	0.1553	27.44
Chemplast right	10° 17' 38"	79° 48' 56"	16-10-2020	7.64	66.2	32.8	9177.15	670	56	614	184.2	463.3	0.1459	72.76
Bird sanctuary	10° 17' 56"	79° 49' 33"	16-10-2020	7.84	15.5	7.39	1119.65	470	24	446	153.7	359.1	0.1093	81.7
Panchanadikulam water	10° 21' 54"	79° 42' 41"	16-10-2020	6.78	27.9	14.1	3958.77	1050	32	1018	149.2	250.8	0.0731	78.51
Vaimedu West canal	10° 24' 15"	79° 38' 21"	16-10-2020	8.31	0.965	0.483	59.98	340	16	324	232	316.6	0.1157	52.3
Vaimedu West bore well	10° 24' 18"	79° 37' 52"	16-10-2020	7.34	2.3	1.16	129.95	120	16	14	68.8	19.7	0.1658	63.61
Vaimedu hydrualic structure shutter freshwater back	10° 22' 55"	79° 38' 07"	16-10-2020	7.96	1.88	0.93	109.96	720	8	712	148.7	299.5	0.2028	51.2
Vaimedu hydraulic structure shutter saltwater front side	10° 22' 55"	79° 38' 07"	16-10-2020	7.71	2	0.99	139.95	1840	4	1836	125.8	566.2	0.3288	44.68
Kodiakarai saltpan-1	10° 20' 28"	79° 59' 24"	16-10-2020	6.58	64.7	32.5	9244.13	7070	2684	4386	83.9	157.5	0.0885	129.57
Kodiakarai salpan-2	10° 20' 28"	79° 59' 24"	16-10-2020	7.33	27.3	15.8	6597.95	3300	13.2	3286.8	143.7	596.6	0.0883	71.4
Kodiakarai saltpan- 3	10° 20' 28"	79° 59' 24"	16-10-2020	7.48	36.4	19.8	8497.36	2380	20	2360	184.2	620.3	0.1097	27.65
Thalainayar Aquafarm water sample	10° 30' 24"	79° 49' 48"	16-10-2020	8.14	23.4	12.1	1359.57	450	16	434	209.4	748.7	0.2032	40

Location	Latitude	Longitude	Date	pH	EC (mS)	TDS (g/l)	Cl (mg/l)	Total Hardness (mg/l)	Calcium Hardness (mg/l)	Magnesium Hardness (mg/l)	Sodium (ppm)	Potassium (ppm)	Fluorides (mg/l)	Sulphates (mg/l)
Vellapallam well water-1	10° 30' 59"	79° 51' 0"	16-10-2020	7.51	2.03	1.01	99.769	270	16	254	128.7	456.6	0.2447	65.53
Vellapallam well water-2	10° 30' 59"	79° 51' 0"	16-10-2020	7.46	1.21	0.6	79.97	90	12	78	228.2	714.1	0.2479	51.48
Harichandran river inlet	10° 33' 05"	79° 49' 01"	16-10-2020	8.35	2.59	1.29	119.96	110	8	102	189.9	482.9	0.2056	39.36
Harichandran river outlet	10° 33' 05"	79° 49' 01"	16-10-2020	7.96	40	20.1	2099.34	670	40.01	629.99	214.7	854.9	0.4316	61.91
Thalainayar Muthal Sathy village paddy field sample	-	-	16-10-2020	7.77	1.46	0.6	69.97	270	12	258	178.9	418.7	0.2319	23.19
Muthupet lagoon	10° 18' 56"	79° 31' 30"	17-10-2021	7.83	59.7	29.8	3598.58	480	60	420	170	112.2	0.1205	73.4
Vowal thottam	10° 20' 51"	79° 32' 12"	17-10-2022	6.23	40.1	19.9	1889.41	4360	24	4336	154.3	594.1	0.1199	19.85

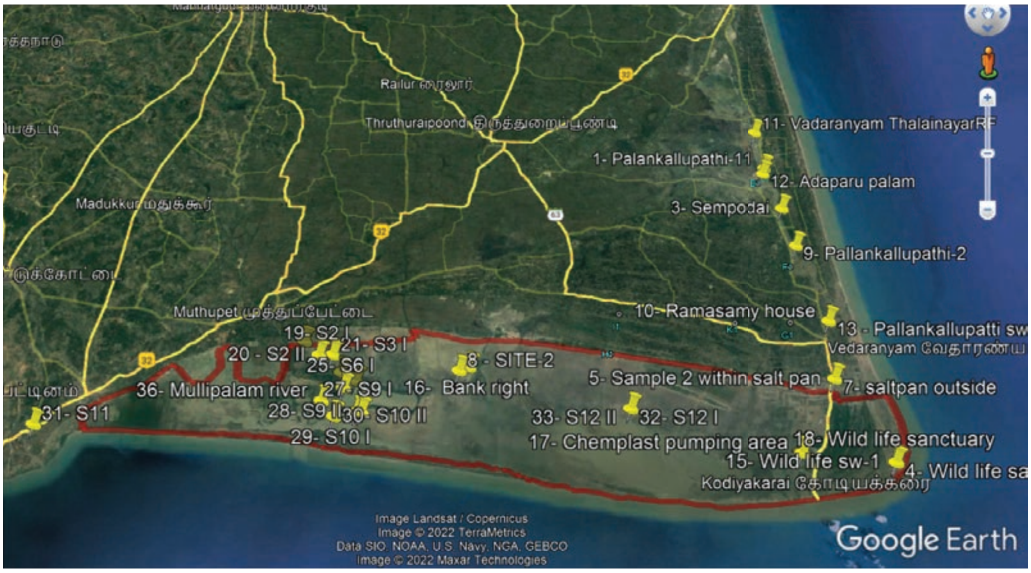


Fig.4.23 *Sampling locations*

4.7 SUMMARY

The temporal distribution of the flows to the delta has improved after the final award of the Cauvery Water Dispute Tribunal (CWDT). The analysis of streamflow data using IHA indicates that after the Interim Award of 1991 by CWDT, there is a decline in the rate and frequency of the flows to the delta. After the Final Award of 2007 of the CWDT, the flow to the delta has slightly improved.

- The annual flows to the Muthupet Lagoon and associated water bodies is 3.447 TMC from the three rivers namely, Paminiyar, Koraiyar and Marakkakoraiyar according to the recent PWD data.
- In the month of July, the flow available in the Vennar Sub-basin is less than that in the Cauvery Sub-basin.
- The flow is diverted to the wetland complex only during the flood period, that too only into the Koraiyar and Paminiyar. The flow is not diverted to the Marakkakoraiyar, Valavanar, Mulliyar and Harichandranadi rivers which act as feeding channels for the PCWC (Muthupet Lagoon, Siruthalaikadu Lagoon and Thalainayar Reserve Forest). This has led to almost minimal freshwater flow also into the Siruthalaikadu Lagoon during the flood season.
- There is a drainage problem in the Vennar Sub-basin during the north-east monsoon because by the time the upland catchment forces the flood waters down the Vennar, the flow in the lower reaches is already fully congested with the flood generated.
- Since the flow has increased during the months of November and December, during the north-east monsoon season, some additional storage structures can be planned in the direct catchment of the wetland complex to provide water during the low-flow period.

5. APPLICATION OF SOIL AND WATER ASSESSMENT TOOL (SWAT): CAUVERY AND VENNAR SUB-BASINS

5.1 Introduction

The rainfall pattern and all other hydrologic parameters, including the sediment yield, have an overall impact on the wetland ecosystem since the water and sediments available downstream depend on the hydrology of the upstream reaches. The regulation and control of upstream reservoirs will depend on the hydrology of upper sub-basins. The sedimentation of reservoirs is bound to restrict their capacity and subsequently the downstream releases. The changes in hydrologic regime upstream are expected to have a greater impact on the availability of water in the downstream reaches. For example, when the southwest monsoon is above normal in the catchments of the tributaries in Kerala, the water managers are able to provide an adequate supply of water for irrigation in the Cauvery Delta. The water that comes to the delta can be used for the wise use of downstream wetlands if a scientific water allocation policy considering the wetlands is evolved. Therefore, it will not be appropriate to consider the direct catchment of the wetlands independent of the entire basin which provides considerable amount of water in space and time to the downstream reaches. The criterion for selecting four major sub-basins upstream for detailed study is that they have important reservoirs downstream, the operation of which has to be regulated considering the temporal requirements of water in the downstream ecosystems.

Efficient watershed management requires a rational and efficient decision support system for tackling a wide range of environmental and resources management issues. In the past few decades, with the advent and rapid progress of computer and geo-information technologies, numerical simulation models have increasingly become important and effective tools for tackling a wide range of environmental and resources management issues. As land and water processes are intimately linked, watershed scale modelling has emerged as an indispensable tool for understanding the complex natural processes, assessment of pollutant loads and developing sustainable agricultural management practices at the basin scale over the last two decades. Distributed parameter models, necessary for basin-scale studies, have large input data requirements. One such versatile and popular model available for the water resources professional is the Soil and Water Assessment Tool (SWAT), a distributed parameter model developed by the United States Department of Agriculture. The SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over a long period of time. The SWAT model has application from a small watershed to river basin-scale to simulate the quality and quantity of surface and groundwater and predict the environmental impact of land use, land management practices, and climate change. This model is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds.

The primary purpose of using the SWAT rainfall-runoff model is to simulate the transition of the precipitation falling directly into the drainage basin system into surface storage, evaporation, runoff, soil moisture storage and infiltration into the groundwater in a range of climate change scenarios. The application of SWAT model will give knowledge about the response of runoff to rainfall in basin and delta. The changes to the hydrology of drainage basins are expected to have impact on the downstream wetlands. The water availability and sediment yield in the basin as a whole and in the sub-basins upstream, influence the wetlands downstream. The use of the SWAT model in the catchment of the wetland complex has a direct relevance to the wetlands of Point Calimere.

5.2 Database

The hydrological modelling was carried out in three phases, namely, data collection, modelling, calibration and validation. The data collection covered meteorological, land use/land cover, soil, digital elevation model (DEM) and hydrological data. The sources and details of the data utilised in the model for the Harangi Sub-basin are shown, as an example, in Table 5.1.

Table 5.1 *Data utilised for the study of the Harangi sub-basin*

Data Set	Source	Data Description/Properties
Terrain	USGS	Digital Elevation Model: 30 m × 30 m (SRTM)
Land use	USGS – Earth Explorer	LANDSAT 4: 80 m LANDSAT 5: 30M, 72 m LANDSAT 8: 30 m, 15M SENTINEL 2: 10 m, 20 m, 60 m
Soil	FAO	Soil Classification: 1/25,000
Weather	www.tamu.edu	Daily precipitation, minimum and maximum temperature, mean wind speed, relative humidity; 1980–2020
Stream Flow	WRIS	Three gauging stations: Madikeri, Sulya, Somvarpet

The weather data for the watershed modelling were collected from IMD (Indian Meteorological Department) and included the rainfall data in mm, temperature in °C, wind speed in km/hr, relative humidity in % and solar radiance (daily basis). The GRD data (Gridded data) from IMD (Indian Meteorological Department) were converted to SWAT files to import the weather database into the ArcSWAT workspace. The GRD is widely used in image processing grid format to represent data in a grid pattern. The data corresponding to the years 1970–2019 were collected for the watershed modelling. The years 1970–1980 was taken as a warm-up period for the ArcSWAT simulation.

The land use/ land cover data required for the SWAT analysis were collected from the Earthdata repository. The data were derived from Landsat 4 and 5 Enhanced Thematic Mapper Plus (ETM+), Multispectral (MSS) data, Thematic Mapper (TM), Landsat 7,8 and Sentinel 2, ground truth surveys and visual interpretation. The temporal resolution considered for data construction was decadal. The land use/land cover data for the years 1990, 2000, 2010 and 2020 were collected from Earthdata, and the details related to the sensors and spatial resolution are given in Table 5.2.

Table 5.2 *Land use/land cover data source*

Period	Satellite	Sensor	Spatial resolution
1990–1991	LANDSAT-5 & IRS	Thematic mapper, Enhanced Thematic mapper (ETM+), Linear Imaging Self-Scanning Sensor -1 (LISS-1)	30 m, 72 m
2000–2001	LANDSAT-5and Resourcesat	ETM+, LISS III	30 m, 23.5 m
2010–2011	LANDSAT 8	Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS)	30 m
2020	Sentinel 2	S2A, S2B	20 m, 10 m

5.3 Methodology

The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modelled by SWAT using these input data. The model allows a number of different physical processes to be simulated in a watershed. For modelling purposes, a watershed may be partitioned into a number of sub-watersheds or sub-basins. The input information for each sub-basin is grouped or organised into the following categories: climate; hydrologic response units or HRUs; ponds/wetlands; groundwater; and the main channel, or reach, draining the sub-basin. Hydrologic response units are lumped land areas within the sub-basin that comprise unique land cover, soil and management combinations. The simulation of the hydrology of a watershed can be separated into two major divisions.

The first division is the land phase of the hydrologic cycle, depicted in figure 5.1. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. The second division is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet. The SWAT simulation is based on

$$SW_t = SW_0 + \sum (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

Where,

SW_t - final soil water content at time t, SW0 - initial soil water content,

t - time (in days)

R_{day} - amount of precipitation on day i,

Q_{surf} - amount of surface runoff on day i,

E_a - amount of evapotranspiration on day i,

w_{seep} - amount of water entering the vadose zone from the soil profile on day i

Q_{gw} - amount of return flow on day i

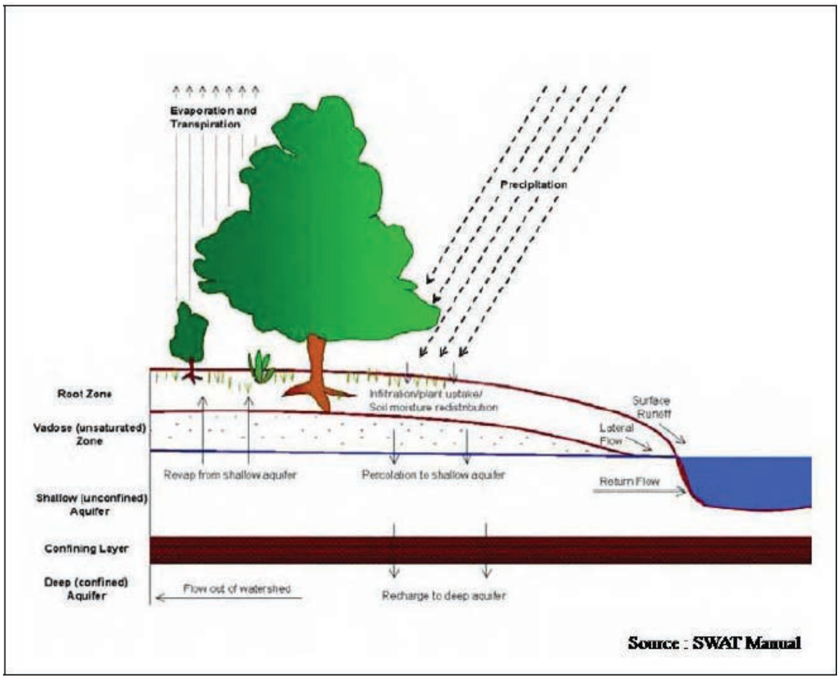


***Figure 5.1** Schematic representation of hydrologic cycle*

The SWAT-CUP is an application used for calibration and validation of SWAT models. The program can run algorithms such as SUFI2, GLUE, ParaSol. The SWAT-CUP project involves one method of calibration that allows the user to run the experiment several times before consistency is achieved. The target of SWAT- CUP is to calibrate, validate and visualise the results in a faster way to avoid other time - consuming calibration techniques with graphs and data comparison. The whole process is divided into three phases. The digital elevation model forms the basis for delineation of the basin and sub-basins in the study area. The SWAT simulation generates sediment yield and water yield from the provided input data. The simulated data is calibrated with discharge data and validated further.

5.4 SWAT Output

Hydrological simulation using SWAT modelling has been carried out and discussed at three different levels, namely, the Cauvery basin, four sub-basins of the Cauvery at different elevations and climatic zones, and the Vennar Sub-basin in which the wetland complex is located.

5.4.1 SWAT modelling of Cauvery Basin

The results from SWAT for the period 1981–1990 are given in Table 5.3 and figures 5.2 and 5.3.

Table 5.3 *SWAT output for 1981–1990 – Cauvery basin*

Year	Annual average precipitation (mm)	ET (mm)	Water yield (mm)
1981	1282.93	288.17	896.36
1982	783.87	251.57	522.19
1983	1041.33	259.71	697.63
1984	1120.51	252.31	1067.01
1985	896.95	248.28	1963.71
1986	980.79	269.1	597.67
1987	972.48	263.43	529.55
1988	907.16	290.05	683.47
1989	923.65	281.87	492.57
1990	889.67	237.78	589.45

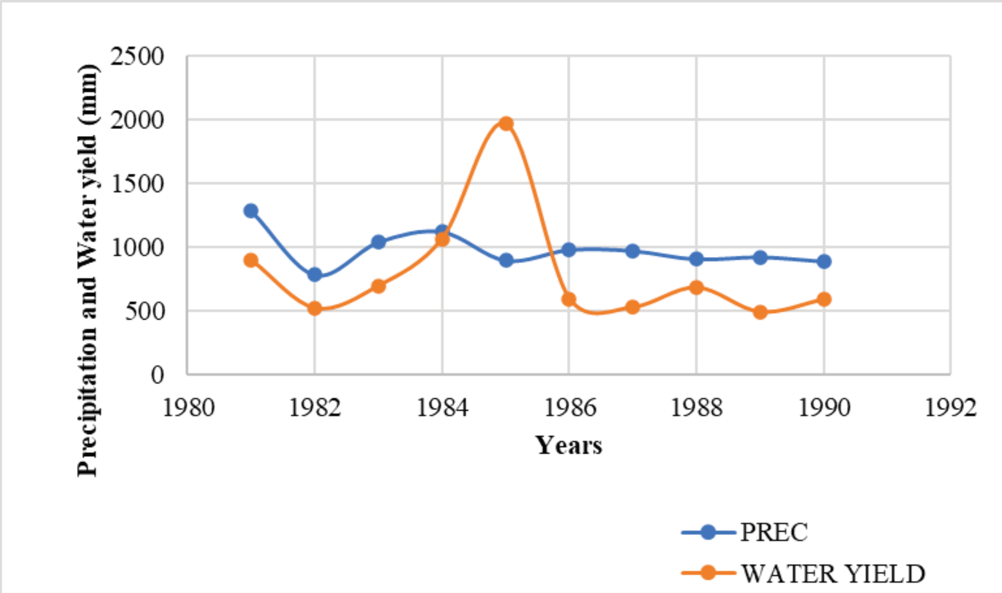


Figure 5.2 *Temporal variation of water yield and precipitation simulated for 1981-1990*

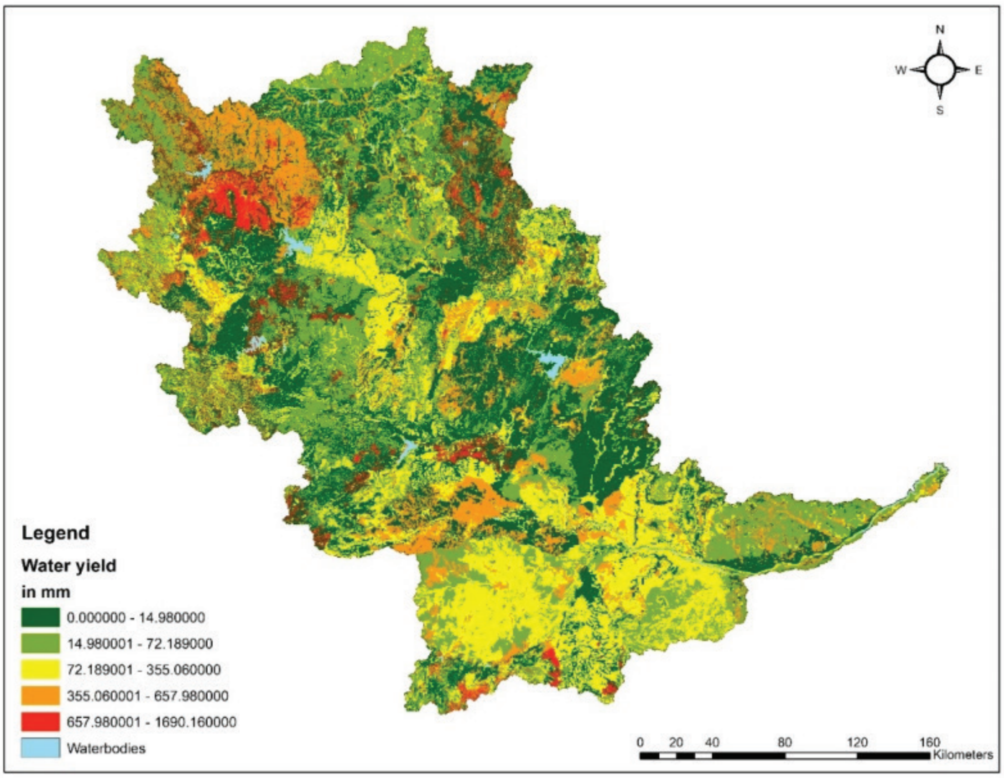


Figure 5.3 S*patial variation of water yield for 1981-1990 using HRUs*

Comparing the spatial variation of water yield with land use in 1985, parts of Karnataka such as Hassan, Mysuru and the catchment area of Krishna Raja Sagara (KRS) Dam have high water yields. Downstream reaches of the KRS Dam that are covered with deciduous forests and scrublands were observed to have moderate water yields. Downstream of Bhavanisagar Dam, Tamil Nadu is observed to have a high-water yield whereas the areas surrounding Stanley Reservoir in Tamil Nadu have low water yields. Coimbatore, Tiruchirapalli and Namakkal districts of Tamil Nadu are observed to have low water yields.

Corresponding to the period 1991-2000, the water yields in the catchment area of Krishna Raja Sagara (KRS) Dam, Bhavanisagar Dam, Stanley Reservoir and Namakkal District in Tamil Nadu have high yields. The districts in Tamil Nadu, in the southern part of the river basin, experienced moderate water yields. A spike in the water yield was found in 1998 due to low evapotranspiration.

Corresponding to the years 2001-2010, the catchment area of Krishna Raja Sagara (KRS) Dam, in Karnataka, and Stanley Reservoir, in Tamil Nadu, gained high water yields, whereas the Bhavanisagar Dam experienced a moderate water yield. The sediment yield during the year 2007 was observed to be high because of the high-water yield and high rainfall during the period. The runoff simulated during the period was also observed to be high.

Corresponding to 2011-2019, the water yield in the Cauvery River Basin was found to be drastically reduced whereas the water yield was high in the parts of Krishna Raja Sagara (KRS) Dam and stretches downstream of KRS, in Karnataka, and Karur, in Tamil Nadu. This is likely due to the high urbanisation in the streamflow area, which has increased by 26% from 2010.

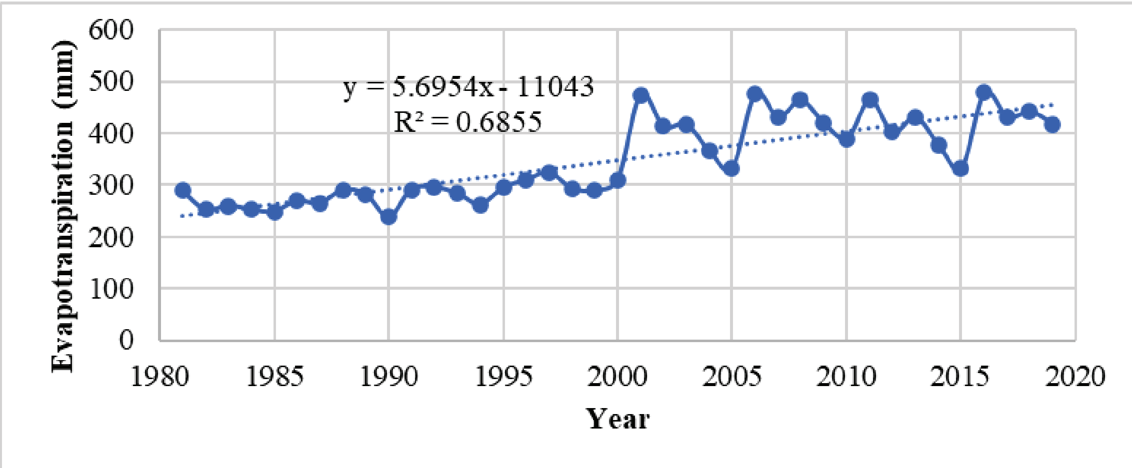


***Figure 5.4** Temporal variation of average precipitation simulated from SWAT in the Cauvery basin for 1981-2019*

Figure 5.5 shows the average evapotranspiration in the study area following a linear pattern during the first two decades of the study period, whereas in the years 2001-2019, periodic rises and decreases in the rate of evapotranspiration were experienced.

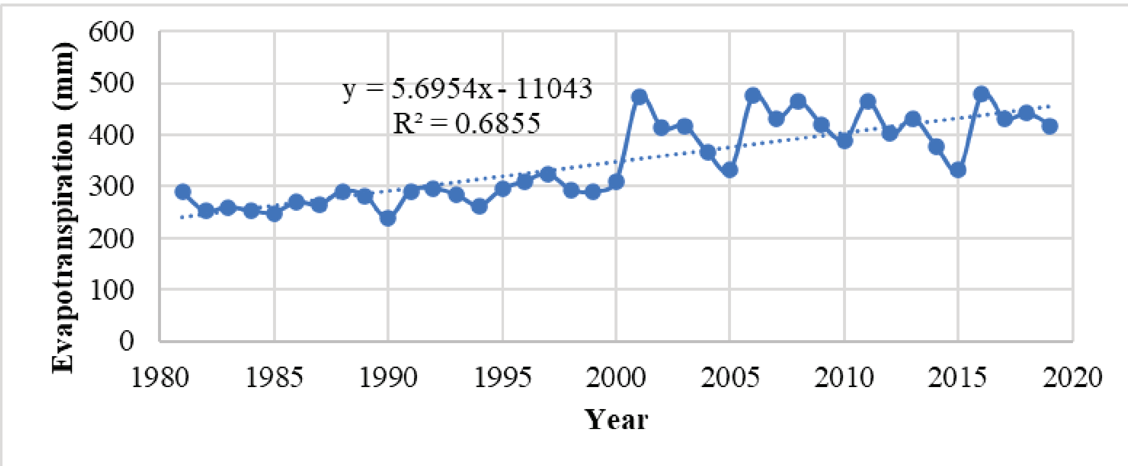


***Figure 5.5** Temporal variation of average evapotranspiration simulated for 1981-2019*

Figure 5.6 shows the average water yield in the study area, which is high during 1984-1986, 1990-1992, 2005-2007 and 2015-2017. During the period 2011-2019, the discharge was found to be high during the year 2014. Furthermore the calibration and validation gave a good R2 value of 0.9803 for the years between 2011 and 2019.

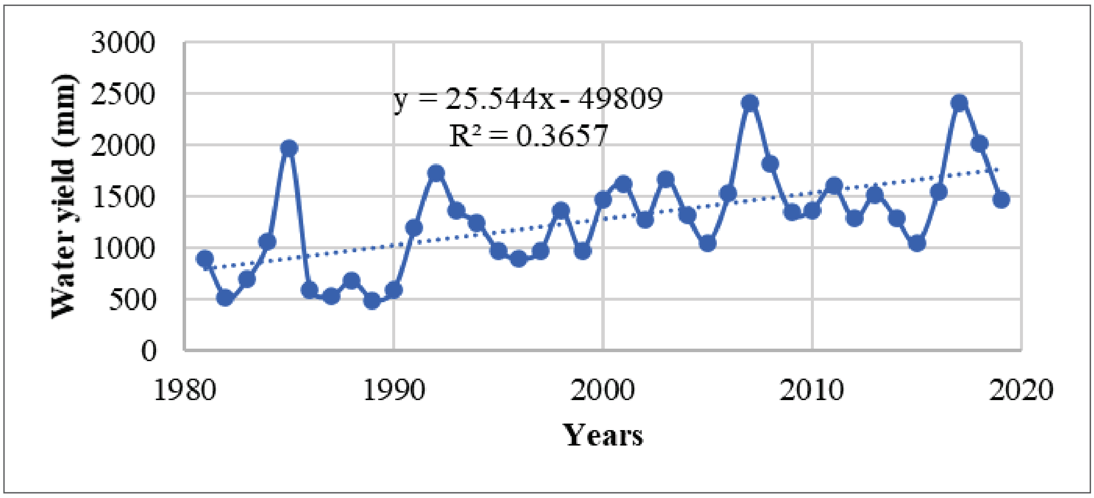


Figure 5.6 *Temporal variation of average water yield simulated for 1981-2019*

The SWAT-CUP calibration process was implemented for the years 1993–2005. The calibration process gave a percent bias (PBIAS) of 14% and Nash-Sutcliffe (NS) coefficient of 0.77. The validation process implemented for the years 2006–2019 returned a percent bias (PBIAS) of 11% and a Nash-Sutcliffe (NS) coefficient of 0.81.(figure 5.7)

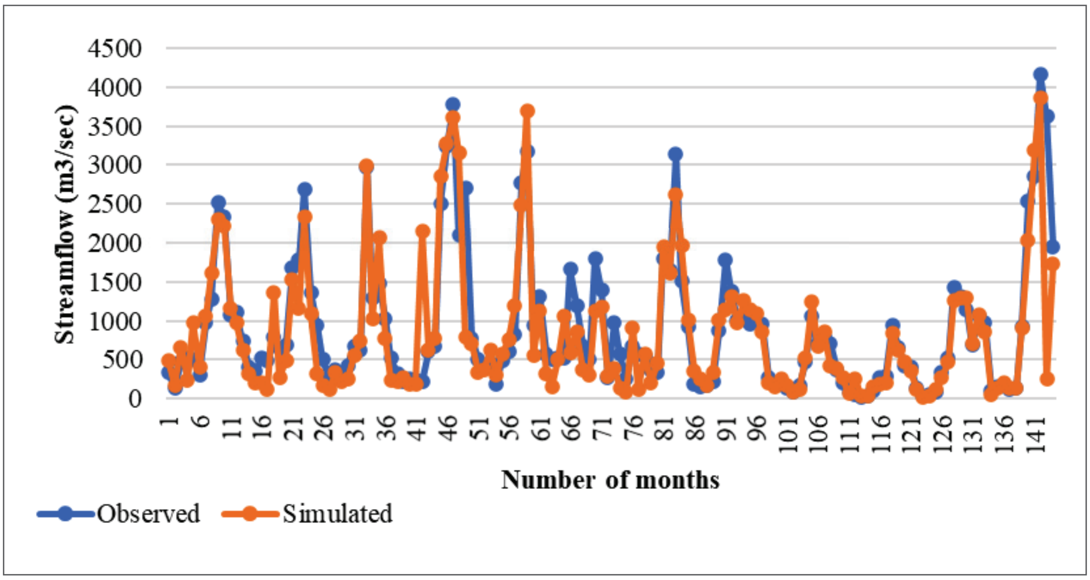


Figure 5.7 *Observed and simulated runoff during calibration period (1993-2005)*

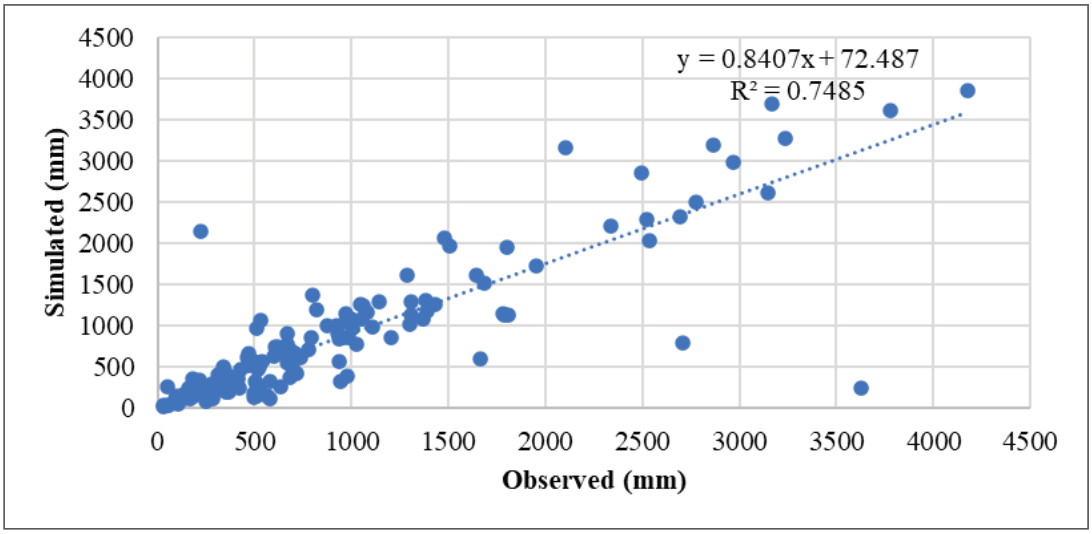


***Figure 5.8** Correlation between observed and simulated streamflow values*

Figure 5.8 shows that the correlation between the observed and simulated values has been good. The calibration period 1993 - 2005 returned an R^2 value of 0.74 and the validation period returned an R^2 value of 0.98.

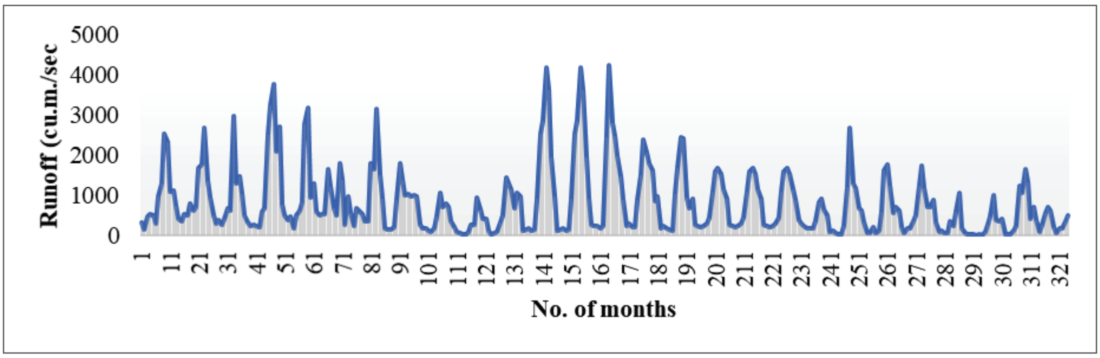


***Figure 5.9** Simulated runoff during 1993–2019 (324 months)*

From the observed runoff during the period 1993 - 2019, it is noted that the study area experienced high runoff during the years 1995, 1996, 2005, 2006, 2007 and 2011. In comparison, the rainfall received during the period is high, resulting in high runoff. Moreover the water yield and evapotranspiration are also observed to be high.

5.4.2 SWAT modelling for Harangi, Kabini, Bhavani and Amaravathi sub-basins

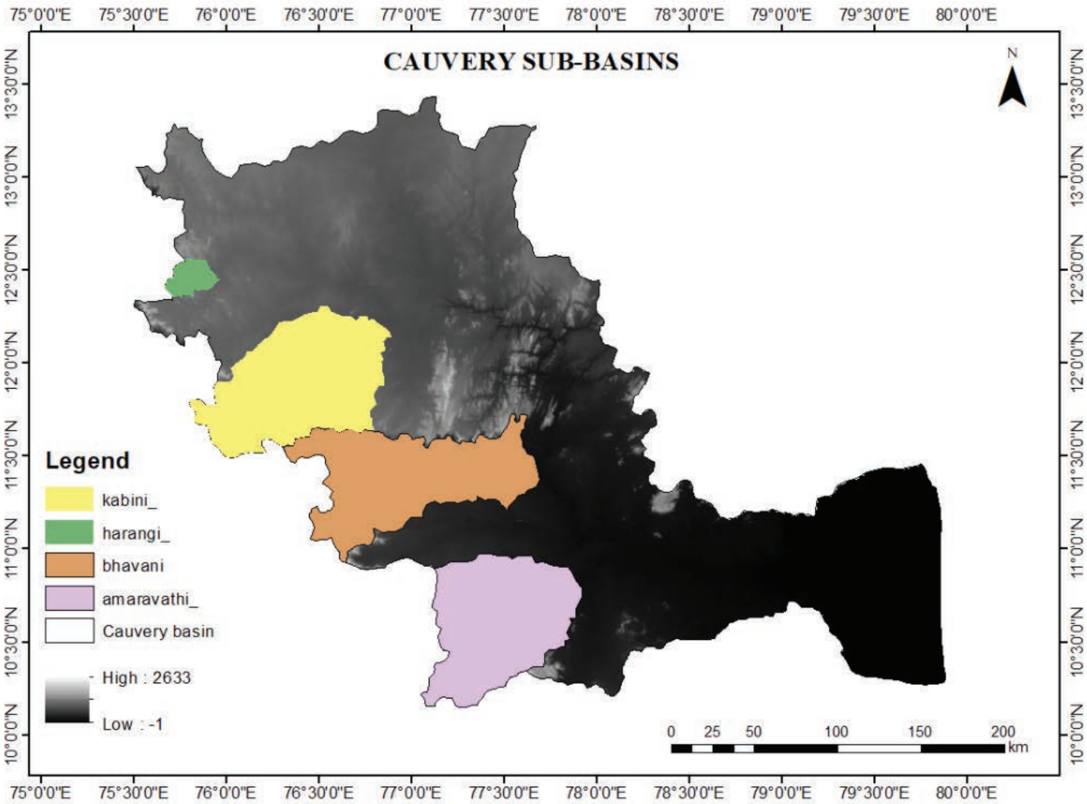


Figure 5.10 *Sub-basins of Cauvery considered for hydrological modelling*

The sub-basins were identified in such a way that they represent various elevation levels, soil types, land use categories and climate zones. On the basis of these criteria, four sub-basins, namely, Harangi, Kabini, Bhavani and Amaravathi, were selected for the study. The location and basic details of the four sub-basins are given in figure 5.10.

The Harangi sub-basin is formed by a tributary of the Cauvery, which originates in the Pushpagiri Hills of the Western Ghats. The sub-basin of the tributary Harangi is 535 km^2. The Harangi joins the Cauvery near Kudige, in Madkeri, and its length from the origin to the joining point with the Cauvery is 50 km. The elevation of the Harangi sub-basin ranges from 818 m to 1635 m above mean sea level. It is located in the wet humid tropical zone.

The Kabini river basin lies between latitudes 11° 45′ and 12° 30′ N and longitudes 75° 45′ and 77° 00′ E, with an area of 7040 km^2. The basin covers the taluks of Wayanad, in Kerala, and Chamarajanagar, Gundlupet, Heggadadevana Kote, Hunsur, Nanjangud, Tirumakudalu, Narasipur and Mysore, in Karnataka. The sub-basin represents an uneven landscape with intermingling hills and valleys. The central part is a plain area with minor undulations. The overall slope of the basin is towards the south. The average annual rainfall is 1470 mm and the river basin is located in the humid tropical zone. Weathering is noticed up to a depth of about 35 m in the basin. Red loamy soil and sandy loam represent the major soil types of the area. The thickness of the soil cover generally varies from 1 to 3 m. Alluvium is found on the gently sloping and flat valley bottom.

The tributary Bhavani originates from the Western Ghats, flowing through the Nilgiri Biosphere, in Kerala, draining the western parts of Tami Nadu, covering 217 km and finally joining the main Cauvery River. The whole basin occupies 0.62 million ha (6200 km^2) between latitudes 11° 15′ N and 11° 45′ N and longitudes 77° 00′ E and 77° 40′ E. This part of the state is semi-arid, with an annual average rainfall of 618 mm. The temperature rises up to 40°C in summer and sinks to 13°C in winter. The potential yearly evapotranspiration (ET) is 1600 mm in the lower Bhavani Basin. The drainage pattern of the basin is mostly dendritic, which is an indication of the uniform resistance of the rocks, a typical characteristic of hard rock terrain.

The Amaravathi is one of the main tributaries of the river Cauvery, situated in its mid-reach. It rises from Naimakad, at an elevation of 2300 m above MSL, in the Western Ghats (Anaimalai), in Idukki District, of Kerala. The sub-basin is located in the semi-arid zone. It flows for a distance of 256 km in the north-east direction till its confluence with the Cauvery on its right bank. The Amaravathi basin lies between latitudes 10° 06′ 51” and 11° 02′ 10” N and longitudes 77° 03′ 24″ and 78° 13′ 06″ E. The river has a catchment area of 8280 km^2 spreading over four districts namely Coimbatore, Erode, Dindigul and Karur in Tamil Nadu.

The water balance analysis of the Kabini river basin shows that, for instance, the lowest recorded annual precipitation was 570.71 mm in 2017, and the surface flow of that year was 63.37 mm. The highest annual precipitation of 2379.61 mm was observed in 2007, and the surface flow of that year was 843.14 mm. The precipitation was found to be least in January and highest between August and October. The proportion of surface runoff is 26.5% and the lateral flow (or subsurface flow) is about 2.8%. Shallow aquifer flow accounts for about 30.08% of the water yield. The overall sediment loading from the Kabini catchment, as estimated by the SWAT model, is 33.619 metric tons/ha. The water balance components and model performance evaluation coefficients are given in Tables 5.4 and 5.5.

Table 5.4 *Water balance components in the sub-basins*

Parameters	Kabini	Harangi	Bhavani	Amaravathi
Precipitation (mm)	1650	2655	871	666
Surface runoff, Q (mm)	438	772	143	169
Groundwater flow (mm)	516	908	143	228
Total water yield (mm)	1030	1848	284	223
ET (mm)	598	845	938	388
PET (mm)	1439	2135	1828	1254

Table 5.5 *Model performance evaluation coefficients*

Objective function	Kabini	Harangi	Bhavani	Amaravathi
NSE	0.42	0.90	0.62	0.56
R^2	0	0.92	0.73	0.74
p-factor	0.11	0.78	0.61	0.96
r-factor	0.37	0.42	0.38	0.29

Calculations revealed that the surface runoff and lateral flow were 27% and 32% in the Harangi Watershed. The percentage ET loss was significantly low for the forested Harangi Watershed. The result analysis of Amaravathi Basin revealed that actual evaporation rate was high during the summer, which usually brings a substantial amount of rainfall to the study area. Precipitation is higher than ET from May to December. High groundwater recharge was noticed in the months of October and November; during these months it receives the highest rainfall and reaches its maximum peak which later decreases from the month of December and the lowest rainfall is observed in the month of January. The lowest groundwater recharge recorded in Amaravathi River Basin is 0.01 mm in the month of January and the maximum rainfall received is 96.19 mm in the month of October. In the case of the Bhavani Basin, the maximum and minimum groundwater recharge values of 351.89 mm and 2.15 mm were observed in 2017 and 2005, with an average groundwater recharge of 105.43 mm.

5.4.3 SWAT Modelling of Vennar sub-basin

As per the report (ADB, 2014) the present management practices to tackle floods and water distribution for irrigation are not entirely satisfactory in the Vennar Sub-basin. Therefore, by utilising the modern technologies and for ensuring efficiency and transparency, hydrologic and hydraulic modelling of the rivers linked with the Vedaranyam Main Canal (VMC) have been carried out using SWAT and HEC-RAS software. The purpose of the study has been to assess the present flood carrying capacity of VMC and other rivers flowing to the east.

The VMC canal receives flows from inland, from the Vennar system through a complex system of channels. Discharge from the main rivers is controlled through the use of tail-end regulators which maintain water levels upstream and prevent saltwater intrusion from the Vedaranyam Canal and from the drainage outfalls from coastal irrigation command areas. From 1960s to mid-1970s, additional connections to the sea were cut from the Vedaranyam Canal directly to the Bay of Bengal as an attempt to accelerate the drainage of canal during floods. A total of six straight cuts were formed along the coast. It was observed that there is a high rate of sediment transport from the north to the south. Many of the outlets have become restricted or closed completely at their coastal extent. In general, the narrower straight cuts (<30 m wide inland) are closed or heavily restricted, showing that narrower outfalls are more susceptible to sediment transport than are wider outfalls.

During the north-east monsoon (October to December), flooding is common in the Vennar system. The flooding of 2008 is an evidence of the extreme nature of flood events and the severe impacts on the system. The flooding during this period was caused by intense and prolonged rainfall resulting in high runoff which exceeded the capacity of the drainage system. Furthermore, flooding was exacerbated by tidal effects caused by the poor state of the tail-end regulators and straight cuts. This flood event has been considered for the validation of the models. The ‘Delineate Watershed’ function of SWAT was used to delineate 112 rainfall catchments within the Vennar system. During this stage, a stream network shape file and a shape file showing existing regulators as outlet points of the sub-basins were added to the 112 catchments. Using the HRU function of MWSWAT and applying threshold values for land use, soil and slope percentages, all delineated rainfall catchments were divided into multiple HRUs. A total of 471 HRUs in 112 catchments were created. The catchments and stream reaches are shown in figure 5.10.

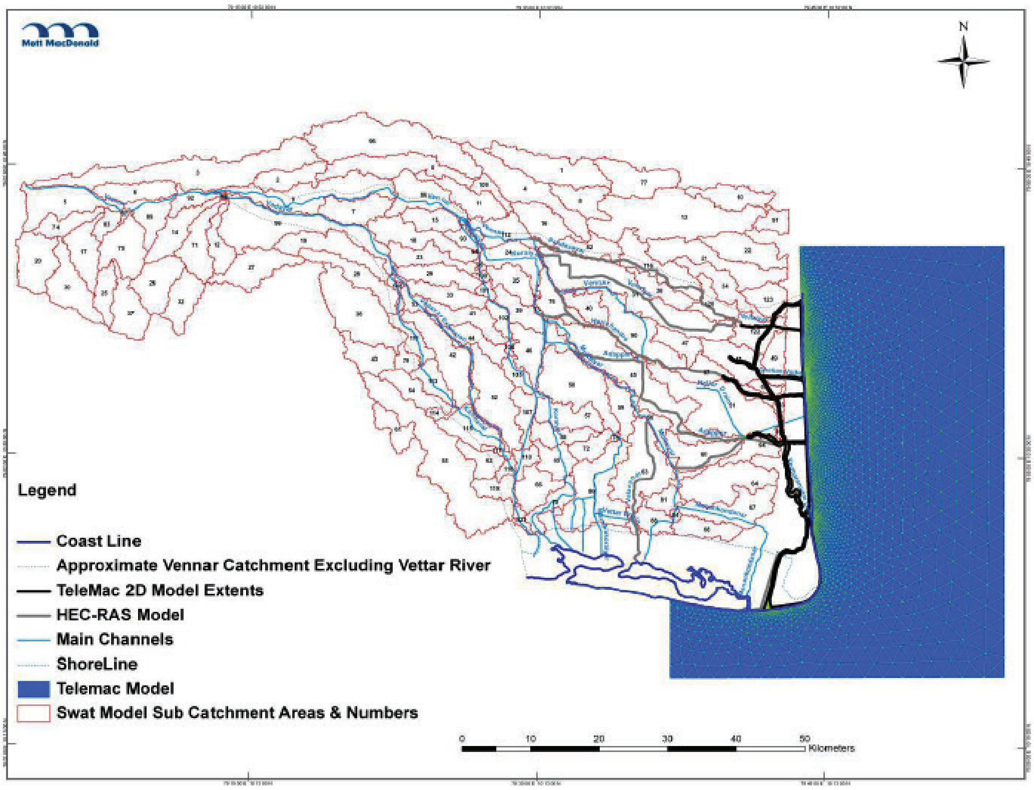


Figure 5.10 *SWAT watersheds in the Vennar system (Source: Mott MacDonald)*

SWAT simulation of the Vennar system was carried out for a period of 12 calendar years from 2001 to 2012. The observed rainfall event used for flood assessment is the 24-28 November 2008 storm, during which the rainfall was 560 mm. The return period of this storm is estimated to be 35 years. The storm total was factored to give 5-day storms for the 100-year event without climate change of 802 mm and with climate change of 962 mm), an increase of 20%.

The HECRAS model was run for the period 2001-2012 and the simulated flows at the tail-end regulator were compared with the flows recorded by the Water Resources Department, Government of Tamil Nadu. In the absence of recorded level data, the tail-end flows were used to adjust the SWAT inflows and to check on the volume of water that leaves the main channel as spill. The model does not simulate flood plain storage or the return of water to the main channel.

The comparison of annual observed and simulated peak flows at the Umbalachery regulator indicates that the simulated peak in the largest event (2008) was too large by 30-40%. The reason for this was almost certainly an overestimate of the peak runoff from contributing SWAT catchments caused by assumptions that runoff is not time lagged by travel time and impeded by drainage congestion and that all the runoff drains to the Adappar River. For these reasons the SWAT flows into the Adappar River in 2008 were reduced by 40%. The reduction in the SWAT flows is supported by the evidence from the Water Resources Department and from the field visits, which showed that the area draining to the river is not always contingent with the natural catchment. Furthermore, according to information from the Water Resources Department, the Adappar head regulator is usually closed during the floods; inflows into the Adappar model from the Koraiyar River were set to 10% of the SWAT flows. These adjustments provided reasonable simulated levels and flows for the 2008 flood event. There was an observation that the water levels increase by about 9% with climate change.

Moreover, the simulated water levels at the regulators are not inconsistent with the observations of the Water Resources Department during the 2008 event, there is consistency between the areas flooded in 2008 and the locations where the model simulates out-of bank flow. Therefore to improve confidence in the model, it is recommended that the water level and flow monitoring instruments are installed at the head and tail-end regulators and selected cross regulators. In the case of the Harichandra river, the water levels increase by about 15% with climate change. To improve the confidence in the model for detailed design or development of operational rules, it is recommended that the water levels and the flows be recorded during the flood flows and be used to improve the calibration. In the simulation of Valavanar, the results are reasonably consistent with the 2008 flood map for the upper reach. It indicates that the assumed inflows are acceptable, given the lack of flow and water level data. The lack of flow and water level records for the Valavanar Drain has restricted the validation and comparison among simulated water levels, anecdotal information from the Water Resources Department and the 2008 flood map.

5.5 Summary

The meteorological parameters in the first two decades (1981 to 1990) considered had a regularity, whereas the recent two decades (2001 to 2019) had a dissimilarity, with sudden rise and fall in the hydrological parameters.

- The water yield from scenario 1 (1981 - 1990) was moderate, those of scenario 2 (1991 - 2000) and 3 (2001 - 2010) were observed to be high, and that of scenario 4 (2011 - 2019) was low.
- The SWAT modelling for the Cauvery basin as a whole resulted in good performance in the evaluation indicators for the years 1993 - 2005 and 2006 - 2019 obtaining PBIAS (percentage bias) of 14% and 11% and NS (Nash-Sutchiffe) efficiency of 0.77 and 0.81 from the SWAT statistics.
- The results from the model simulation conducted for Harangi revealed that 101 out of the 109 sub-watersheds has a moderate soil loss in the range of 30-90 tons/ha/year.
- The evapotranspiration losses obtained for the Harangi watershed were comparatively less when compared with the Bhavani and Amaravathi. As a result, the percentage of water yield is high in the case of Harangi watershed.
- The water yield is as high as 69% in Harangi followed by Kabini with 62%, both in the humid tropical zone.
- The recharge is high in the Harangi and Amaravathi basins with 34.2% each, followed by Kabini with 31.2%. The Amaravathi Basin has the least recharge of 16.41% which has more hard-rock area compared to the other basins.
- It is observed that the water levels may increase by about 9% and 15% with climate change in the Adappar and Harichandra rivers, respectively.

6. GROUNDWATER AVAILABILITY AND UTILISATION IN CAUVERY DELTA AND POINT CALIMERE WETLAND COMPLEX

6.1 Introduction

Groundwater abstraction has increased to complement the increasing water demand of the continuously growing population. Groundwater is mostly exploited through dug wells, dug-cum-bore wells and bore wells for irrigation, as well as for domestic and industrial purposes. The main source of groundwater is precipitation and to a lesser extent, infiltration of water from the tanks and surface water during monsoon periods. Groundwater recharge to the aquifer system is thus the most important variable to be estimated for management of groundwater resources. In order to implement artificial groundwater recharge, it is essential to delineate potential groundwater recharge zones. Conventionally, remote sensing, photo-geological, hydro-geological and geophysical methods are deployed to select favourable sites for implementation of artificial recharge schemes. These methods are indirect, time consuming and sometimes uneconomical, particularly, when one has to deal with a large drainage basin. Instead, one can adopt simple and rapid methods to scan the entire area and arrive at suitable zones where a detailed study can be taken up.

- In Tamil Nadu, the surface water resources are fully utilised by various stakeholders. The demand of water is increasing day by day. So, groundwater resources play a vital role in meeting the additional demand by farmers, industries and households, which leads to rapid development of groundwater.
- About 63% of available groundwater sources are now being used. However, the development is not uniform all over the State. In certain districts of Tamil Nadu, intensive groundwater development had led to declining of water levels, increasing trend of overexploited and critical taluks, saline water intrusion, etc.
- The geohydrology of the study area i.e., the Cauvery Delta and Point Calimere Wetland Complex has been investigated, and a detailed analysis has been carried out with reference to the groundwater availability, abstraction and management.
- The study helps in categorising the Revenue Blocks/Firkas of the Cauvery Delta on the basis of groundwater using the method recommended by the Central Ground Water Board (CGWB, 2017). It also helps in identifying potential recharge zones using groundwater delineation method and some of the groundwater recharge measures adopted in the area have been highlighted.

6.2 Methodology

Groundwater level data were obtained from the State Surface and Groundwater Resources Data Centre, PWD, Taramani, Chennai for the districts of Nagapattinam, Tiruvarur and Thanjavur from observation (OB) and piezometric (PZ) wells for the past 40 and 20 years, respectively. The locations of selected wells in the Cauvery Delta are shown in figure 6.1.

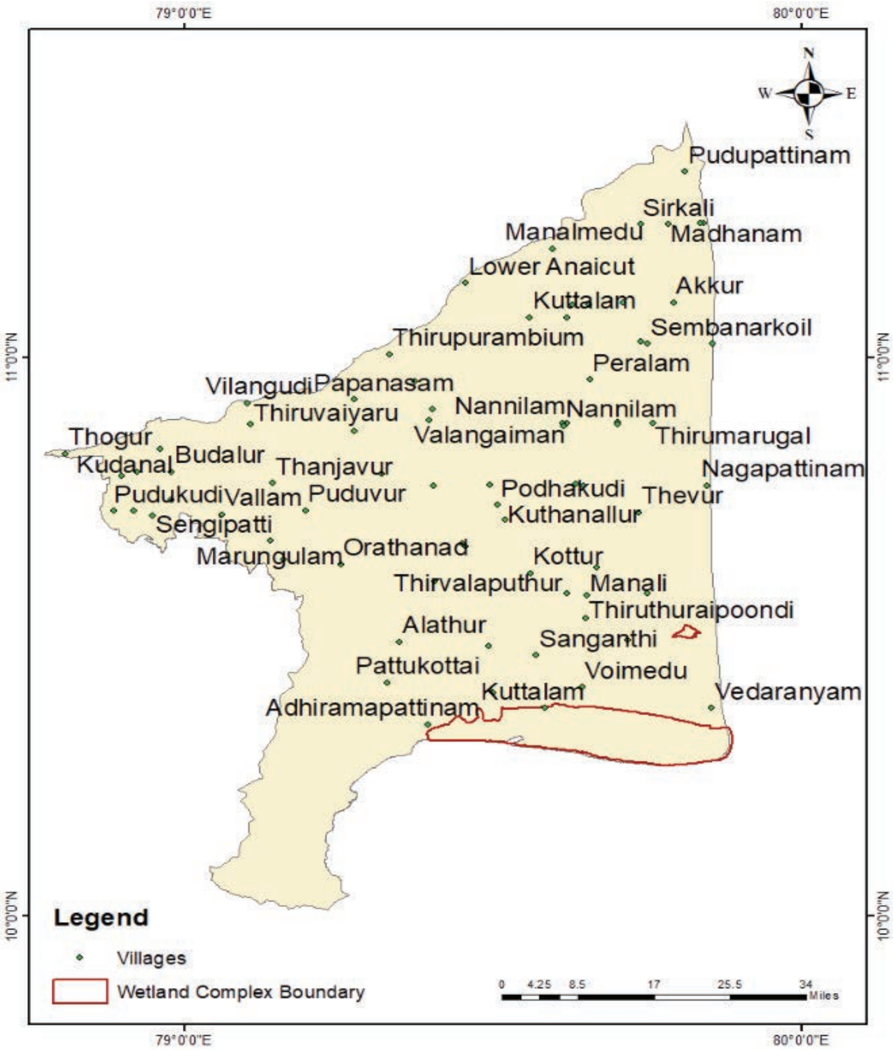


Figure 6.1 *Locations of selected observation wells in the Cauvery delta*

6.2.1 Groundwater Resource Assessment

6.2.1.1 Water Level Fluctuation Analysis

The present methodology used for resources assessment is recommended by the Groundwater Estimation Committee (GEC), 1997. There are two approaches recommended by the GEC, namely (i) the water level fluctuation method and (ii) the rainfall infiltration method. The water level fluctuation method is based on the concept of storage change due to differences between input such as recharge from rainfall and subsurface inflow and output components such as groundwater draft, groundwater evapotranspiration, baseflow to streams and subsurface outflow from the system.

The total annual groundwater recharge of the area is the sum total of the monsoon and non-monsoon recharge termed as net groundwater availability.

Net groundwater availability = Annual groundwater - Discharge during non-monsoon season

6.2.1.2 Groundwater Availability and Utilisation

Groundwater parameters have been assigned a weight (wi) between 1 and 5. The gross yearly groundwater draft is calculated for irrigation, domestic and industrial uses. The gross groundwater draft includes the groundwater extraction from all existing groundwater structures during the monsoon and non-monsoon periods. While the number of groundwater structures should preferably be based on the latest well census, the average unit draft from different types of structures has to be based on specific studies or ad hoc norms given in the GEC 2007 report. The stage of groundwater development is obtained from:

$$\frac{\text{Existing gross groundwater draft for all uses}}{\text{Net annual groundwater availability}} \times 100$$

6.2.1.3 Groundwater Delineation Method

Delineation of groundwater recharge potential zones is of vital importance to augment groundwater resources. It is particularly significant in hard rock regions where groundwater is the primary source for domestic, irrigation and industrial purposes. Water continues to diminish due to indiscriminate exploitation. Therefore, unconfined aquifer response to precipitation by using cross-correlation matrix has been evolved for Cauvery delta districts, namely, Nagapattinam, Thiruvarur and Thanjavur to delineate groundwater recharge potential zones for sustainable groundwater resources utilisation.

In this method, a plot with the independent variable, rainfall (r) and dependent variable, depth to water level (d) with one/more month's lag to rainfall was made. Considering the mean of rainfall (r') and depth to water level (d'), origin may be shifted to the point (r', d'). Therefore, the new coordinates may be defined as R (= r – r') and D (= d – d').

The correlation coefficient (r) is given as (Grewal, 1993):

$$r = \Sigma RD/(n\sigma r\ \sigma d) \quad \text{----- 6.1}$$

where R = Deviation from the mean r (= r – r'),
D = Deviation from the mean d (= d – d"),
σ_r = Standard deviation of r-series,
σd = Standard deviation of d-series, and
n = the number of datasets of depth to water level corresponding to the rainfall

6.2.1.4 Salinity Intrusion

The Ground Water Spatiotemporal Data Analysis Tool (GWSDAT) is a user-friendly, open source, decision support tool for analysis and reporting of groundwater monitoring data. It was developed by Shell Global Solutions (UK). Data inputs are entered using a standard Microsoft Excel template, while the underlying statistical modelling and graphical output are generated using the open-source statistical program R. The monthly groundwater level data collected from PWD for each observation well were converted to metres above MSL The data were entered into the Microsoft Excel input sheet of GWSDAT, under the 'Historical Monitoring Data' table and the groundwater flow estimation has been done using the model.

6.3 Water Level Fluctuation in the Delta and Wetland Complex

The water level fluctuation in wells located in Thanjavur, Thiruvaiyaru, Budalur, Orthanadu, Kumbakonam, Thiruvidaimarudhur, Thirupandal, and Papanasam, of Thanjavur district; Thiruvarur, Muthupet, Nannilam, Manali and

Needamangalam, of Thiruvarur district; and Vedaranyam, Sirkazhi, Keezhvelur, Nagapattinam and Thiruthuraipoondi, of Nagapattinam district; of the Cauvery Delta, were studied. In all the wells the shallowest water table occurs during the months of June, July and August and a rise in the water table occurs in the months of September and October, reaching its peak in December and January due to the north-east monsoon. However, the water level gradually declines, depending upon the rainfall and groundwater abstraction during the post-monsoon season (figure 6.2) There is a close relationship among the rainfall, regulated streamflow and groundwater table fluctuation in the delta, as shown in figure6.3.

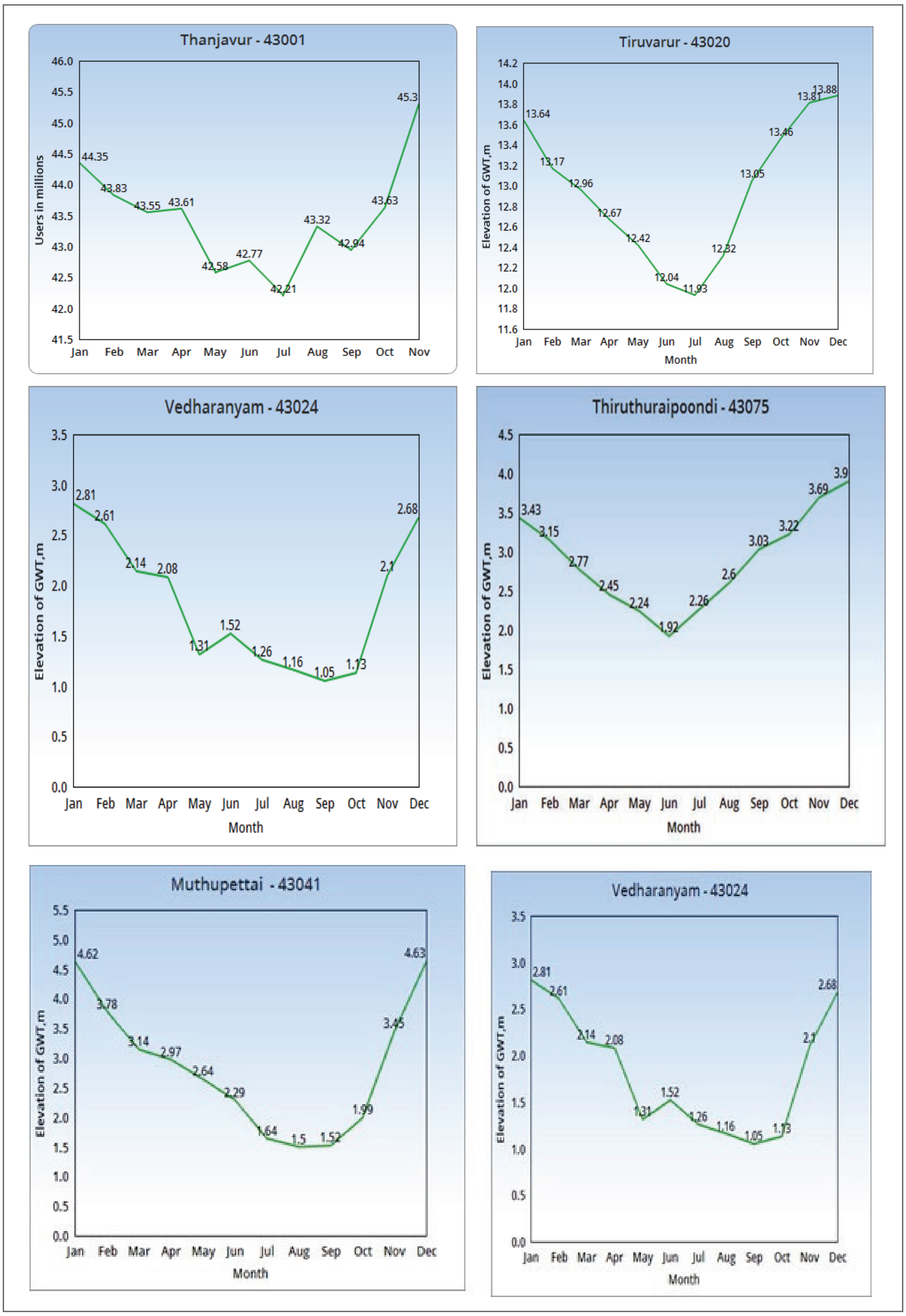


***Figure 6.2** Water level fluctuation in some of the observation wells located in the Cauvery dD lta near the Point Calimere Wetland Complex*

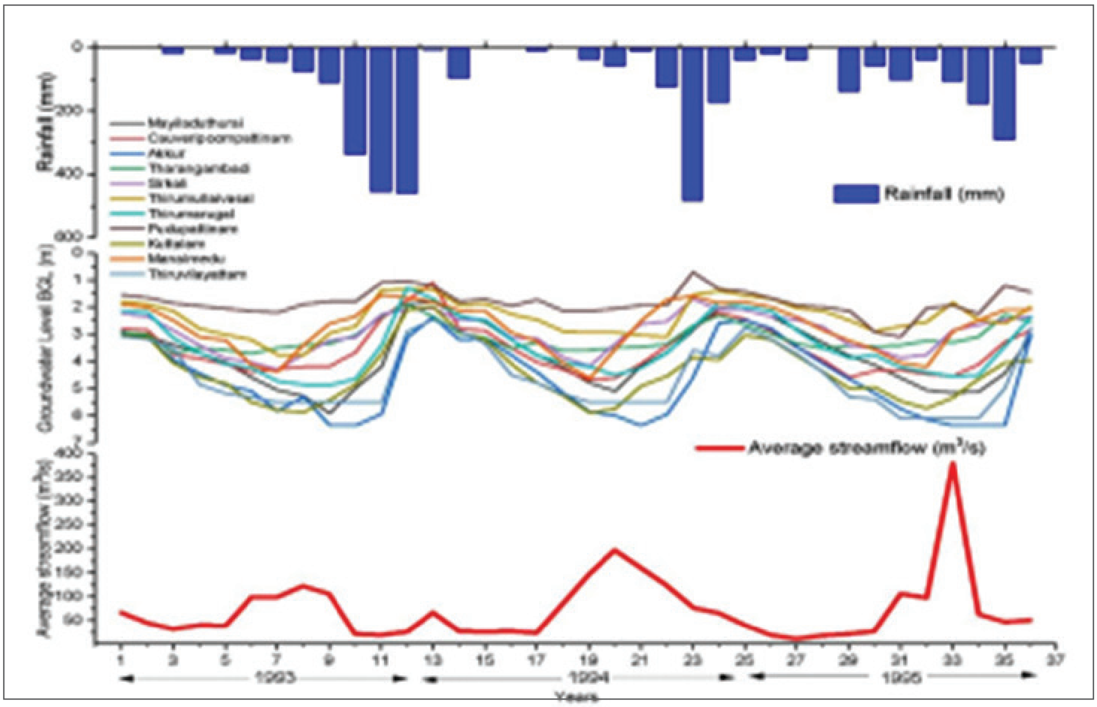


Figure 6.3 *Relationship between rainfall, regulated streamflow and groundwater table fluctuation*

6.4 Aquifer Systems

The occurrence and storage of groundwater depend upon three factors, viz., geology, topography and rainfall. Apart from geology, wide variations in topographic profile and intensity of rainfall constitute the prime factors of groundwater recharge. Aquifers are part of the more complex hydro-geological system. In hard rock terrain, the occurrence of groundwater is limited to top weathered, fissured and fractured zone, which extends to maximum 40 m below ground level and on an average, it is about 10-15 m in the coastal districts of Nagapattinam and Thiruvarur. In Thanjavur district the bore wells drilled from 30 m to 300 m show that the behaviour of aquifer varies in space. Moreover the alluvium and tertiary formations have got good-yielding potential aquifer zones with varying thickness.

6.5 Groundwater Availability and Utilisation

Since groundwater is dynamic in nature, the following factors are to be considered for assessment: geology, total irrigated area, total number of wells used for irrigation, water level data for the past five years, average rainfall, total recharge, irrigation methods adopted in the area, cropping pattern details, seepage factor, specific yield, geological conditions prevailing in the area and recharge through artificial recharge structures.

In these assessments, the Revenue Blocks/Firkas were categorised as overexploited, critical, semi-critical, safe and saline blocks. The blocks with more than 100% extraction were categorised as ‘overexploited’, those with 90% to 100% extraction as ‘critical’, those with 70% to 90% extraction as ‘semi-critical blocks’, those with less than 70% extraction as ‘safe blocks’ and those with poor quality were categorised as ‘saline’ (figure 6.4). The assessment of blocks pertaining to Tiruvarur, Nagapattinam and Thanjavur districts is given in Tables B1-B3 in Annexure 2.

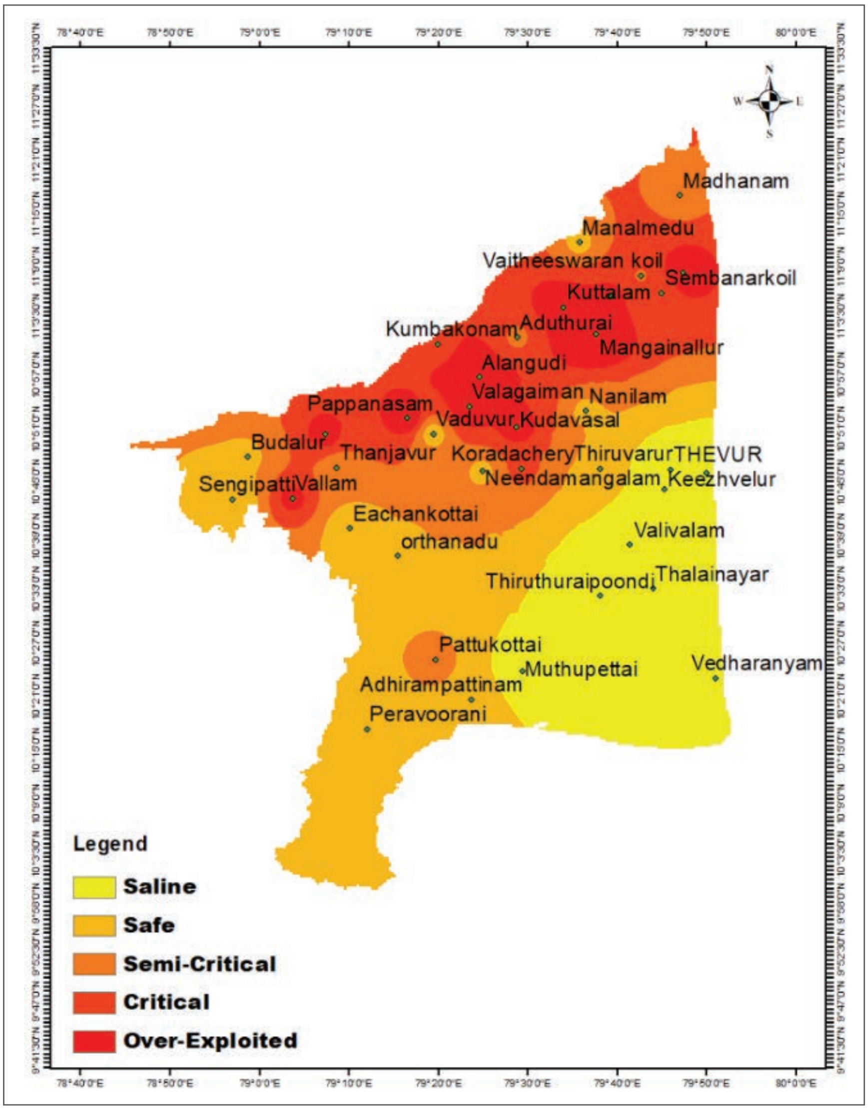


Figure 6.4 *Groundwater abstraction in different blocks of Cauvery Delta*

6.6 Groundwater Delineation Method

Since rainfall occurs mostly during the north-east monsoon period in the Cauvery Delta, the water levels of unconfined aquifers in the study area respond after one/two months of rainfall. The cross-correlation coefficient was determined between the depth of the water table and the corresponding rainfall. The correlation coefficients are shown in Tables B4-B6 in Annexure 2 for Nagapattinam, Thiruvarur and Thanjavur districts, respectively. Since the number of wells located within the buffer zone of Point Calimere Ramsar Site is limited, the values were extracted for 24 locations from the geo-spatial interpolation map. The distribution of wells across the Point Calimere Wetland Complex is as shown in figure 6.5. From the correlation matrix table, it was observed that sufficient recharge takes place in a one-month lag period and then subsequently it shows a declining trend. These wells representing immediate responses within a one-month lag are selected as potential recharge zones. On the basis of the results from the correlation matrix table, excellent, good and moderate recharge zones in the study area were identified as shown in figure 6.6.

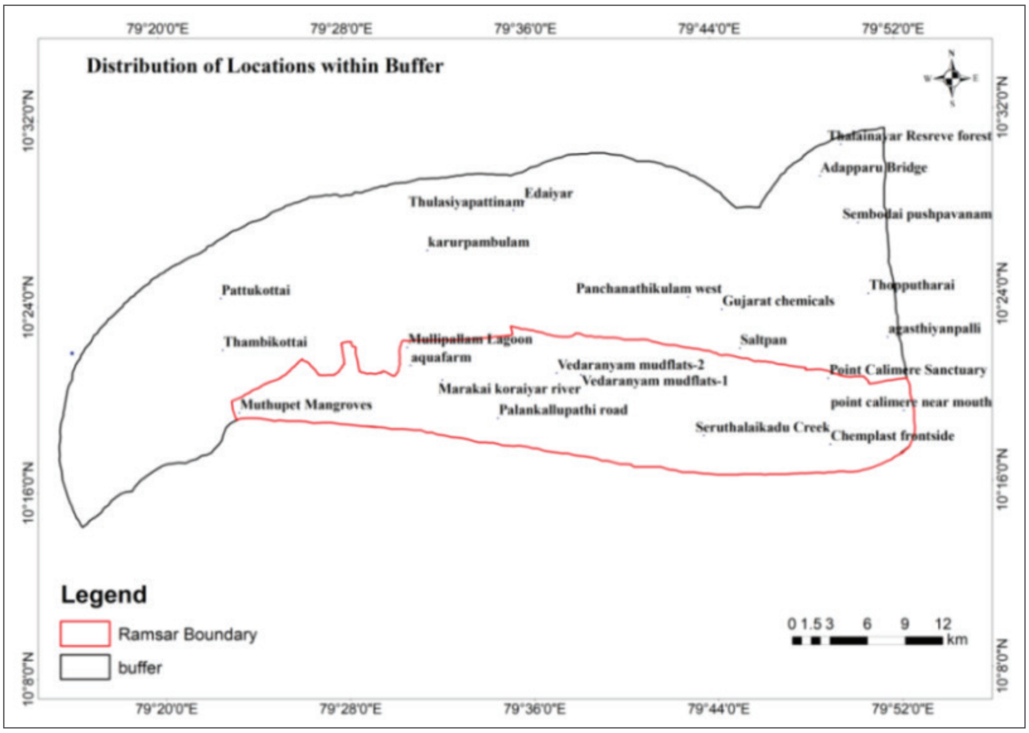


__Figure 6.5__ Locations of wells within the buffer zone of Point Calimere Ramsar site

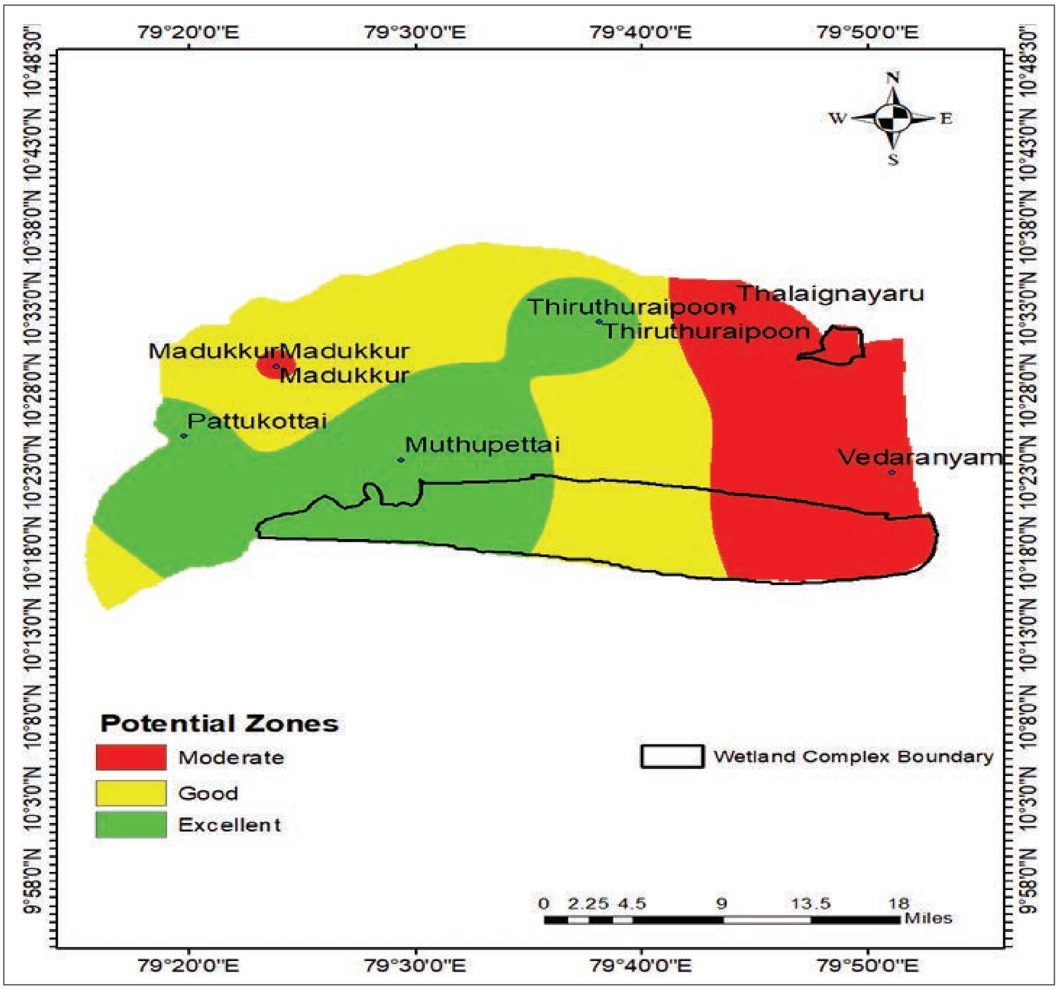


__Figure 6.6__ Potential recharge zones in the direct catchment

The response of the water table variation to the rainfall was observed using the cross-correlation analysis and the time lags of 1 month and 2 months show the maximum response of the aquifer to the rainfall. The amplitude of correlation showed the increasing/decreasing trend with the lag periods in a systematic manner. From the analysis, zones of high recharge ($r > 0.60$), moderate recharge ($0.50 \leq r \geq 0.60$), low recharge ($0.40 \leq r \geq 0.50$) and poor recharge ($r < 0.40$) were identified.

In Point Calimere Wetland Complex, the wells near Adhirampattinam, Muthupet and Kuttalam were found to have high recharge, whereas Voimedu comes under the moderate recharge zone, and Point Calimere and Vedaranyam come under the poor recharge zone. Therefore, certain recharge measures are recommended for the Point Calimere and Vedaranyam areas.

6.7 Groundwater Flow

The GWSDAT software package was used to estimate the flow direction of groundwater. It is based on the theory that the local groundwater flow will follow the local direction of steepest descend (hydraulic gradient). The flow directions were determined for the Cauvery and Vennar Sub-basins separately for the years 1981, 1986, 1991, 1996, 2001, 2004, 2011 and 2015 and figure 6.7 to 6.8 show ground flow for the Vennar sub-basin for the years 2011 and 2015. In general, the groundwater flows from higher hydraulic head towards zones of lower hydraulic head, i.e., from the land towards the coastal zone and then to the sea (Barackman and Brusseau, 2002; Mulligan and Charette, 2009).

- The groundwater flow direction in the Cauvery sub-basin indicates flow towards the sea and in the Vennar sub-basin it was towards inland from the sea.
- The geomorphic features of the delta are perhaps one of the causes for the flow directions towards the land from the sea.
- The extraction of groundwater in the coastal region can also further accelerate the flows from the sea as hydraulic head is lowered. It leads to intrusion of seawater into the coastal aquifer, leading to the contamination of fresh groundwater (Rajmohan et al., 2007, Vijay et al., 2011).
- The trend analysis of groundwater level data showed an increase in most of the observation wells in the coastal regions; the increase in the southern Vennar sub-basin is attributed to a change in the groundwater flow direction from the sea to the land.

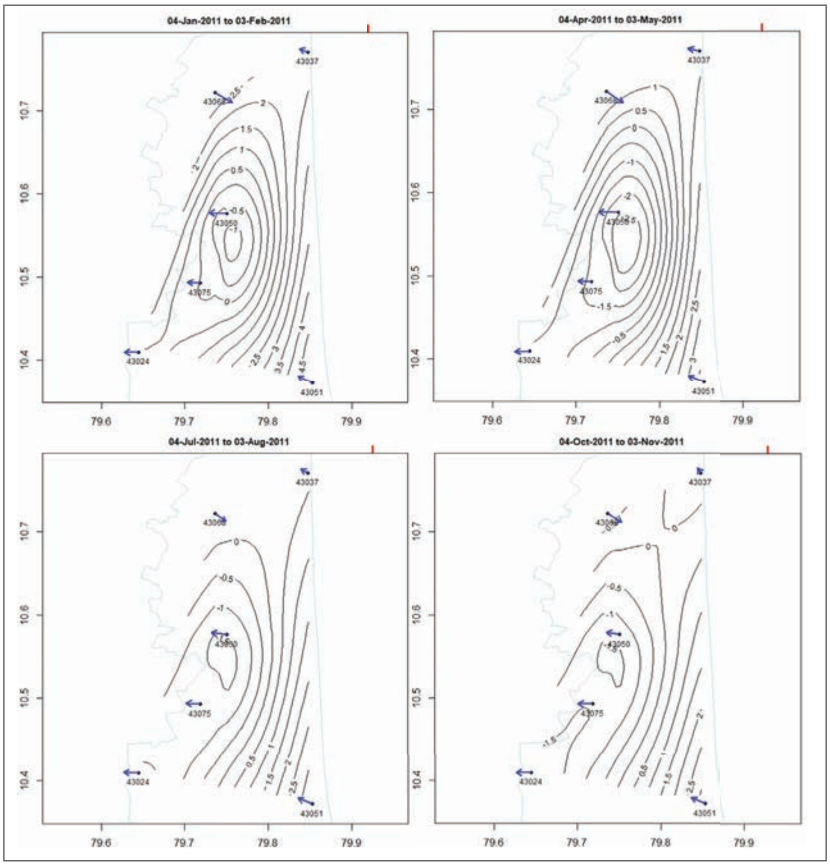


Figure 6.7 *Groundwater flow direction: 2011 - Vennar Sub-basin*

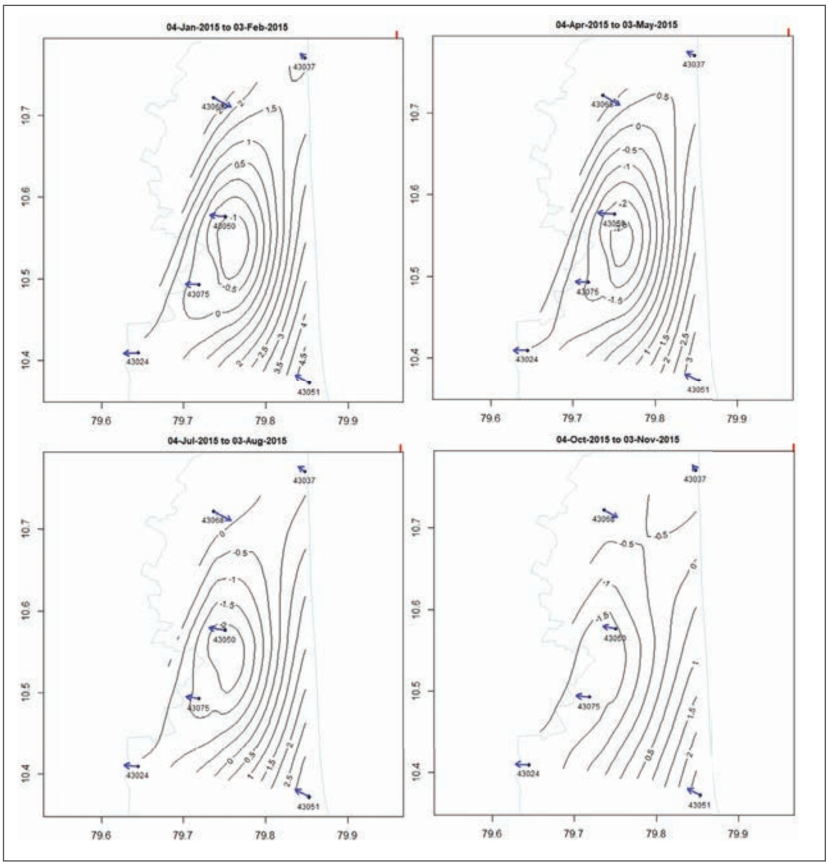


Figure 6.8 *Groundwater flow direction: 2015 - Vennar Sub-basin*

6.8 Existing Status of Water Management in Point Calimere Wildlife and Bird Sanctuary and Block B

6.8.1 Water Structures

A review of the existing water storage structures in Point Calimere Wildlife and Bird Sanctuary (PCWBS) created to augment the groundwater recharge and water supply to the surrounding area has been done. Water management in the Point Calimere Sanctuary is carried out using a total number of 102 water structures of 7 different types (source: Forest Department, Nagapattinam), as given below.

(i) **Check dams:** There are around seven major and nine mini check dams located in the area. They are small barriers built on shallow rivers and streams in the ditch, swale, or channel across the direction of water flow that interrupt the flow of water and flattens the gradient of the channel, thereby reducing the velocity of water and soil erosion for the purpose of water harvesting. The small dams retain excess water flow during the monsoon rains from the small catchment area behind the structure, which induces infiltration and reduces erosion.

(ii) **Earthen bunds:** An earthen bund is a type of water harvesting structure that has an external catchment and long slope. Typically, farmers build a U-shaped earthen bund on their cultivated lands to harvest runoff from adjacent upslope catchments. This technique usually collects rainwater and sometimes, floodwaters and reduces land degradation. There are ten earthen bunds located in the Point Calimere Sanctuary.

(iii) **Lakes:** There are two lakes in the area, i.e., Muniappan and a newly constructed lake. They function as purification filters for the groundwater and replenish the sources. They help in preserving the biodiversity and habitat and can also be used for water supply for industry as well as an irrigation source for agriculture.

(iv) **Canals:** There is only one canal, i.e., Peralam, in the area. This is a man-made waterway that allows passage of water for domestic, agriculture and industrial activities. This also helps in irrigation as a hydraulic system to convey water from sources such as dams or rivers to different users.

(v) **Ponds:** They are either a part of an existing water system, or local flooding causes lakes and rivers to overrun their shores, emptying water into new valleys and low-lying land, creating new ponds when the flood waters recede. They provide water for agriculture and livestock, aid habitat restoration, serve as fish hatcheries and contribute to landscape architecture. A total of 38 ponds have been identified in the area.

(vi) **Wells:** A well is a hole drilled into the ground to access water contained in an aquifer. Recharge or injection wells are used to directly recharge water into deep aquifers. The recharged groundwater can be accessed by wells and boreholes tapping the same aquifer or feeding natural springs. Seven wells are located in the area.

(vii) **Water troughs:** A water trough (or artificial watering point) is a man-made or natural receptacle intended to provide drinking water to animals, livestock on farms or ranches or wild animals. There are 28 water troughs present in the Point Calimere Sanctuary. The key benefits of troughs are improved water quality, storage of more water and increased dry matter intake. The size of a water trough depends on whether a herd is taken for watering periodically or is given water on a continuous basis.

6.9 Summary

- From the groundwater level fluctuation analysis, the water level was observed to be lowest in the months of June and July, with an increasing trend towards the months of August and September, reaching its peak in December and January due to the north-east monsoon rains.

- The correlation coefficients obtained from groundwater delineation method showed increased recharge response in one-month lag period with declining trend subsequently. The wells with immediate response within one-month lag have been considered as potential recharge zones.
- From the observations of previous studies and the best practices evolved, it has been found that desilting of existing tanks and their proper maintenance as also construction of percolation pond with recharge wells and recharge shafts are viable solutions.
- Due to the range and scale of problems, responses of wells to recharge and the pace of social and economic changes, developing effective strategies for groundwater overdraft is still a challenging task. For effective management of groundwater resources, responses of wells need to be closely tailored to local conditions for adaptation.
- Small impoundments, detention storage structures and radial wells may be well suited for recharging the groundwater table in PCWBS.

Photo credit: GIZ_ Prasanth

7. GROUNDWATER QUALITY ASSESSMENT IN POINT CALIMERE WETLAND COMPLEX

7.1 Introduction

In general, most coastal aquifers are sandy with high permeability, which leads to seawater intrusion. Both higher hydrostatic pressure and low density of freshwater column play a significant role in maintaining the saline and freshwater balance. Excessive pumping from wells in and around the coastal areas may disturb this balance resulting in movement of seawater into coastal aquifers. Possible zones of salinisation, their origin and associated geochemical processes in the transition-zone between salt and freshwater can be explained by analysing the groundwater chemistry.

Geomorphologically, the northern part of Vedaranyam Swamp is in the coastal plain with beach ridges and the southern part adjoining the Bay of Bengal is of muddy salt marsh. As Point Calimere is the seaward apex of the Cauvery Delta, the soil deposits are essentially of fluvial origin, besides sand dunes. In most of the places, pedologic horizons are inseparable and the surface zones exhibit more or less specific characteristics. The surface soil mainly consists of clayey sand, pebbles, gravel and concretions with little organic matter. The average depth of this horizon is 30 to 40 cm. Below 40 cm, the layers are permanently humid, rich in clay but poor in organic matter which can be penetrated by deep roots. The soils are halomorphic with a muddy structure in a moistened state and a compact structure in dry state. A saline efflorescence is often formed at the surface due to the capillary rise of salt (mainly sodium chloride), influenced by the proximity to the sea and the length of the dry season. The sand in the dunes is fine yellowish-white and is continuously altered by aeolian erosion whenever exposed. In the depressions within dunes called as swales the soil is fertile, rich in clay and silt, and is widely converted into agricultural lands for paddy, vegetables and aquaculture ponds. Nearly half of the area falls under agricultural lands which demand good quality groundwater for irrigation and domestic water usage in Point Calimere. In the area of Muthupet Lagoon and associated mudflats, the soil types commonly found are alluvial, red ferruginous or lateritic, Irugur or black, arenaceous and Kallar. The mudflats look like a desert in summer, and the soil erosion at the centre of the mudflats reveals submergence of mudflats during floods. The soil of these mudflats is mainly clayey silt in nature with sparse vegetation such as *Prospis juliflora* and mangroves.

For the past several decades, the groundwater quality in the Point Calimere Wetland Complex has been greatly affected by natural and anthropogenic activities such as saltwater intrusion, production of edible and industrial salts using saltpans adjacent to the bird sanctuary, livelihood activities at aquaculture farms, presence of mudflats, inlets and estuaries, the influence of freshwater- saltwater mixing, the sediment deposit from the upstream end of the wetland complex, growth and decay cycle of mangroves and vagaries of weather in Point Calimere Wetland Complex. Though the availability of primary groundwater quality data is limited for Point Calimere Wetland Complex, secondary data on the groundwater level and quality for several decades are available for the Cauvery Delta. The primary and secondary data on groundwater quality parameters can be converted into useful information for the policy and decision makers, engineers and scientists to evolve strategies and decisions for sustainable groundwater management. The relevance of the work, a brief methodology and key findings of the work, carried out in three phases, are presented in this chapter.

7.2 Relevance

Since groundwater is utilised for domestic, agricultural and industrial activities, it is necessary to assess the groundwater quality and its suitability.

- The utilisation of saltwater and brackish water for saltpans and aquafarms in Point Calimere Wetland Complex has necessitated the study of deterioration of groundwater quality.
- The occurrence of hydro-geochemical reactions such as rock-water interactions, dissolution, precipitation, adsorption, degradation, bio-transformation, ion exchange and saltwater intrusion in the confined and unconfined layers of coastal aquifers has led to an investigation of their impact on the groundwater quality.
- The influence of coastal sand dunes in
  - protecting inland areas from sea water inundation during natural disasters
  - providing medicinal, value-added nutritional, agricultural, veterinary, pharmaceutical and fodder values for the livestock
  - preventing storm surges and beach erosion and
  - improving the freshwater availability through inter-dune swales

  has drawn attention to stabilise the existing sand dunes in the study area.
- The deterioration of groundwater quality by the various interconnected sources/activities such as domestic, agricultural and industrial activities, saltpans, aquaculture, saltwater intrusion and mudflats have entailed identification of the sources of pollution. Suitable remedial measures are suggested.

7.3 Database

7.3.1 Field and Secondary Data

Data on groundwater level and quality across the Cauvery Delta during the pre-monsoon and post-monsoon seasons for 40 years were collected from the State Groundwater and Surface Water Resources Data Centre, Chennai and analysed. The secondary data pertain to samples collected from dug wells and tube wells and a few bore wells. The groundwater quality assessment was conducted on the data for 8 years, i.e, 1985, 1989, 1994, 1999, 2005, 2009, 2013 and 2018, for which a maximum of 14 water quality parameters were available for comparison, and the results have been presented in the interim report. Since 2009, the development of dug, bore and tube wells has been high in the Cauvery Delta and the number of wells located within the buffer zone of the Point Calimere Wetland Complex is limited. Water quality parameter values were extracted for 24 locations within the PCWC complex from the geo-spatial interpolation map, which is based on the spatio-temporal maps of groundwater quality developed for the delta region.

The locations in the buffer zone for which groundwater quality data have been interpolated are given in Fig. 7.1. The locations are selected such that they are distributed well across the buffer zone. A few important locations within the major ecosystems of Point Calimere site are Muthupet (Muthupet mangroves), Marakakoraiyar River, Pallankallupathi Road (Muthupet), Siruthalaikadu Lagoon, Point Calimere Wildlife Sanctuary, aquafarm, Agasthiyanpalli (aquaculture farms), Vedaranyam Salt Swamp /mudflat-1,2 (mudflats) and saltpan (Chemplast).

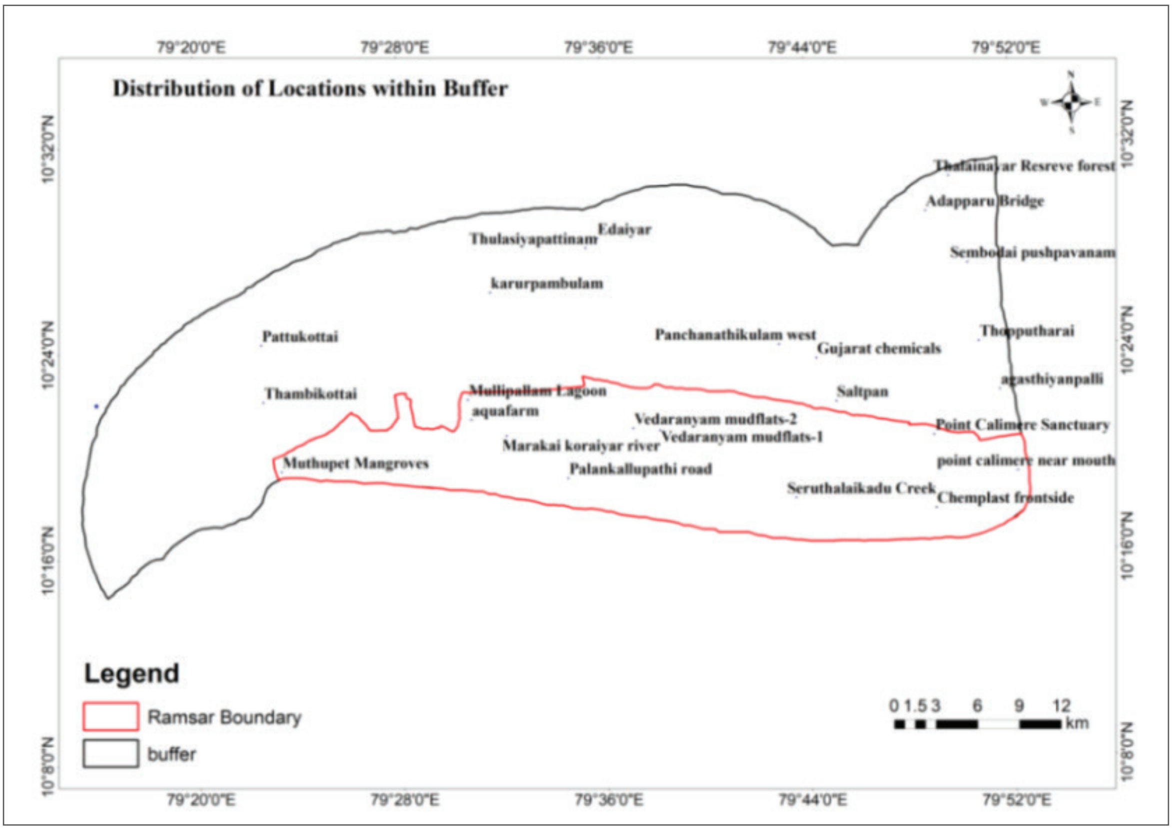


Figure 7.1 *Points of interpolation for groundwater quality in the buffer zone of the Point Calimere Ramsar Site*

7.3.2 Satellite Imagery

The Sentinel 2A level 1C product, with radiometric and geometric corrections, including ortho-rectification and spatial registration, on a global reference system with sub-pixel accuracy, for 15 February 2020, was downloaded from the website of United States Geological Survey for carrying out the study of remote sensing indices. It consists of 13 spectral bands that range from the visible and near-infrared to the shortwave infrared with varying spatial resolutions from 10 to 60 m.

Sl. no.	Parameter	WHO standard (S_i)	Amount in seawater (35 ppt) (mg/l)
1	Total dissolved solids (mg/L)	500	500
2	Sodium (mg/L)	200	200
3	Chloride (mg/L)	250	250
4	Magnesium (mg/L)	30	30
5	Total nitrates (mg/L)	50	50
6	Sulphate (mg/L)	250	250
7	Electrical conductivity (mS/cm)	250	250
8	Potassium (mg/L)	10	10
9	Fluoride (mg/L)	1	1

Sl. no.	Parameter	WHO standard (S_i)	Amount in seawater (35 ppt) (mg/l)
10	pH	6.5-8.5	6.5-8.5
11	Bicarbonate (mg/L)	350	350
12	Calcium (mg/L)	100	100
13	Total hardness (mg/L)	100	100

7.4 Results and Discussion

7.4.1 Suitability of Groundwater for Drinking and Irrigation

7.4.1.1 Spatial mapping of water quality parameters

The water quality parameters that exceed the permissible limits when compared with WHO standards for the years 2009, 2013 and 2018 are shown in Table 7.1.

7.4.1.2 Suitability for drinking water

The suitability of groundwater for drinking purpose was identified by means of the WQI calculated with reference to the WHO standards. The WQI of the years 2018, 2013 and 2009 for the post-monsoon and pre-monsoon are plotted against the classes of water suitability. The classes excellent, good, poor, very poor and unsuitable are given values from 1 to 5, respectively. The post-monsoon and pre-monsoon graphs are shown in figures 7.5 and 7.6, respectively.

- Deterioration in groundwater quality in PCWC for drinking is observed from 2009 onwards for both the seasons. The water quality is poor in the pre-monsoon when compared to the post-monsoon season.
- The groundwater quality remains poor in the post-monsoon and becomes very poor during the pre-monsoon over the years for the Muthupet and adjoining mangrove areas.
- Deterioration of groundwater quality was observed from 2009 to 2018 during both the seasons for the areas around Siruthalaikadu Lagoon, Point Calimere Wildlife and Bird Sanctuary and aquaculture farms. In the saltpan area, water quality remains good in the post-monsoon and decreases during the pre-monsoon over the years.
- Groundwater quality remained poor from 2009 to 2018 for the post-monsoon and very poor during the pre-monsoon from 2013 to 2018 in the mudflats.

7.4.1.3 Suitability for irrigation

The suitability of groundwater for irrigation was identified by six different indices. The average values of these indices for the years 2018, 2013 and 2009 for the post-monsoon and the pre-monsoon were plotted against eight water quality classes (classes excellent, very good, good, fair, permissible, poor, doubtful and unsuitable) to identify their suitability for irrigation. The post-monsoon and the pre-monsoon graphs are shown in figures 7.4 and 7.5, respectively.

- A deterioration in the groundwater quality for irrigation was observed from 2009 onwards during both the seasons. However, when compared to the post-monsoon season, the suitability of groundwater for irrigation is poor in the pre-monsoon, which may be due to the overexploitation/pumping of groundwater.
- In both the pre-monsoon and post-monsoon seasons of 2009, groundwater was good/fair for irrigation in many places over the years (figure 7.4), which may be due to a smaller number of aquafarms.

- Even though groundwater quality is deteriorating since 2009, it remains suitable for irrigation in the post-monsoon season for the adjoining areas of Muthupet Estuary, Muthupet Mangroves, Point Calimere Wildlife and Bird Sanctuary, mudflats and aquaculture farms. This may be due to the lithology and aquifer characteristics of the study area.
- The water quality remains consistent in the areas in and around Siruthalaikadu inlet and saltpans during the post-monsoon season and is not suitable for irrigation in the Siruthalaikadu inlet area during the pre-monsoon.

***Table 7.1** Groundwater quality parameters exceeding permissible limits in the buffer zones of ecosystems of Point Calimere Wetland Complex*

Ecosystem	Post-monsoon			Pre-monsoon		
	2018	2013	2009	2018	2013	2009
Muthupet lagoon	TDS, chlorides, magnesium, EC, potassium, bicarbonate, hardness	TDS, magnesium, EC, potassium, bicarbonate, hardness	TDS, chlorides, EC, bicarbonate, hardness	TDS, sodium, chlorides, magnesium, sulphates, EC, potassium, pH, bicarbonate, hardness	TDS, chlorides, magnesium, sulphates, EC, potassium, pH, bicarbonate, hardness	TDS, magnesium, sulphates, EC, bicarbonates, hardness
Siruthalaikadu lagoon	TDS, magnesium, EC, potassium, hardness	TDS, sodium, magnesium, EC, hardness	TDS, magnesium, EC, hardness	TDS, sodium, chlorides, magnesium, sulphates, EC, potassium, pH, bicarbonate, hardness	TDS, sodium, chlorides, magnesium, sulphates, EC, pH, bicarbonate, hardness	TDS, sodium, chlorides, sulphates, EC, bicarbonates, hardness
Muthupet mangroves	TDS, chlorides, magnesium, EC, potassium, hardness	TDS, chlorides, magnesium, EC, potassium, hardness	TDS, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, potassium hardness	TDS, sodium, magnesium, EC, potassium, hardness	TDS, sodium, magnesium, EC, potassium, hardness
Saltpan	TDS, chlorides, magnesium, EC, potassium, hardness	TDS, chlorides, magnesium, EC, hardness	TDS, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, potassium, bicarbonates, hardness	TDS, sodium, chlorides, magnesium, EC, bicarbonates, hardness	TDS, sodium, chlorides, magnesium, EC, bicarbonates, hardness
Aquaculture farms	TDS, chlorides, magnesium, EC, potassium, hardness	TDS, chlorides, magnesium, EC, hardness	TDS, magnesium, EC, hardness	TDS, sodium, chlorides, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, hardness

Ecosystem	Post-monsoon			Pre-monsoon		
	2018	2013	2009	2018	2013	2009
Mudflats	TDS, sodium, chlorides, magnesium, EC, potassium bicarbonates, hardness	TDS, sodium, chlorides, magnesium, EC, bicarbonate, hardness	TDS, sodium, chlorides, magnesium, EC, potassium bicarbonates, hardness	TDS, sodium, chlorides, magnesium, sulphates, EC, potassium, pH, bicarbonates, hardness	TDS, sodium, chlorides, magnesium, sulphates, EC, potassium, pH, bicarbonates, hardness	TDS, sodium, chlorides, magnesium, sulphates, EC, potassium, bicarbonates, hardness
Point Calimere Wildlife and Bird sanctuary	TDS, magnesium, EC, potassium, hardness	TDS, sodium, magnesium, EC, potassium, hardness	TDS, sodium, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, potassium, hardness	TDS, sodium, chlorides, magnesium, EC, potassium, hardness

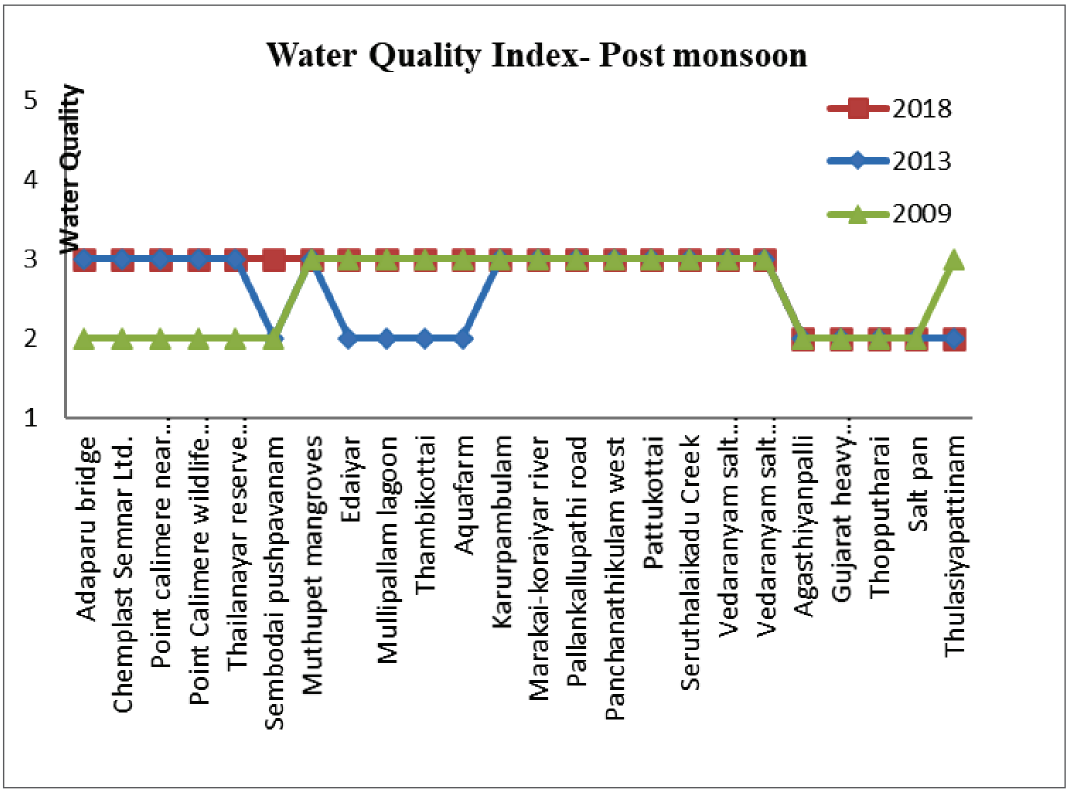


Figure 7.2 *Drinking water suitability graphs for post-monsoon season in the buffer zone and Point Calimere Wetland Complex*

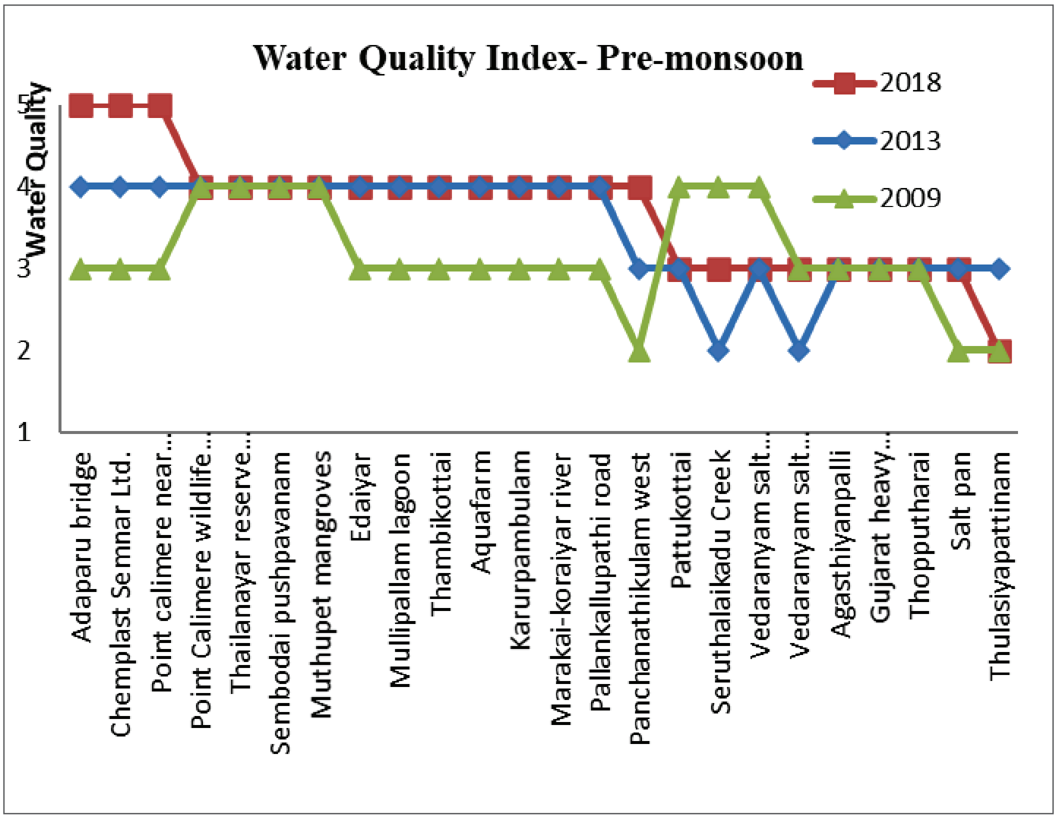


Figure 7.3 *Drinking water suitability graphs for pre-monsoon season in the buffer zone and Point Calimere Wetland Complex*

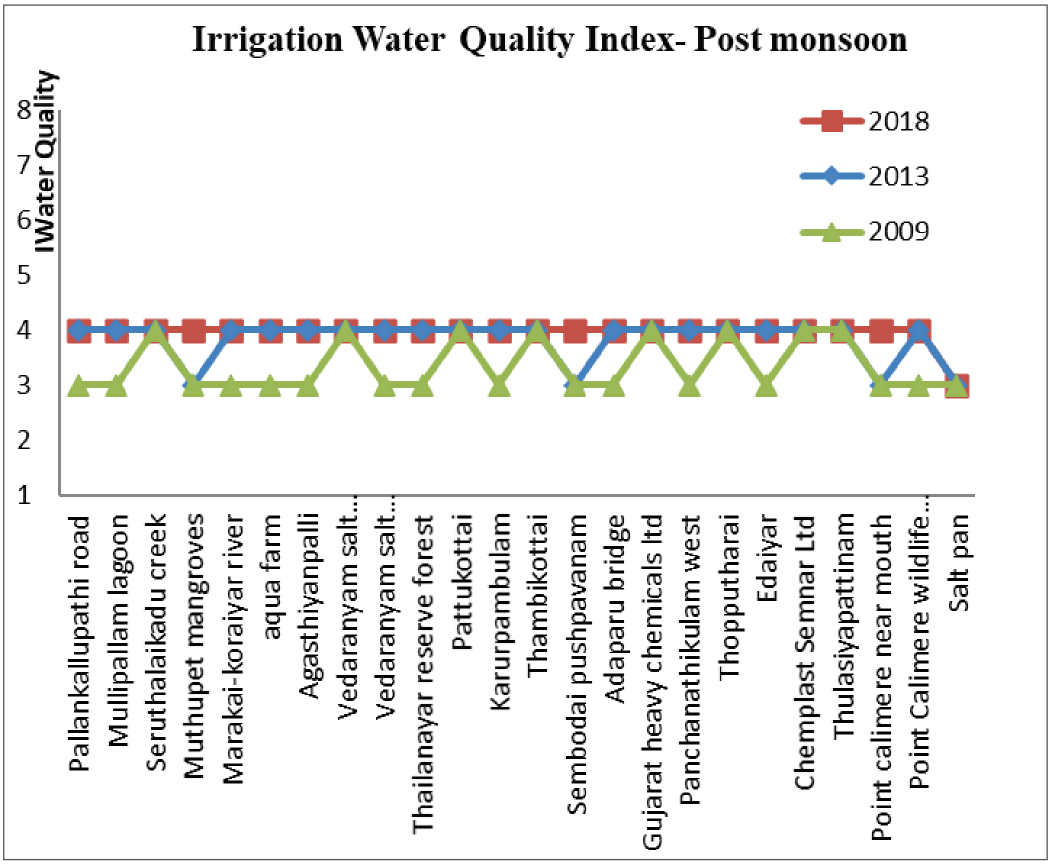


Figure 7.4 *Irrigation water suitability graph for post monsoon in the buffer zone of Point Calimere Wetland Complex*

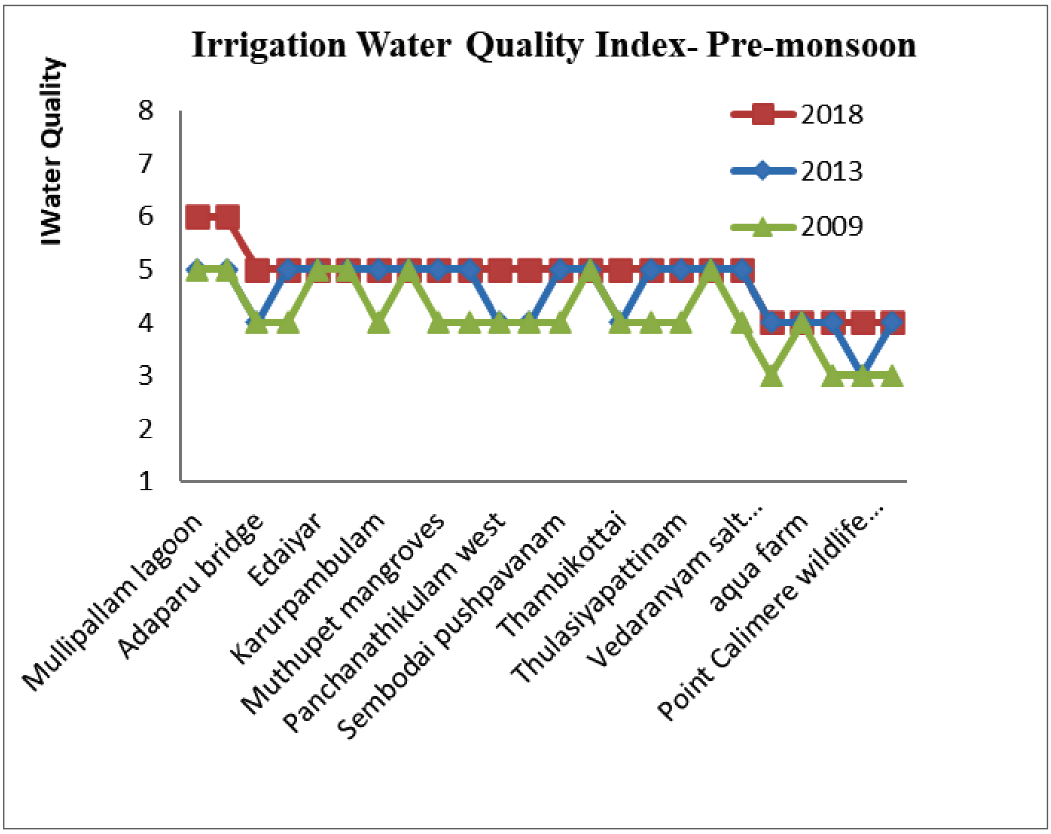


Figure 7.5 Irrigation water suitability graph for pre-monsoon in the buffer zone of Point Calimere Wetland Complex

7.4.1.2 Sources of pollution

The main sources of pollution in Point Calimere Wetland Complex are:

- In the area of Muthupet Estuary, salinity is the main source of pollution in all the years except for the post-monsoon of 2018, where other anthropogenic sources from the domestic and industrial waste also contributed to pollution.
- In the Muthupet Mangroves, mudflats and aquaculture farms, the sources of pollution are salinity intrusion, rock-water interaction, agriculture and domestic activities.
- The pollution in saltpans and Siruthalaikadu Lagoon is mainly due to salinity.
- In Point Calimere Wildlife and Bird Sanctuary, the source of pollution is mainly from agriculture and domestic activities. The presence of fluoride may be due to geogenic origin.
- The main causes of pollution in the mudflats, Muthupet Lagoon and Muthupet Mangroves are reverse ion exchange (Na gets exchanged with Ca^{2+} and Mg^{2+} in the soil matrix) and saltwater intrusion. This is confirmed by similar results obtained from raw groundwater quality data, factor analyses and the prediction algorithm: presence of excess TDS/EC, chloride, magnesium, hardness in the groundwater (secondary data) and the observed significant parameters (magnesium, TDS/EC, chloride, hardness) using ANN model and Factor 1 (from factor analysis).
- In the saltpan, aquaculture farms and Siruthalaikadu Lagoon, the main cause of pollution is salinity.

7.4.2 Water Quality Analysis Using Remote Sensing

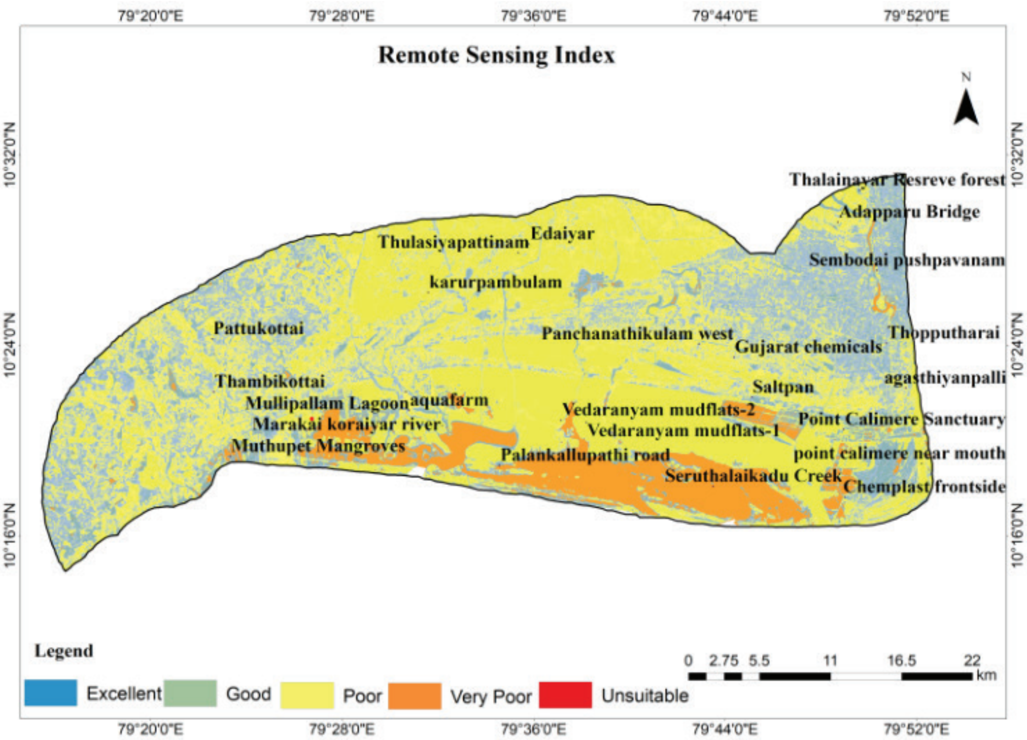


Figure 7.6 *Remote sensing index for the Point Calimere Ramsar buffer zone of the wetland complex in 2020*

The final remote sensing index, representing the water quality on the basis of the results of weightage analysis for the sub-indices, is shown in figure 7.6. Except for the Point Calimere Wildlife and Bird Sanctuary and Muthupet Mangroves, the water quality is not suitable for drinking in other areas. This may be due to the presence of sand dunes, freshwater sources, percolation ponds in the forest area and the flow of freshwater drainage channels. The water quality is poor in the mudflats, aquaculture farms and saltpans is also found to be poor.

7.5 Summary

- In Point Calimere Wetland Complex, the groundwater quality in the pre-monsoon is comparatively poorer than in the post-monsoon season.
- Calcium, sulphates, total nitrates and fluorides are within the permissible limits whereas total dissolved solids, electrical conductivity and hardness exceed the limits in both the seasons.
- Water quality for the purpose of drinking and irrigation is deteriorating over the years for both the seasons.
- The groundwater is suitable for irrigation during the post-monsoon whereas the quality is not suitable during the pre-monsoon.
- During the post-monsoon, groundwater quality in the Muthupet lagoon and mangroves remains suitable for drinking and irrigation, whereas the quality is poor in the pre-monsoon; seawater intrusion might be the reason for the increase in salinity over the years along with other natural and anthropogenic causes such as saltpans and aquafarms.

- Water quality during the post-monsoon is suitable for drinking and irrigation in the saltpan areas; a decrease in quality during the pre-monsoon is due to the release of effluent, 'brine' from the industries located near them.
- Even though the quality is decreasing with time, the groundwater is suitable for irrigation in the aquaculture farm and saltpan areas. This might be due to the freshwater sources in their vicinity, which are getting mixed up with the groundwater during recharging.
- A variation in water quality is observed in the mudflats as the physical properties of the soil are varying with seasons.
- The groundwater quality is not suitable for irrigation and drinking in the Siruthalaikadu Lagoon area over the years in the pre-monsoon season; the main reason is saltwater intrusion from the sea.
- The TDS, chloride, hardness and magnesium are the main water quality parameters that represent the deterioration of groundwater quality in the PCWC (with a more than 60% influence on pollution in both the pre-monsoon and the post-monsoon seasons).
- The least influencing water quality parameters are pH, fluorides and total nitrates in both the seasons.
- To protect the groundwater and soil from contamination due to the leaching of effluents, deadly diseases and inconsistent crop yields, it is suggested that a polyethylene lining system (HDPE/LDPE) be provided.
- In order to remove the organic, inorganic and toxic pollutants in the effluent released from the aquafarm, it is suggested that a wastewater treatment plant with unit operations such as screening, settling tank, secondary /biological unit (suspended/attached growth process) and tertiary treatment (filtration) may be provided.
- The effluent that is released from the industrial salt ('Bittern' solution) may be treated using a membrane process

Photo credit: GIZ

8. HYDRODYNAMICS AND FLUVIAL HYDRAULICS OF MUTHUPET LAGOON

8.1 Introduction

The hydrodynamic processes of Muthupet Lagoon are investigated under different freshwater flow conditions. The formation of a salt plug during no-flow conditions in the Muthupet Lagoon indicates the possibility of its formation even in a tropical wet and dry climate zone. The knowledge of the formation of a salt plug in an estuary or a lagoon is important in the study of the transport of suspended matter, dissolved matter, fish species and other marine organisms. Similarly, the turbidity maxima throw light on the pollutant flushing, fish migration and primary productivity of the estuary and lagoon. The freshwater flow has a role in the development of vertical salinity gradient, and hence, on the settling velocity of suspended sediments of a shallow estuary. This information on the dependence of settling velocity on salinity gradient helps researchers to apply the concept in other shallow estuaries that develop vertical salinity gradient. The salinity levels in the lagoon with respect to different flow regimes have been worked out to recommend the flow rate to be maintained for the health of mangroves and for serving other ecosystem services.

8.2 Data collection

The rainfall during the north-east monsoon in this region is mainly confined to October - December (ICMAM 2005). The influence of rainfall on the streamflow and subsequently on the processes in the lagoon continues till February. From March to September there is neither rainfall nor any stream flow, leading to hypersaline conditions in the lagoon. The monsoon, the post-monsoon and the pre-monsoon seasons are defined in the present work considering the rainfall characteristics and its influence on the hydrodynamics of the lagoon during the period of study. The freshwater availability in the estuary to a great extent depends on the release of water from the upstream rivers. The flow through these tributaries is regulated on the upstream side. The release of water from the storages is subjected to the availability of water in the upstream storage reservoirs and the flow is also regulated downstream just before the stream discharges into the wetlands. In order to understand the hydrodynamics and fluvial hydraulics, data related to salinity and suspended particulate matter were collected from the sampling shown in figure 8.1.

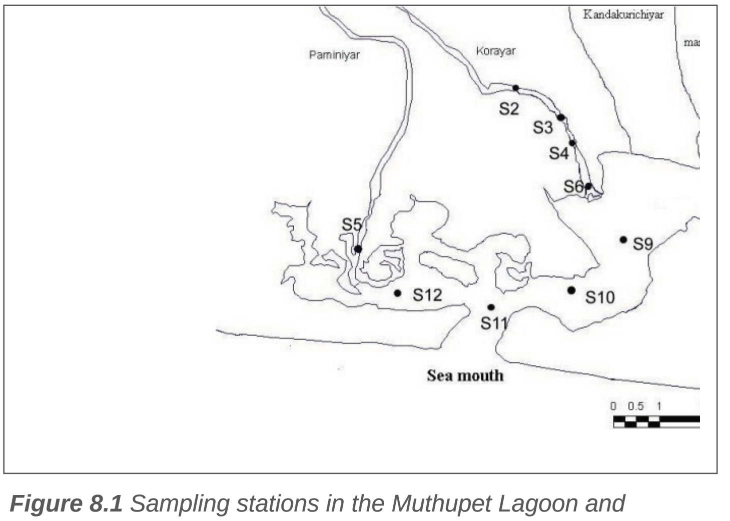


Figure 8.1 *Sampling stations in the Muthupet Lagoon and associated water bodies*

It is observed that the Muthupet Lagoon falls under the well mixed category, showing no vertical stratification during the pre-monsoon season and that it comes under the partially stratified category during the post-monsoon and monsoon seasons. The stratification parameter was lower during the monsoon than that during the post-monsoon. Also, the stratification parameter during the spring tide was higher than that during the neap tides.

8.3 Pre-monsoon Season (March to September)

8.3.1 Longitudinal and Tidal Variation of Salinity and SPM

The salinity intrusion went up to 15 km upstream from the lagoon mouth, up to the Koraiyar regulator, during the pre-monsoon. The peak concentration of salinity was not observed at the mouth, but at a distance of 5 km upstream of the mouth, with the concentration of salinity exceeding 30 g/l during the pre-monsoon, reaching more than 40 g/l. During the dry and hot seasons, the occurrence of this salinity maximum zone, called as salt plug is due to high evaporation and negligible freshwater discharge. Seaward of this salt plug, the density decreases as in the case of an inverse estuary; landward of the salt plug, the density decreases as in the case of a positive estuary. Further, a peak salinity of 36 g/l was recorded at a distance of 7 km from the mouth during the late pre-monsoon. The salinity intrusion went up to the regulator in September; the intrusion in January has been up to 9 km from the mouth. Thus, the upstream shift in the location of salinity intrusion limit was observed over a seasonal cycle.

The lack of freshwater during the period from March to September resulted in a change in the hydrodynamic characteristics of the estuary, thereby causing a reduction in the resuspension mechanism of Suspended Particulate Matter (SPM). These have a consequence on the biodiversity of the lagoon and associated water bodies.

8.3.1.2 Transport of salt and SPM

The total salt transport during the spring tide of the pre-monsoon was 3.542 kg/s/m at station S11, and it was in the upstream direction. The fluvial advection, consisting of tidal discharge, was a predominant factor causing the landward transport of salinity of 3.41 kg/s/m. The total salt transport of 0.589 kg/s/m at station S6 was also found to be in the upstream direction. During the neap tide of the pre-monsoon, the average salinity at the upstream station S6 was higher than that at the station near the mouth, S11. Thus, the net transport of salt was directed seaward, -0.3284 kg/s/m at S11 and 0.4835 kg/s/m (landward) at S6 (figure 8.2). The direction of transport of salt gives some insight into the circulation of the lagoon during the pre-monsoon. The upstream movement of salt at S6 and its downstream movement at S11 show that there is a common source of higher salinity region from where the salinity is dispersed into the upstream and downstream sides. This source is the salt plug, located at an intermediate distance between S6 and S11, as shown in figure 8.2. The tidal forces have caused the dispersion of salinity at the salt plug and it can be seen that tidal correlation and tidal dispersion are the dominant mechanisms in the transport of salt at both the stations. The gravitational circulation at both the stations have changed the direction during the pre-monsoon (transport towards sea) compared to the post-monsoon (transport towards land). During the pre-monsoon, the density at the upstream reaches is appreciable; further the formation of the salt plug causes denser water inside the lagoon, making the current to move in the downstream direction. Thus, the formation of salt plug has caused the seaward transport of salt due to gravitational circulation, even though it is secondary. The total transport of salt during the late pre-monsoon (figure 8.2) showed similar trend as during the neap tide of the pre-monsoon (March). Though there was a transport from the location of salt plug, it was much less compared to that during the early pre-monsoon in March, the values being -0.038 kg/s/m and 0.0059 kg/s/m at station S11 and S6, respectively. The transport of SPM at station S11 was 0.121 kg/s/m in the upstream direction and 0.007 kg/s/m at S6 during the spring tide of the pre-monsoon. The gravitational circulation, shear and residual transport created a small downstream transport of SPM at S11, but the impact on the transport was not significant. At station S6, gravitational circulation was the only process affecting the downstream transport of SPM, but its effect on the net transport was negligible. During the neap tide, the SPM transport was upstream at both the stations; 0.105 kg/s/m at station S11 and 0.484 kg/s/m at S6 (figure 8.3). The Stoke's drift, tidal correlation and tidal dispersion mainly contributed to the upstream transport of SPM, together with fluvial advection and residual transport at S11. Gravitational circulation and shear were the only forces causing its downstream transport. The upstream transport of SPM was dominated by fluvial advection, tidal correlation and tidal dispersion, followed by Stoke's drift and residual transport at S6. The transport of SPM was comparatively less during the late pre-monsoon and it was directed upstream, having a value of 0.042 kg/s/m at S11 and 0.003 kg/s/m at S6, respectively.

The dominant mechanisms controlling the transport of SPM were tidal correlation and dispersion, while fluvial discharge controlled the transport of salt. The influence of all other factors on the transport was insignificant.

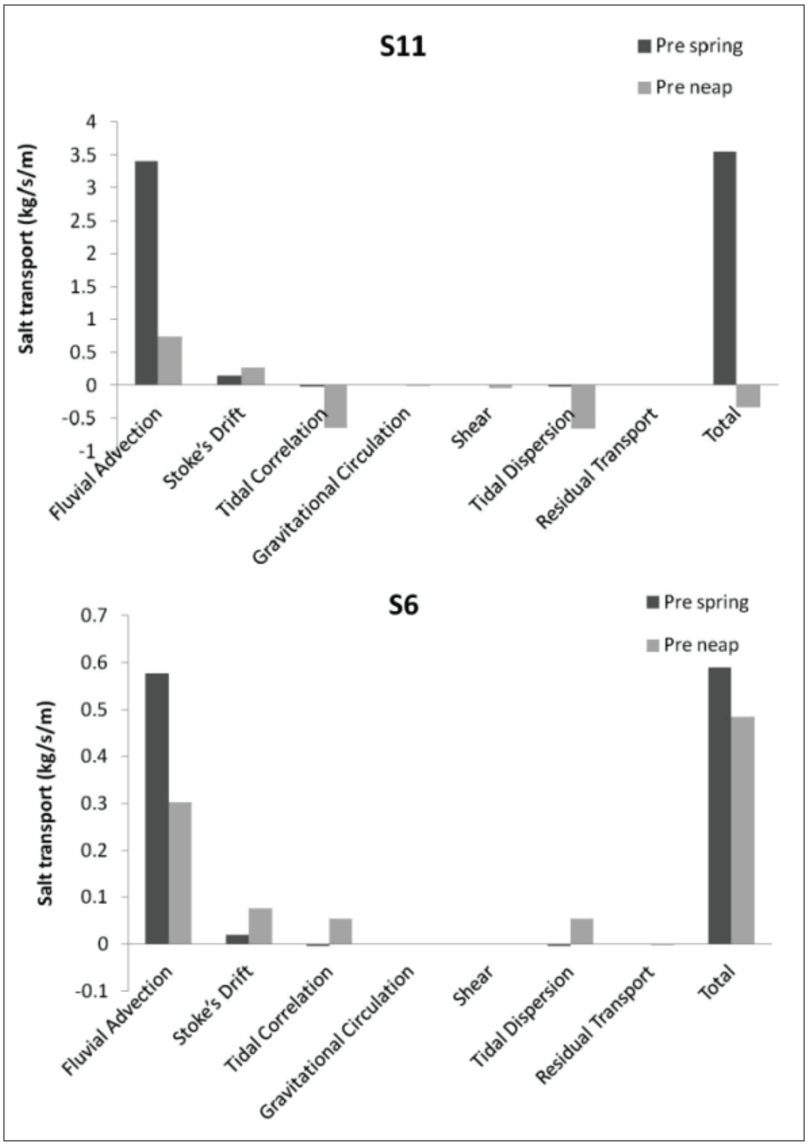


Figure 8.2 *Pre-monsoon transport of salt at S11 and S6 during the spring tide (March) and the neap tide (March)*

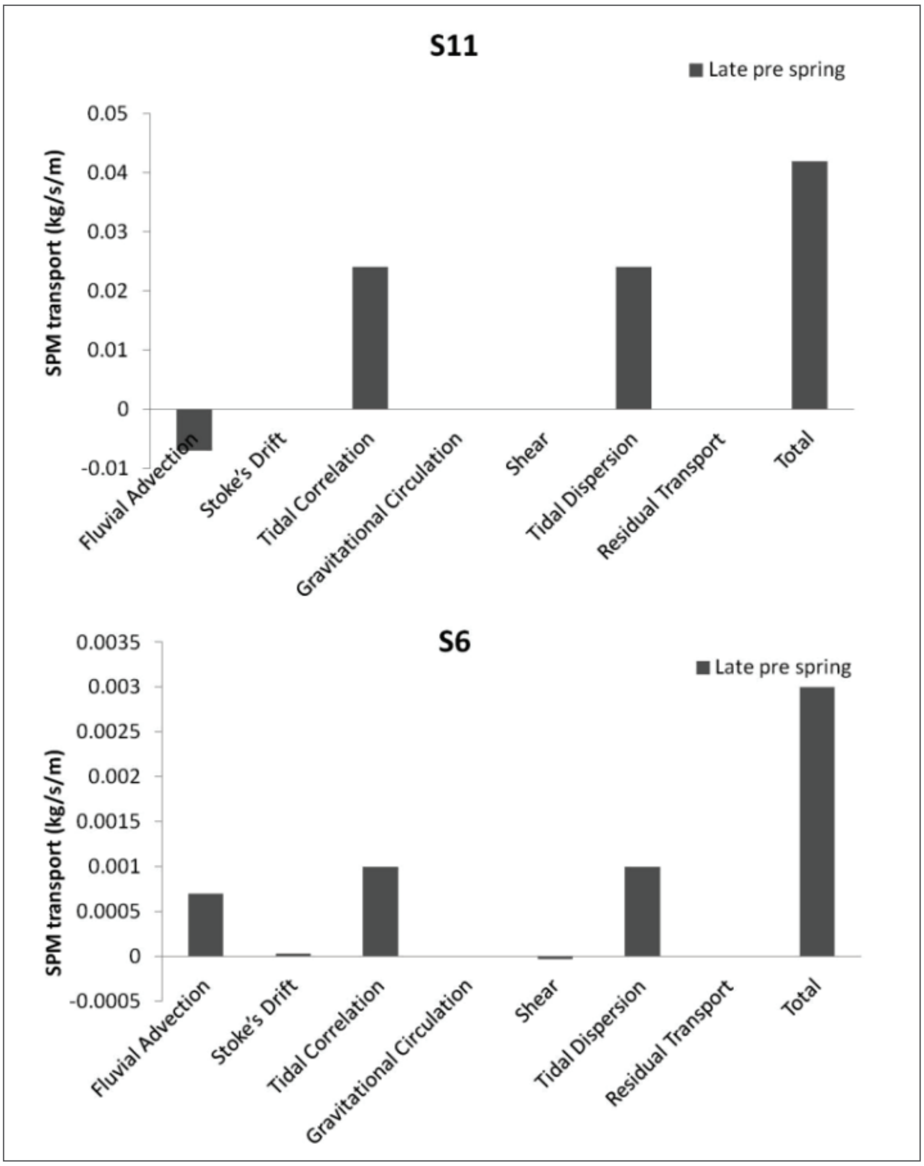


Fig. 8.3 *Late pre-monsoon transport of salt at S11 and S6 during the spring tide (September)*

8.4 Post-Monsoon season (January to February)

8.4. 1 Longitudinal and tidal variation of salinity and SPM

The salinity variations were distinct from the head to the mouth of the lagoon during the spring tide of the post-monsoon. In the present study, the longitudinal distances are specified with respect to the sea mouth. The salinity intrusion limit is taken as the upstream position where the salinity falls below 1 g/l. The salinity intrusion occurred up to 9 km upstream from the sea mouth during the spring tide of the post-monsoon. The salinity intrusion was up to 10.5 km during the neap tide. The longitudinal variation of salinity was highest during the post- monsoon. The highest salinity was observed at the mouth of the lagoon during the post-monsoon.

The SPM concentrations were higher at the downstream reaches than at the upstream reaches of the lagoon. The turbidity maximum occurred near the mouth of the lagoon. The SPM concentration varied between 0 g/l and 1.4 g/l during the period of study.

8.4.1.1 Transport of salt and SPM

Estuaries and lagoons are characterised by the occurrence of turbidity maximum (ETM) where the concentration of SPM is higher than that in the seaward and landward directions from the ETM (Nicholas and Biggs, 1985, Dyer, 1988, 2000). The estuarine hydrodynamics play a key role in the formation and dynamics of ETM. The hydrodynamics of the estuary and lagoon can be understood by studying the major processes causing the transport of salinity and SPM. The transport of SPM is considerably affected by the freshwater flow, tidal asymmetry, gravitational circulation and channel shoal erosion (Van Straaten and Kuenen, 1957, Postma, 1967). Knowledge on the transport of salt and SPM and its seasonal variation will give insight into the circulation phenomena. Further, the understanding of the transport of suspended particulate matter will throw light on the pollution characteristics of an estuary or a lagoon since many contaminants are adsorbed on the SPM and are transported through the estuary or lagoon (Nicholas, 1986).

The salt transport was estimated, and the net transport of salt at stations S11 (-1.017 kg/s/m) and S6 (-0.104 kg/s/m) was in the downstream direction during the spring tide of the post-monsoon. The fluvial advection component was the major controlling factor for the downstream transport of salt at both the stations. Shear and residual transport also played a minor role in the transport of salt in the downstream direction. Though not significant, tidal dispersion, tidal correlation, Stoke's drift and gravitational circulation created an upstream transport of salt. The tidal dispersion contributed much more than the gravitational circulation. During the post-monsoon, when the density-driven force was comparatively higher at the upstream stations, a circulation is induced where the seaward density is higher than the landward causing the dense sea water to move landward, causing a current in the upstream direction. Thus, the transport due to gravitational circulation was upstream during the post-monsoon. Gravitational circulation was of much less intensity than Stoke's drift, tidal dispersion and tidal correlation. The controlling factor of salt transport at station S6 was not different from that at S11. However, the magnitude of the transport of salt at S6 was less by 10 times than that at S11. The effect of river discharge on the net salt transport was higher at S6 than at S11, the fluvial advection component being more dominant than the barotropic and baroclinic components.

During the neap tide, the fluvial advection and tidal dispersion created a downstream transport of salt. Shear and residual transport, which acted in the downstream direction during the spring tide of the post monsoon, contributing to the upstream transport of salt during the neap tide at station S11. The change in the direction of salt transport of these components can be attributed to the reduction in the seaward current. The fluvial advection component was less during the neap tide compared to the spring tide. The reduction in the freshwater flow during the neap tide observations may have reduced the seaward current, resulting in the reduction of the fluvial advection. As a result of the reduction in the seaward current, the deviation of the instantaneous velocity from the average velocity was directed upstream, resulting in an upstream transport of salt due to shear at both the stations. The reduction in the freshwater flow caused a reduction in the vertical salinity gradient, and the deviation of instantaneous depth average salinity from the tidal mean depth average salinity was negligible. This has resulted in the residual transport of salt in the upstream direction at station S11. The case was different at S6 because it is located at the upstream side and a marginal vertical gradient of salinity was felt, resulting in the seaward residual transport of salt at this station. The transport of SPM at S11 during the spring tide of the post-monsoon was -0.037 kg/s/m and it occurred in the downstream direction. The SPM transport was dominated by the river discharge followed by tidal dispersion, tidal correlation and shear, causing a downstream transport. Some of these forces were counteracted by residual transport, gravitational circulation and Stoke's drift in the upstream direction, but the magnitude of transport by these forces was less than that caused by the river discharge. The net transport of SPM at station S6 was-0.003 kg/s/m and was much less than that at station S11. The SPM transport at S6 was controlled more by the river discharge, and the net transport was towards downstream. Tidal correlation, tidal dispersion, shear and residual transport aided the downstream transport of SPM. Stoke's drift and gravitational circulation caused an upstream transport of SPM, but their magnitude was much less so as to cause an impact on the total transport.

The net transport of SPM in the downstream direction at station S11 was less during the neap tide (-0.021 kg/s/m) compared with the spring tide (-0.037 kg/s/m). This was due to the decrease in the freshwater flow, thereby causing a reduction in the fluvial advection component. Fluvial advection, tidal correlation and tidal dispersion were the controlling factors for the downstream transport of SPM. Stoke's drift, gravitational circulation, residual transport and shear created an upstream transport of SPM, but of much less intensity. At station S6, the net downstream transport of SPM was -0.0022 kg/s/m and it was driven by fluvial advection, shear and tidal dispersion. The other factors created an upstream transport of less intensity. As the upstream station S6 is more influenced by the river discharge than S11, the deviation of the instantaneous velocity from the average velocity was towards the sea at S6. As such, the shear component caused an upstream transport of SPM.

8.5 Monsoon Season (October to December)

8.5.1 Longitudinal and tidal variations of salinity and SPM

During the onset of monsoon, the salinity and SPM retained during the pre-monsoon are flushed out of the lagoon. The maximum salinity occurred at the downstream reaches of the lagoon. As sandy silt predominates in the upstream reaches (at distances of ca. 15 km upstream of the sea mouth), they are not carried into the semi-enclosed portion of the lagoon because of the large settling velocity. They get settled in the vicinity of the river itself. During the neap tide, the currents are not strong enough to resuspend the sediments. On the other hand, the strong spring currents caused resuspension of sediments. This phenomenon was also observed during the post-monsoon, the nose being sharper than the tail during all the spring tides. Even though the salinity stratification was less, the SPM was stratified during the spring and neap tides of the monsoon.

8.5.2 Transport of salt and SPM

By the onset of the subsequent monsoon, the entire hydrodynamics of the lagoon changed, making it a positive lagoon and the earlier existing salinity and SPM started moving towards the sea. Thus, the seaward transport of salt and SPM was mainly controlled by fluvial discharge, the total transport of salt being - 4.78 kg/s/m and-0.164 kg/s/m at stations S11 and S6, respectively, and the total transport of SPM being -0.086 kg/s/m and -4×10^{-4} kg/s/m, respectively, during the neap tide. The transport of SPM much reduced in comparison to the pre-monsoon, while the transport of salt enhanced by 9-fold and 3-fold at stations S11 and S6, respectively.

The transport of salt and SPM occurred downstream during the spring tide. The transport of SPM had enhanced and the transport of salt reduced marginally compared to the neap tide conditions. This reduction in the downstream transport of salt is due to the higher influx of salinity into the lagoon in the spring conditions than in the neap conditions. Even though the SPM was transported downstream during the monsoon, the magnitude of transport was less than that during the pre-monsoon, thereby implying that on an annual average, the net transport of SPM is directed upstream leading to sediment deposition in the lagoon. However, to predict the annual average sediment transport with accuracy, historical data on tides, current and SPM are necessary.

To have a better understanding of the circulation and mixing process in the lagoon, the exchange ratio was estimated. It was found that the eastern branch of the lagoon was more vigorous in the exchange process than was the western branch. Due to its geometrical shape, 80% of the flood water finds its way to the eastern branch, while the remaining 20% enters its western branch. As such, the flushing characteristics of the lagoon differ at its eastern and western branches, the western branch having more flushing time than the eastern one. The salt budget was higher at the eastern branch than that at the western branch. It is concluded that more tidal action is experienced in the eastern branch. The classification of the Muthupet Lagoon on the basis of hydrodynamics indicates that the lagoon is well mixed during the pre-monsoon and partially stratified during the post-monsoon and monsoon seasons. Freshwater flow has been one of the major factors for the seasonal variability in the behaviour of the lagoon. A pronounced seasonal variability in the salinity and SPM concentration is evident. The lack of freshwater during the pre-monsoon leads to hypersaline conditions, with salinity levels higher than that of sea water. The variability in the geographical location of the peak salinity anddevelopment of a salt plug at a distance of 5 km from the mouth during the pre-monsoon is an interesting feature of the Muthupet Lagoon. A pronounced seasonal cycle in the transport of salt and SPM was observed in the lagoon. Fluvial advection is identified as the major cause for the transport of salt and SPM. Seasonal reversals in the direction of transport are another feature observed during the study. The total transport of SPM during the pre-monsoon season was three and even five times greater than that during the post-monsoon in the spring and neap tides, respectively. The estimation of the transport of SPM shows that the quantum of SPM transported upstream from the station near the mouth do not reach the upstream station, but they settle down on its path. This is attributed to be one of the reasons for the reduction in the water depth of the lagoon. In spite of the fact that Muthupet lagoon is shallow, the freshwater creates a vertical salinity gradient, and this causes a reduction in the settling velocity of SPM. This indicates that during the pre-monsoon, when there are well-mixed conditions in the lagoon, the salinity gradient is negligible, resulting in the settling of SPM.

8.6 Flushing Time

The flushing time will give an insight into the time required for a pollutant to get flushed out of the estuary or lagoon and hence the results are helpful to understand the dispersion of pollutants. The flushing time was estimated using the fraction-of-freshwater method, and the observations are mentioned below:

- Time required to flush the water particle from the eastern side of the lagoon at station S6 was 10 hours 31 minutes.
- The flushing time required from the western side at station S5 was 5 days 2 hours 46 minutes during January 2012.
- The flushing time on the western side was much higher than that on the eastern side due to two reasons: (i) the freshwater flow from the western side is comparatively low; (ii) tidal flow in the western direction is lesser compared to the eastern side, as it was observed that the exchange of freshwater and saltwater is less on the western side.

The exchange ratio was higher in the downstream reaches (S11) than the upstream stations of the lagoon. This is because the exchange of freshwater and saltwater is more vigorous near the mouth. Moreover, the exchange ratio towards the eastern side (stations S9 and S10) was comparatively higher than the western side (stations S5 and S12) of the lagoon, even though the distance of station S9 (5.2 km) from the mouth is more than that of station S12 (3.2 km). This may be due to the fact that more tidal action takes place on the eastern side than on the western side.

8.7 Estimation of freshwater flows to the wetlands

The monthly inflows into the lagoon during the last decade and prior to 2010 are shown in figures 8.4 and 8.5 and in Table 8.1. There is an increase in flows during the months of October, November and December, and the flow decreases during the month of January.

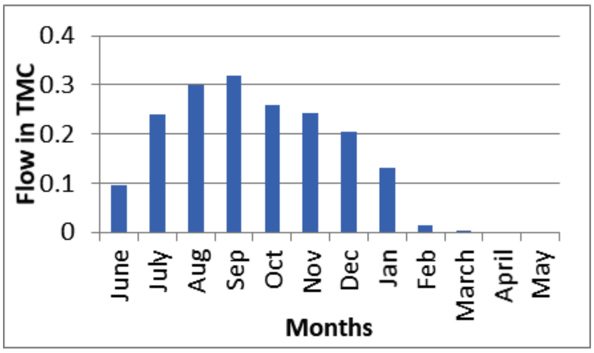


Figure 8.4 *Flow at the tail-end regulators during 2011 -2020*

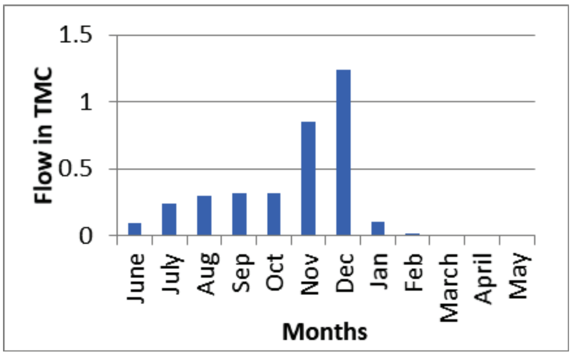


Figure 8.5 *Flow in the tail-end regulators during 1990 - 2010*

Table 8.1 *Freshwater inflow into the Muthupet lagoon*

Month	Inflow into the lagoon during 2011–2020 (TMC)	Inflow into the lagoon during 1990–2010 (TMC)
June	0.095	0.095
July	0.24	0.24
Aug	0.3	0.3
Sep	0.319	0.319
Oct	0.315	0.259
Nov	0.849	0.243
Dec	1.238	0.203
Jan	0.102	0.131
Feb	0.015	0.015
March	0.004	0.004
April	0	0
May	0	0

As part of the consultancy assignment, salinity data at different cross-sections of Muthupet Lagoon were measured at three depths to gain a proper understanding of the exchange processes within the lagoon. As part of an earlier project, the salinity collections were made at different cross-sections. The samples collected belong to December, January and March of 2012 as well as February and September of 2020. The samples collected from the field at three depths from different cross-sections for high and low tides were averaged and plotted for different seasons of the year by dividing the lagoon into two major parts, namely the downstream reach of Koraiyar River and the complex lagoon with other rivers joining at the downstream, forming a Y-shape at the mouth. Figures 8.6 and 8.7 show the longitudinal distribution of salinity along the downstream reaches of the Koraiyar and the Y-shaped portion of the lagoon joining the mouth from Koraiyar. A detailed study on the mangroves in this reach, based on satellite data, Google Maps and field verification, brought to light the fact that most of the mangroves that are healthy, with thick growth, are located on either side on the downstream reach of Koraiyar and the downstream fringes where it joins the Y-shaped complex lagoon. Therefore, in computing the freshwater required for the healthy growth of mangroves, an 8 km length on the downstream reaches of the Koraiyar, up to its mouth of the lagoon, was mainly considered.

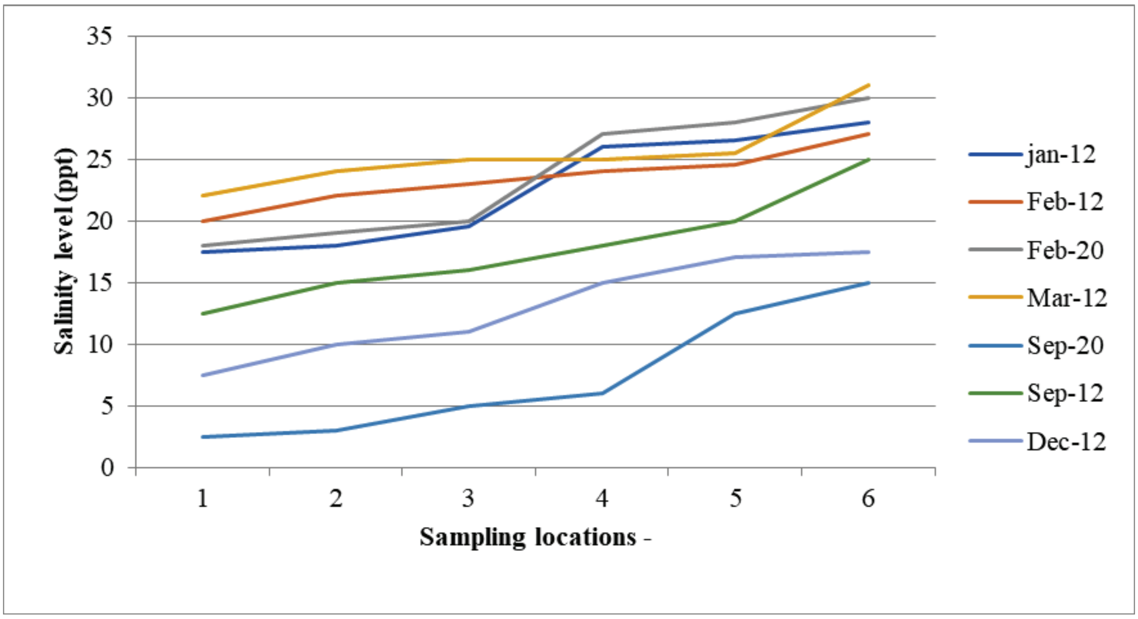


Figure 8.6 *Longitudinal distribution of salinity in the downstream reaches of the Koraiyar river*

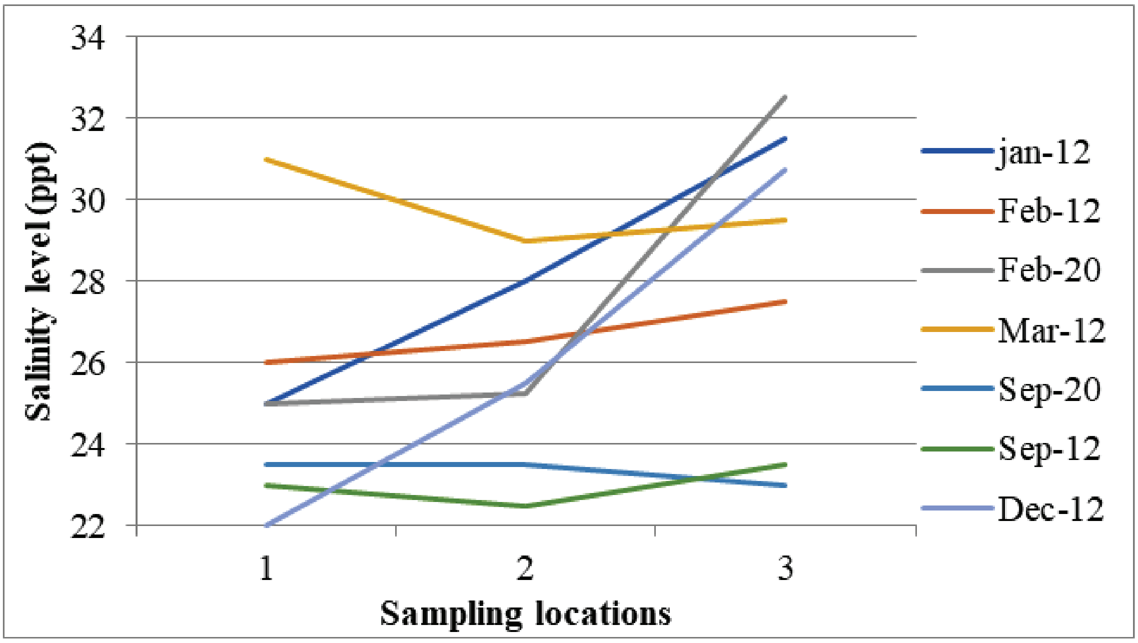


Figure 8.7 *Longitudinal distribution of salinity along the Y-shaped portion of the lagoon*

A straight-line relationship between the salinity along the length of the lagoon and different flow conditions was obtained and plotted in figure 8.8. It is seen that with a flow of 8.6 m^3/s, the salinity at the lower end of Koraiyar is only 17 ppt; the value for December 2012 may be referred to in figure 8.8, when the flow was close to this value (Priya et al., 2012a, 2012b).

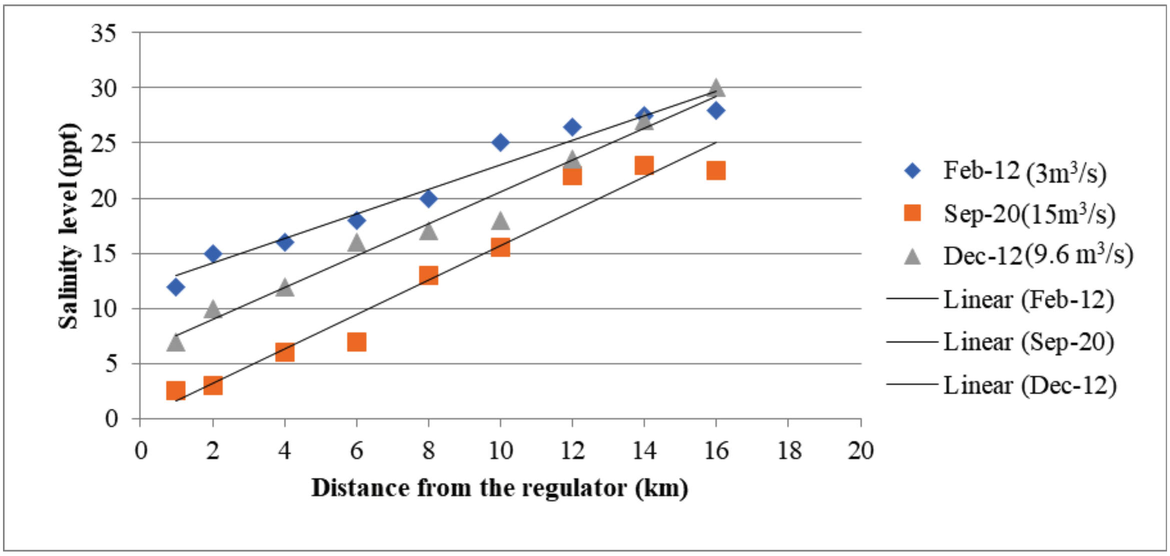


Figure 8.8 *Salinity along the length of the lagoon for different flow conditions*

Selvam et al; (2003) have suggested that a 17 ppt salinity is ideal for mangroves in this area. Therefore, it is recommended that a 10 m^3/s flow be released from the regulators at the tail-end of the Paminiyar and Koraiyar together during the eight months when there is no flow caused by monsoon rainfall. The existing downstream regulators in Koraiyar and Paminiyar may be operated for this purpose only during the low tide period. If required, the allocations from Koraiyar head reach may be regulated to optimally cater to the requirements of irrigation and downstream wetland. The annual quantum of water to be released downstream for the purpose of the wetland will work out to 11.13 TMC. This is a very minor fraction of the total surface water potential of Cauvery, which is 790 TMC as per the Cauvery Water Disputes Tribunal, and of that awarded to Tamil Nadu by the Supreme Court, namely, 404.25 TMC. The flushing time from the regulator to a downstream point (around 10 km) of the Koraiyar River is estimated to be 10 hours for a flow of 10 m^3/s. This is applicable for anything suspended or dissolved in water.

It is also recommended that 10 m^3/s water be released at the tail-end regulators of the Mulliyar, Valavanar and Marakkakoraiyar together to enable a thick growth of mangroves on the fringes of Siruthalaikadu Lagoon and in the mudflats of Thondiakkadu and Panchanadikulam. This will also help in diluting the salinity levels of Siruthalaikadu Lagoon. This figure has been arrived at by a simulation method in which the fraction of freshwater was estimated. However, with more data collected from the field, it would be possible to fine tune the model. The consultancy team had only limited data at their disposal for the study reported.

8.8 Summary

Freshwater flow is the major factor influencing salinity intrusion, formation of a salt plug, movement of ETM and the transport of salt and SPM.

- The freshwater flow influences the settling velocity of SPM – the higher the freshwater flow, the greater is the salinity gradient and the less the settling velocity.
- A minimum environmental flow has to be maintained in the river that flows into the lagoon for sustaining the ecosystem values of the Muthupet lagoon
- It is estimated that a minimum flow of 10m3/s be maintained from Koraiyar and Paminiyar combined all through the year to maintain the salinity level in the downstream reaches of the lagoon and for the healthy growth of mangroves and to cater to the ecosystem services.
- Another flow of 10 m3/s may be maintained in the Mulliyar, Valavanar and Manakundan together to sustain the health of the mudflats and Siruthalaikadu inlet.

9. IMPACT OF SHORELINE CHANGE AND SEA LEVEL RISE

9.1 Introduction

The shoreline is the dynamic interface of the terrestrial and marine environments. It is constantly affected by natural coastal processes including waves, tides, littoral drift and cyclonic storms as well as coastal development activities. The shoreline is defined as the fringe of land at the edge of a large sea water body.

The shoreline is one of the rapidly changing landforms in the coastal areas. They are the key elements dealt within the coastal GIS and which provides most of the information on coastal landform dynamics. Therefore, accurate detection and frequent monitoring of shorelines are very essential to understand the coastal processes and dynamics of various coastal features. Long-term monitoring of shoreline by traditional methods is time consuming, requires manpower, and is not perhaps economical. In contrast, the synoptic coverage provided by the satellites offers great advantage in shoreline monitoring (Adams et al., 2016).

In the coming decades, an accelerated sea level rise will increase the need for shoreline protection. The sea level rise and coastal protection works may impact the geomorphology, hydrology and ecology of the coastal wetlands (Addo et al., 2008, Mujabar and Chandrasekar, 2013, Selamat, 2017, Shenbagaraj et al., 2018, Syed et al., 2018). The sea level rise is expected to increase the inundation risk to low-lying areas (Barth and Titus, 1984). Moreover, due to rising water temperatures, storm intensities are expected to increase concurrent with the rapid sea level rise, exacerbating the coastal risk, especially in low-lying coastal areas (IPCC, 2007).

9.2 Relevance of Investigation

The present investigation is relevant from the following points of view:

(i) To identify the areas vulnerable to erosion on the eastern and southern side of wetland complex;

(ii) To understand the stability of the mouth of Muthupet lagoon;

(iii) To assess the morphometric stability of the coastline adjacent to the wetlands;

(iv) To ascertain the areas prone to erosion on the coastal stretch of sand dunes;

(v) To estimate the areas of wetlands prone to submergence due to sea level rise.

The changes to the shoreline adjacent to the Ramsar site have been ascertained. The vulnerability of the shoreline has been studied by developing vulnerability indices.

9.3 Database

The data sources used in the present study are listed in Table 9.1.

Table 9.1 Sources of data

Year	Date	Satelite Image/Topsheet
1970		Survey of India Toposheet
1990	25 August	LANDSAT 5
2000	15 December	LANDSAT 5
2005		Survey of India Toposheet
Before tsunami – 2004	24 August	LANDSAT 5
After tsunami – 2005	3 March	LANDSAT 5
2010	16 October	LANDSAT 8
Before Gaja Cyclone – 2018	7 July	SENTINEL 2
After Gaja Cyclone – 2019	15 March	SENTINEL 2
2020	15 February	SENTINEL 2

9.4 Methodology

9.4.1 Shoreline Change

The methodology adopted to study the shoreline changes is shown in figure 9.1.

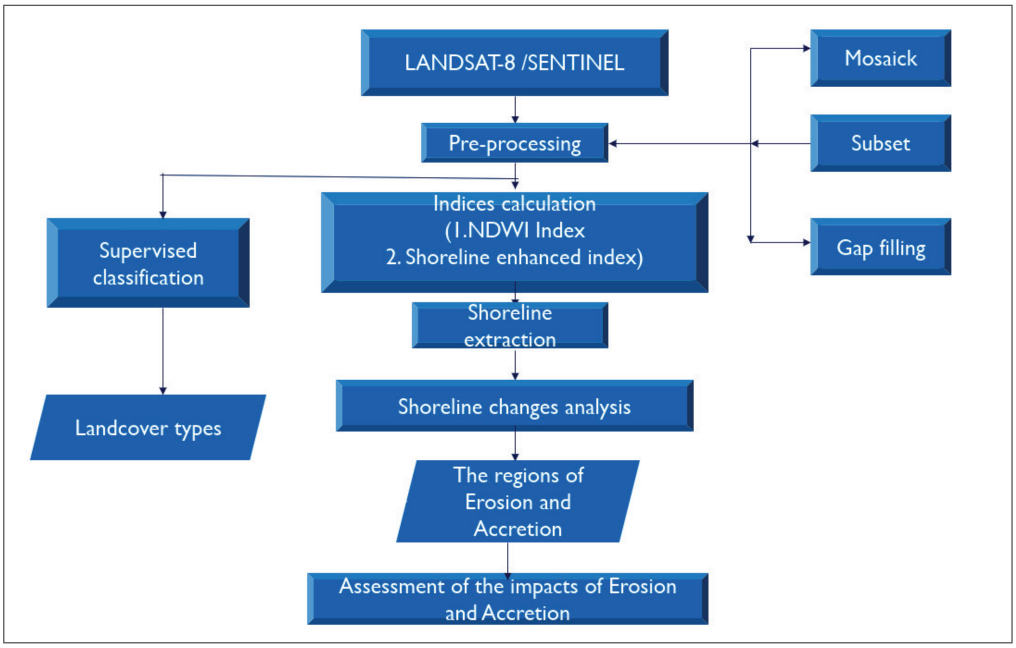


Figure 9.1 *Methodology followed to study shoreline change*

The Normalised Difference Water Index (NDWI) was made use of for satellite imagery and supervised image classification of toposheets. The image was then converted to polygons and the shoreline was extracted from the polygon. Then the shorelines were compared to understand the variations due to erosion and accretion. The vulnerability points were extracted to find out the places where erosion/accretion is continuously occurring.

Coastal Vulnerability Index is a strong management tool to highlight potential coastal hotspots to a given set of climatic hazards (Gornitz 1991, Wigley and Raper, 1992, Webster et al., 2005). This permits the identification of coastal hotspots to be analysed for climatic hazards at regional scale, which is a crucial step in long-term and large-scale coastal planning and help in defining coastal protection and adaptation strategies.

Considering the importance of the zone, an initial attempt has been made to understand the vulnerability level along the Nagapattinam and Point Calimere Coast using tools such as remote sensing and GIS. The erosion and accretion experienced at different stretches of the study area have been measured and analysed. The Coastal Vulnerability Index (CVI) has been derived to know the relative vulnerability of the study area and to characterise the vulnerability of the coast due to the coastal processes and human activities as highlighted in figure 9.2.

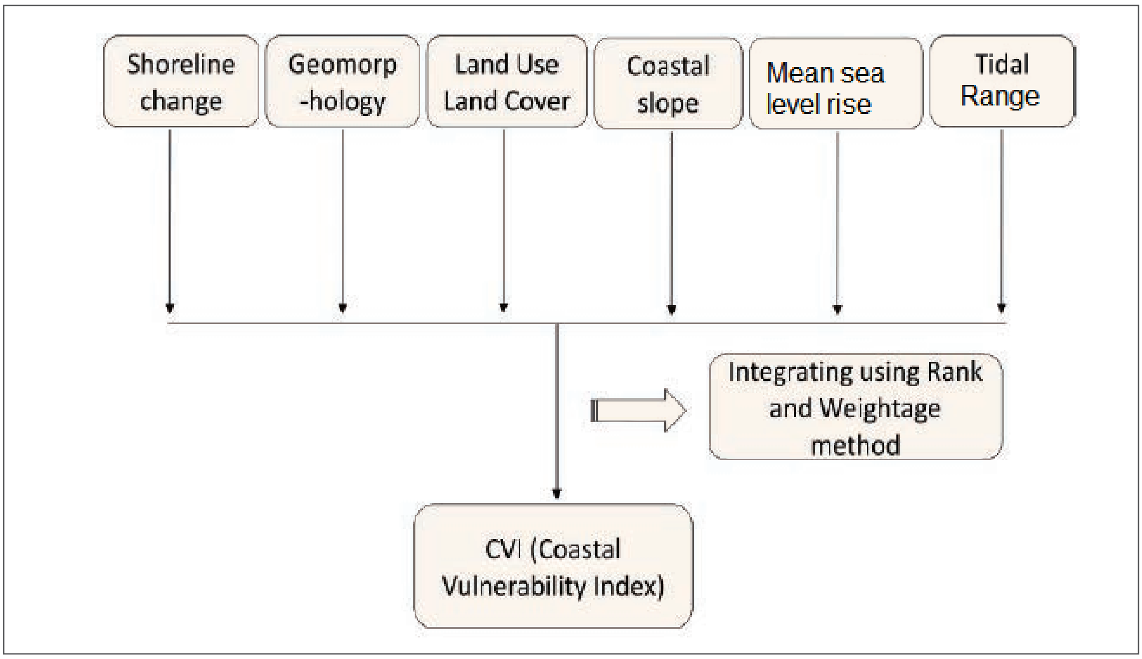


Fig.9.2 *Methodology for deriving CVI*

The CVI was computed on the basis of six parameters related to vulnerability, namely, shoreline change rate, LULC, coastal slope, relative sea level change, mean wave height and mean tidal range.
E. R. Thieler and E. S. Hammar-Klose, "National assessment of coastal vulnerability to sea level rise," U.S. Atlantic Coast. U.S. Geological Survey Open-File Report 99-593, 1999.

The process is mathematically described as

$$CVI = [a\times b\times c\times d\times e\times f/ 6]$$

where a = geomorphology, b = rate of accretion (m/yr), c = rate of erosion (m/yr), d = relative sea level rise (m/yr), e = land use, f = mean tidal range (m).

These variables can be divided into two groups: i) geologic variables and ii) physical process variables. The geologic variables are geomorphology, rate of shoreline change, and land use. These variables account for the relative resistance of a shoreline to erosion, long-term erosion/accretion trend, and its susceptibility to flooding, respectively. The physical process variables are tidal range and sea level rise, which contribute to the inundation hazards of a particular section of a coastline over a timescale from hours to centuries. A relatively simple vulnerability ranking system allows the six variables to be incorporated into an equation that produces the CVI.

9.4.2 Inundation Risk Analysis

The Intergovernmental Panel on Climate Change (IPCC) reported that sea level rise as a consequence of global warming is one of the most serious problems to be faced by the coastal communities (IPCC, 2007).

In this respect, risk assessment of coastal inundation under different scenarios of sea level rise that may result from global warming, cyclone, storm surge or tsunami becomes essential (Church and White, 2006; Unnikrisnan et al., 2006, Murthy et al., 2006). Quantifying the risk associated with such a scenario is important for various purposes such as its impact on the coastal population, land use, and economy and ecology. Such a risk analysis calls for details on the areas of submergence under different sea level rise scenarios using Geographical Information System (GIS). In inundation modelling, the current sea level is considered to be normal and a maximum value of sea level rise is chosen on the basis of the expected sea level rise due to various reasons such as global warming, storm surges, tsunami, etc. In this study, the spatial distribution of coastal inundation and flood hazards in Point Calimere Wetland Complex was determined using land use and land cover (LULC) change maps derived from satellite imagery and a digital elevation model (DEM) of SRTM DEM. By integrating these two data sets, a coastal inundation map for the study area was prepared.

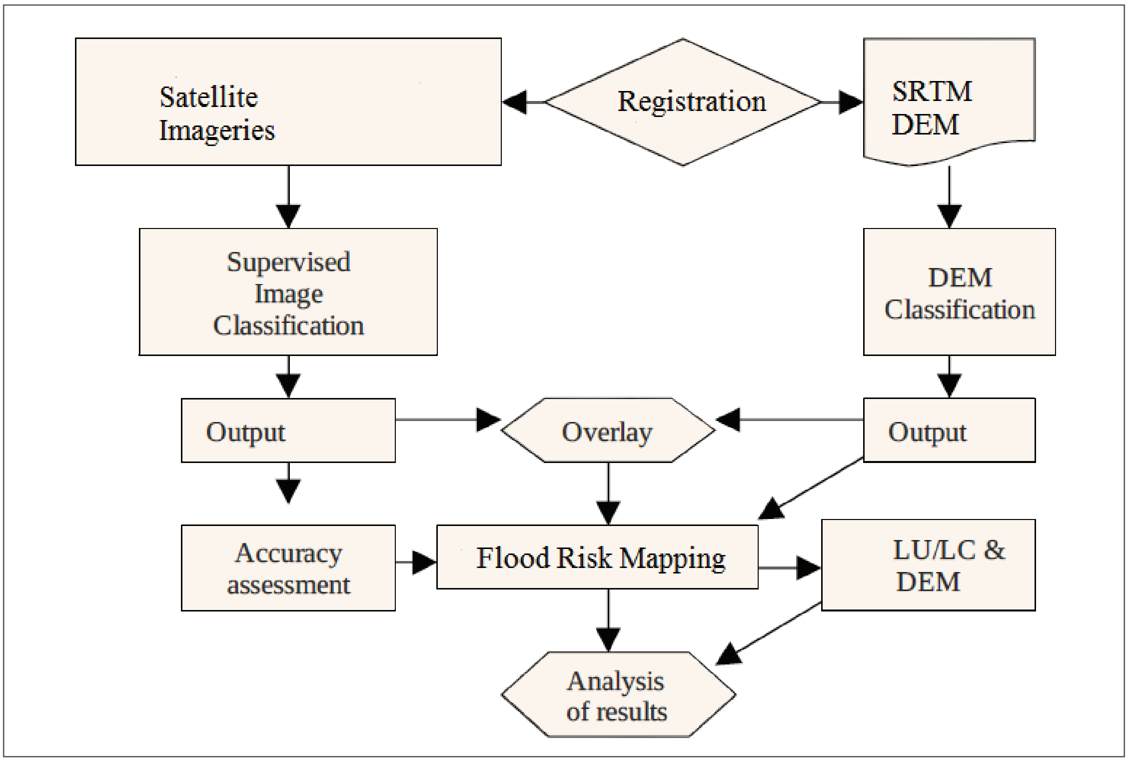


Fig.9.3 *Methodology followed for inundation mapping*

Inundation maps were prepared using the Spatial Analyst module of ArcGIS software for three runup values, i.e., from 0.5 to 1 m, with an interval of 0.5 m, as shown in fiure 9.3. The digital elevation model [DEM] of the study area with a reference baseline of the current mean sea level was utilised for this purpose. This DEM was prepared using STRM Global DEM data, which are available with a 30 m resolution.

9.5 Results and Discussion

9.5.1 Accretion and Erosion in the Study Area

The area of the beach under erosion was more than that under accretion throughout the study period. Erosion and accretion along this stretch have resulted from both natural causes and human interventions. Most of the shoreline was exposed to natural shoreline processes such as waves, tides and periodic storm surges apart from even coastal tectonic activities. The shoreline changes during the period 1970-2020 are given in figure 9.4. The quantum of erosion and accretion at different stretches are shown in Table 9.2. The estimated shift of the shoreline and long-term accretion and erosion are given in Tables 9.3 and 9.4.

During most of the periods, it is observed that erosion is experienced along the coastal areas of Nagapattinam and Karaikkal. Littoral drift has a major role in the processes associated with shoreline changes in this coastal stretch as in the case of many other coastal stretches on the East Coast of India. During the period 1970-2020, the net rate of erosion and accretion are 2.805 m/year and 1.884 m/year, respectively. The Thirumullaivasal-Nagapattinam-Vedaranyam Coastal Stretch had undergone erosion with a maximum of -340.06 m at Nagore and a minimum of -23.95 m at Vellapallam. The long-term rate of erosion of this stretch was 0.47 m/year at Vizhunthamavadi. It is noted that the erosion tendency is comparatively low at the nose of Point Calimere facing the south and at limited stretches on the eastern side of the shoreline.

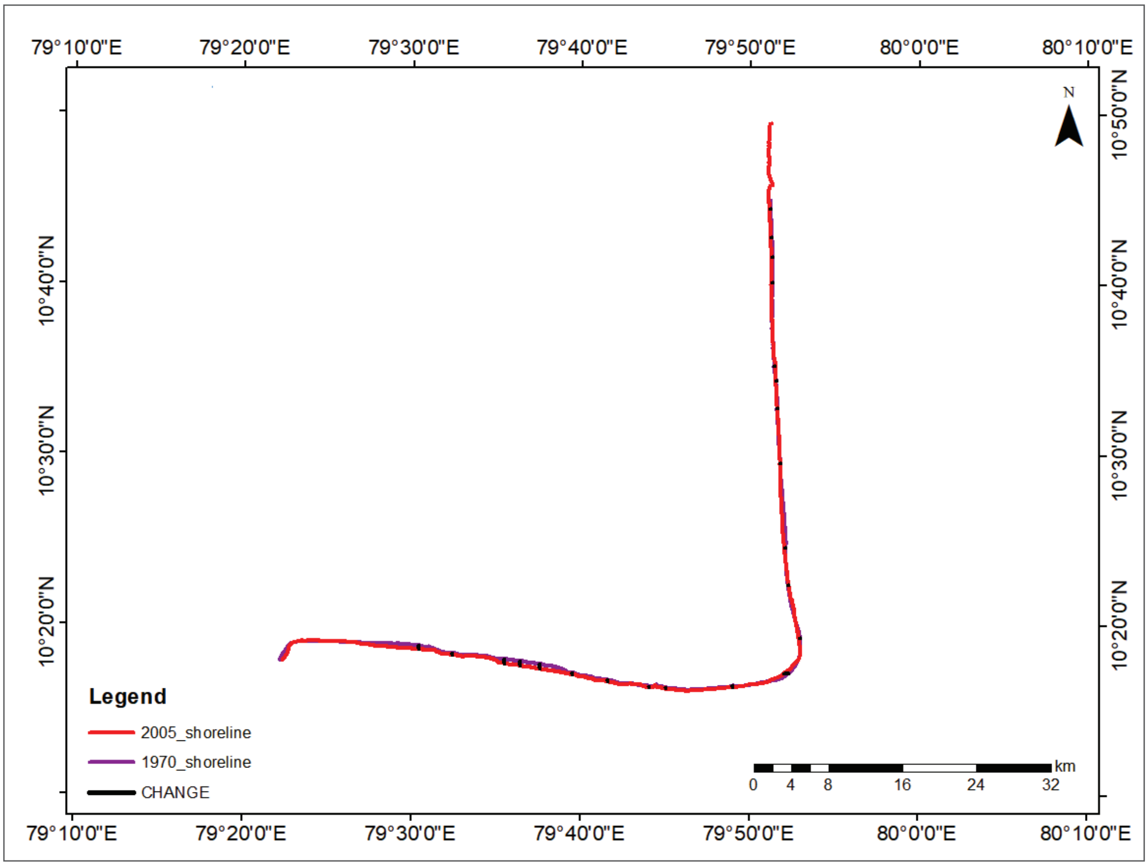


Figure 9.4 Shoreline changes, 1970–2020

__Table 9.2__ Erosion/accretion stretch from 1970 to 2020

From		To		Length (km)	Area (km²)	Erosion (E)/ Accretion (A)
Lat. (N)	Long. (E)	Lat. (N)	Long. (E)			
10.73	79.85	10.68	79.86	7.3	1.02	E
10.73	79.85	10.67	79.86	6.46	1.43	
10.58	79.86	10.57	79.86	0.76	0.03	
10.36	79.88	10.35	79.98	1.03	0.09	A
10.34	79.88	10.31	79.88	2.44	0.26	E
10.29	79.88	10.28	79.86	3.05	0.8	
10.28	79.83	10.27	79.83	0.68	0.05	
10.28	79.79	10.27	79.74	5.75	0.61	A
10.28	79.73	10.28	79.74	0.58	0.06	
10.29	79.59	10.28	79.7	13.8	4.47	
10.31	79.46	10.31	79.52	5.24	2.15	
10.29	79.37	10.32	79.38	2.09	0.56	
10.58	79.86	10.57	79.86	0.72	0.03	E
10.28	79.82	10.28	79.82	0.5	0.05	A
10.27	79.8	10.27	79.81	0.6	0.06	
10.3	79.56	10.3	79.58	2.15	0.26	
10.31	79.52	10.31	79.53	1.73	0.4	
10.31	79.55	10.3	79.54	1.29	0.25	

__Table 9.3__ Estimated shift in the shoreline

Name of the place	Shift in the Shoreline (m)					
	1970 - 1990	1990 - 2000	2000 – 2010	2010 - 2020	After Tsunami	After Cyclone
Neithal Nagar	-126.3	+20.7	+21.3	+53.6	+9.03	-9.8
Nagapattinam	-136.2	-46.3	+28.4	+27.2	-4.4	+7.8
North Poigainallur	-109.4	-25.3	+1.84	+66.3	-7.8	-1.7
Velankanni	-102.7	-23.5	+33.8	+44.92	-3.2	+18.31
Vettaikaraniruppu	-68.3	+6.5	+40.7	+35.4	35.8	+19.6
Kallimedu	-18.48	-39.3	+39.3	+38.0	+13.7	+17.1
Pushpavanam	-63.2	-25.7	+38.6	+36.3	+27.4	+56.5
Thethakudi south	-175.2	+6.7	+7.4	+24.93	-14.68	-10.6

Name of the place	Shift in the Shoreline (m)					
	1970 - 1990	1990 - 2000	2000 – 2010	2010 - 2020	After Tsunami	After Cyclone
Vedaranyam	+11.2	+22.6	+76.3	+35.4	-54.4	-14.9
Point Calimere	+12.4	-138.3	-21.2	-65.8	-39.8	-136.6
Kodikkarai	-64.0	-16.9	+4.7	+6.2	-11.8	+9.0
Lagoon Mouth	-109.1	-80.2	-55.4	-123.4	-36.5	-30.3
Estuary mouth	+363.0	-19.5	-23.78	+14.3	-27.0	-16.6
Maravakkadu RF	-120.7	-22.9	-18.1	+12.09	-49.8	-8.3

***Table 9.4** Long-term accretion/erosion*

Sl. No.	Location	Reference latitude (N)	Rate of shoreline accretion (A)/erosion (E) (m/year)		
			1970 -1990	1970 - 2000	1970 - 2020
1	Nagapatiinam	10° 45′ 56.02″	-3.823 0	-3.849 0	-3.882 0
2	Vadakkupogainallur	10° 43′ 35.16″	-3.771 0	-3.655 0	-3.798 0
3	Therkupogainallur	10° 42′ 15.08″	-3.802 0	-3.915 0	-3.872 0
4	Velankanni	10° 40′ 55.09″	-3.95 0	-3.90 0	-4.30 0
5	Prathabaramapuram	10° 39′ 43.34″	-1.66 1.24	-1.68 1.04	-1.58 1.24
6	Thirupoondi	10° 37′ 36.36″	0 1.93	0 1.98	0 1.93
7	Vizhunthamavadi	10° 34′ 43.86″	-0.45 1.27	-0.49 1.25	-0.46 1.40
8	Vettaikaraniruppu	10° 34′ 23.74″	-0.73 2.68	-0.79 2.53	-0.85 1.98
9	Vellapallam	10° 30′ 54.80″	-0.45 1.67	-0.86 1.79	-0.16 1.34
10	Naluvedapatti	10° 29′ 35.55″	-1.03 0.7	-1.08 0.91	-0.81 0.67
11	Pushpavanam	10° 27′ 45.41″	-3.25 0	-3.30 0	-3.31 0
12	Periyakuthagai	10° 25′ 37.38″	-3.43 0	-3.05 0	-3.35 0
13	Vedaranyam	10° 21′ 52.14″	0 5.1	0 5.20	0 5.14
14	Vedaraniyapuram	10° 22′ 27.10″	-1.37 4.660	-0.73 4.66	0 4.18
15	Kodiakkarai	10° 17′ 04.21″	-3.88 2.53	-4.75 2.34	-4.03 2.15
16	Muthupet	10° 23′ 44.48″	0 13.41	0 13.64	0 13.59

9.5.2 Pre- and Post-Tsunami and Gaja cyclone

The impacts due to the Tsunami of 2004 and Gaja Cyclone of 2018 were studied by investigating the status of the shoreline before and after these events. The results are given in Tables 9.5 and 9.6, respectively.

Table 9.5 *Erosion/accretion: Pre- and post-tsunami*

From		To		Location	Length (km)	Area (km²)	Erosion (E)/ Accretion (A)
Lat. (N)	Long. (E)	Lat. (N)	Long. (E)				
10.77	79.85	10.76	79.85	Nagapttinam	0.27	0.01	A
10.58	79.86	10.58	79.86	Vettaikaraniruppu	0.59	0.17	
10.47	79.86	10.47	79.86	Naluvethapathi	0.28	0.02	
10.29	79.88	10.29	79.87	Point Calimere	1.1	0.09	E
10.31	79.88	10.29	79.88	Point Calimere	0.81	0.09	A
10.27	79.82	10.27	79.81	Kodikkarai	0.41	0.03	
10.28	79.74	10.28	79.74	Lagoon mouth	0.67	0.07	E
10.28	79.69	10.28	79.69	Lagoon mouth (left)	0.58	0.05	A
10.29	79.56	10.3	79.57	Estuary mouth (right)	1.04	0.06	E
10.31	79.52	10.31	79.51	Estuary mouth	1.28	0.12	

Table 9.6 *Erosion/accretion: pre- and post - Gaja Cyclone*

From		To		Location	Length (km)	Area (km²)	Erosion (E)/ Accretion (A)
Lat. (N)	Long. (E)	Lat. (N)	Long. (E)				
10.77°	79.85°	10.76°	79.85°	Nagapttinam	0.27	0.02	E
10.58°	79.86°	10.58°	79.86°	Vettaikaraniruppu	0.6	0.18	A
10.47°	79.86°	10.47°	79.86°	Naluvethapathi	0.2	0.02	
10.29°	79.88°	10.29°	79.87°	Point Calimere	1.13	0.1	E
10.31°	79.88°	10.29°	79.88°	Point Calimere	0.8	0.09	A
10.27°	79.82°	10.27°	79.82°	Kodikkarai	0.29	0.03	
10.28°	79.74°	10.28°	79.74°	Lagoon mouth	0.65	0.07	E
10.28°	79.69°	10.28°	79.69°	Lagoon mouth (left)	0.58	0.05	A
10.3°	79.56°	10.29°	79.57°	Estuary mouth (right)	1.02	0.06	E
10.31°	79.51°	10.31°	79.52°	Estuary mouth	1.27	0.12	

9.5.3 Total Shift in Shoreline

It is seen that the net shoreline movement is seaward, i.e., the coast is progressive, with an average rate of 5 m/year. A maximum shoreline displacement of 1.3 km towards the sea is observed near Point Calimere. The adjacent sides of Vedaranyapurams and dune, Velankanni - Nagapattinam, and a small portion near the lagoon have experienced erosion; the rest of the study area experienced accretion.

The present geomorphology of the coastline is found to be more or less stable. However, changes may be triggered by a natural disaster such as a major tsunami or cyclone. Anthropogenic activities either in this stretch or on the north or south of the stretch may also cause adverse impacts on the stretch under consideration. As such, there is no immediate threat to the wetland ecosystems at this Ramsar Site due to the shoreline changes. However, some stretches of mudflats are vulnerable.

9.5.4 Geomorphology of Point Calimere

There is an overall accretion trend at the nose of Point Calimere as shown in Table 9.7, mainly due to the alignment of the shore in this stretch.

Table 9.7 *Shoreline change at the nose of Point Calimere*

	1990–2000		2000–2010		2010–2020		1970–2020	
	Area (km^2)	Length (km)	Area (km^2)	Length (km)	Area (km^2)	Length (km)	Area (km^2)	Length (km)
Erosion	0.04	1.02	0.01	0.29	0.01	0.26	0.03	0.55
Accretion	0.1	1.52	0.22	2.16	0.23	2.33	0.39	2.15

Point Calimere, also known as Kodiakarai, where the coastline takes a turn from the east-west direction to the north-south direction, experiences accretion. Topographic and remote sensing data for the coastline at Point Calimere for the period 1970 to 2020 show accretion tendencies for the coastline along the Palk Strait and Muthupet area. Therefore, the Point Calimere Ramsar site as such does not face an immediate threat due to coastal erosion under normal conditions. However, there are some stretches adjacent to the mudbanks and sand dunes, which have a tendency for erosion. These stretches can be protected by artificial nourishment and regenerative measures.

9.5.5 Sediment Transport Processes

The grain size distribution can serve as an indicator in studies pertaining to changes in coastal geomorphology (Folk and Ward, 1957, McLaren, 1981, Gao and Collins, 1992, Crowell et al., 1993, Lucio et al., 2002, Weber et al., 2003, Usha et al, 2004). The linear regression statistic can help in calculating the long-term rate of shoreline change. A study in Point Calimere inferred that the area is a major sink while Agastiyampalli and Kodiakkarai are identified as major sources for sediment supply (Usha et al., 2013). The formation of Point Calimere projection can be attributed to the two constantly opposing wave directions such as that from the north-east and south-east, with one set of waves predominant over the other. The coastline is consequently affected, predominantly by waves from the north-east. Sediment distribution at Vedaranyam during different seasons show that the sediments move towards the north during the south-west monsoon and vice versa during the north-east monsoon (Natesan, 2004). The net quantum of littoral sediments entering into the Palk Bay from the Nagapattinam Coast is $0.27\times106m^3$ (Sanil Kumar et al., 2002).

There is a maximum shoreline displacement of 1.3 km towards the sea near Point Calimere. The overall accretion and erosion before and after the tsunami are computed as 0.27 km^2 and 1.73 km^2, respectively. The net shoreline movement in this stretch is seaward, i.e., the coast is progressive with an average rate of 5 m/year (Usha et al., 2013).

9.5.6 Coastal Vulnerability Map

The total stretch considered for vulnerability mapping is from Thondi in the south to Karaikkal in the north. figure 9.5 shows the vulnerability range in the study area, which has been categorised into five classes, namely, very low, low, medium, high and very highly vulnerable. It shows that Vedaranyam Coast and Nagapattinam Coast are more vulnerable, when compared to the Point Calimere region. The Muthupet Lagoon zone falls under low vulnerable category, whereas the mouth is classified under moderate vulnerability. It is also observed that Point Calimere zone as such is comparatively safer when compared to the Siruthalaikkadu lagoon. The Palanjur, Maravakkad, Thaamarankottai and Vadakkadu Reserve Forest areas are located in highly vulnerable zone. The coastal region adjacent to the Thalainayar Reserve Forest is located in the moderately vulnerable zone. The status of the coastline stretch with reference to vulnerability is shown in Table 9.8.

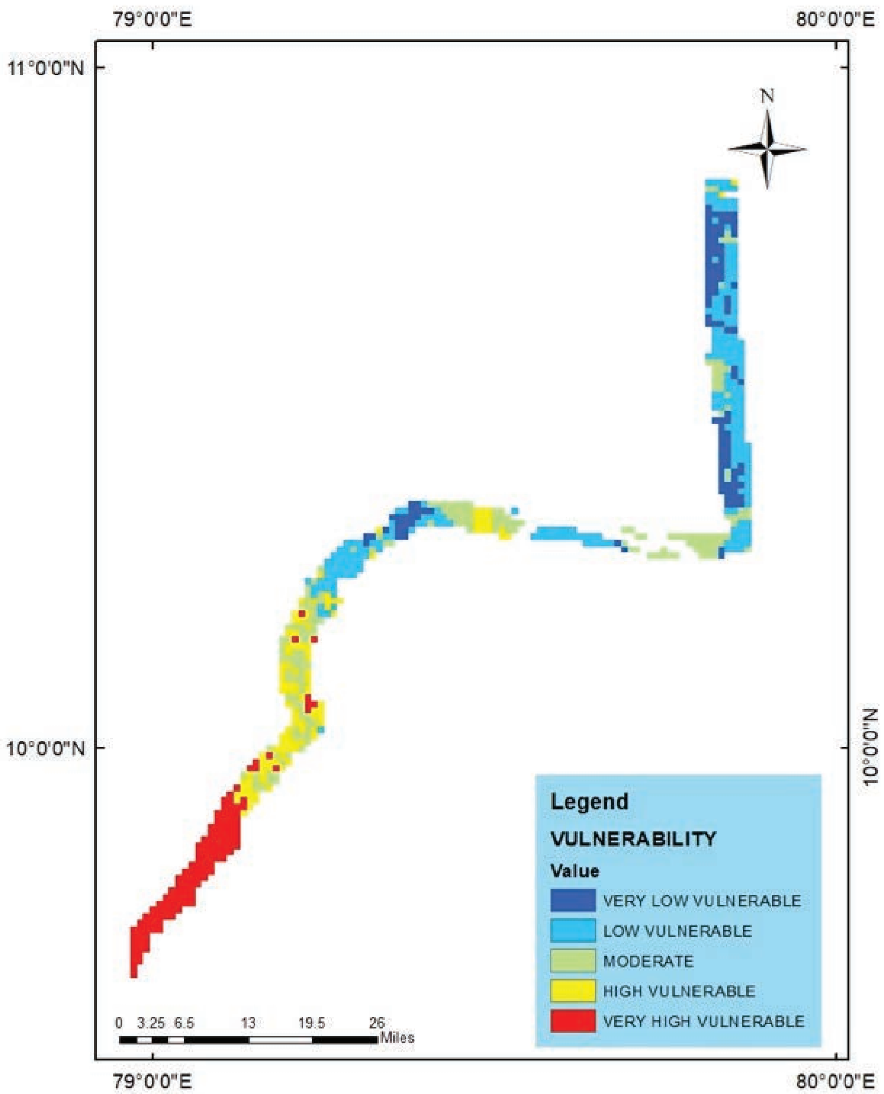


Figure 9.5 *Vulnerability map*

__Table 9.8__ Areal extent of shoreline classified under different vulnerability categories

Vulnerability Category	Length (km)	Percentage
Very Low	23	15.9
Low	17	11.8
Moderate	8	5.5
High	78	54.1
Very High	18	12.5
Total	**144**	**100**

By making use of the vulnerability map, areas requiring special attention are identified as Periyakuthagai, Pushpavanam, Prathabaramapuram, Thirupoondi, Kodiakkadu, mouth of the Seruthalaikadu Lagoon, Maravakkadu Reserve Forests and on both sides of the mouth of the Muthupet Lagoon. With reference to the areas under forests, it is observed that a stretch of length 4 km at Palanjur, Tamarankottai, Maravakkadu and Vadakkadu Reserve Forests is prone to erosion. Along the Thalainayar Reserve Forest, a shoreline stretch of 8.45 km including Kallimedu, Naluvethapathi and Vellapallam is prone to erosion. Moreover with reference to the water bodies, erosion-prone areas are observed along stretches of 1 km on either side of the mouth of the Muthupet lagoon and a stretch of 7.32 km on either side of the mouth of Siruthalaikadu lagoon. Along the coast, over a stretch of 66 km, the erosion length is 8.4 km from Thethakudi South to the saltpans at Point Calimere.

9.5.6.1 Vulnerability Mapping of Wetland Complex

The total length of the wetland complex along the coast is estimated as 60.33 km. From the study, it has been identified that 31.68 km of the coastal stretch is subjected to change. Out of the total stretch, 20.37 km falls under highly vulnerable category, 11.31 km under moderately vulnerable category and the remaining 28.64 km as stable coast. From the analysis, the following inferences are made: the stretch south of Thethakudi is highly vulnerable, whereas Point Calimere as such is categorised as moderately vulnerable; this is due to the land building activity that is taking place during the past two or three decades; and Maravakkadu and Palanjur Reserve Forests, situated on the western side of Muthupet Lagoon, are classified as highly vulnerable.

The results show that on both sides at the mouth of Muthupet Lagoon there are points that are categorised as highly vulnerable; this is because of the fluctuations that are happening near the mouth due to the movement of water and its energy level variations during the high and low tides.

9.5.6.2 Inundation due to sea level rise

Inundation due to a sea level rise has been estimated for two scenarios, namely 0.5 and 1 m above sea level.

__Table 9.9__ Inundated area (km²) in different land use/land cover categories

Land cover category affected	0.5 m	1 m
Cultivated land	1.54	7.42
Aquafarms	0.58	0.88
Estuary and inlet	4.98	6.13
Barren land	2.15	3.32
Scrub forest	0.023	0.045
Mangroves	3.23	4.34
Mudflats and swamp	12.36	16.87
Saltpans	0.30	0.48
Settlement	1.48	2.21
Scrubland	2.02	3.15

The results given in Table 9.9 show that if the sea level rises by 0.5 m, an area equal to 37.19 km² will be submerged. For a 1 m rise, an area of 54.52 km² will be submerged.

From the inundation analysis, with a sea-level rise of 1m the following observations are made:

i. Increase in water spread area of Muthupet Lagoon and associated waterbodies by 3.546 km² on the western side, 2.71 km² on the north and 0.628 km² on the north-east

ii. Increase in water spread area of the Siruthalaikadu lagoon by 3 km² on the western side and 1.28 km² on the north

iii. Submergence of Thalainayar Reserve Forest to an extent of 13.2 km²

iv. Submergence of swampy area in the Karpadikai south to an extent of 2.279 km²

v. Submergence of mudflats on the northeast of Siruthalaikadu Lagoon to an extent of 0.23 km²

vi. Possibility of merging Muthupet Lagoon and Siruthalaikadu Lagoon

9.6 Summary

- The studies making use of remote sensed data, toposheets and ground truthing of the changes to the geomorphology of the coast adjacent to the Point Calimere Ramsar site show that a 21.41 km stretch of the total 60.33 km stretch in the zone shows erosion tendencies. Most of the stretch on the southern side at the bottom of the nose of the Point Calimere facing Palk Strait shows accretion tendencies, except at the mouth of the inlet.
- During the past five decades, the area subject to erosion has been 3.62 km² and subject to accretion being 8.96 km²; the net rate of erosion in the period has been 2.805 m/year.
- The coastline along the Reserve Forests of Palanjur, Thamarankottai, Maravakkadu, Vadakkadu and Thalainayar is vulnerable to erosion; the mouths of Muthupet Estuary and Siruthalaikadu inlet are to be protected, considering the importance of these wetlands.
- Some stretches of sand dunes are prone to erosion as stated in the text; some pockets of sand dunes are also prone to submergence due to sea level rises.

- The Vulnerability Index identified 20.37 km as highly vulnerable, 11.31 km as moderately vulnerable and 28.64 km having low vulnerability in PCWC; the mouth of Muthupet estuary comes under the low vulnerability category and the mouth of Siruthalaikadu inlet comes under the moderate vulnerability category.
- The projected sea level rise of 0.5 m is expected to submerge 2.18 km^2, 3.23 km^2, 2.67 km^2 and 12.36 km^2 of lagoons, mangroves, inlets and mudflats. A sea level rise of 1 m is projected to submerge 6.8 km2, 4.34 km^2, 4.28 km^2 and 16.87 km^2 of lagoons, mangroves, inlets and mudflats.
- There may be a possibility of a new mouth opening from the waterspread area of the Muthupet Estuary on the eastern side; this has to be monitored periodically during the north-east monsoon.
- The sediment transported from the Kodikkarai and Vedaranyam areas causes accretion in the Point Calimere nose region.
- Due to accretion and siltation, the mouth of Adappar and Harichandra rivers are heavily silted up.
- Certain areas have been identified for artificial nourishment and protection by vegetation.

Photo credit: WISA_ Harsh

10. ECOSYSTEMS OF POINT CALIMERE WETLAND COMPLEX: EVOLUTION, CHARACTERISTICS, VEGETATION DYNAMICS AND ECOSYSTEM SERVICES

10.1 Introduction

Wetlands are one of the most productive ecosystems, playing a vital role in establishing a nexus between water, food and energy through interconnections and interdependent hydrological, nutrient and energy cycles and in maintaining the ecological sustainability of the region. On the basis of the Ramsar classification, wetlands are categorised into marine and coastal, inland and man-made wetlands. The coastal wetlands provide multiple ecosystem services through seasonal and relatively permanent coastal plains, coastal beaches, rocky shorelines, estuarine salt marshes, freshwater swamps and marshes, mangrove swamps, mud flats and sand bars.

The Ramsar Convention has defined wetlands as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters”. The state of Tamil Nadu has a total of 1175 wetlands, with a surface area of 1,61,512 hectares, of which only Point Calimere has been declared a Ramsar Site.

In order to conserve and manage the wetland ecosystem services in a wise and efficient manner, it is necessary to formulate management action plans not only for the wetlands per se but also for their drainage basins, which contribute water, sediments, nutrients and even pollutants to the downstream wetlands. Policies and strategies have to be evolved and implemented, for which an appropriate institutional mechanism is essential. Hydrology is identified as the single-most important factor in the formation and sustenance of Point Calimere Wetland Complex and the hydroperiod indicates the energy balance as well as physical, chemical and biological processes in the individual ecosystems, in the entire wetland complex and in the delta as such. In this context, an attempt has been made to understand the evolution, characteristics, vegetation dynamics and ecosystem services of this wetland complex as part of the consultancy project entitled “Hydro-ecological Assessment for Integrated Management of Point Calimere Ramsar Site”. The background information, major observations, inferences and interpretations on the important ecosystems of Point Calimere are presented in this chapter.

10.2 Cauvery Delta Ecosystem and Point Calimere Wetland Complex

The fan-shaped arcuate delta of the Cauvery on the Coromandel coast drains the river to the Bay of Bengal. The delta lies in Nagapattinam, Thiruvarur, and Thanjavur districts and part of Pudukkottai, Cuddalore and Tiruchirappalli districts of Tamil Nadu and Karaikal district of the Union Territory of Pondicherry. The Cauvery delta is bounded by Kollidam river on the north, the Grand Anicut and the Grand Anicut Canal System on the west, Palk Strait on the south and Bay of Bengal on the east. This delta of 7500 km2 is known as the ‘rice bowl’ of Tamil Nadu, forming 11% of the total area of Tamil Nadu. The natural wetlands and sand dunes in the delta are formed as a result of the hydrodynamic processes and sediment transport due to the freshwater flow from the upstream and the coastal processes downstream. Anthropogenic activities mainly related to irrigation also have an impact on the delta.

The Point Calimere Wetland Complex (PCWC) covers an area of 385 km^2, which includes five major ecosystems, namely, Point Calimere Wildlife Sanctuary (22.5017 km^2), Muthupet Mangroves (118.8591 km^2), Panchanathikulam wetland (80.9696 km^2), Un-surveyed salt swamp (150.3019 km^2) and Thalainayar Reserve Forest (12.3677 km^2). The Point Calimere Wetland Complex comprises natural and man-made ecosystems that are inter-connected; the major habitats identified in the complex are the Point Calimere Wildlife and Bird Sanctuary, Muthupet Lagoon, Siruthalaikadu Lagoon, mangroves, mudflats, saltpans, aquaculture farms and the shoreline. This classification is adopted in the present study considering the morphometry, hydrologic and hydrodynamic processes, sediment dynamics, ecological and biodiversity characteristics and ecosystem services of these specific aquatic and terrestrial ecosystems forming part of Point Calimere Wetland Complex .

The sanctuary derives its name from the term ‘Point Calimere’, the spot in the sanctuary where the coast takes a 90 degree turn from the Bay of Bengal towards Palk Strait. In terms of biodiversity, Point Calimere Wildlife Sanctuary is one of the richest ecosystems of the Ramsar Site within which a large patch of Tropical Dry Evergreen Forest (TDEF) exists. The wetland complex has also been listed as one of the important bird habitats of the country by the Bombay Natural History Society. A large number of terrestrial and aquatic birds are found in this habitat. Migratory birds visit the wetland complex every year during December - January, with Greater Flamingos being the main attraction. Muthupet Wetland Complex is one of the largest mangrove wetlands in Tamil Nadu, with an area of 11,900 hectares. It defines the western boundary of the Ramsar Site.

It is claimed that the Point Calimere Wildlife and Bird Sanctuary along with the Great Vedaranyam Swamp, and the mangrove forests of Thalainayar Reserve Forest play an important role in disaster management during the tsunami and cyclones by serving as a bioshield. The wetland ecosystem of Point Calimere provides many services that support the livelihoods of local people, such as fishing, agriculture, aquaculture and salt production. The wetland also serves as an uninterrupted habitat for many birds and animals, breeding ground for fishes while protecting the coastline from soil erosion and other natural disasters.

The general observations, inferences and interpretations of the study are given in the following sections.

10.2.1 General Observations

General observations with regard to the delta zone and Point Calimere Wetland Complex are given in the following section.

- The focus of the government and large number of stakeholders of the water in the delta was only on agriculture since the delta is considered to be the ‘rice bowl’ of Tamil Nadu.
- The delta contains alluvium deposited over a period of several centuries and the entire delta as well as its communication with the sea was the result of hydrodynamic and sediment dynamic processes triggered by the interaction between the natural and regulated river flow and the coastal processes.
- The delta has several natural and man-made criss-cross channels feeding and draining the rice fields; some of these channels have free communication with the sea.
- According to the data from four rain gauge stations, the highest rainfall received in Point Calimere Wetland Complex during the past decade was recorded in 2015 (1552.8 mm) and the lowest in 2016 (573.8 mm); the variation in annual rainfall was conspicuous but spatial variation was minimum from station to station.
- Stream flows and regulated flows are mainly confined to the irrigation periods; the requirements of wetland complex are not considered in the water allocation policy.
- According to the CGWB classification (2017), there are 12 overexploited (100% extraction) and 17 saline Blocks (revenue administration units) in Nagapattinam District, 10 overexploited, 1 critical (90% extraction), 3 semi-critical (65 - 90% extraction), 9 safe (< 65% extraction) and 4 saline Blocks in Thiruvarur district and 31 overexploited, 7 critical, 6 semi-critical and 5 safe Blocks in Thanjavur District.

- The groundwater level in the delta is influenced by both rainfall and regulated flows and shows a declining trend during the pre-monsoon and the south-west monsoon seasons and an increasing trend during the north-east monsoon.
- According to the groundwater level data collected for 40 years (1980-2019), the groundwater level varies from 0.07 m to 7.4 m during the post-monsoon and from 1.02 m to 15.46 during the pre-monsoon seasons.
- The area under coconut plantation on the north of Muthupet Lagoon and mudflats, outside the wetland complex, at Thambikottai and Karpaganatharkulam belt remains undisturbed during the past two decades.
- Groundwater is found in unconfined, semi-confined and confined conditions, and salinity is the major water quality problem. The impact of the agro-chemicals used in the buffer zone on the groundwater quality of both the buffer zone and Point Calimere Wetland Complex needs to be investigated.
- The field observations and water quality analysis conducted for the samples collected during the field visits (February and October 2020) show that there is significant variation in the water quality with respect to only four parameters, namely, sulphates, sodium, chlorides and total hardness, in the areas on the periphery of Vedaranyam sanctuary, saltpan cluster of Chemplast, Muthupet Lagoon and aquaculture farms adjacent to Thalainayar Reserve Forest.
- The groundwater analysis conducted using data from 1980 to 2019 shows that out of 24 stations in the study area, from 19 to 24 stations were affected by TDS, EC, magnesium, potassium and total hardness during the post-monsoon season; in the case of the pre-monsoon, almost all the sampling locations were affected by TDS, EC, magnesium, potassium, sodium and total hardness.
- Thalainayar Reserve Forest is an isolated low-lying patch, which does not have any drainage from upstream. It is located between two rivers, namely, the Adappar and Harichandranadhi, but they do not flow through Thalainayar Reserve Forest. However, an artificial navigation canal has been made for the fishermen to move from Adappar. The Thalainayar Reserve Forest receives saltwater from the Adappar straight-cut and freshwater from the artificial Vedaranyam Main Canal.

10.2.2 Inferences and Interpretations

- The hydrology and water quality decide the agriculture production and livelihood of people in the delta and the health of the Point Calimere Wetland Complex.
- The rainfall trend analysis shows that during the pre-monsoon and north-east monsoon seasons, rainfall exhibited a statistically significant increasing trend, the trend being more in Cauvery Sub-basin compared to the Vennar Sub-basin in the delta.
- The precipitation concentration values suggest strongly irregular rainfall in the delta; variation in rainfall concentration was observed for both the Cauvery and Vennar sub-basins; 69.33% of annual rainfall is received during the north-east monsoon season.
- A decreasing trend is observed for both the consecutive dry days and consecutive wet days; the seasonality index showed that most rain is obtained in three months or less.
- Global phenomena such as the El Nino-Southern Oscillation have a positive impact on the rainfall in the delta.
- The streamflow analysis conducted using IHA indicates a decrease in monthly flows to the delta except in the months of August and September when compared with the period before the final award of the Cauvery Water Disputes Tribunal; however, the distribution of temporal flows has improved.
- On the basis of the water quality index, the majority of the areas in the Vennar Sub-basin come under the categories “very poor water” and “water unsuitable for drinking purpose” in all the seasons, while most of the areas in the Cauvery Sub-basin come under the categories “good water” and “poor water”.
- The comparison of the electrical conductivity and groundwater level shows that there is an increase in the EC value with a fall in the groundwater level.

- The bivariate plot of Na over Cl suggests a promising freshening mechanism in the Cauvery Sub-basin while salinity intrusion plays a major role in the Vennar Sub-basin; similar trends are observed from a study using environmental isotopes.
- The conservation of the wetlands at the tail-end of the Cauvery Delta calls for a water management policy and regulation for the entire delta system in particular and the basin in general, apart from maintaining the water quality status of the entire basin so as not to degenerate the wetlands, the degradation of which would adversely affect the biodiversity of this Ramsar site.
- The field data collected as part of the consultancy assignment show that the reduction of the four water quality parameters (total hardness, sodium, chloride and sulphate) is due to the dilution effect of the monsoon rain and exchange processes of fresh and saline water.
- In the Cauvery delta, large amounts of chemical fertilisers are being used annually during the past 15 years, ranging from 31,107 to 54,306 metric tons (Govindaraj et al., 2010). The percentages of nitrogenous, phosphatic; and potassic fertilisers were 52.84% (N), 22.47% (P) and 24.69% (K) (Department of Environment, 2001). The sampling stations in the delta recorded higher levels of TDS and phosphate, the phosphate concentration is attributed to runoff from agricultural fields and from other non-point sources (Girija et al., 2007). When the regulators are open, this water from the agricultural fields straightaway drain into the Muthupet Estuary. When there is flooding, it spreads over the entire wetland belt. On the basis of these past studies, the investigators attributed the pollution in the estuary to agro-chemicals applied in the rice fields. A high phosphate value has been reported from Muthupet (Srilatha et al., 2013). However, samples from the estuary were not tested by the investigators to understand the effect of agro-chemical pollution. It is recommended that samples from Muthupet Estuary and other wetland areas be collected and tested to understand the magnitude of the problem.

10.3 Estuaries, Lagoons, Mudflats and Mangrove Ecosystems

The estuaries, inlets, mudflats and mangroves of this wetland complex are considered together in this section, mainly because most of these ecosystems are inclusive or are close to or even connected to each other and the sources of water-fresh and saline, sediments and nutrients are often the same, and all the more they share several of the ecosystem services. However, each of these ecosystems differs in its formation, evolution, geomorphology, exchange processes of freshwater and saline water, sediment dynamics and floral and faunal characteristics. Therefore, inferences and interpretations of these unique ecosystems are presented separately to help in evolving the management action plans for each of these specific ecosystems. The characteristics of each of these ecosystems, distinguishing it from others, have also been highlighted under each of the ecosystems. The Thalainayar Reserve Forest, with mangroves, is the only major ecosystem slightly away from the main Point Calimere Wetland Complex.

Tamil Nadu has the second longest coastline in the country (1076 km length). However, the continental shelf in most of the stretches has only a width varying between 4.0 and 6.0 km, except in the Vedaranyam-Muthupet stretch of Thiruvarur-Thanjavur districts, wherein it is wider and where extensive mudflats are also present. The major mangrove wetlands in Tamil Nadu are at Muthupet and Pichavaram, both of which receive their freshwater supply from the Cauvery drainage basin. The Muthupet Lagoon and mangrove wetland ecosystems receive freshwater mainly from a few small tributaries, distributaries or drains of the Cauvery system, namely, Nasuvanniyar, Pattuvanachiyar, Paminiyar, Koraiyar, Kilaithangiyar, Marakkakoraiyar and Valavanar.

Till around 1924, the Muthupet and Pichavaram areas received practically unregulated freshwater flow from the Cauvery for nearly six months from July to December (from the onset of south-west monsoon to the end of north-east monsoon) and even low flows in the post-monsoon season. Thereafter, a number of dams and regulators were constructed both on the main Cauvery River as also in its tributaries. With the increase in cultivated command areas upstream, large quantity of freshwater was diverted for irrigation, depriving the freshwater availability downstream. This in turn resulted in the gradual decline in the quantity of freshwater and altered the frequency of freshwater availability in the downstream ecosystems. There was no systematic investigation conducted to estimate the requirement of environmental flows. The Cauvery Water Disputes Tribunal and even the Supreme Court allocated arbitrarily 10 TMC (thousand million cubic feet) of water for 'environmental protection'; the Tribunal directed that this water be shared by the riparian states during a drought year. This brings out the least importance assigned to the environmental flows and conservation of downstream ecosystems such as the coastal wetlands in the country.

The freshwater flow into the Coleroon River was brought down from 73 TMC to 5 TMC in different phases during the period from 1930 to 1990. This reduction in freshwater flow increased the salinity levels in the coastal water bodies, thereby providing a habitat suitable for the survival of only salt tolerant mangrove varieties. The mangroves sensitive to salinity slowly disappeared from the coastal wetlands of Tamil Nadu. The literature highlights the fact that the salinity-sensitive species such as *Rhizophora* and *Sonneratia* that once dominated the Muthupet Wetlands, before 150 years, have practically disappeared from the area. In the Pichavaram Wetlands, species such as *Xylocarpus granatum, Kandelia candel, Sonneratia apetala* and *Bruguiera gymnorriza,* present earlier, have disappeared mainly due to increasing salinity.

The Muthupet Mangroves are situated on the southern part of the Cauvery Delta covering an area of 118.8 km^2 of which only about 15% is seen as well grown mangroves. Past records indicate that the management of the Muthupet mangrove wetland started as early as 1740. After the British established control over Thanjavur in 1799, the entire Muthupet mangrove wetland was surveyed and boundaries were marked. The first working plan for Muthupet included clear felling with 12 years rotation which continued till 1936. The mangrove forest was declared as reserve forest in February 1937 by the then Government of India. The Muthupet mangrove ecosystem comprises of a heterogeneous combination of plants and animals. Four major mangrove and associate species have been identified in the area, namely, *Avicennia marina, Exoecaria agallocha, Aegiceros corniculatum* and *Acanthus ilicifolius,* their dominance in the habitat being in that order. Most of the area under mangroves, about 95%, is occupied by *Avicennia marina.* Five species of seaweed, viz., *Chaetomorpha* sp., *Enteromorpha* sp., *Gracilaria* sp., *Hypnea* sp. and *Ulva* sp., and two species of seagrass, namely, *Halodule* sp. and *Halophila* sp., are found in the water bodies of this area. It is reported that there are 88 species of phytoplankton, 78 species of zooplankton, 113 species of insect, three species of amphibian, seven species of reptile and 13 species of mammal in this area. In the recent bird census conducted in 2018 by the Forest Department of Muthupet Region, 29 species of water bird were recorded in the estuary, while 36 different species of terrestrial bird were observed in the vicinity.

In spite of its multifarious ecosystem values, the area under mangroves has shown a decreasing trend in the first three quarters of the twentieth century due to direct and indirect natural and anthropogenic pressures. Several brackish water aquaculture farms and saltpans have been developed recently in and around this area. However, in the recent past, there has been a concerted effort by the fishermen community, the Forest Department and NGOs such as M.S. Swaminathan Research Foundation to create fishbone channels in this habitat to maintain salinity levels and plant mangroves, and their efforts have been reported to be of considerable help to the fishing community. The water quality of the Muthupet Mangrove biotope has indicated seasonal variations in the physical, chemical and biological characteristics, highlighting the typical mangrove habitat features (Ajithkumar, 1998).

10.3.1 Major Observations

As part of the present investigations, the following major observations were made with regard to the Muthupet estuary, inlets, mudflats and mangrove ecosystems:

1. The analysis of remote sensing data shows that the area under mangroves increased from 5.4 km^2 in 1970 to 16.88 km^2 in 2019; data based on remote sensing showed a sudden reduction in the land cover area of mangroves to 11.79 km^2 from the data for February 2019, presumably due to the impact of Gaja Cyclone of November 2018; this has been discussed with forest officials and verified from local population. The cyclone had destroyed only the canopy and the plants regenerated immediately after. A significant increase in the land cover area of mangroves is observed as 16.88 km^2 due to regeneration in late 2019.
2. Around 4.035 km^2 of degraded mangroves and 1.48 km^2 of lagoon have been transformed into mangroves during the past three decades, mainly due to the efforts of the local fishing community and the Forest Department. Some NGOs such as MSSRF have also been actively involved in these initiatives.
3. Changes in the extent of the area under mangroves have been observed more at the northern and western sides of the lagoon; however, some pockets of mangroves have emerged in the eastern area of the lagoon.
4. The significant freshwater flows into the estuary from Paminiyar and Koraiyar are confined to the October–January period during the water year.
5. The most dominant species of mangrove identified in the area is *Avicennia marina,* followed by species such as *Exoecaria agallocha, Aegiceros corniculatum* and *Acanthus ilicifolius,* in that order of coverage.
6. It is noticed that the major species of mangroves found in Pichavaram are not seen at Muthupet and the species sensitive to salinity such as *Rhizophora* and *Sonneratia* are not common in the area.
7. Fishermen engaged in channelisation and planting of mangroves have reported better fish catch from the area, especially in and around Muthupet Estuary and lagoons.
8. The depth of Muthupet Lagoon has come down considerably and the area under the mudflats adjacent to the lagoons are also on the decline.
9. The water spread area of the Muthupet Lagoon slowly migrated to the Siruthalaikadu Lagoon and joined it for a short while forming a single water body in the early part of this decade; however, the depth of the lagoon has considerably come down to an average of less than 0.5 m during the low tide.
10. There have been attempts to plant mangroves on the mudflats in Panchanadikulam, Thondiakadu and other mudflats by channelisation (fishbone channel) for the entry of water; however, the attempts have not been totally successful since the high berms on the seaside did not permit enough tidal water to enter, and except during the monsoon season, the freshwater availability was limited and the mudflats remained practically dry.
11. It is also reported by the stakeholders that some of the newly planted mangroves on the mudflats are in a state of regeneration, especially after Gaja cyclone in November 2018.
12. In 1970, the waterspread area of Siruthalaikadu Lagoon was 43.12 km^2. Fluctuations in the waterspread area of Siruthalaikadu Lagoon (shown as Siruthalaikadu Creek in the Survey of India maps) was observed during the last three decades with 40.92 km^2 in 2000, 46.35 km^2 in 2010 and a significant decrease in 2020 with 38.42 km^2, mainly attributed to the reduction in freshwater availability.
13. The waterspread area of Muthupet Lagoon has increased by 39.5% over a period of five decades, from 15.62 km^2 in 1970 to 25.83 km^2 in 2020 due to the reduction in freshwater inflow, sediment dynamics and proliferation of mangroves in the eastern and western sides of the ecosystem; this has made the lagoon a shallow water body with average depth of 0.5m; the increase in the waterspread area is due to widening of a stream on the eastern side of the lagoon by an area of 3.508 km^2 towards the Siruthalaikadu lagoon during 2010.

14. The area of mudflats has reduced from 272.96 km^2 in 1970 to 204.95 km^2 in 2020, a reduction of 24.91% due to its conversion to cultivated lands, saltpans, aquafarms, mangroves, human settlements and other anthropogenic interventions.
15. The salinity levels at various cross sections of Muthupet Lagoon mainly depend on the regulated flows from the upstream, the only consideration for flow regulation by the authorities being irrigation in the delta; there is practically no freshwater flow to the Siruthalaikadu Lagoon, since the stream draining into it got silted up or dried up.
16. The water from the upstream reach of the lagoon recorded comparatively high salinity due to the discharge of wastewater from the aquaculture farms, the impact of which on water quality is found only in a limited stretch; proper flushing of the lagoon would bring down the salinity level.
17. There are around 150 to 200 aquaculture ponds close to the mangroves on the eastern side of the Muthupet Estuary, which utilise water from the lagoon and associated canals and discharge the untreated water with chemicals back to the water body.
18. The concentration of sediments closer to the mouth has brought down the depth of the estuary near the mouth, which may lead to the closing of the mouth in due course.
19. The fishbone channels dug within the mangrove forest for planting mangroves have been silted up and call for desilting and proper maintenance.

10.3.2 Inferences and Interpretations

10.3.2.1 Muthupet Lagoon

1. The Muthupet Lagoon (formerly referred to as Mullipallam Lagoon in Survey of India maps) is a semi-enclosed coastal body of water with drainage of freshwater from upstream and with free communication with the Palk Strait of the Bay of Bengal downstream. The salinity levels dwindle from the mouth upstream. Muthupet falls well within the definition of a lagoon, a shallow choked lagoon to be precise.
2. The distributaries of the Cauvery, namely the Paminiyar, Koraiyar, Marakkakoraiyar, Nasuvanniyar, Pattuvanachiyar and Kilaithangiyar, empty their water to the Palk Strait of the Bay of Bengal through this lagoon and associated estuarine system. The spatial and temporal availability of regulated flow to the wetland system is minimum and erratic.
3. The Muthupet Lagoon receives freshwater mainly during the north-east monsoon (October – December); there is no freshwater flow during March - September period.
4. The substrate of the lagoon is composed of clayey silt, and it changes into sandy silt towards the upstream; the nutrient content is high in the soil in the upstream reaches of the lagoon.
5. The soil types generally found in this area are alluvial, red ferruginous or lateritic, Irugur or black, arenaceous and Kallar.
6. The geomorphology of the estuary has undergone considerable changes; the width of the mouth has reduced from 2.5 km to around 1 km in a period of 20 years and the average depth of water has reduced from 2.5 m to 1 m during high tides (ICMAM, 2005); appropriate measures are called for to make the ecosystem survive.
7. Because of the shallowness, the estuary is highly influenced by the wind turbulence disturbing the bottom sediments and the fine clay which remains in suspension makes the estuary turbid (ADB IND, 2014).
8. According to the studies conducted by KITS for MoEF&CC and considering the latest available data of PWD, the rate of freshwater flow into the estuary ranged between 0 and 80 m^3/sec; the flow was confined to the monsoon and post-monsoon periods and there was no flow during the pre-monsoon and the post monsoon periods; scientific regulation of flows for ecosystem conservation is necessary.

9. The freshwater flow has a direct impact on the salinity levels in the estuary which ranges from 16 ppt to 31 ppt in the downstream reaches (near the mouth) and from 9 ppt to 13 ppt in the upstream reaches (around 10 km from the mouth) of the estuary.
10. The estuary is micro-tidal in nature and the tidal range is between 0.3 m and 0.5 m; the tidal action directly depends on the geomorphology at the mouth of the estuary.
11. The average Suspended Particulate Matter (SPM) ranged between 0 and 1.2 ppt, while the current (velocity) ranged between 0.1 and 0.6 m/s.
12. During the high tide, 80% of the tidal flow at the mouth enters the eastern part of the lagoon and the rest moves towards the west; the flushing characteristics of the lagoon differ in both the branches.
13. The salt budget has been higher in the eastern branch than that in the western branch of the lagoon; these changes in exchange process are mainly due to the geomorphologic features.
14. The tidal action is more significant in the eastern branch than the western branch; the changes in the waterspread area and depth are the major causes for this apart from the geomorphology at the mouth.
15. According to a hydrodynamic classification, the Muthupet Lagoon is well mixed during the pre-monsoon and partially stratified during the post-monsoon and the monsoon; this mainly depends on the freshwater availability from the upstream drainage basin.
16. Reduction in freshwater discharge resulted in the formation of a salt plug (5 to 7 km from the mouth downstream of Koraiyar with salinity values of 36 ppt) and salinity intrusion upto the lower reaches of Koraiyar River to the weir at a distance of 15 km upstream of the mouth in the post-monsoon season.
17. A discharge of 20 m^3/s throughout the year would be ideal to prevent the intrusion of salinity and SPM to the upstream head of the estuary; however, a minimum flow of 10 m^3/s will bring down the salinity level in the lower reaches of Koraiyar to 17 ppt considered to be a threshold value for the healthy growth of mangroves.
18. The estuary acts as a sink for Fe, Cu, Cd and Zn of geogenic origin, with higher concentrations found at the downstream reaches.
19. Settling velocity is minimum at the turbidity maximum location and higher at the upstream locations and settling velocity showed a direct relationship with SPM concentration and turbulence and an inverse relationship with salinity gradient.
20. The waterspread area of the lagoon has increased over a period of time due to the sediment dynamics and consequent reduction in depth; the increase in waterspread area brought the Muthupet Lagoon closer to the Siruthalaikadu Lagoon and once made both the water bodies to be connected together for some time in the early part of this decade.
21. It is found that the freshwater flow is one of the major factors influencing the seasonal variability of the lagoon. Climate change and the consequent changes in availability of freshwater and the sea level rise are bound to change the mixing and circulation characteristics of this estuary.
22. The stability of the mouth, the width of which reduced to just around 800 m, has to be further investigated to understand the sustenance and survival of this estuarine ecosystem.
23. During the monsoon season, the dissolved oxygen in water is reportedly high which might be due to the cumulative effect of higher wind velocity coupled with heavy rainfall or because of the freshwater mixing in the lagoon (Saravana et al., 2018).
24. The presence of carbon at the surface indicates adsorption of organic materials. The increase in the carbon content at greater depths might be due to erosion of sediments from the mangrove forest by heavy rainfall, vascular plants, phytoplanktons and mangrove leaves.

10.3.2.2 Siruthalaikadu Lagoon

1. The Siruthalaikadu Lagoon has widened over a period of time and currently is connected to the sea by a very narrow and deep mouth. A minimum freshwater availability is confined to the peak north-east monsoon period. Thus, it is considered to be a choked type of lagoon.
2. The present area of the Siruthalaikadu Lagoon is 38.42 km^2; the waterspread area in the Muthupet Lagoon that had briefly connected with the Siruthalaikadu Lagoon in the early part of the present decade can be attributed to the hydrodynamic and sediment dynamic processes taking place in the Muthupet aquatic ecosystem.
3. The depth of the inlet has considerably decreased to an average of 0.5 m; the tidal flushing is limited in this inlet thereby reducing the Dissolved Oxygen (DO) content; the inlet is as saline as sea water during the monsoon and the post-monsoon seasons, and hypersaline (>40 ppt) during the summer months.
4. The lack of tidal flushing and absence of freshwater drainage to this water body has deprived the mangroves vegetation on the fringes of the inlet.
5. It would be useful from the point of view of biodiversity and ecosystem services if the hydrodynamic processes of Siruthalaikadu Lagoon are made congenial for wetland fauna. A few model studies are called for to achieve this goal.
6. An attempt made to plant mangroves on the upstream fringes of Siruthalaikadu by providing a freshwater drainage by diverting water from Valavanar tributary and by constructing fishbone channels in the area has not been fully successful due to lack of environmental flows and tidal action.
7. The Siruthalaikadu Lagoon is practically inaccessible on road but is accessible from the artificial canal in the mudflats dug by fishers of Serthualaikadu Village and from Palk Strait.
8. It would also be worthwhile to study the implications of the sea level rise on the Siruthalaikadu Lagoon. Due to increased tidal flushing, this aquatic body could become a better habitat for birds.

10.3.2.3 Mudflats

1. The mudflats in Point Calimere may be defined as areas with mostly alluvial and clayey soil subjected to occasional tidal action in areas close to the sea and limited freshwater availability in the upper transitional areas for about three months from October to December (monsoon season) without much of hydrophytes.
2. In the degraded central part of the mudflat, soft fine silt is found just around the salt swamps. The remaining barren ground is hard (clay), which may be due to the erosion of surface silt by flood water or even wind.
3. The tidal waters occasionally cross the high berm and enter the mudflats.
4. There are two insignificant streamlets, namely, Mulliyar and Manakundan joining the Panchanathikulum Mudflat.
5. The areal extent of the mudflat was 272.96 km^2 in 1970 and has drastically reduced to 204.95 km^2 during 2020; the mudflats have been converted into saltpans, aquafarms and mangroves and these areas are often inundated with water.
6. A few barrages/dykes were constructed in the mudflats by the company involved in large-scale salt production in the area. They divided the mudflats into grids by constructing dykes in an extent of almost 25 km^2 for either storing water pumped from the sea for salt production or for discharging the effluents after salt production. One such grid of area 3 km^2 to which the water is discharged from the pumping station within the mudflat has been designated a bird sanctuary.
7. The water in the sanctuary has high algal growth and the birds feed on the small fish available in the stagnated effluent water stored in the compartments.
8. It is observed that *Prosopis juliflora* covers an area of around 6 km^2 on the mudflats of Point Calimere.

9. The dyke constructed by the company producing salt right across the mudflats of Kodiakadu separates the western and eastern halves and there is a tendency for encroachment into the dry eastern part for settlement.
10. With the availability of more freshwater from the Valavanar tributary and a channel cut for entry of tidal waters, the mudflats in Panchanathikulam and Thondiakadu can be converted into a brackish water bird sanctuary with more biodiversity and mangroves can be planted on the periphery of the water bodies; however, a hybrid hydrodynamic and environmental model has to be evolved to predict the ideal conditions for the wise use of these mudflats.
11. There was an attempt earlier to divert fresh water from the Valavanar tributary to the mudflats on the upstream fringes of Siruthalaikadu to enhance mangrove planting activities; however, it failed due to the non-availability of environmental flows downstream.
12. The mudflats are an important interface between terrestrial and marine habitats and are among the most important and ubiquitous coastal wetlands along with salt marshes in the world.
13. The mudflats in Point Calimere are the result of hydrodynamic processes going on in the Cauvery Delta, wherein riverine sediments are deposited behind spits and bars that offer protection from the waves and longshore currents.
14. Major rivers carrying large sediment loads build mudflats into shallow estuaries or are deposited onto the shallow continental shelf where the ocean is fairly quiet.
15. Tidal energy contributes a subsidy to the mudflat that could influence a wide range of physiographic, chemical and biological processes including sediment deposition, nutrient and organic influx and efflux, flushing of toxins and control of sediment redox potential – all these contributing to the aquatic life and their productivity.
16. The mudflats flourish wherever the accumulation of sediment is equal to or greater than the rate of land subsidence, and where there is ideal exchange of freshwater and saltwater and adequate protection from the destructive waves and storms/cyclones.
17. It is reported that the sanctuary maintained by the Chemplast Sanmar Limited in the areas inundated due to activities connected with salt production serves as feeding grounds for resident and migratory birds; November-January is the peak season for the migratory birds.
18. The Vedaranyam Bird Sanctuary has the second largest congregation of migratory water birds, the peak number exceeding 100,000; the mudflats are the main habitat of this bird population; according to the census conducted by the Forest Department in February 2020, there are 7766 birds belonging to 134 species, which include 6314 water birds from 66 species and 1452 land birds from 68 species.
19. Among the birds observed in the Point Calimere Wildlife and Bird Sanctuary are Curlews, Plovers, Egrets, Stints, Painted Storks, Common Teal, Greenshanks, Redshanks and Lesser Flamingos (classified as Near Threatened by Birdlife International (2007)). All the species except the Lesser Flamingo are categorised as “Least Concern”.
20. Some of the water birds arrive from the Rann of Kutch, eastern Siberia, northern part of Russia, Central Asia and parts of Europe for feeding and breeding in October and return in January. Their migration is greatly affected by the availability of food, quality of water, water level and abiotic changes in the wetlands (Padma et al., 2013).
21. Due to availability of feed during the monsoon, the Greater Flamingo, a generalist feeder, gets attracted to the impoundment of the industrial saltpans, while the Lesser Flamingo, a specialist feeder, avoids salt zones.
22. *Prosopis,* an aggressively invasive plant species, has become one of the most dominant landcover at Point Calimere, that has doubled its extent from 3.03 km^2 in 1990 to 6.16 km^2 in 2019.
23. The survey of unsurveyed swamps/ mudflats has not been completed for evolving management action plans for this area.

10.3.2.4 Mangroves

1. The mangrove swamps evolve as a result of topography, substrate, and freshwater hydrology in combination with tidal action; the mangrove ecosystem in Muthupet may be classified under three categories as given by Mitsch and Gosselink (1986), namely, Riverine Mangrove Wetlands found along the flood-plains of estuaries and creeks, Basin Mangrove Wetlands found in the depressions with stagnant water as in the inlets and Dwarf Mangrove Wetlands in nutrient-poor locations, especially in the pockets closer to the sea mouth.
2. There is a tendency for the mangrove wetlands to replace the salt marshes and mudflats as the dominant coastal ecosystem as often observed in Muthupet and Thalainayar area, which is generally the case in the tropical and semi-tropical zones throughout the world.
3. Most of the mangrove marshes are found in areas with low and moderate tidal ranges between 0.5 - 3m (Chapman, 1976), the tidal fluctuation in the Muthupet Lagoon and associated water bodies being generally between 0.3 and 0.5 m.
4. The range and duration of flooding and the tides play a major role in deciding the extent and functioning of the mangrove swamps, the role of which is importing nutrients, aerating the soil water and stabilising soil salinity, apart from eliminating competition between the mangroves and freshwater species and propagating seeds.
5. Tides in Muthupet also help in circulating the organic sediments in some fringe mangroves for the benefit of filter feeding organisms such as oysters and for deposit feeders such as snails and crabs.
6. Mangroves are found along the banks of the Muthupet Lagoon for a few kilometres upstream, where there is limited tidal action; Lugo (1981) believes that these types of mangroves are dependent on storm-surges and 'are not isolated from the sea but critically dependent on it as a source of fresh sea water'.
7. Due to less flushing caused by tides, the soils in the Basin Mangrove Wetlands, especially in the inlets and lagoons, have high salinity levels and low redox potentials; these are ideal for black mangroves, such as Avicennia, the ground surface being covered by pneumatophores as seen in the shallow areas of Muthupet.
8. The reduction in a coastal wetland depends on the duration of flooding and conditions of freshwater and tidal flows; the reduced conditions are not very severe when there is increased drainage and continuous importing of oxygenated water.
9. The salinity in Muthupet is the highest during the pre-monsoon season and the characteristics of this ecosystem, on the basis of salinity, may be summarised as follows: (i) there is a wide annual variation in salinity, (ii) the salinity levels are an advantage for mangroves of salt-tolerant species, and (iii) the salinity fluctuates less in the interstitial soil water compared with the surface water of these wetlands.
10. The observations show that mangroves require a greater percentage of their energy for maintenance rather than for growth in high salinity conditions.
11. The mangrove wetlands in Muthupet, and for that matter anywhere else, do not reclaim or build land by encroaching into other water bodies. Only after the substrate is established by tides and currents does the vegetation follow, as observed in the case of the mangroves occupying the mudflats and migrating to the estuary when substrate extends to the estuary by sediment deposition.
12. It is to be kept in mind that zonation in these wetlands does not necessarily recapitulate succession because a zone may be a climax maintained by a steady or recurrent environmental condition as stated by Lugo (1980); the steady state attained by the dynamics of fresh and saline water prevailing for a specific time period plays a major role in zonation of the mangroves in Muthupet.
13. The highly productive estuarine and riverine mangroves in Muthupet export considerable amount of organic matter to the adjacent coastal food chains of the nearby estuary and lagoon; these are subject to freshwater flow, sediments and nutrients delivered by upstream rivers and are affected by upstream alterations as in the case of Cauvery.

14. It has been already established that wetlands are important sources of detritus for the adjacent aquatic systems; the excess of leaf fall twice a year and rapid decomposition of the leaves are attributed to be the main cause for this by the local population of Muthupet; these are exported to the adjacent aquatic food chains.
15. The average inorganic N and P concentrations of the lagoon in the area are almost equal to their riverine concentrations, while the organic phosphorus concentration was lower by 30% and the organic nitrogen was higher by 26%. Inputs from the drainage basins transported by the streamflow and mixing and circulation processes were the major factors in maintaining the nutrient concentrations in the lagoon (Gupta, et al., 2006).
16. Primary productivity is the highest in mangrove wetland ecosystems; environments flushed frequently by seawater and exposed to high nutrient concentrations are favourable for mangrove ecosystems; the mangrove forests in the upper reaches of Muthupet show higher rates of productivity than those closer to the mouth.
17. Carter et al., (1973) emphasise that even with low transpiration rates in mangroves due to high salinity levels, productivity can be high with abundant availability of nutrients; high productivity reported before 1924 in the delta is perhaps due to the free transport of sediments and nutrients from the upstream to the downstream reaches before the construction of dams and regulators.
18. The primary productivity in the mangroves is generally controlled by tidal and runoff factors as well as water chemistry; the primary productivity values in Muthupet ranged between 26.65 and 152.35 $mgC/m^3/h$; the minimum values of 26.65 $mgC/m^3/h$ are observed in the north-east monsoon period; the maximum values of 152.35 $mgC/m^3/h$ are observed in the pre-monsoon period and seasonal average of gross and net primary productivity is maximum in summer, gradually decreasing during the pre-monsoon and post-monsoon and attaining minimum values during the monsoon period (Suganthi et al., 2015).
19. Mangroves provide physical stability to the shorelines against erosion; the stability of banks of the estuary and lagoon along with both sides of the mouth of the estuary may to some extent be attributed to the dense growth of mangroves on the periphery.
20. It is reported that the mangroves in Muthupet helped protecting the shoreline and inland areas from the tsunami of December 2004 and to some extent from the Gaja cyclone of November 2018.
21. Mangroves play a major role in serving as a sink for nutrients and carbon. Mangroves can sequester more carbon than do rainforests, depending on the rainfall, streamflow, temperature and salinity characteristics. Mangrove forest soils act as a long-term carbon sink (Science News, USDA Forest Service, Pacific Southwest Research Station, April 2011).
22. It is suggested by some experts that non-salt-tolerant species were growing in the delta prior to the diversion and regulation of waters from the upper basin of the Cauvery before 1924; as it is, the riverine and basin mangrove areas are now dominated by *Avicennia* (Alai-atti), which is comparatively more tolerant to salinity.
23. Along with the deep-rooted mangrove trees, the trees locally known as Thillai *(Excoecaria agallocha),* Nari Kanthal *(Aegiceras corniculatum)* and Nirmuli *(Acanthus ilicifolius)* also grow in the area.
24. Some of the adaptations of the mangroves, as summarised by Kuenzler (1974) and Chapman (1976), relevant to Muthupet are: (i) salinity control by reverse osmosis in the root zone, which acts as an ultra-filter, and the salt-secreting glands on the leaves; (ii) pneumatophores of *Avicennia;* and (iii) viviparous seedlings for propagation and invasion of newly exposed substrate.
25. When the pneumatophores or prop roots of mangroves are continuously flooded for a long time, the submerged pneumatophores and prop roots die (Macnae, 1963; Day, 1981); this highlights the importance of hydroperiod of the wetland in the sustenance and survival of mangroves in any area including that of Point Calimere.
26. Several filter feeders or detritivores are found in the mangrove area of Muthupet since it provides them shelter and food.

27. The notable species of birds in the area are herons, egrets, darters, plovers, cormorants, terns and brahminy kite, to name a few; several migrant birds visit the area, especially in the winter season.
28. The conversion of swampy and saline areas to dry or freshwater areas by the construction of artificial structures may lead to the destruction of salt marshes and mangroves as seen at Thalainayar, where the high dyke on the banks of Vedaranyam Main Canal deprived the western side from saline water and made it practically dry; the barrage of Vedaranyam Main Canal (VMC) has a length of 25 km and width of 5.5 m, with a side slope of 1:0.81, stretching from Velankanni to Kallimedu, which separates the freshwater and brackish water bodies of the area.
29. Maintenance of mangroves is cumbersome in areas with low tidal flushing where there is a competition with freshwater plants and in areas where there is high tidal action and limited nutrients; encroachment by plants adapted to low salinity is observed in the mangrove areas on both the banks in the upper reaches of the estuary and poor growth of mangroves is observed in areas with low nutrient availability at the mouth of the estuary.
30. The area under *Rhizophora* decreased with salinity levels while that under *Avicennia* increased with higher levels of salinity. Avicennia has practically taken over 95% of the area under study since the freshwater flow has dwindled during the past few decades.
31. The ability of the *Avicennia marina* growing in Muthupet region to sequestrate carbon shows that there is a greater potential for development of the mangrove ecosystem to offset global warming.
32. On the basis of the reports of the local fishermen, it is surmised that the disappearance of mangrove wetlands will cause a significant decline in the fisheries and adversely affect the livelihood of the fishermen depending on fishing in the estuary, lagoons and canals in the mangrove areas.

10.4 Point Calimere Wildlife and Bird Sanctuary

Four landscape elements have been identified in the Point Calimere Wildlife and Bird Sanctuary, namely, (i) tropical dry-evergreen forest (8.91 km^2), (ii) open-scrub (11.23 km^2), (iii) mudflat (3.57 km^2), and (iv) water bodies (2.78 km^2).

10.4.1 Major Observations

The major observations on the Point Calimere Wildlife and Bird Sanctuary based on the present investigation are listed below:

1. The Point Calimere Wildlife and Bird Sanctuary is a unique habitat located on the top of a sand dune formed at the tail-end of the delta mainly due to the interaction between the river flow and coastal processes over a long period of time; the nose-like promontory/headland has given birth to a peculiar geomorphologic formation with sea on the eastern side and the Palk Strait on the southern side.
2. There is generally a tendency for deposition of littoral materials on the southern side of the promontory, the shelf towards the east is also wider and shallower providing a very peculiar configuration to this coastal zone.
3. There is an erosion tendency farther north of the nose-like formation as well as farther south of this formation. This is because materials are picked up from the southern stretch and deposited on the southern side of the promontory. The littoral current is starved of the sediments when it moves towards the north from the promontory.
4. It is observed that the height of the sand dune is around 12 m above sea level from the measurements taken at the shoreline at the tip of Point Calimere, where the vertical height of the sand dune could be measured.
5. A few freshwater wells are found in the northern pockets of the sand dunes.
6. The proliferation of Prosopis has resulted in a significant loss of open grasslands, which is a major threat to the endangered Blackbuck *(Antelope cervicapra)*. In addition, the invasion of *Prosopis* has led to fragmentation of the TDEF, with a 63% loss in the native trees (Ali 2005; Baskaran et al., 2016).
7. The LULC change analysis shows that 0.618 km^2 of water bodies changed into open-scrub in 2020.

10.4.2 Inferences and Interpretations

1. The PCWBS is a habitat situated on sand dunes that provides a unique ecosystem different from the rest of the coastal area in Point Calimere.
2. The PCWBS habitat is plain, and it is presumed that the depth of the sand dune is fairly uniform all over the sanctuary.
3. The overburden of silt has helped in recharging the groundwater table in the area covered by the sand dunes and freshwater is available at the upper portion over the dense saline water table at the sea level.
4. The availability of freshwater in this habitat due to rainfall and impoundments in the depressions over the sand dunes during the monsoons and fresh groundwater in the upper layer have been responsible for freshwater flora and terrestrial wildlife in this habitat, close to the sea surrounded by saline water bodies all around.
5. The depressions with small areas in the sanctuary recharge the groundwater table in the sand dune area, thereby making freshwater available during the summer months.
6. It is noticed that when the groundwater table is high, the soil samples from some of the depressions show salinity due to the capillary movement of saline water from the bottom layers of the strata; however, this phenomenon has to be further investigated.
7. The major animal species seen in the Point Calimere Wildlife and Bird Sanctuary are: Blackbuck (a flagship species of the sanctuary), Chital, Jackals, Feral Ponies, Small Civets, Wild Boars and Monitor Lizards (http://cpreec.org, accessed on 16/11/20).
8. Among the avian fauna, the notable birds are the Blue-tailed Beeeater, Yellow-wattled Lapwing, Larks, Pipits and the Paradise Flycatcher.
9. The anthropogenic activities within the sanctuary limited the regeneration potential of tree species, and thereby reduced the species diversity; the selective cutting of old trees and restriction on harvesting younger trees by local residents are the best practices that can be adopted.
10. Some of the suggestions for the protection and conservation of the sanctuary, arising out of discussions, are as follows:

- Areas close to the sea to be artificially nourished to prevent erosion, grazing to be restricted to areas outside the sanctuary, more water conservation practices such as small impoundments and radial wells to be encouraged,
- Exotic tree species consuming more water to be removed from the sanctuary and measures to protect the area from natural hazards such as storm surges, cyclones and tsunami to be adopted.

11. It was observed that the water in the area of the sanctuary was slightly alkaline with pH ranging from 7.3 to 8.5; high values of electrical conductivity were exhibited due to the intrusion of saltwater into the PCWBS; sodium, a natural softener of water, was observed at high levels along with potassium (Saravana et al., 2018); the amount of iron was found to be higher along with nitrates which might be due to the leachate of crop nutrients and nitrate fertilisers from agricultural lands.

10.5 Saltpans

A salt evaporation pond is a shallow artificial saltpan designed to extract salts from sea water or other brines. Natural saltpans are geological formations that are also created by water evaporating and leaving behind salts. The seawater or brine is fed into large ponds, and water is drawn out through natural evaporation, which allows the salt to be subsequently harvested. The ponds also provide a productive resting and feeding ground for many species of water bird, which may include endangered species.

10.5.1 Major Observations

The major observations of the study with regard to the saltpans are listed here:

1. From the field work, it is understood that 6000 acres of state government land are used by two major private salt-producing companies and 3000 acres of government land has been leased out to 750 units involved in saltpan operation. These units are presently operated by marginal and medium producers and cooperative societies. Around 2000 acres of land is being utilised by small-scale saltpan operators for edible salt production.
2. It is observed that the area under saltpans in Point Calimere wetland has increased from 11.47 km^2 in 1970 to 29.25 km^2 in 2020 over a period of 5 decades.
3. Around 30 villages are involved in salt production in and around Vedaranyam; the saltpans of Point Calimere are providing direct and indirect employment to around 10,000 people.
4. The preliminary survey shows that 900,000 tonne of salt is produced during six months every year from these saltpans.
5. Individual licenses are issued for 700,000 tonne and company licenses are issued for 200,000 tonne.
6. Most of the small-scale saltpan operators use groundwater extracted from bore wells going down to depths such as 50 m for producing edible salt, which will have an adverse impact on the groundwater quality. It is reported that they were earlier drilling to a depth of 20 m, which has now increased to 50 m.
7. From interaction with the small-scale saltpan owners, it was found that one tonne of salt is sold at Rs.500 to Rs.1000. For one acre of land, an amount of Rs. 60,000 is invested for creating a plot of size 8 m × 16 m, in which 2000 tonnes of salt is produced.
8. Two major private companies, Chemplast Sanmar and Gujarat Heavy Chemicals own large salt-producing units in the wetland complex. They draw saltwater from the sea, produce salt and discharge the effluents into the mudflats.
9. Chemplast Sanmar produces PVC resins, caustic soda, chlorinated solvents and refrigerants. Gujarat Heavy Chemicals produces edible salt at its Vedaranyam plant.
10. A salt production process flowchart is provided here:

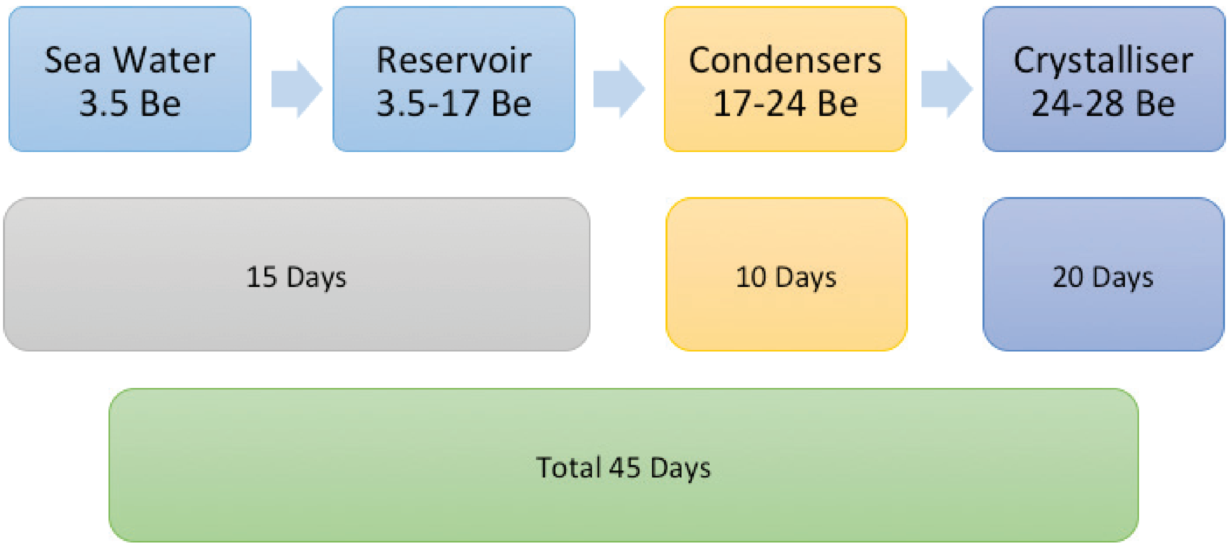


Figure 10.1 *A typical salt production process flow*

10.5.2 Inferences and Interpretations

1. The major interventions involved in the operation of saltpans where water from the ocean is pumped into the mudflats for salt production, discharging seawater into the mudflats and pumping out water from deep bore wells and spreading it on the ground surface.
2. The groundwater is pumped out from bore wells constructed within the saltpans for producing edible salts; the depth of bore wells are increasing and groundwater quality is deteriorating in the area.
3. A road-cum-dyke is laid that divides the mudflats into two different parts, converting the zone into wet and dry areas.
4. Natural flows and tidal influx are disrupted by the interventions meant for salt production.
5. The major disadvantages due to salt producing units are- fragmentation of mudflats, salinisation of soil and groundwater, and the impact on the habitat, flora and fauna and biodiversity.

10.6 Aquaculture Farms

Aquaculture is a broad term covering culture of a variety of organisms such as fish and shrimps. Prawn culture is practised in the areas adjacent to the coastal regions by pumping or channelising brackish water into a pond. Although aquaculture is a non-consumptive water use, it has specific water requirements regarding depth of water, quality of water and reliability of the water supply.

10.6.1 Major Observations

The major observations of the study with regard to the aquaculture farms are listed here:

1. The flood water from the Adappar River is brought to the Vedaranyam Main Canal by a straight cut; several fishermen are involved in fishing activities in the straight cut, and several aquafarms are constructed on the western side of the road.
2. All along the sides of the Vedaranyam Main Canal (VMC), aquafarms are seen; brackish water suitable for these farms are available in this stretch.
3. The shift to aquafarms by some of the local farmers and agricultural labourers is attributed to the scarcity of water for irrigation at the tail-end of the delta.
4. According to MPEDA, the expansion of aquaculture was mainly due to the introduction of the species *Penaeus vannamei* in 2009, which opened up a new avenue in Indian aquaculture and created increased demand among farmers.
5. It was also observed that Vedaranyam canal and tributaries of Cauvery such as the Uppanar and Vellar were found suitable for aquaculture farms leading to unregulated growth of small-scale farms.
6. The aquafarms have now spread to 9.37 km^2, posing a serious threat to the wetland complex; the major expansion has taken place on the northern side of the estuary due to availability of brackish water from the estuary.
7. The increase in aquafarm area is mainly by conversion of vegetated and cultivated land and mudflats; the conversion of agricultural land to aquaculture was due to the non-availability of water, reduction in profit margin in the agriculture sector and increase in demand for shrimp.
8. The effluents discharged from the farms contain bio-degradable wastes and toxic chemicals that pollute the groundwater in the adjoining areas, even up to a distance of 6 km (Ramesh et al., 2008).
9. The income from aquafarms is estimated to be Rs.1.5 lakh per acre and Rs.10,000 per month per person who is directly or indirectly engaged in aquafarm activities.
10. The existing British Bund (5-valve Bund) has breached over a period of time and brackish water required for aquafarms are readily available due to the incursion of saline water to the area; the yield of the standing rice crop in the nearby farms has also been greatly affected.

10.6.2 Inferences and Interpretations

1. Some of the disadvantages related to aquaculture farms are- increase in salinity due to discharge of water with higher levels of salinity from the farms/ponds. A gradual increase in soil salinity is observed from Thalainayar to Vettiakaraniruppu and from Umbalacheri to Avarikaadu.
2. The medicines and nutrients used in the aquaculture farms are indiscriminately discharged into the nearby areas, which would adversely affect the water quality.
3. The major environmental concerns are increased levels of nutrients including nitrogen and phosphorus, excess quantities of suspended solids and particulate organic matter in the wastewater discharged (Ramesh et al., 2008).
4. Some of the other harmful interventions include digging of the wetland for making farms/ponds and bringing saline water to freshwater areas by pumping and through canals.

10.7 Coastal Zone Ecosystem

The stability of the shoreline adjacent to the coastal wetlands is important for the sustenance of the wetlands. Coastal erosion, breaching of sand bars, opening of new mouths or closing of existing mouth of wetlands are capable of changing the habitat and its biodiversity. All the wetlands/ecosystems of Point Calimere are close to the shoreline and changes in the morphometry of the shore would have its impact on the wetland. The sea level rise is expected to have a major impact on these coastal wetlands, especially the estuary, inlets and mudflats.

10.7.1 Major Observations

The major observations of the study on the coastal zone ecosystem are given here:

1. On the coastal belt of Nagapattinam and Thiruvarur districts, there has been a net erosion of 2.97 km^2 during 1970 - 2000, while a net accretion of 2.79 km^2 is observed during 2000 - 2020, indicating a net erosion of 0.18 km^2 over a period of 5 decades;
2. The nose-like promontory of Point Calimere is observed to be a major sink while Agasthiyampalli and Kodiakkarai (Usha et al., 2013) are seen as major sources of sediment supply;
3. At Vedaranyam, the sediments move towards the north during the south-west monsoon and vice versa during the north-east monsoon, depending on the littoral drift; the net quantum of littoral sediments entering into Palk Strait from Nagapattinam coast is estimated to be 0.27 × 106 m^3 (Sanil Kumar et al., 2003); and
4. The total length of the coast adjacent to the wetland complex is estimated to be 60.33 km, of which 31.68 km has been subjected to change during the past 5 decades.

10.7.2 Inferences and Interpretations

1. The accretion tendencies are mainly along the coastline of Palk Strait and Muthupet Lagoon.
2. The promontory at Point Calimere is attributed to be the cause for two opposing wave directions from the north-east and south-east, with one set of waves predominant over the other.
3. The foreshore formation is mainly dependent on the rate of discharge of stream sediments and the role of waves in moving the sediments to both the sides of the mouth.
4. Out of the total stretch of 60.33 km, 20.37 km falls under highly vulnerable category (unstable), 11.31 km under moderately vulnerable category and the remaining 28.64 km as stable coast, Thethakudi being highly vulnerable and Point Calimere being moderately vulnerable while Maravakkaadu and Palanjur Reserve Forests of Muthupet Lagoon mouth area again being under highly vulnerable category.

5. On either side of the mouth of lagoon there are locations which are highly vulnerable; this is because of the fluctuations that happen nearer to the mouth due to the movement of water and its energy level variations during the high and low tides.
6. The Muthupet Lagoon region as such falls under the low vulnerability category, whereas the Siruthalaikkadu Lagoon is under the moderate vulnerability category. This indicates the continual changes taking place in the Seruthalaikadu Lagoon.
7. The impact of the sea level rise was estimated using Spatial Analyst module of ArcGIS software and DEM using STRM global DEM data; a rise in sea level by 1 m is estimated to submerge an area of 37.19 km^2, which include water bodies (8.53 km^2), aquafarms (0.58 km^2), lagoons and associated water bodies (4.98 km^2), mangroves (3.23 km^2), mudflats (12.36 km^2) and saltpans (0.30 km^2) and the rest being cultivated land, scrub, barren land and settlements.
8. A sea level rise up to 1 m is expected to bring more tidal action in the Seruthalaikadu Lagoon and the mudflats, probably contributing to the enhancement of the aquatic and avian fauna in these ecosystems. The Muthupet Lagoon will experience more tidal action and possibly become more productive, requiring more fresh water for flushing.
9. Some of the recommendations for the protection and conservation of the coastal zone are: artificial nourishment of beaches and providing vegetation cover with mangroves and mangrove associations.

10.8 Bird Diversity in Point Calimere Wetland Complex

The impact of water level and water quality affects the bird diversity in the Point Calimere Wetland. The major observations and inferences are presented in this section.

10.8.1 Major Observations

The three major observations Point Calimere Wetland Complex are mentioned below:

1. Influence of Water level and Salinity level on Greater Flamingos

Figure 10.2 *Flocks of Greater Flamingos during 2017 monsoon*

During the monsoon in 2017, large flocks of Greater Flamingos were observed (figure 10.2) in Point Calimere Bird Sanctuary, indicating that the density of flamingos is higher soon after the rains, with the increase in the depth of the water and decrease in salinity level in the salt reservoirs. This observation is similar to the earlier studies reported by Sumathi et al., 2008, that the density of the Greater Flamingos is higher in the low salinity condensers of salt works as they are general feeders, while the Lesser Flamingos do not survive in the salt environment being specialist feeders feeding on blue green algae. It is also reported that in lower saline areas, the Flamingos use deeper waters and prefer shallow water in higher saline areas. In the December 2017 study by the team from KITS, the flocks were observed in the distant deeper waters confirming that the density of these birds is higher in the areas with 15-20 cm water depth and lesser in the metahaline areas of 40-80 ppt of salt (Sumathi et al., 2008).

2. Impact on Waders and Shore birds

It is reported that small waders or shore birds such as Plovers, Sandpipers, Greenshanks, Red Shanks and Stints are adversely affected by salinity, while fish-eating birds such as Egrets, Storks, Herons and Terns are benefitted. The water level fluctuation and mudflat exposure time greatly influence the density of shore birds (Manikannan et al., 2012). In our field visits during the year 2017 (figure 10.3), large congregations of Ringed Plovers were observed foraging on the mudflats submerged in tidal waters, while the frequent and spectacular flights of thousands of Little and Temminck's Stints were an added attraction highlighting the robust health of the ecosystem.

Figure 10.3 *Flocks of small waders foraging in nutrient-rich mudflats, December 2017*

3. Species Diversity

Seasons and months play a major role in the arrival of migratory birds, their density and diversity. Just after Northeast monsoon, the sanctuary comes alive with thousands of flocks of birds representing hundreds of species - Eurasian Curlews, Painted Storks, Openbill Storks, Pintailed Ducks, Greater Egrets, Cormorants, Caspian and Whiskered Terns, Spoonbills, Pelicans and many others, transforming the Point Calimere Wetlands into a hotspot for biodiversity (figures 10.4-10.6).

Figure 10.4 *Species Diversity – Eurasian Curlew, Sandpiper, Pintail Ducks Green Shank, December 2017*

Figure 10.4 *Species Diversity – Eurasian Curlew, Sandpiper, Pintail Ducks Green Shank, December 2017*

Figure 10.5 *Vibrant Bird Life (Egrets, Storks, Herons, Terns and Cormorants) during 2017 Monsoon*

Figure 10.6 *Terns in flight (pre-monsoon and Monsoon, 2020)*

10.8.2 Inferences and Interpretation

The major threats responsible for the decline in aquatic bird diversity in 2020 are attributed to the increased salinity due to salt production, expansion in small-scale salt works and effluent discharge by aquafarms, all of them affecting the water quality parameters such as pH, nitrate, salinity, turbidly, water depth, temperature, and phytoplankton blooms. Intense agricultural activities in the vicinity of the sanctuary and anthropogenic activities reduce the flow of fresh water necessary for the migratory birds to thrive.

11. INDICATORS, DRIVERS OF CHANGE, ACTORS, POLICY GAPS AND MANAGEMENT ACTION PLANS

11.1 Introduction

For a better comprehension of the indicators, direct and indirect drivers of changes, actors, proposed management action plans (MAP) and need for policy interventions (PI), it has been found expedient to present these details for each of the major ecosystems included in the Point Calimere Ramsar Site. Some of these factors may be unique in the case of certain ecosystems considered though some of the factors or components may be common to two or more of the ecosystems. However, for a proper understanding of the ecosystem, changes taking place, cause for the changes, specific actors involved, management action plans and policy interventions required have been considered separately for each of the major ecosystems. The indicators have been identified on the basis of actual observations in the field, analysis of primary and secondary data, discussions with the stakeholders, literature survey or analysis of satellite data. The block diagrams, considering all these factors, presented in this chapter have been evolved on the basis of the following five exercises:

i) Detailed data collection during field visits and experiments;
ii) Reports, literature and maps available on the topics;
iii) Interviews and discussions with officials and stakeholders belonging to different sectors;
iv) Testing of samples, analysis of data and modelling;
v) Experience in the preparation of management action plans and policies for different Ramsar sites in the country.

11.2 Connectivity Among the Ecosystems and Integrating the Wetland Complex with the Cauvery Delta

All the ecosystems of Point Calimere Ramsar Site are not wetlands per se. For example, the Point Calimere Wildlife and Bird Sanctuary is not a wetland but a tropical dry evergreen forest, the major part of which is located on a sand dune formed as a result of the sediment dynamics in the Cauvery Delta over a long period of time. The Ramsar site also has artificial and natural wetlands within it. For example, the saltpans and aquaculture farms are artificial wetlands created for commercial and livelihood purposes. All the natural wetlands are not interconnected. For example, the Muthupet Lagoon and associated mangroves on its fringes are not connected with the Siruthalaikadu Lagoon. The mudflats are also practically independent entities and are not connected with other wetland ecosystems except for a few days every year either due to a cyclone or due to a flood due to heavy rainfall when the water will be spread out in the coastal belt of the delta. However, these mudflats are largely exploited for impounding saline water for salt production or for discharging the effluents from the salt manufacturing units.

The aquaculture farms have encroached into the mudflats, and a few farms utilise the water from the Muthupet Lagoon and discharge their wastewater back to the lagoon. Five streams draining into the Muthupet lagoon are regulated upstream at different levels. The regulation of freshwater is mainly intended for irrigation purpose. The agro-chemicals applied in the upper delta drain into the downstream wetlands, especially the Muthupet Lagoon. The connectivity among the wetlands of Point Calimere Ramsar site is mainly due to freshwater flow from upstream and sea water intrusion from downstream. The major connectivity links of the wetland complex of Point Calimere are listed below:

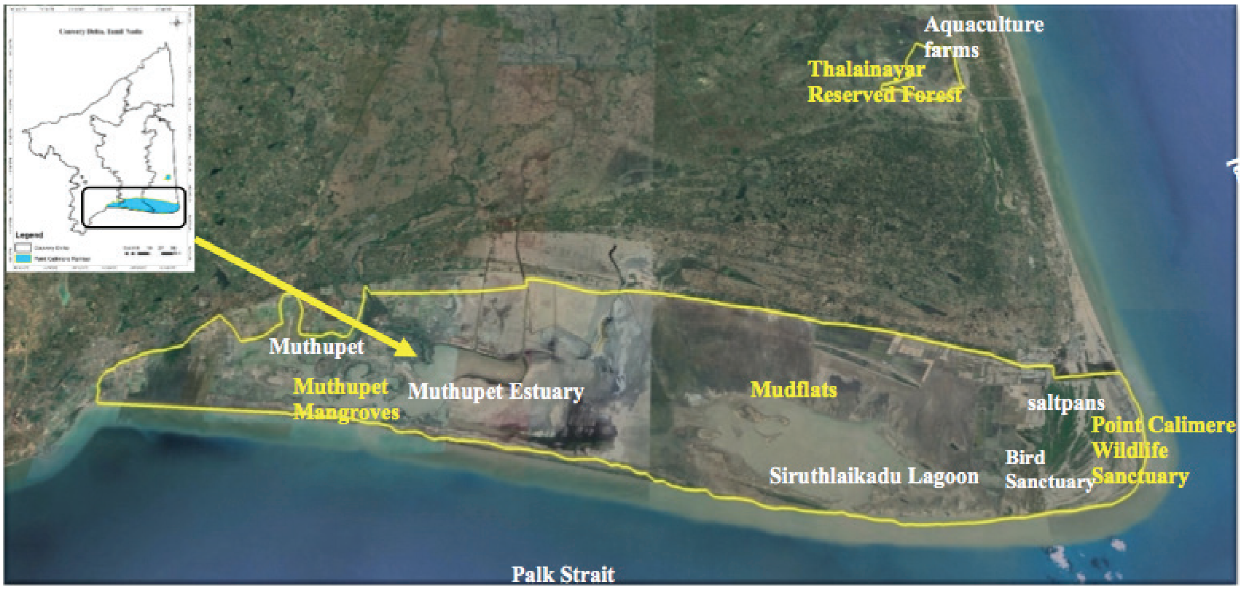
1. The five rivers draining into the Muthupet Lagoon are subject to upstream regulations before the water joins the lagoon and the mangroves on the fringes of the water body.
2. The water from these five drainages is subjected to pollution due to the application of agro-chemicals in the rice fields and sewage from thickly populated clusters.
3. There are a few aquaculture ponds on the sides of Muthupet Lagoon that take water from the estuary and discharge their wastewater back to the estuary.
4. The micro-tidal and shallow lagoon enters the Palk Strait through a narrow mouth of 800 m and establishes communication with the sea.
5. The saline water enters the mangrove areas on the fringes of the lagoon through a number of natural tidal creeks and through fishbone canals artificially made for this purpose; on the western side of the mangrove canals dug by fishers for a unique traditional fishing facilitate flushing by tidal water.
6. As it is, there is no connectivity between the Muthupet and Siruthalaikadu lagoons, and there is practically no freshwater flow to the Seruthalaikadu Lagoon from upstream, but it is connected to the Palk Strait through a deep entrance channel.
7. The mangroves planted on the fringes of Siruthalaikadu Lagoon and in the Panchanadhikulam and Thondiakadu mudflats following fishbone type canal method are practically deprived of freshwater flows.
8. Most of the saltpans are located over the mudflats and divide the mudflats into grids for activities connected with salt production.
9. Some of the saltpans pump out saltwater from deep bore wells to produce edible salts.
10. Large number of aquaculture farms are on the mudflats and near Thalainayar Reserve Forest; these aquafarms make use of the groundwater and some of them bring brackish water to freshwater areas for shrimp production.
11. The streams flowing to Thalainayar Reserve Forest are independent of those draining to Muthupet and Siruthalaikadu Lagoons.
12. The Perelam stream flowing to the Point Calimere Wildlife and Bird Sanctuary has practically ceased to flow in the recent years.
13. The Adappar and Harichandranadhi have been regulated, diverted and silted up so much so their connectivity with Thalainayar RF is only marginal.
14. The branch of Valavanar flowing into Siruthalaikadu Lagoon has silted up and dried; both Mulliyar and Manakundan rivers are ephemeral and flows only for three months in a year.
15. The only freshwater stream flowing into Point Calimere Wetland Authority has been the Peralam River, which no more drains into the sanctuary.

From the above description, it is clear that the connectivity among the wetland ecosystems of Point Calimere Ramsar site is marginal either due to natural causes or due to anthropogenic interventions. It is to be remembered that the delta is a highly dynamic system; due to considerable regulations and interventions upstream, the Cauvery Delta has become less dynamic from the point of view of natural processes. The only consideration in allocating water has been irrigated rice cultivation in the delta. With all these, the delta to some extent is the unifying factor of all the wetlands within it because the freshwater supply to these wetlands totally depends on the releases from the regulators in the delta and the rainfall received in the delta. It is worthwhile to note that the exploitation of groundwater from the delta has an overall impact on the entire delta and the areas covered by the wetlands. Considering all these factors, apart from the individual wetland ecosystems, the delta, direct catchments and buffer zone of the wetlands have been considered in an integrated manner.

11.3 Specific Wetland Ecosystems Considered

The specific ecosystems of the Point Calimere Ramsar site considered are listed below (the figure numbers of the respective block diagrams are given in parenthesis):

1. Muthupet Lagoon (figure 11.1)
2. Siruthalaikadu Lagoon (figure 11.2)
3. Mudflats (figure 11.3)
4. Mangroves (figure 11.4)
5. Point Calimere Wildlife and Bird Sanctuary (figure 11.5)
6. Saltpans (figure 11.6)
7. Aquaculture farms (figure 11.7)
8. Cauvery Delta (figure 11.8)
9. Coastal zone ecosystem (figure 11.9)



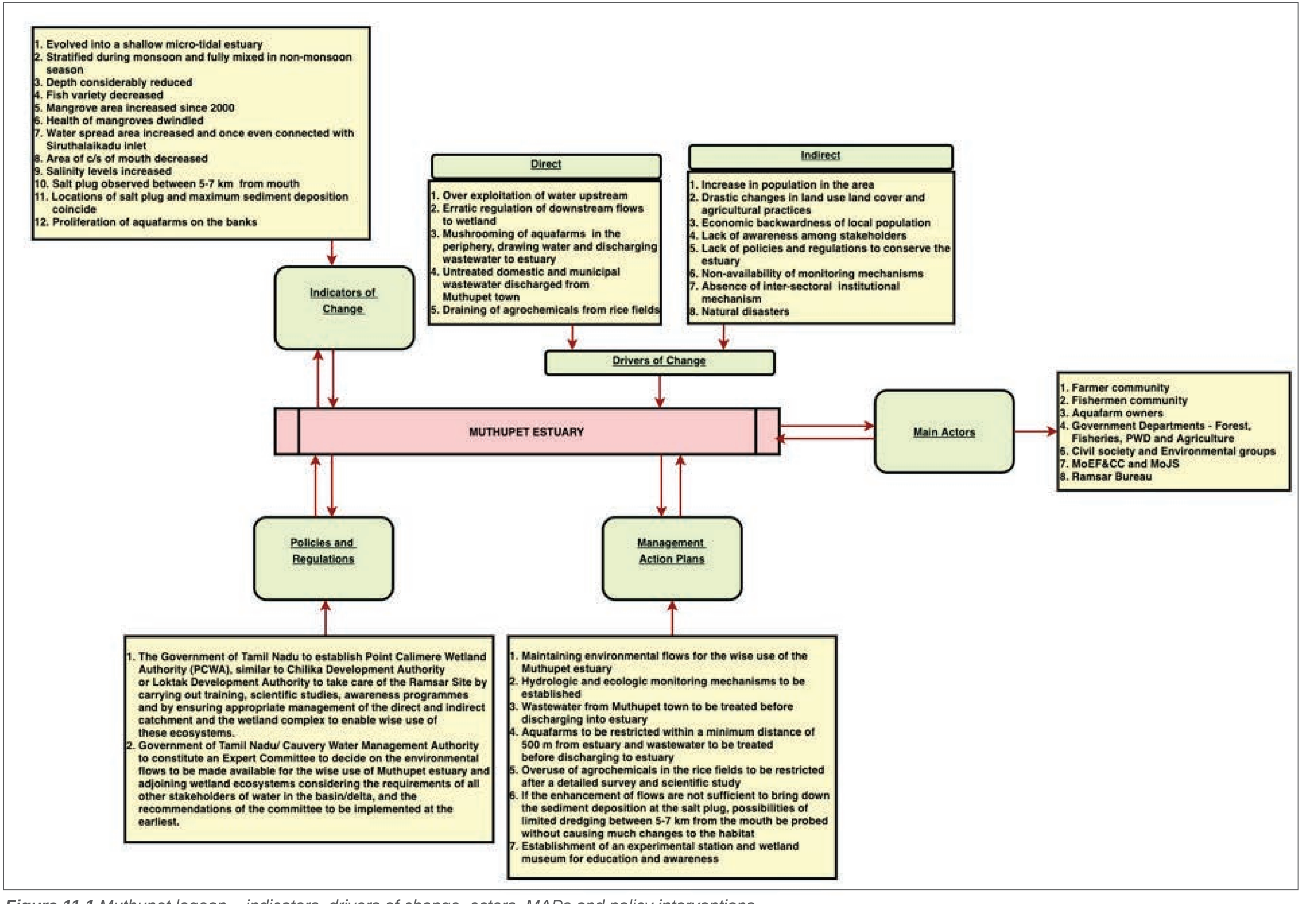


Figure 11.1 *Muthupet lagoon – indicators, drivers of change, actors, MAPs and policy interventions*

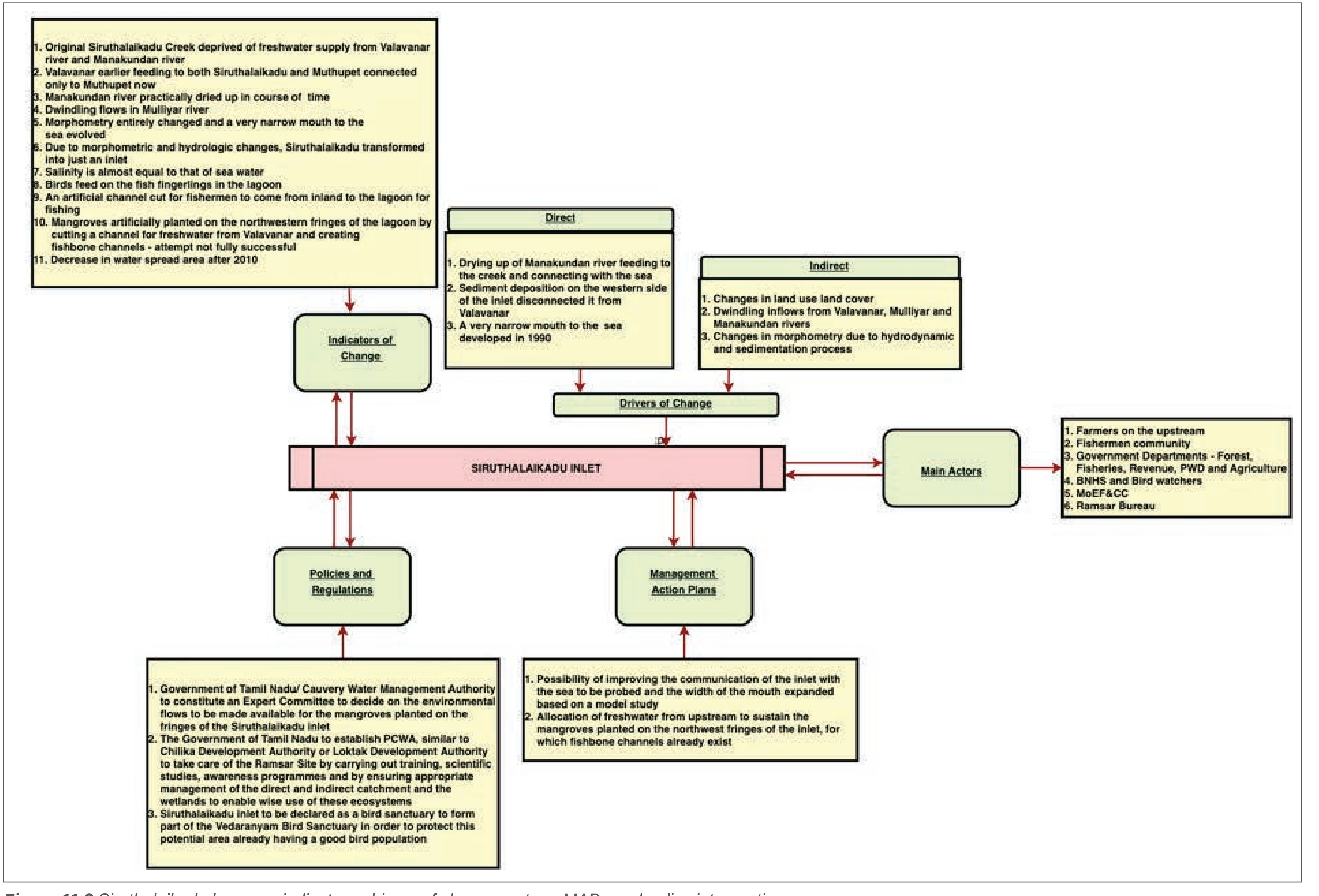


Figure 11.2 *Siruthalaikadu lagoon – indicators, drivers of change, actors, MAPs and policy interventions*

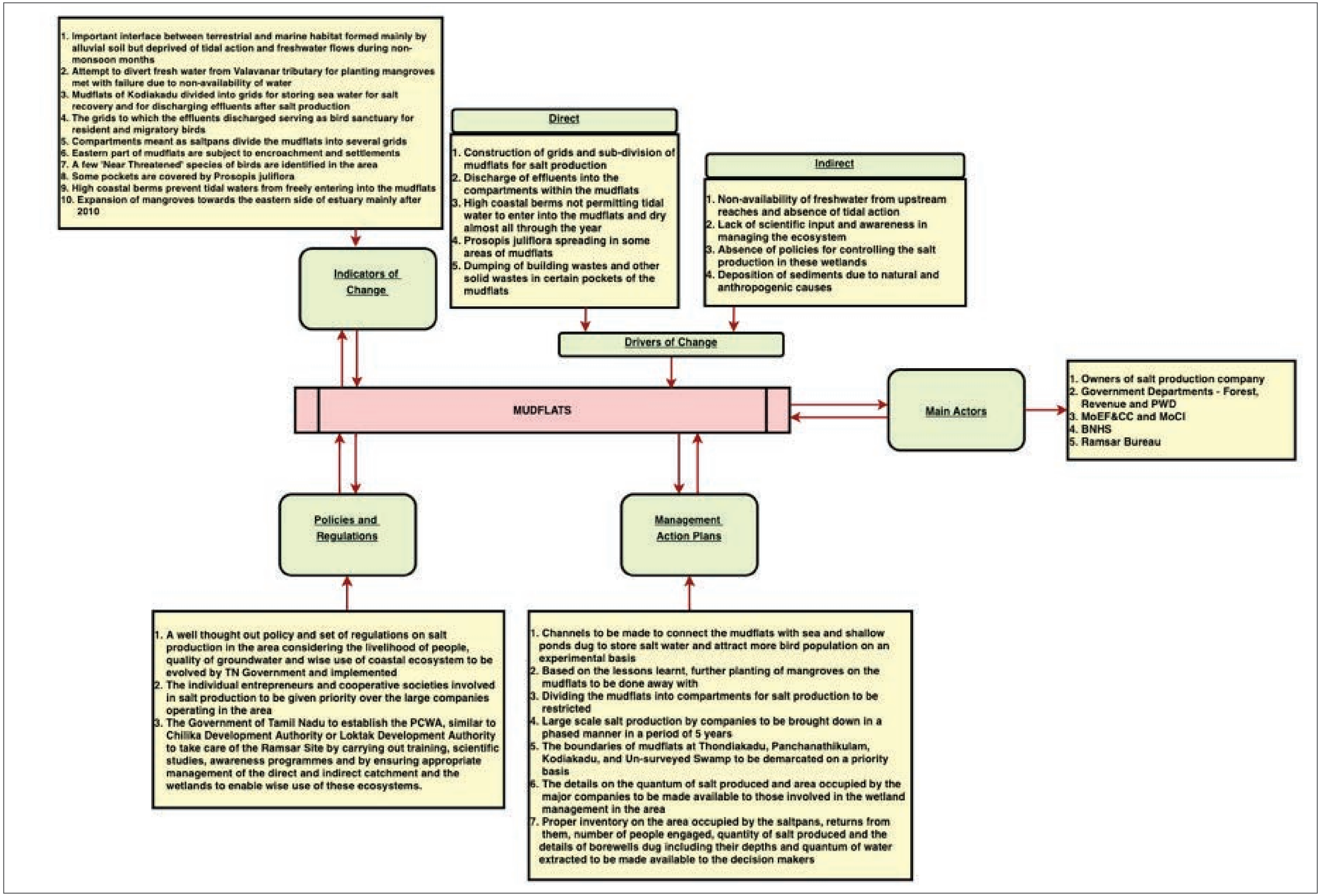


Figure 11.3 *Mudflats - indicators, drivers of change, actors, MAPs and policy interventions*

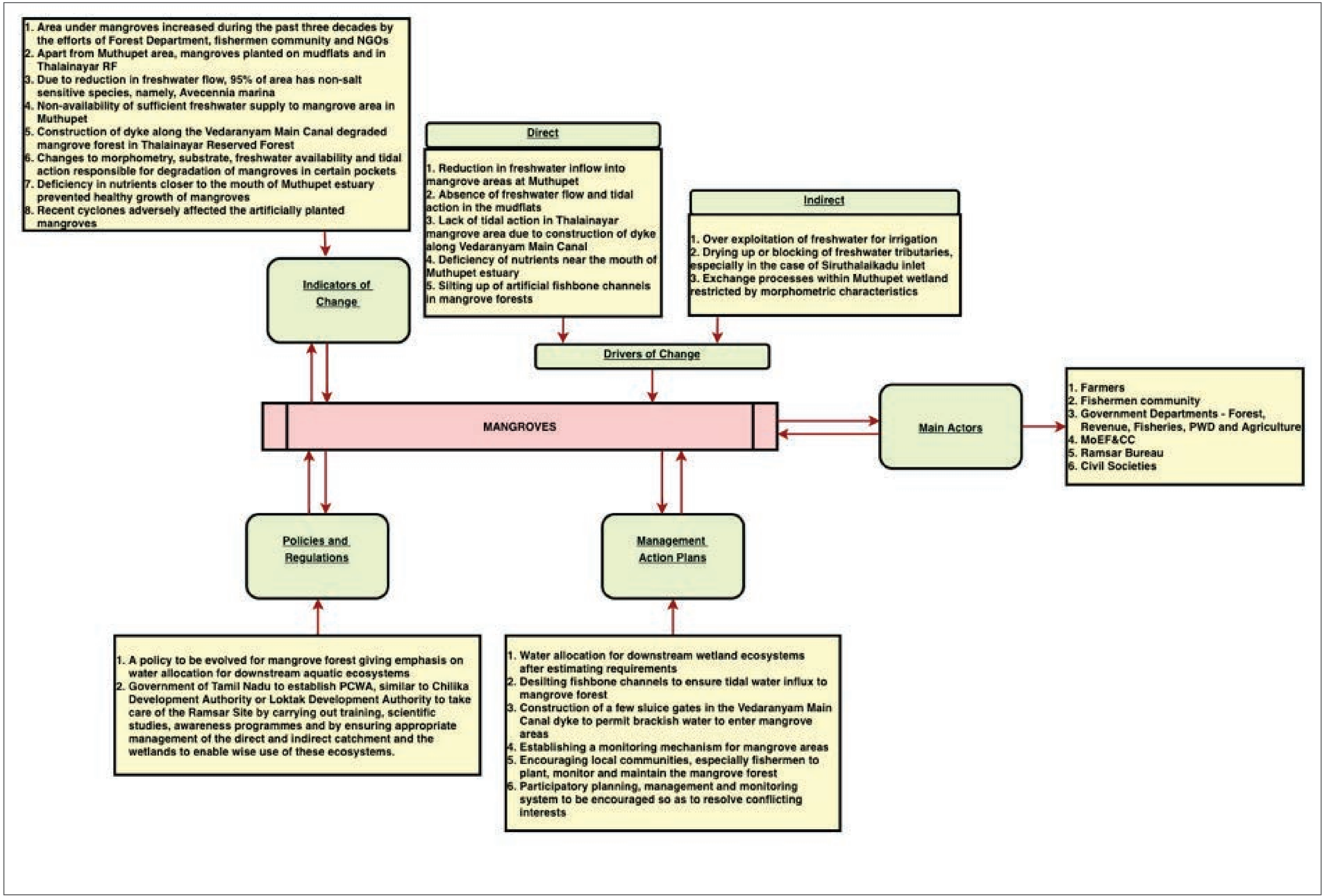


Figure 11.4 *Mangroves - indicators, drivers of change, actors, MAPs and policy interventions*

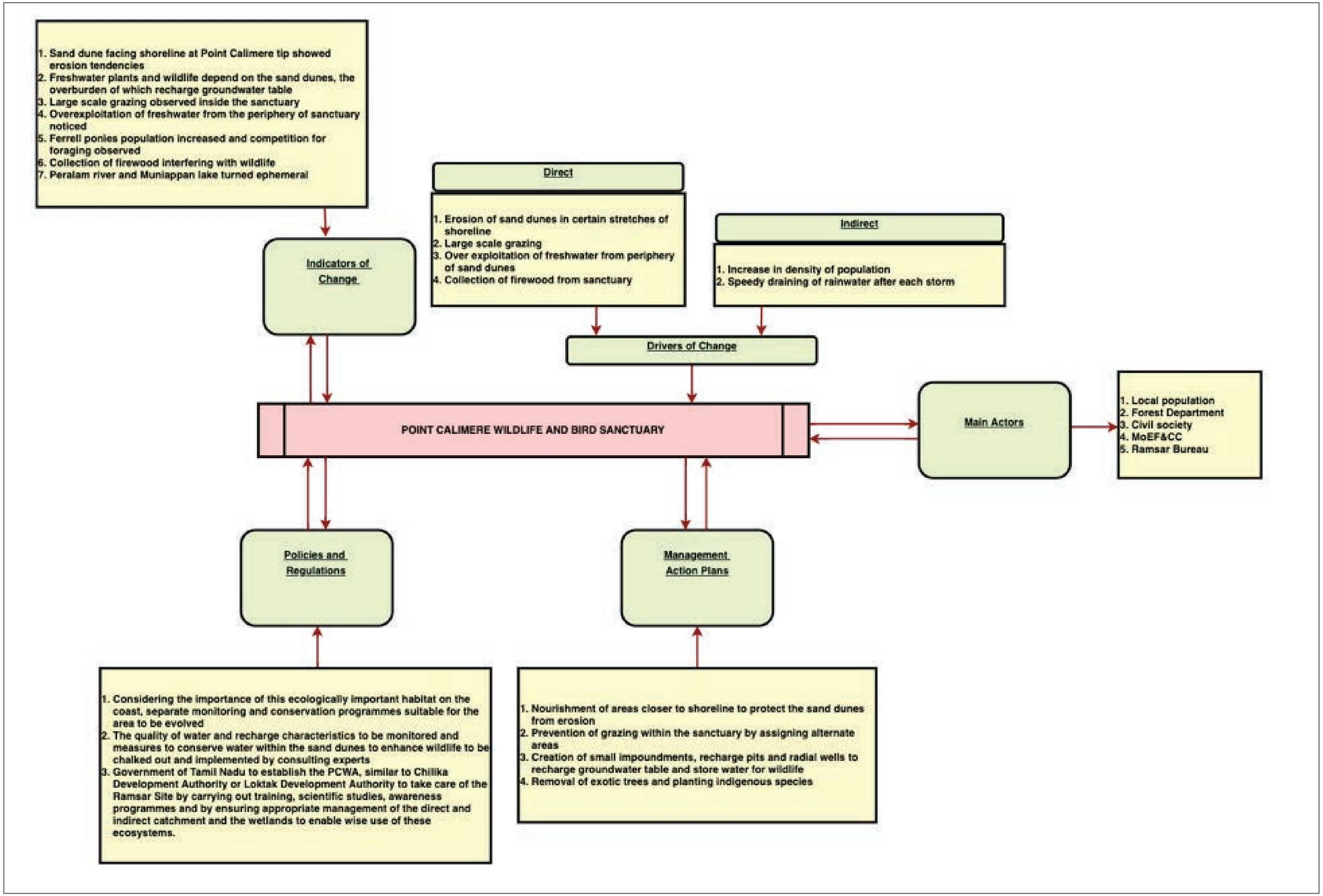


***Figure 11.5** Point Calimere Wildlife and Bird Sanctuary – indicators, drivers of change, actors, MAPs and policy interventions*

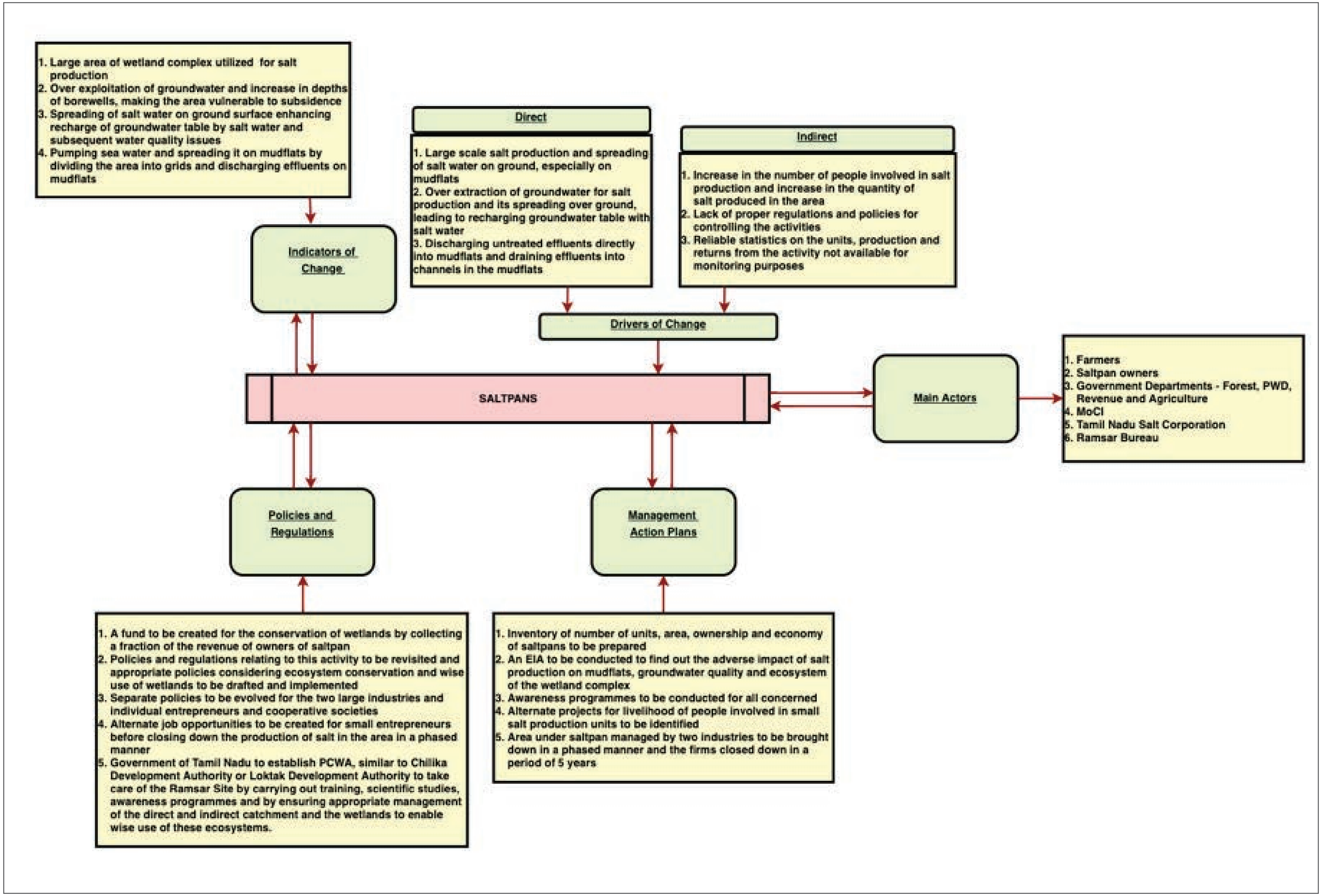


Figure 11.6 *Saltpans - indicators, drivers of change, actors, MAPs and policy interventions*

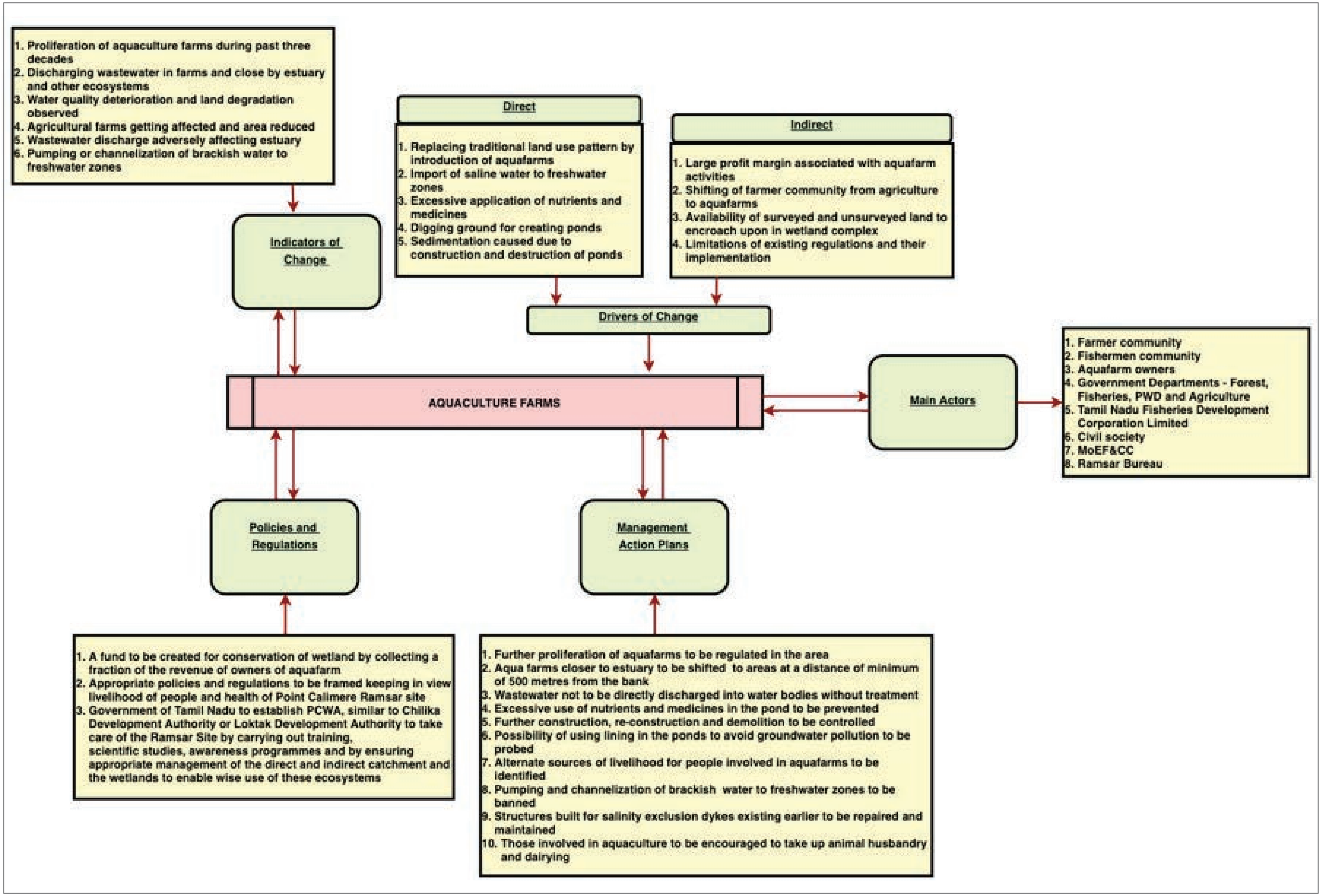


Figure 11.7 *Aquaculture farms – indicators, drivers of change, actors, MAPs and policy interventions*

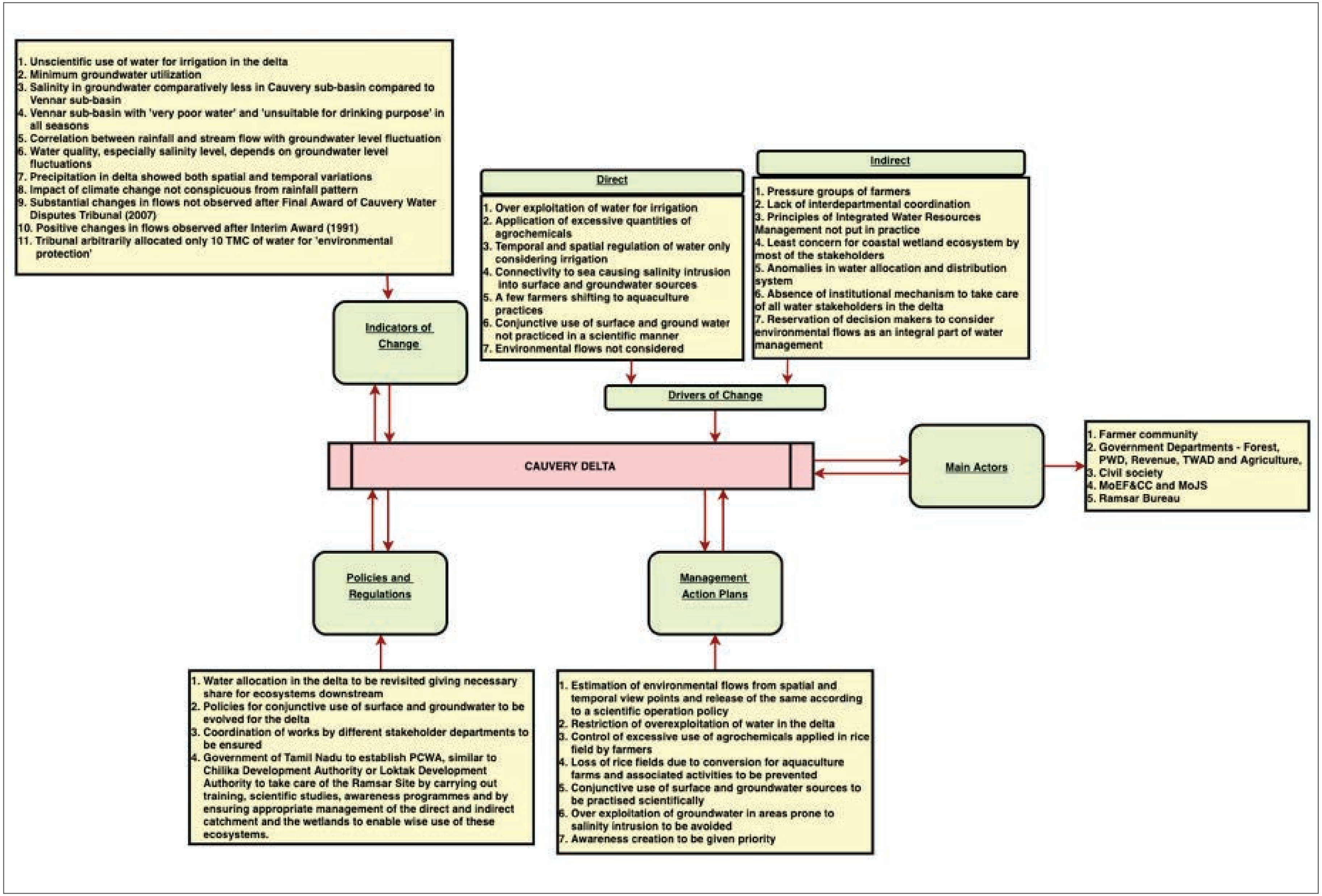


***Figure 11.8** Cauvery delta – indicators, drivers of change, actors, MAPs and policy interventions*

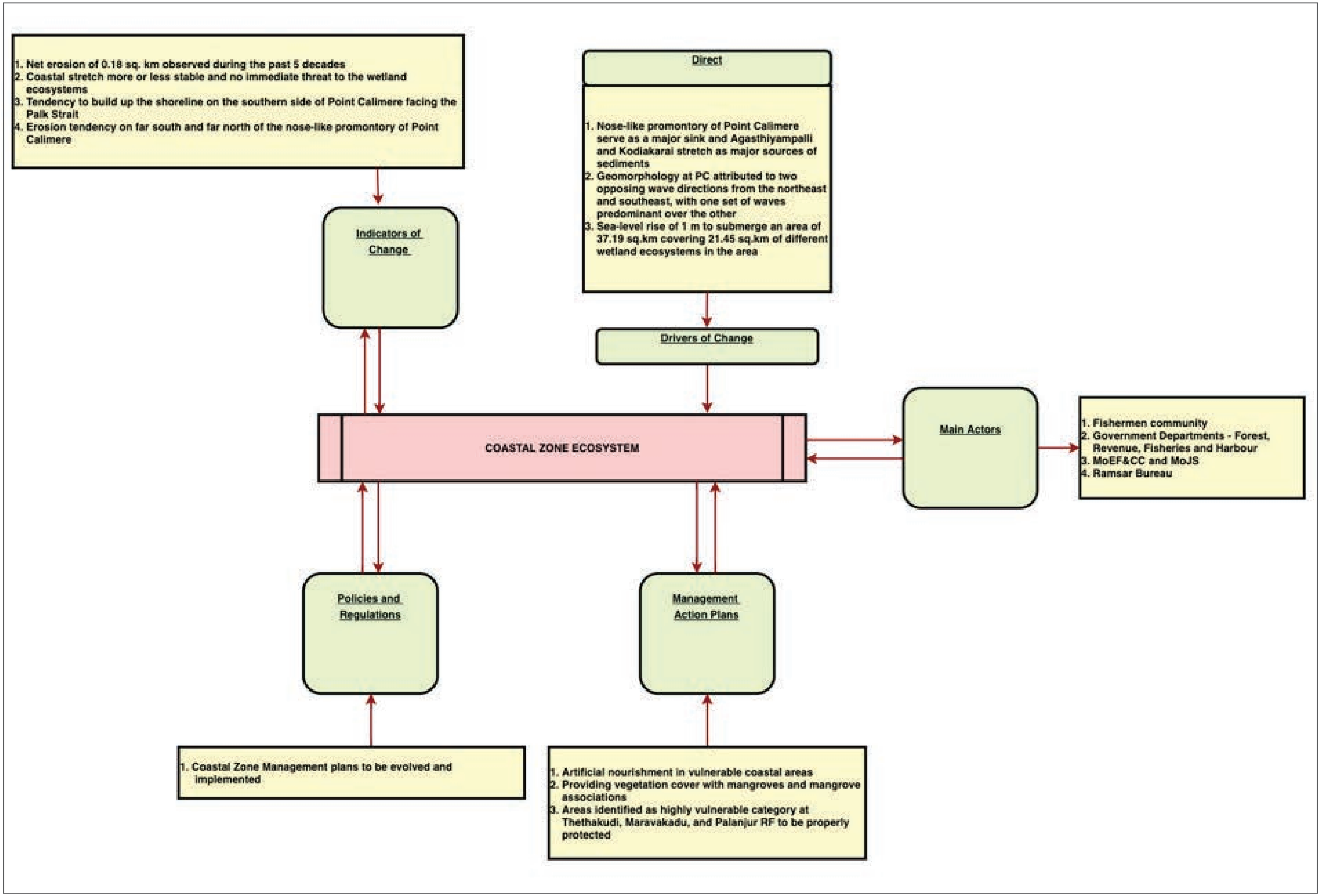


Figure 11.9 *Shoreline change – indicators, drivers of change, actors, MAPs and policy interventions*

11.4 Proposed Policy Decisions and Management Action Plans

11.4.1 Point Calimere Wetland Authority (PCWA)

Integrated management of river basins in relation to wise use of wetlands has been well recognised by the Ramsar Convention and international agencies such as Wetlands International, IUCN and CBD. In fact, the Dublin Conference (1992) identified the need for integrated water resource management considering not only its use for development purposes but also for ecosystem management. This was elaborated in Agenda 21:18 of the Rio Conference (1992) and subsequently reflected in the Millennium Development Goals and the Sustainable Development Goals. The approach was experimented in the case of Mekong River basin and Agusan River basin in the Asia-Pacific region. The need for integrated river basin management in the context of downstream wetlands was recognised by India, and plans were drawn up for Ramsar sites such as Vembanad-Kol (WISA), Chilika (WISA) and Loktak (WISA), and some of the recommendations were successfully implemented in the field to conserve water and biodiversity of these wetland systems.

The study on Point Calimere wetland complex has brought to light that the management of basins of rivers draining into the wetland is important from the point of view of freshwater input, reduction in pollution load and finally the health of the ecosystem, biodiversity in it and ecosystem services offered by these diverse wetlands and forest ecosystems. The entire delta of Cauvery can be considered as a wetland within which there are several smaller wetland ecosystems with their unique identity and characteristics. For the wise use of these wetlands and to ensure their ecosystem values, there is a need to adopt integrated management of the Cauvery basin in relation to the coastal ecosystems. One of the major problems encountered by the present study is a lack of environmental flows, especially during the summer months. This has adversely affected the health of the coastal wetlands and their ecosystem services. Moreover, there are a variety of activities going on in the complex causing problems to the quality of water, such as aquaculture farms, saltpans and salt-manufacturing units, apart from agricultural practices that overuse agro-chemicals. Considering all these aspects, the need for an integrated management of the wetland complex located within the delta has been recognised. Since most of the natural and regulated flows from the river basin available for the State is used for agriculture purpose, there is a need to adopt an integrated management to ensure the health of the wetlands. This can be achieved only through an organisational setup in which all the actors and stakeholders are involved. Therefore, the need for Point Calimere Wetland Authority (PCWA) in line with that of the Chilika and Loktak is suggested for integrated management of the diverse wetlands and forest ecosystems in the delta of the Cauvery. The recommended organisational structure of Point Calimere Wetland Authority is given in figure 11.10. The recommended policy decisions may be referred to the State Wetland

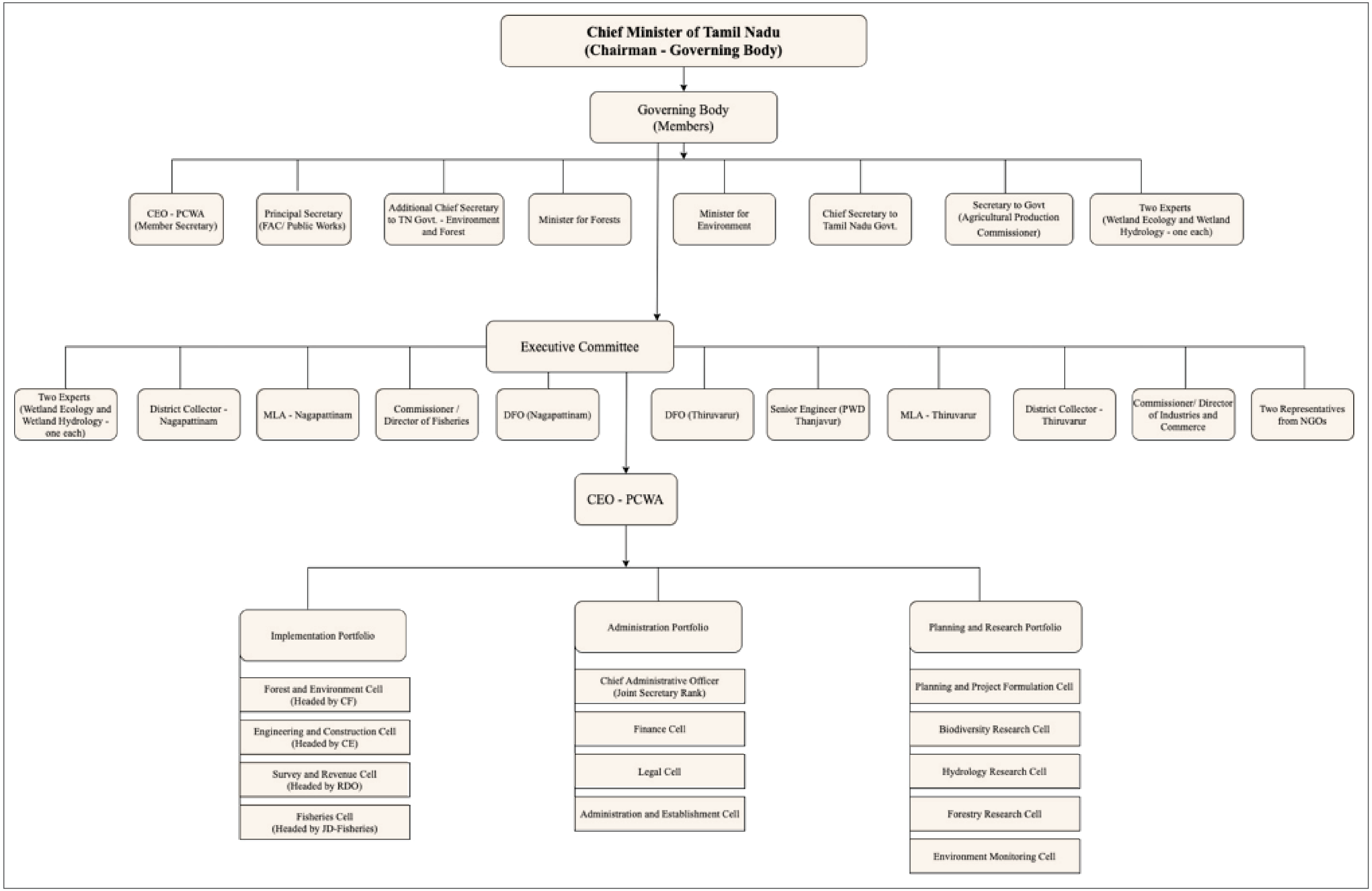


Figure 11.10 *Recommended organisational structure of PCWA*

11.4.2 Hydrology and Ecology Monitoring Mechanism

The need for systematically monitoring the direct catchment of the wetland and the wetland as such has been recognised since the available data collected from the field by different departments may not be sufficient to come out with a scientific management of the wetland system. The monitoring mechanisms may be broadly classified into those dealing with hydrology and related parameters and ecology and related parameters. Since the hydrology and ecology of a wetland are highly dynamic, constant monitoring in space and time is essential. Historical data alone can help in drafting and implementing management action plans for these fragile ecosystems. The monitoring and management of the wetland system, including its direct catchment, have to be managed by Point Calimere Wetland Authority.

The following recommendations are made with regard to the monitoring of hydrology and related parameters:

i) An IoT enabled automatic weather station may be established close by the Mulliyar head which is more or less a central location of the direct catchment which contribute to the natural flows to the wetland.

ii) One Class-A meteorological yard as per the IMD specification may be established at Jambuvanodai on the upstream of Muthupet Estuary and another one in the Point Calimere Wildlife and Bird Sanctuary.

iii) One standard and one automatic rain gauge may be installed in addition to the meteorological yard at each of the following five sites: (i) on the east of Muthupet estuary in the unsurveyed mudflats, (ii) upstream of the Siruthalaikadu lagoon, (iii) Panchanadhikulam mudflats, (iv) adjacent to the pumping station near the bird sanctuary and (v) Point Calimere Wildlife and Bird Sanctuary.

iv) Using staff gauges and IoT enabled sensors, the water level at all the regulators in Paminiyar, Koraiyar, Kilaithangiyar, Marakkakoraiyar, Valavanar, Mulliyar, Adappar and Harichandranadhi may be monitored. The outflow from each of the regulators during ebb tides may be measured by IoT enabled flow measuring devices.

v) Using sensors as well as collecting samples, the water quality and suspended sediment load at all the stations mentioned under (iii) may be monitored; the sensors may be enabled by IoT.

vi) The physical, chemical and biological parameters of the wetland have to be monitored both by IoT enabled sensors and by manual collection of samples from the field and tested in the laboratory, if needed.

vii) The network of stations may have to be decided on the basis of field investigations.

viii) The inflow into the Vedaranyam main canal and outflow as well as salinity levels are to be systematically monitored by IoT enabled sensors and by installing staff gauges.

ix) The soil characteristics, especially the soil moisture content, have to be monitored using sensors/tensiometers, especially in the mudflats.

x) An inventory of both aquaculture farms and saltpans has to be taken, and water utilisation and water quality are to be systematically monitored.

xi) The groundwater table fluctuations in the direct catchment and the periphery of wetlands are to be monitored using IoT enabled sensors and by physical measurements.

xii) The water quality parameters of groundwater also have to be monitored using IoT enabled sensors and by physically collecting the samples.

xiii) The groundwater table fluctuations and quality parameters are to be measured in Point Calimere Wildlife and Bird Sanctuary and tropical semi-evergreen forest to understand the role of sand dunes in groundwater recharge and quality status.

xiv) The water level fluctuations at different cross sections of the lagoons and the bird sanctuary may be monitored by IoT-enabled sensors along with salinity levels and transmitted to the central monitoring station.

The network of hydrologic and related monitoring stations recommended are given in figure 11.12. The proposed interventions in the direct catchment and wetland complex are given in figure 11.11.

The following 19 characteristics and parameters with regard to the ecosystems are to be monitored:

i) The availability and supply of nutrients
ii) The availability and supply of sediments
iii) The availability and supply of freshwater
iv) The primary productivity
v) The secondary productivity
vi) The food chain
vii) The characteristics of the soils
viii) The mixing, circulation and dispersion
ix) The flora and fauna
x) Changes to the ecosystem characteristics
xi) Impact of climate change
xii) Impact of sea level rise
xiii) Impact of coastal erosion
xiv) Impact of anthropogenic activities
xv) Impact of natural hazards
xvi) Ecosystem services
xvii) Changes in land cover and land use in the direct catchment
xviii) The biodiversity
xix) Ecosystem values and benefits such as agriculture, fisheries, tourism and salt production

A detailed study has to be conducted before deciding on the exact locations for monitoring.

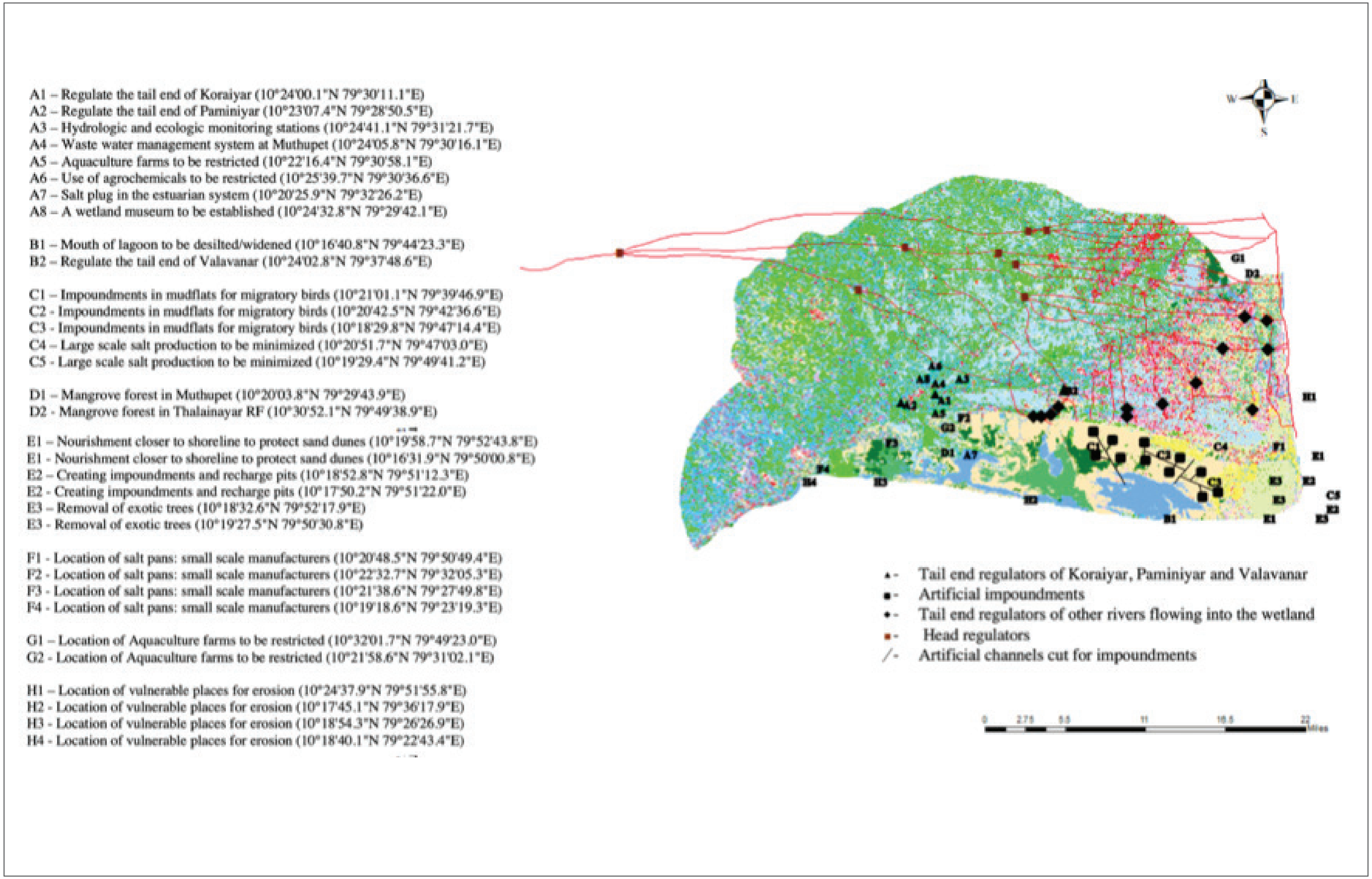


Figure 11.11 *Interventions in the direct catchment and wetland complex*

1	Automatic weather close by the Mulliyar head
2, 3	Class-I meteorological yards at Jambuvanodai and Vedaranyam Wildlife Sanctuary
4 to 8	Standard and automatic rain gauges on the east of Muthupet estuary, upstream of Siruthalaikadu inlet, Panchanadhikulam mudflats, adjacent to the pumping station near the bird sanctuary and Vedaranyam wildlife sanctuary
9 to 17	Staff gauges and IoT enabled sensors at all the regulators in Paminiyar, Koraiyar, Kilaithangiyar, Marakkakoraiyar, Valavanar, Mulliyar, Adappar and Harichandra nadhi
18 to 24	Physical, chemical and biological parameters monitoring stations
25, 26	IoT enabled sensors to monitor the inflow and outflow in the Vedaranyam main canal
27 to 29	Sensors/tensiometers to monitor soil characteristics in the mudflats.
30, 31	Monitor the inventory of both aquaculture farms and salt pans
32	IoT enabled sensors to monitor the groundwater table fluctuations in the direct catchment and the periphery of wetlands

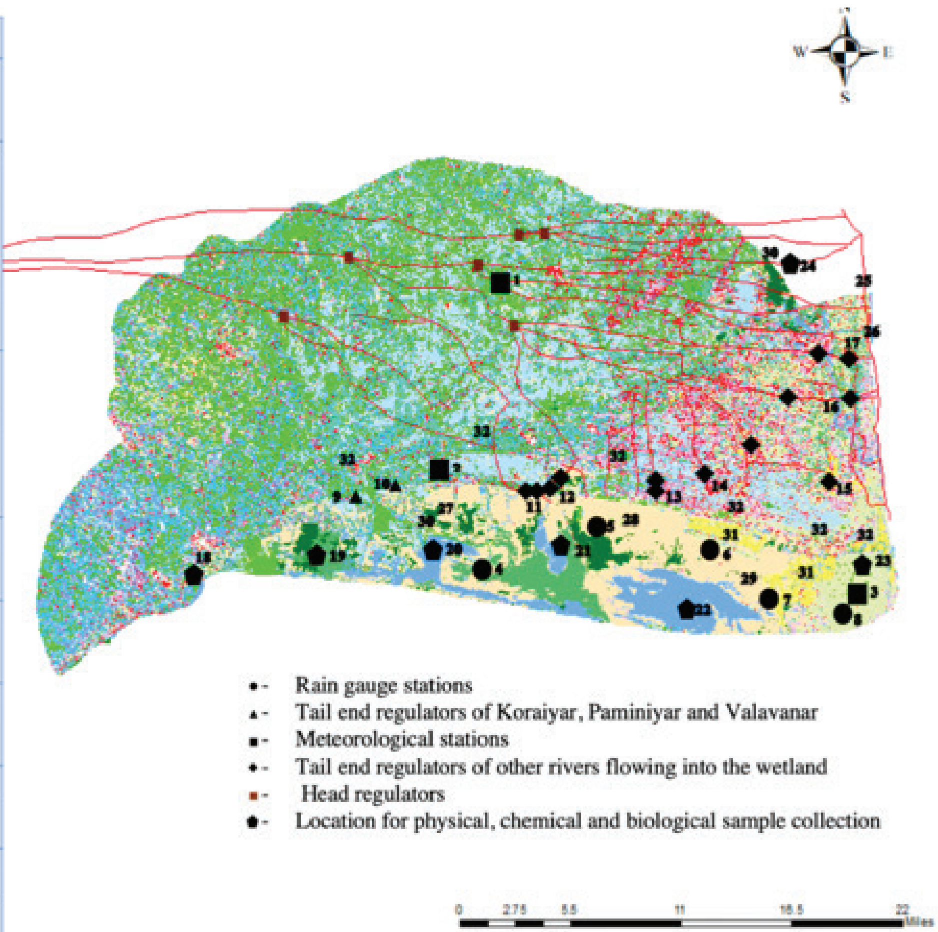


Figure 11.12 Network of hydrologic and related monitoring stations

12. RECOMMENDED MANAGEMENT ACTION PLAN

These are the recommended management action plans:

- Release of 10 m^3/s of water all through the year from the regulators of the Koraiyar and Paminiyar will bring down the salinity levels in the lower reaches of the Koraiyar to 17 ppt, which has been suggested as being ideal. A thick growth of mangroves is found in the lower reaches of the Koraiyar, where the nutrient values may be high. The water released will definitely go to the wider portion of the Muthupet estuary on its way to the Palk Strait and proportionately dilute the salinity levels in that stretch also. The investigators had suggested a 10 m^3/s flow in certain other rivers also in the report to rejuvenate the mangroves planted on the fringes of the Siruthalaikadu inlet and other parts of the Panchanadhikulam mudflats. In fact, the CWDT had recommended 10 TMC of water for environmental flows. Flows are available during the three monsoon months to cater to the requirements of mangroves. Selvam et al., have suggested 17 ppt as the threshold salinity level for the healthy growth of mangroves.
- The hydroperiod and water balance of the ecosystems concerned are to be estimated to come out with scientific management action plans.
- The wastewater from the Muthupet town is to be treated before discharging into the water course, especially into Muthupet wetland. Since land is available, artificial wetlands can be attempted for the treatment of sewage water.
- Aquaculture farms are to be restricted within 500 m from the existing water sources, and wastewater from such farms has to be treated before it is discharged into the water courses.
- The present use of agro-chemicals in rice fields has to be ascertained and restricted to the minimum to avoid pollution of surface and groundwater sources.
- If flushing is found to be insufficient to transport the sediments beyond the salt plug in the estuary, possibilities of dredging between 5-7 km from the mouth be probed without causing much changes to the habitat, after a detailed study.
- An experimental station and wetland museum for educational purpose and awareness creation may be established at Point Calimere Wetland Complex.
- It is suggested that 10 m^3/s flow be maintained in the Mulliyar, Valavanar and Marakkakoraiyar so as to bring down the salinity levels in the mudflats and Siruthalaikadu Lagoon.
- Increase water flow from the Manakundan river to the Seruthalaikadu Lagoon and nearby mudflats, at least from July to September; this will help create an environment for the proliferation of soil fauna, a feed for waterbirds.
- The width of the Siruthalaikadu Lagoon mouth may be increased from 300 m to 600 m to ensure proper tidal flushing.
- The degradation of mudflats due to activities related to saltpan, aquaculture farms and encroachment are to be brought down by formulating a set of policies and enactments.
- On an experimental basis, shallow impoundments may be attempted on the mudflats on the sides of the existing inlet channels to attract more birds. If successful, more such impoundments are to be made in the mudflats.
- The un-surveyed salt swamps and other wetland areas are to be surveyed at the earliest and boundaries demarcated.
- The small-scale salt producers may be trained for other skilled jobs so that they are discouraged from focusing on salt production in the area.
- Desilting of fishbone channels in mangrove areas is to be ensured to permit water to enter the habitat.

- A few sluice gates may be made in the Vedaranyam Main Canal dyke to permit brackish water to enter in to the Thalainayar Reserve Forest for the healthy growth of mangroves.
- The area under mangroves and the health of the ecosystem are to be monitored systematically.
- Participatory planning, management and monitoring mechanisms are expected to be of use for managing mangrove ecosystems and resolving conflicts.
- The grazing within Point Calimere Wildlife and Bird Sanctuary has to be prevented and alternate sites assigned for grazing.
- Small impoundments, recharge pits and radial wells are to be created in Point Calimere Wildlife and Bird Sanctuary, and sand dunes are to be created for recharging the groundwater and storing water for the wildlife.
- Exotic trees are to be discouraged in Point Calimere Wildlife and Bird Sanctuary, and indigenous species are to be planted.
- The areas of sand dunes closer to the seashore are to be protected to prevent the sand dunes from erosion. Intensive monitoring of the sand dunes is to be undertaken considering the importance of this ecologically sensitive habitat.
- Policies to restrict and control the activities related to saltpans and aquafarms in this fragile zone have to be reviewed and revisited and appropriate policies introduced.
- An EIA has to be conducted to find out the adverse impact of salt production and aquaculture on the mudflats, groundwater quality and health of ecosystems in the wetland complex.
- Further proliferation of aquafarms has to be discouraged.
- Excessive use of medicines and nutrients in the aquafarms is to be prevented, and further construction and reconstruction and demolition are to be discouraged.
- The possibility of lining the aquaculture ponds to avoid pollution is to be probed.
- Pumping and channelisation for bringing brackish water to freshwater zones are to be controlled.
- The structures built for salinity exclusion right from the British period are to be maintained and repaired.
- The water allocation policy in the Cauvery Delta is to be revisited providing due share to the ecosystems downstream.
- Conjunctive use of surface and groundwater is to be evolved for the delta.
- The overexploitation of water in the delta for agriculture purposes is to be discouraged.
- Loss of rice fields due to conversion of aquafarms has to be prevented.
- Coastal zone management plans are to be evolved and implemented.
- Artificial nourishment in vulnerable coastal areas is to be initiated.
- Providing vegetation cover with mangroves and mangrove associations at the appropriate stretches of coastal belt has to be encouraged.
- The coastal areas identified under the highly vulnerable category at Thethakudi, Maravakadu and Palanjur are to be protected.
- The freshwater flow into the bird sanctuary has to be enhanced to 10 m^3/s during the last phase of the north-east monsoon, during which there is availability of water in the delta.
- A water level of around 20 - 25 cm has to be maintained in the bird habitat.
- The non-point pollutants discharged from the rice fields will have to be controlled such that they do not pollute the bird sanctuary and the aquatic ecosystem.
- Promote traditional canal fishing involving more fishers.
- A local-level forum involving many stakeholders, fishers, the Fisheries Department, the Forest Department, NGOs, etc. can be formed to promote and sustain traditional canal fishing so that mangroves will thrive and livelihood security will be provided to local fishers.

- Small impoundments, detention storages and radial wells may be well suited for recharging the groundwater table in PCWBS
- It may be noted that saltpans have considerably disturbed the mudflat ecosystem by the construction of dykes for detaining saltwater and construction of pathways for movement of people. Moreover, pumping large quantity of seawater into the mudflats completely changes its characteristics. The suggestion for small impoundments for saltwater for attracting fish and birds for a vibrant biodiversity should be distinguished from large-scale development activities in the mudflats for salt production. The compartments and grids within the mudflats have totally degraded the natural ecosystem. The large-scale extraction of saltwater from groundwater sources and spreading it on the saltpans for producing edible salts may have far reaching consequence on the ecosystem. Therefore, it is recommended in the report to bring down the area under salt pan in a phased manner and permit only marginal stakeholders to continue with salt production in the area.

List of priority waterbodies within the wetland complex that should be taken up for restoration with supporting information or data:

- It is suggested that after detailed investigation, the possibility of dredging the Muthupet Estuary, where a salt plug is formed and sediments settle down, should be explored. The flow dynamics may have to be thoroughly investigated with the support of model studies before identifying the exact area to be dredged in the longitudinal and lateral directions. A grain size analysis of sediments has to be carried out to understand the gradation and origin – riverine or marine.
- In the case of Muniappan Lake, desilting may be done after identifying the locations of recent sediment deposition. This will enable the storage of more water for different purposes as mentioned in the original report. However, deepening beyond the threshold level may lead to salinity intrusion into the water body.
- Water storage structures. The suggestion of exploring the possibilities of existing water storage structures to cater to the requirements of Muthupet estuary, 10 m^3/s, is impractical. To store the water for releasing 10 m^3/s flow for one month, it requires 2 m - depth of water with an area of 12.95 km^2. For ten non-monsoon months, we may require ten such water bodies to store water. However, high evaporation and infiltration losses are not considered in this estimate. Depth of 2 m is assumed because of fear of salinity intrusion.

- The following existing water bodies were identified just upstream of the wetland complex as suggested during the meeting:
    - Water body with a waterspread area of 27.6 ha near Melammankurichi already linked to Paminiyar
    - Water body with a waterspread area of 42.09 ha near Uthayamarthandapuram already linked to Koraiyar
    - Water body with a waterspread area of 32.14 ha near Chokkanavur already situated on the banks of the Paminiyar
    - Water body with a waterspread area of 13.81 ha near Mangal to be linked to the Paminiyar (0.89 km)
    - Water body with a waterspread area of 36.46 ha near Kovilankadu to be linked to the Paminiyar (0.43 km)

The total water storage capacity of these water bodies works out to only 2.614 Mcum. This is quite insignificant in the context of the requirements of the Muthupet Estuary. In the management action plan, locations have been identified (E2 – creating impoundments and recharge pits at 10º 18′ 52.8″ N, 79º 51′ 12.3″ E and 10º 17′ 50.2″ N, 79º 51′ 22.0″ E) for artificial recharge. These points are located in the bed of the Peralam river, and there is a stream flowing from Peralam towards the sea. These proposed recharge pits can enhance the freshwater availability. In the PCWLS, it is observed that the connectivity between the mudflats in the VWS, Peralam River and the backwaters has been lost. Since there is no flow in the Peralam River in the sanctuary, the Muniappan Lake, which has been serving as a source of water for the village community in Kodikkarai, has dried up. The flow to the Peralam River from the mudflats ceased due to the construction of saltpans in the mudflats near the seacoast. The restoration of Muniappan Lake and Peralam river may provide a perennial source of water in the PCWLS. The discharge of effluents near the Muniappan Lake should be restricted from entering the lake. The ponds situated across the road in VWS may be connected with the lake. To connect the Peralam River and Muniappan Lake with the existing channel of 0.68 km, it has to be extended for 0.405 km. Desilting of the lake may be carried out in a phased manner. Water has to be released from the Koraiyar and Paminiar to meet the water requirements of the Muthupet Estuary. It is also suggested that water be released from the Marakakoraiyar, Mulliyar and Valavanar to meet the water requirements of mangrove areas on the fringes of the Siruthalaikadu inlet and Panchanadhikulam mudflats as mentioned in the report.

12.1 Proposed research studies

i. An inventory of saltpans including the details on owners, area occupied, returns from them, number of people engaged, quantity of salt produced and the number of bore wells dug and the quantum of water extracted to be made to support the decision-making system.

ii. Assess the impact of the industrial and edible salt (small-scale) production on the groundwater quality in the Point Calimere Wetland Complex ecosystems.

iii. Investigate the role of the saltpans as a feeding ground for waterbirds.

iv. A comprehensive study on the impact of aquafarms on the ecosystems of Point Calimere Wetland Complex and on the groundwater quality. It should cover the quantity of effluents discharged, quality of effluents, nature and concentration of pollutants in the effluents, migration of pollutants by tidal currents, residential time of the pollutants etc.

v. The impact of agro-chemicals used in the buffer zone on the groundwater quality of both the buffer zone and PCWC needs to be investigated thoroughly

vi. Data on soil and water quality of different wetlands/ecosystems are inadequate for preparing detailed management action plan. It is in this context, a network of stations for detailed data collection suggested in the report. These stations are to be installed, maintained and data collected following the latest advancements in the field of hydrologic instrumentation, as suggested in the report.

vii. The impact of climate change could not be understood with the limited data available. Therefore, a network of hydro-meteorologic stations is recommended.

viii. The implications of largescale extraction of groundwater for maintaining the saltpans has not been properly understood. Do they cause subsidence? Do they increase the level of salinity in groundwater sources? Does it have any geogenic impact?

ix. The water quality, nutrient load and primary productivity and finally the food chain are to be studied in detail for coming out with a scientific management action plan.

x. The role of mudflats in balancing the ecosystem has not been properly understood. This has to be investigated in detail because the sea and river interaction, the water and sediment dynamics, formation of different wetland ecosystems and biodiversity of Point Calimere are closely related to the mudflats.

xi. The formation of sand dunes and their role in providing freshwater in the coastal belt of Point Calimere requires further investigation.

xii. Carry out a survey of the status and extent of mudflats and *Prosopis proliferation - Prosopis juliflora* covers an area of 3.75 km^2 on the mudflats of Point Calimere near the saltpans. Saurav Gupta (2019) has reported that Prosopis juliflora, an exotic plant species introduced in 1961 as a wind barrier has doubled its extent of coverage from 3.03 km^2 in 1990 to 6.16 km^2 in 2019 in VWS. FERAL (2005) has reported that the sand dunes are largely colonised by invasives such as *Prosopis juliflora* and *Calotropis gigantea.* Prosopis has invaded both the TDEF in the Kodikarai area and the mangroves near Muthupet. It has taken over expanses near the coast. The presence of Prosopis correlates with a reduction in plant diversity. It is not clear yet whether the Prosopis invades open patches or replaces the vegetation in existing patches. This would be an interesting research topic, but this research does not need to be carried out as a priority. In any case, its presence as an invasive alien species mandates its removal as a top priority. The fuelwood requirements of the villagers of Kodiyakadu Village can be met by allowing them to remove only Prosopis, provided they remove the roots as well. Thought may be given to contracting out Prosopis removal for charcoal manufacture as an alternate fuel material.

ANNEXURE I

Table A1 *Villages in the direct catchment*

Sl. No.	Village	Area (km²)
1	Adhanur	7.69
2	Adirampattinam	4.24
3	Adirangam	6.07
4	AkkaraiKottagam	6.51
5	Aladikkadu	1.13
6	Aladikkumulai	1.33
7	Alaginayagipuram	1.51
8	Alamathikkadu	1.57
9	Alangadu	6.16
10	Alanpallam	3.58
11	Alathur	3.30
12	Alivalam	0.72
13	Ambalapattu North	3.07
14	Ambalapattu South	1.83
15	Ambalapattu South Sivakollai	4.01
16	Anaikkadu	5.23
17	Andagathurai	3.39
18	Andami	5.62
19	Andikkadu	3.42
20	Ariyalur	5.56
21	Athikkottai	4.91
22	Athivetti East	4.93
23	Athivetti West	5.01
24	Avaikkottai	3.87
25	Ayakkarambulam III Sethi	8.11
26	Ayakkarambulam IV Sethi	4.89
27	Ayakkaranbulam II Sethi	6.86

Sl. No.	Village	Area (km²)
28	AyakkaranbulamIstSethi	6.58
29	Ayemoor	7.82
30	Balajireguramasamudram	0.62
31	Bavajikkottai	2.21
32	Chatramthokkalikadu	0.29
33	Chettipulam	17.23
34	Chettiyamoolai	1.09
35	ChinnaavadayarKoil	5.25
36	Chokkanathapuram	7.79
37	Chokkanavur	6.35
38	Deevambalpuram	6.31
39	Desingurajapuram	4.15
40	Devadanam	5.34
41	Edaiyur	8.63
42	Ekkal	3.86
43	Elangadu	0.25
44	Elangadu	3.39
45	Elangadu	0.43
46	Elavanur	7.47
47	Eralivayal	1.06
48	Eripurakarai	4.50
49	Ethangudi	1.95
50	Ettivayal	2.25
51	Ettupulikkadu	1.77
52	Ezhilur	5.70
53	Gangadharapuram	1.23
54	Gopalapuram	0.50

Sl. No.	Village	Area (km²)
55	Gopalasamudram	1.43
56	Idumbavanam	15.12
57	Jambuvanodai	12.54
58	Kadanthethi	1.83
59	Kadathankudi	6.17
60	Kadinevayal	5.38
61	Kaduvakothamangalam	1.08
62	Kalichankkottai	0.42
63	Kalikudy	3.57
64	Kallimedu	9.37
65	Kallivayal	1.15
66	Kalyanaodai	3.07
67	Kaniyakurichi	1.51
68	Kannugudi (West) Addl.	0.04
69	Kannugudi (West) Chief	1.46
70	Kannugudi East	5.75
71	Karagavayal	6.53
72	Karambakkadu	1.16
73	Karambayam	0.27
74	Karappankadu	2.31
75	Karisavayal	2.02
76	Karppaganatherkulam	10.93
77	Karuppukilar	4.93
78	Karuppur	4.68
79	Karurpambulam	9.21
80	Kasangadu	4.08
81	Katharipuram	14.35
82	Kattaiyankadu	1.31
83	KattayankaduUkkadai	1.40
84	Kattimedu	3.30
85	Keelakurichi East	5.03
86	Keelakurichi West	4.53
87	Keelaperumazhai	5.88
88	Keerakkalur	3.40

Sl. No.	Village	Area (km²)
89	Keezhapandi	4.13
90	Kelaammankurichi	7.24
91	Keluvathur	4.01
92	Kodiakarai	11.26
93	Kodiakkadu	3.54
94	Kodiyalam	1.63
95	Kokkalady	7.11
96	Koopachikkottai	0.21
97	Korukkai	14.41
98	Kothamangalam	6.87
99	Kothangudi	1.88
100	Kotthadivayal	1.97
101	Kottur	2.64
102	KotturThottam	0.62
103	Krishnapuram	5.47
104	Kulamanickam	4.20
105	Kullukkadu	4.33
106	Kuluvankadu	0.77
107	Kunnalur	15.67
108	Kunnur	4.58
109	Kuravapuram	10.12
110	Kuruchi	4.20
111	Kuruchimoolai -I	2.79
112	Kuruchimoolai -II	4.03
113	Kurumbal	3.31
114	Kuruvikarambai I	0.35
115	Kuruvikarambai II	4.55
116	Madukkur	4.42
117	Madurabashanipuram	2.19
118	Mahadevapuram	3.21
119	Maharajapuram (East)	4.57
120	Maharajapuram (West)	6.58
121	Mahilankottai	3.85
122	Manakkudi	1.22

Sl. No.	Village	Area (km²)
123	Gopalasamudram	1.43
124	Idumbavanam	15.12
125	Jambuvanodai	12.54
126	Kadanthethi	1.83
127	Kadathankudi	6.17
128	Kadinevayal	5.38
129	Kaduvakothamangalam	1.08
130	Kalichankkottai	0.42
131	Kalikudy	3.57
132	Kallimedu	9.37
133	Kallivayal	1.15
134	Kalyanaodai	3.07
135	Kaniyakurichi	1.51
136	Kannugudi (West) Addl.	0.04
137	Kannugudi (West) Chief	1.46
138	Kannugudi East	5.75
139	Karagavayal	6.53
140	Karambakkadu	1.16
141	Karambayam	0.27
142	Karappankadu	2.31
143	Karisavayal	2.02
144	Karppaganatherkulam	10.93
145	Karuppukilar	4.93
146	Karuppur	4.68
147	Karurpambulam	9.21
148	Kasangadu	4.08
149	Katharipuram	14.35
150	Kattaiyankadu	1.31
151	KattayankaduUkkadai	1.40
152	Kattimedu	3.30
153	Keelakurichi East	5.03
154	Keelakurichi West	4.53
155	Keelaperumazhai	5.88
156	Keerakkalur	3.40

Sl. No.	Village	Area (km²)
157	Nathapalam	0.59
158	Nattuchalai	6.41
159	Nayagathivayal	0.91
160	Neermulai	4.38
161	Neivilakku	3.72
162	Nemmeli	2.90
163	Nochiyur	5.03
164	Nokkanukkadai	0.99
165	Nunakkadu	4.53
166	Olayakunnam	9.58
167	Orathur	3.17
168	OttankaduUkkadai	0.11
169	Ovarur	7.29
170	Pachanathikulam Middle	6.29
171	Pachanathikulam Middle	1.05
172	Painganadu	5.22
173	Paingattur	5.75
174	Paingattuvayal	0.90
175	Palacherikkadu	0.11
176	Palaiyur	5.19
177	Palanjur	15.26
178	Palaverikadu	4.38
179	Palayakottaiparasapuram	3.99
180	Palayanatham	1.16
181	Palayangudi	1.19
182	PalayeeAgraharam	0.67
183	Pallathur	6.83
184	Pallikondan	4.44
185	Palliodiaivayal	0.94
186	Palliodiaivayal	1.75
187	Pamani	6.00
188	Panaiyur	3.95
189	Panaiyur	5.81
190	Panchanathikulam East	4.61

Sl. No.	Village	Area (km^2)
191	Panchanathikulam West	7.13
192	Pandi	3.99
193	Pannaitheru	4.21
194	Pannaivayal	4.82
195	Pannal	5.94
196	Parakakalakottai	4.08
197	Paravakkottai-I	2.24
198	Paravakkottai-II	2.79
199	Paravathur	3.69
200	Periyakkottai	7.11
201	Periyakuthagai	4.28
202	Perungavalandan	7.12
203	Perungavalandan	4.36
204	Peruvidamaruthur	1.90
205	Pichankottagam	7.03
206	Pinnathur	6.56
207	Piranthiyankarai	2.26
208	Ponkundu	0.56
209	Ponnavarayankottai	0.95
210	PonnavarayankottaiUkkadai	2.72
211	Poosalangudi	2.76
212	Poovanam	7.32
213	Pudukkottagam	4.92
214	Pudukkottai Ullur	5.34
215	Pudupattinam	0.97
216	Pudupattinam	0.93
217	Pudupattinam	0.92
218	Pudurivayal	0.91
219	Pukkarambai	4.26
220	Pulavanji	4.60
221	Puliyakudi	0.77
222	Pushpavanam	15.02
223	Puthagaram	8.06
224	Puthur	0.43

Sl. No.	Village	Area (km^2)
225	Puzhuthikudi	2.20
226	Radhanarasimmapuram	3.49
227	Rajamadam	5.61
228	Rajasambal Puram	2.69
229	Ramapuram	0.08
230	Rayanallur	5.79
231	Regunathapuram	0.84
232	Regunayagipuram	0.01
233	Reguramasamudram	0.40
234	Rendampulikadu	1.74
235	Renganathapuram	4.14
236	Sandampettai	1.05
237	Sanganthi	2.96
238	Santhankadu	1.97
239	Sarabendrarajanpattinam	0.93
240	Sathangudi	2.22
241	Segal	11.15
242	Sembagarayanellur	11.82
243	Sembalur	4.72
244	Sembodai	9.64
245	Sendakkottai	10.94
246	Sendankadu	4.59
247	Serugalathur	3.73
248	Seruvalakkadu	2.76
249	Sethubavachatram	0.28
250	Siramelkudi	1.88
251	Sithamalli	7.35
252	Soorapallam	6.38
253	Soundaranayakipuram	2.70
254	Sundaram	1.58
255	Talanayar	11.50
256	Talayamangalam	4.10
257	Talikkottai	3.09
258	ThagatturPethachikadu	4.27

Sl. No.	Village	Area (km²)
259	ThagatturSubramanyakadu	7.09
260	Thamarankottai North	9.31
261	Thamarankottai South	12.48
262	ThambikottaiMaravakad	21.80
263	ThambikottaiMelakkadu	6.06
264	ThambikottaiVadakadu	10.95
265	Thandamaraikadu	0.76
266	Thanikpttagam	8.16
267	Thennadar	8.26
268	Thenparai	7.89
269	Therkkunanallur	4.24
270	Thethakudi North	7.73
271	Thethakudi South	11.24
272	Thillaivilagam	18.24
273	Thirividaimaruthur	5.78
274	Thirukkalar	4.71
275	Thirumakkottai -I	3.03
276	Thirumakkottai -II	10.57
277	Thiruppattur	1.22
278	Thiruvalanjuli	3.49
279	Thittakudi	3.36
280	Thokkalikkadu	3.00
281	Tholi	3.97
282	Tholi	0.67
283	Thondiyakkadu	8.55
284	Thulasapuram	3.14
285	Thulasendarapuram	1.65
286	Thuraikkadu	3.61
287	Thuraiyur	1.05
288	Thuvarankurichi North	6.70
289	Thuvarankurichi South	4.06
290	Tirumangalakottai East (Colony)	0.00
291	Udayamarthandapuram	12.77
292	Udayamudaiyan	1.12
293	Umbalacheri	5.94
294	Uppur	6.34
295	Vadakadu	3.05
296	Vadamazhai	7.61
297	Vadasanganthi	3.21
298	Vadaseri North	1.69
299	Vadaseri South	5.55
300	Vadiakkadu	2.39
301	Vadugankuthagai	2.96
302	Vadugoor	4.84
303	Vaimedu East	6.51
304	Vaimedu west	16.22
305	Vallur	3.01
306	Vanduvancheri	8.51
307	Vanganagar	5.87
308	Vattakudi	4.45
309	Vattakudi	2.66
310	VattakudiUkkadai	3.08
311	Vattar	5.73
312	Vedaraniyapuram	0.82
313	Veerakurichi	0.19
314	Veeranvayal	6.07
315	Velivayal	1.65
316	Vellapallam	2.60
317	Velur	4.90
318	Vendakkottai	3.08
319	Venkathangudi	4.05
320	Veppankulam	4.64
321	Vikkiramam	8.83
322	Vilakkudi	4.75
323	Vilangady	7.36

__Table A2__ Villages in the buffer zone

Sl. No.	Village	Area (km²)
1	Adhanur	7.69
2	Adirampattinam	4.24
3	Adirangam	5.96
4	Aladikkadu	1.13
5	Alaginayagipuram	1.51
6	Alamathikkadu	1.57
7	Alangadu	6.16
8	Anaikkadu	5.23
9	Andagathurai	3.39
10	Andikkadu	3.21
11	Ariyalur	1.13
12	Athikkottai	1.07
13	Athivetti East	4.93
14	Athivetti West	5.01
15	Ayakkarambulam III Sethi	8.11
16	Ayakkarambulam IV Sethi	4.89
17	Ayakkaranbulam II Sethi	6.86
18	AyakkaranbulamIstSethi	6.58
19	Chatramthokkalikadu	0.29
20	Chettipulam	9.35
21	ChinnaavadayarKoil	5.25
22	Chokkanathapuram	7.79
23	Chokkanavur	4.10
24	Devadanam	3.18
25	Edaiyur	8.34
26	Ekkal	3.86
27	Elangadu	0.25
28	Elangadu	3.39
29	Elangadu	0.43
30	Eralivayal	1.06
31	Eripurakarai	4.02
32	Ettivayal	2.25
33	Gangadharapuram	1.21
34	Idumbavanam	15.12
35	Jambuvanodai	12.54
36	Kadathankudi	6.17
37	Kadinevayal	5.38
38	Kalikudy	3.47
39	Kallimedu	7.85
40	Kallivayal	1.02
41	Kalyanaodai	3.07
42	Karagavayal	6.53
43	Karambakkadu	1.16
44	Karappankadu	2.31
45	Karisavayal	2.02
46	Karppaganatherkulam	10.93
47	Karurpambulam	9.21
48	Kasangadu	4.08
49	Katharipuram	14.35
50	Kattaiyankadu	1.31
51	KattayankaduUkkadai	1.39
52	Kattimedu	2.28
53	Keelaperumazhai	5.88
54	Keezhapandi	4.13
55	Kelaammankurichi	7.24
56	Kodiakarai	9.74
57	Kodiakkadu	3.29
58	Kotthadivayal	1.97
59	Krishnapuram	5.47
60	Kullukkadu	4.02
61	Kuluvankadu	0.77
62	Kunnalur	15.67
63	Kuravapuram	10.12
64	Kuruvikarambai I	0.25
65	Kuruvikarambai II	4.54
66	Madurabashanipuram	2.19
67	Maharajapuram (East)	0.66
68	Maharajapuram (West)	2.28

Sl. No.	Village	Area (km²)
69	Mahilankottai	3.85
70	Mangal	2.07
71	Mannankadu	7.28
72	Mannukkunundan	5.92
73	Maravanvayal	1.27
74	Marudangavayal	2.36
75	MarudurTherku	8.26
76	MarudurVadakku	11.46
77	Melaammankurichi	2.45
78	Melamarathur	7.10
79	Melaperumazhai	4.56
80	Moothakurichi	5.38
81	Mudalcheri	3.88
82	Mulakarai	2.76
83	Murungapallam	2.90
84	Muthupet	0.57
85	Nadiam	6.12
86	Nadubalam	1.16
87	Naduvikurichi	0.40
88	Nagakudaiyan	8.60
89	Nainankulam	1.48
90	Nalavedapathi	5.49
91	Narasingapuram	0.45
92	Nattuchalai	4.75
93	Nayagathivayal	0.87
94	Neivilakku	3.72
95	Nochiyur	5.03
96	OttankaduUkkadai	0.11
97	Ovarur	4.92
98	Pachanathikulam Middle	6.29
99	Pachanathikulam Middle	1.05
100	Paingattuvayal	0.90
101	Palacherikkadu	0.09
102	Palanjur	14.67

Sl. No.	Village	Area (km²)
103	Palaverikadu	4.38
104	PalayeeAgraharam	0.67
105	Pallathur	6.83
106	Pallikondan	4.44
107	Palliodiaivayal	0.94
108	Palliodiaivayal	1.75
109	Panchanathikulam East	4.61
110	Panchanathikulam West	7.13
111	Pandi	3.99
112	Pannaivayal	4.82
113	Pannal	5.94
114	Parakakalakottai	4.08
115	Periyakkottai	4.76
116	Periyakuthagai	4.28
117	Perungavalandan	1.08
118	Perungavalandan	4.36
119	Pichankottagam	7.03
120	Pinnathur	6.56
121	Piranthiyankarai	2.26
122	Ponkundu	0.56
123	Ponnavarayankottai	0.95
124	PonnavarayankottaiUkkadai	2.72
125	Poovanam	7.32
126	Pudukkottagam	4.92
127	Pudukkottai Ullur	5.34
128	Pudupattinam	0.97
129	Pudupattinam	0.93
130	Pudupattinam	0.56
131	Pudurivayal	0.91
132	Pukkarambai	4.26
133	Puliyakudi	0.77
134	Pushpavanam	15.02
135	Puthagaram	8.06
136	Rajamadam	5.48

Sl. No.	Village	Area (km²)
137	Regunathapuram	3.85
138	Reguramasamudram	2.07
139	Rendampulikadu	7.28
140	Sandampettai	5.92
141	Sanganthi	1.27
142	Sarabendrarajanpattinam	2.36
143	Segal	8.26
144	Sembagarayanellur	11.46
145	Sembodai	2.45
146	Sendakkottai	7.10
147	Serugalathur	4.56
148	Seruvalakkadu	5.38
149	Sethubavachatram	3.88
150	Siramelkudi	2.76
151	Sithamalli	2.90
152	Soundaranayakipuram	0.57
153	Sundaram	6.12
154	ThagatturPethachikadu	1.16
155	ThagatturSubramanyakadu	0.40
156	Thamarankottai North	8.60
157	Thamarankottai South	1.48
158	ThambikottaiMaravakad	5.49
159	ThambikottaiMelakkadu	0.45
160	ThambikottaiVadakadu	4.75
161	Thandamaraikadu	0.87
162	Thanikpttagam	3.72
163	Thennadar	5.03
164	Thethakudi North	0.11
165	Thethakudi South	4.92
166	Thillaivilagam	6.29
167	Thokkalikkadu	1.05
168	Tholi	0.90
169	Tholi	0.09
170	Thondiyakkadu	14.67

Sl. No.	Village	Area (km²)
103	Palaverikadu	0.84
104	PalayeeAgraharam	0.40
105	Pallathur	1.74
106	Pallikondan	1.05
107	Palliodiaivayal	2.96
108	Palliodiaivayal	0.68
109	Panchanathikulam East	5.07
110	Panchanathikulam West	11.82
111	Pandi	9.64
112	Pannaivayal	10.94
113	Pannal	3.73
114	Parakakalakottai	2.76
115	Periyakkottai	0.26
116	Periyakuthagai	1.88
117	Perungavalandan	7.35
118	Perungavalandan	2.70
119	Pichankottagam	1.58
120	Pinnathur	4.27
121	Piranthiyankarai	7.09
122	Ponkundu	9.31
123	Ponnavarayankottai	11.98
124	PonnavarayankottaiUkkadai	20.90
125	Poovanam	6.06
126	Pudukkottagam	10.76
127	Pudukkottai Ullur	0.76
128	Pudupattinam	8.16
129	Pudupattinam	8.26
130	Pudupattinam	7.73
131	Pudurivayal	11.24
132	Pukkarambai	18.24
133	Puliyakudi	3.00
134	Pushpavanam	3.97
135	Puthagaram	0.67
136	Rajamadam	8.55

Sl. No.	Village	Area (km²)
137	Regunathapuram	3.85
138	Reguramasamudram	2.07
139	Rendampulikadu	7.28
140	Sandampettai	5.92
141	Sanganthi	1.27
142	Sarabendrarajanpattinam	2.36
143	Segal	8.26
144	Sembagarayanellur	11.46
145	Sembodai	2.45
146	Sendakkottai	7.10
147	Serugalathur	4.56
148	Seruvalakkadu	5.38
149	Sethubavachatram	3.88
150	Siramelkudi	2.76
151	Sithamalli	2.90
152	Soundaranayakipuram	0.57
153	Sundaram	6.12
154	ThagatturPethachikadu	1.16
155	ThagatturSubramanyakadu	0.40
156	Thamarankottai North	8.60
157	Thamarankottai South	1.48
158	ThambikottaiMaravakad	5.49
159	ThambikottaiMelakkadu	0.45
160	ThambikottaiVadakadu	4.75
161	Thandamaraikadu	0.87
162	Thanikpttagam	3.72
163	Thennadar	5.03
164	Thethakudi North	0.11
165	Thethakudi South	4.92
166	Thillaivilagam	6.29
167	Thokkalikkadu	1.05
168	Tholi	0.90
169	Tholi	0.09
170	Thondiyakkadu	14.67
171	Thuraikkadu	3.61
172	Thuraiyur	0.65
173	Thuvarankurichi North	6.70
174	Thuvarankurichi South	4.06
175	Udayamarthandapuram	12.77
176	Udayamudaiyan	1.12
177	Uppur	6.34
178	Vadakadu	3.05
179	Vadamazhai	7.61
180	Vadasanganthi	3.21
181	Vadiakkadu	2.39
182	Vaimedu East	6.51
183	Vaimedu west	16.22
184	Vanduvancheri	8.51
185	Vanganagar	0.30
186	Vattakudi	4.45
187	Vattakudi	2.66
188	VattakudiUkkadai	3.08
189	Vedaraniyapuram	0.82
190	Veeranvayal	6.07
191	Velivayal	1.47
192	Vellapallam	2.60
193	Vendakkottai	3.08
194	Vikkiramam	8.72
195	Vilangady	7.36

ANNEXURE II

***Table A 3** Groundwater abstraction of blocks corresponding to Thiruvarur district*

District		Block name			
	Safe < 70%	Semi-critical 70-90%	Critical 90-100%	Overexploited >100%	Saline
Thiruvarur	1. Kottur	1. Koothanallur	1.Vadapathi-mangalam	1.Agarathirumalam	1.Alathampadi
	2. Kunniyur	2. Nannilam		2.Alangudi	2.Edaiyur
	3. Mannargudi	3. Sannanallur		3.Avoor	3. Muthupet
	4. Needamangalam			4.Kodavasal	4. Thiruthurai-poondi
	5. Palaiyur			5. Koradachery	
	6.Thalaiyamangalam			6. Kulikkarai	
	7. Thiruvarur			7. Peralam	
	8. Ullikottai			8. Thirukkanna-mangai	
	9. Vaduvur			9. Thiruvizhimazhai	
				10. Valangaiman	

***Table A4** Groundwater abstraction of Blocks corresponding to Nagapattinam district*

District		Block name			
	Safe < 70%	Semi-critical 70-90%	Critical 90-100%	Overexploited >100%	Saline
Nagapa-ttinam	1.Manalmedu			1.Vaitheeswaran Koil	1.Kangalancheri
				2.Thiruvilaiyattam	2.Kariyapattinam
				3.sembanarkoil	3.Keelaiyur
				3.Madhanam	4.Kilvelur
				4.Thiruvenkadu	5.Nagappattinam
				5.Palaiyur	6.Nirmulai
				6.Melaiyur	7.Thagatur
				7.Kuttalam	8.Thalainayar
				8.Manganallur	9.Therkupoig-ainallur
				9.Pattavarthi	10.Thevoor
				10.Puthur	11.Thillayadi
				11.Mayiladuthurai 12.sirkazhi	12.Thirukkuvalai 13.Thirumarugal

District		Block name			
	Safe < 70%	Semi-critical 70-90%	Critical 90-100%	Overexploited >100%	Saline
Nagapa-ttinam					13.Thirumarugal
					14.Thiruvengadu
					15.Valivalam
					16.Vedharanyam
					17.Velanganni

__Table A5__ Groundwater abstraction of blocks corresponding to Thanjavur district

District		Block name			
	Safe < 70%	Semi-critical 70-90%	Critical 90-100%	Overexploited >100%	Saline
Thanjavur	1. Perumagalur	1. Thanjavur	1. Nambivayal	1. Thirukkattupalli	
	2. Eachankottai	2. Saliyamna-galam	2. Pattukottai	2. Kandiyur	
	3. Cholanmaligai	3. Kurichi	3.Ulur	3. Melattur	
	4. Thekkur	4. Peravurani	3. Thambikottai	4. Kavalipatti	
	5. Sengipattai	5. Orathandu	4. Periyakottai	5. Kabisthalam	
		6. Budalur	5. Agarapettai	6. Andikkadu	
			6. Adhirampattinam	7. Nachiyarkoil	
			7. Sillathur	8. Thirumanga-lakottai	
				9. Murukkangudi	
				10. Tiruchitram-balam	
				11. Thiruvaiyaru	
				12. Vallam	
				13. Ammapet	
				14. Thanjavur	
				15. Aduthurai	
				16. Tiruppanandal	
				17. Ayyampettai	
				18. Nanjikottai	
				19. Nadukaveri	
				20. Pandanallur	

District		Block name			
	Safe < 70%	Semi-critical 70-90%	Critical 90-100%	Overexploited >100%	Saline
Thanjavur				21. Devanancheri	
				22. Kathiraman-galam	
				23. Madukkur	
				24. Avanam	
				25. Uruvikarambai	
				26. Papanasam	
				27. Thiruvida-marudur	
				28. Thondara-mpattu	
				29. Ramapuram	
				30.Thuvarankurichi	

Table A6 *Cross-correlation matrix between depth of water table and rainfall for different lag periods (Nagapattinam district)*

Well No	Without Lag	One-month Lag	Two-month Lag	Three-month Lag	Four-month Lag
43015	0.26	0.63	0.09	0.07	0.24
43024	0.15	0.76	0.51	0.47	0.27
43031	0.22	0.58	0.24	0.16	0.01
43032	0.02	0.54	0.17	0.04	0.12
43037	0.20	0.84	0.46	0.51	0.36
43058	0.07	0.29	0.00	0.14	0.32
43049	0.13	0.67	0.27	0.19	0.02
43050	0.44	0.67	0.28	0.25	0.02
43051	0.26	0.84	0.38	0.43	0.27
43052	0.15	0.42	0.03	0.17	0.33
43064	0.22	0.52	0.22	0.12	0.00
43068	0.02	0.78	0.35	0.32	0.16
43075	0.20	0.28	0.09	0.21	0.36
9001	0.07	0.31	0.60	0.73	0.68
09002 D	0.13	0.83	0.67	0.74	0.66
09003D	0.44	0.64	0.52	0.71	0.64

Well No	Without Lag	One-month Lag	Two-month Lag	Three-month Lag	Four-month Lag
9004	0.09	0.69	0.25	0.28	0.17
09009D	0.20	0.32	0.55	0.61	0.51
09010D	0.15	0.67	0.32	0.51	0.45
09011D	0.26	0.81	0.64	0.66	0.56

Table A7 *Cross-correlation matrix between depth of water table and rainfall for different lag periods (Thiruvarur district)*

Well No	Without Lag	One-month Lag	Two-month Lag	Three-month Lag	Four-month Lag
43018	0.53	0.42	0.21	0.00	0.20
43020	0.57	0.31	0.08	0.09	0.21
43021	0.36	0.54	0.35	0.17	0.03
43022	0.45	0.52	0.25	0.06	0.08
43041	0.04	0.86	0.63	0.39	0.22
43067	0.58	0.43	0.11	0.16	0.30
43071	0.15	0.80	0.65	0.43	0.16
43073	0.13	0.90	0.81	0.59	0.40
43074	0.03	0.82	0.6	0.38	0.24
10001D	0.24	0.65	0.51	0.33	0.14
10002D	0.15	0.69	0.48	0.33	0.21
10003D	0.24	0.66	0.45	0.25	0.11
10005D	0.34	0.69	0.43	0.20	0.00
10007D	0.09	0.43	0.35	0.33	0.30
10008	0.19	0.92	0.8	0.61	0.47
10009	0.26	0.31	0.84	0.66	0.53
10010	0.05	0.78	0.63	0.44	0.30
10011	0.11	0.72	0.59	0.39	0.24
10012	0.05	0.82	0.63	0.46	0.28

Table A8 Cross-correlation matrix between depth of water table and rainfall for different lag periods (Thanjavur district)

Well No	Without Lag	One-month Lag	Two-month Lag	Three-month Lag	Four-month Lag
43001	0.28	0.74	0.70	0.43	0.26
43003	0.31	0.40	0.16	0.02	0.15
43004	0.31	0.19	0.00	0.06	0.22
43009	0.30	0.76	0.50	0.21	0.02
43033	0.41	0.37	0.19	0.01	0.20
43047	0.35	0.54	0.32	0.15	0.07
43056	0.22	0.74	0.58	0.35	0.13
43061	0.41	0.35	0.08	0.19	0.44
43062	0.35	0.35	0.08	0.19	0.44
43065	0.48	0.37	0.23	0.06	0.09
43072	0.29	0.81	0.60	0.38	0.20
43076	0.12	0.69	0.50	0.32	0.15
08001 D	0.22	0.52	0.40	0.18	0.06
08002 D	0.10	0.45	0.46	0.28	0.07
08003 D	0.02	0.52	0.50	0.34	0.16
08004 D	0.00	0.79	0.64	0.42	0.25
08005 D	0.02	0.65	0.57	0.35	0.15
08006 D	0.04	0.62	0.48	0.35	0.20
08007 D	0.16	0.45	0.37	0.16	0.02
08010 D	0.17	0.61	0.45	0.29	0.11
08011 D	0.25	0.37	0.34	0.16	0.04
08012 D	0.41	0.22	0.09	0.08	0.24
08013 D	0.03	0.43	0.39	0.29	0.20
08014 D	0.08	0.74	0.60	0.38	0.14
8015	0.11	0.73	0.63	0.44	0.30
8016	0.21	0.72	0.79	0.56	0.33
8017	0.22	0.75	0.74	0.55	0.37
8018	0.02	0.56	0.54	0.38	0.21
8019	0.28	0.79	0.80	0.61	0.44
8020	0.22	0.85	0.80	0.57	0.39
8021	0.27	0.48	0.32	0.08	0.11

Well No	Without Lag	One-month Lag	Two-month Lag	Three-month Lag	Four-month Lag
8022	0.26	0.33	0.30	0.12	00.09
8023	0.17	0.43	0.39	0.22	0.05
8024	0.20	0.53	0.45	0.24	0.04
8025	0.22	0.26	0.33	0.12	0.08
8026	0.20	0.41	0.40	0.26	0.07
8027	0.26	0.37	0.37	0.19	0.00
8028	0.51	0.11	0.10	0.09	0.30
8029	0.59	0.07	0.06	0.16	0.40
8030	0.09	0.58	0.67	0.45	0.26

Table A9 *List of water conservation structures in the VWS*

Type of structure	Sl. No.	Structure
Check dam	1	Chinna Nandupallam check dam
	2	Periya Nandupallam check dam
	3	Periya Odaippu check dam
	4	Nallathannipallam check dam
	5	Kuyavan Odaippu check dam
	6	Ahivasi Colony check dam
	7	Mattumuniyankoil check dam
Earthen bund	1	Ramarapadam earthen bund
	2	Chinnanandupallam bund – Part I
	3	Periyanandupallam bund – Part I
	4	Chinnanandupallam bund –Part II
	5	Peralam bund
	6	Aradipalam bund
	7	Sannathithadam bund
	8	Athivasi colony bund
	9	No.3 Gate bund
	10	Extension II earthen bund
Lakes	1	Muniyappan lake
	2	New constructed lake

Type of structure	Sl. No.	Structure
Canal	1	Peralam canal
Ponds	1	Avuliyakani Kulam
	2	Kalappanayakkar Kulam
	3	Nathakuttai Kulam
	4	Muniappanlake Kulam 1 & 2
	5	Periyapalayi Kulam
	6	Chinnapalayi Kulam
	7	ThadamKulam or Navaladikuttai
	8	Aruvunkanni Kulam
	9	Dheertha Kulam
	10	40/1 Railway road Kulam
	11	Modimandapa Kulam
	12	Periayathuraipallam Kulam
	13	Chinnanandupallam Kulam
	14	Periyanandupallam Kulam
	15	Adipallam Kulam
	16	Errukkadikuttai Kulam
	17	Perumanayakkankuttai Kulam
	18	Sanathithadam Kulam
	19	Mattumuniyan Koil Kulam
	20	Kuyavanodipoo Kulam
	21	Nallathannipallam Kulam
	22	Puthu Kulam
	23	Puthuputhu Kulam
	24	Onatheevu Kulam
	25	Servarayankoil Kulam
	26	PeralamNaduthittu Kulam
	27	Periyamaruvilanga Kulam
	28	Chinnamaruvilanga Kulam
	29	VallithittuKulam
	30	Kumuladivayikkal Kulam
	31	Casurina plot – I

Type of structure	Sl. No.	Structure
Ponds	32	Casurina plot – II
	33	Yanaivizhunthanpallam Kulam
	34	Keechanodai Kulam
	35	Old Kighthouse Kulam
	36	Rettaivaikkal Kulam
	37	Kodimarathu Kulam
	38	Thillaiyadivayikkal Kulam
Wells	1	Lakshmi Thadam well
	2	Aradipalam well
	3	Muniyankoil well
	4	Cyclonecentre well
	5	Adhivasi colony well
	6	Nallathannipallam well
	7	Pudukulam well
Water trough	1	Aruvankanni water trough
	2	Nallathannipallam water trough
	3	Muniappan Lake water trough – damaged
	4	Aradipalam water trough
	5	Casurina Plot I water trough – damaged
	6	Casurina Plot II water trough – damaged
	7	Adipallam water trough – damaged
	8	Modimondapam water trough – damaged
	9	Servarayankoil water trough
	10	Alavari Promboke water trough – damaged
	11	Muniyankoil water trough
	12	Lighthouse I water trough
	13	Lighthouse II water trough (frog trough)
	14	Periyapalaye Kulam water trough – damaged
	15	Mattumuniyankoil water trough – damaged
	16	Cyclone Shelter Area water trough
	17	Kuyavan Odippu area water trough – damaged
	18	Athivasi Colony area water trough – damaged

Type of structure	Sl. No.	Structure
Water trough	19	Ramapatham area water trough – damaged
	20	Water trough 2 nos. at Kodikkarai Damaged
	21	Water trough at Poonarailllam Rest House
	22	Water tank at Nallathannipallam
	23	J.J. Tank 2 Nos.
	24	Nallathannipallam water trough (new pipeline)
	25	Mattumuniyankoil trough (new pipeline)
	26	Casuarina plot Square type trough (new pipe line)
	27	Casuarina plot Round type trough (new pipe line)
	28	Peralam Chinnaperalam
Mini check dam	1	Ramarpatham Saraagam
	2	Chinnanandupallam
	3	Periyanandupallam
	4	Peralam
	5	Nallathannipallam
	6	Mattumuniyankoil
	7	Kuyavan Odippu
	8	Erattai Vaikkal
	9	Casuarina Plot

ANNEXURE III

Table A10 *List of water conservation structures in the VWS*

Sl. No.	Location	Latitude	Longitude
1	Muthupet mangroves	10.2914	79.2967
2	Mullipallam lagoon	10.3431	79.5134
3	Marakai-Koraiyar river	10.339	79.548
4	Pallankallupathi road	10.319	79.5527
5	Seruthalaikadu creek	10.302	79.7248
6	Chemplast Sanmar Ltd.	10.2941	79.8155
7	Point Calimere Wildlife Sanctuary	10.3559	79.8273
8	Point Calimere near mouth	10.315	79.87

Sl. No.	Location	Latitude	Longitude
9	Thailanayar Reserve Forest	10.53	79.791
10	Adaparu bridge	10.494	79.82
11	Vedaranyam salt swamp/mudflat-1	10.335	79.662
12	Vedaranyam salt swamp/mudflat-2	10.348	79.618
13	Gujarat Heavy Chemicals Ltd.	10.368	79.792
14	Sembodai Pushpavanam	10.465	79.833
15	Thulasiyapattinam	10.499	79.827
16	Panchanathikulam West	10.4125	79.7111
17	Thopputharai	10.403	79.848
18	Edaiyar	10.476	79.5847
19	Pattukottai	10.43861	79.7086
20	Salt pan	10.3544	79.743

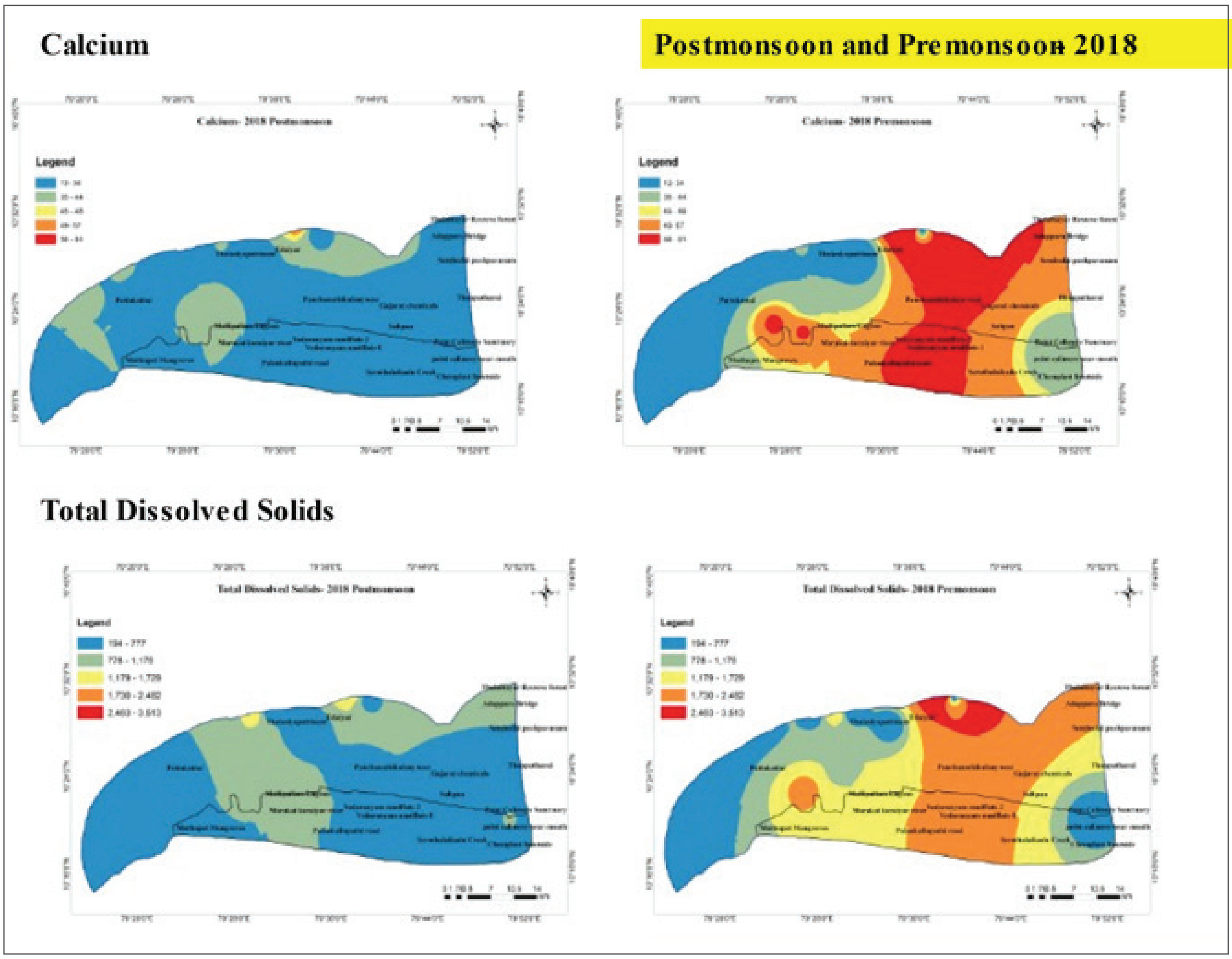


Figure A1. *Spatial Distribution Map of Calcium (ppm) and Total Dissolved Solids (g/l) in Pre and Post Monsoon -2018*

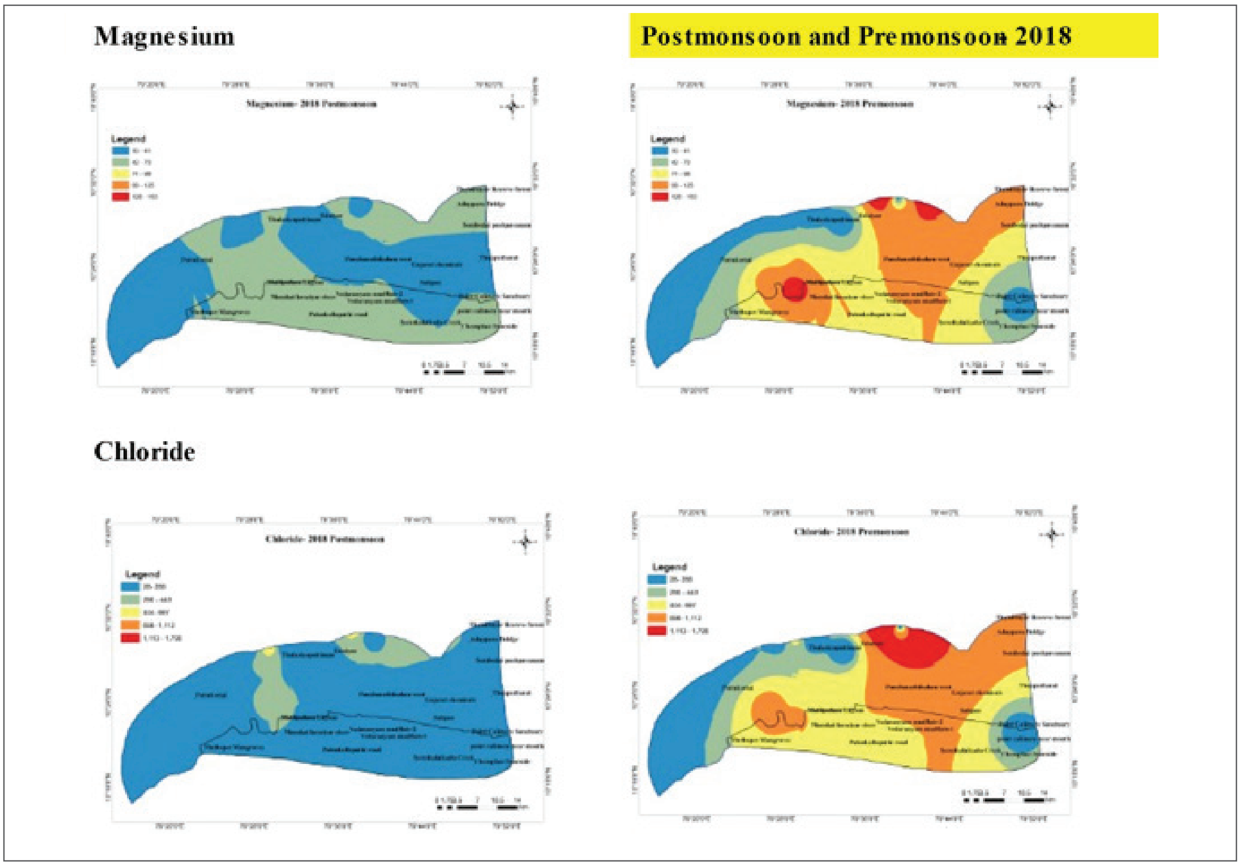


__Figure A-2 -__ Spatial Distribution Map of Magnesium (ppm) and Chloride (mg/l) in Pre and Post Monsoon -2018

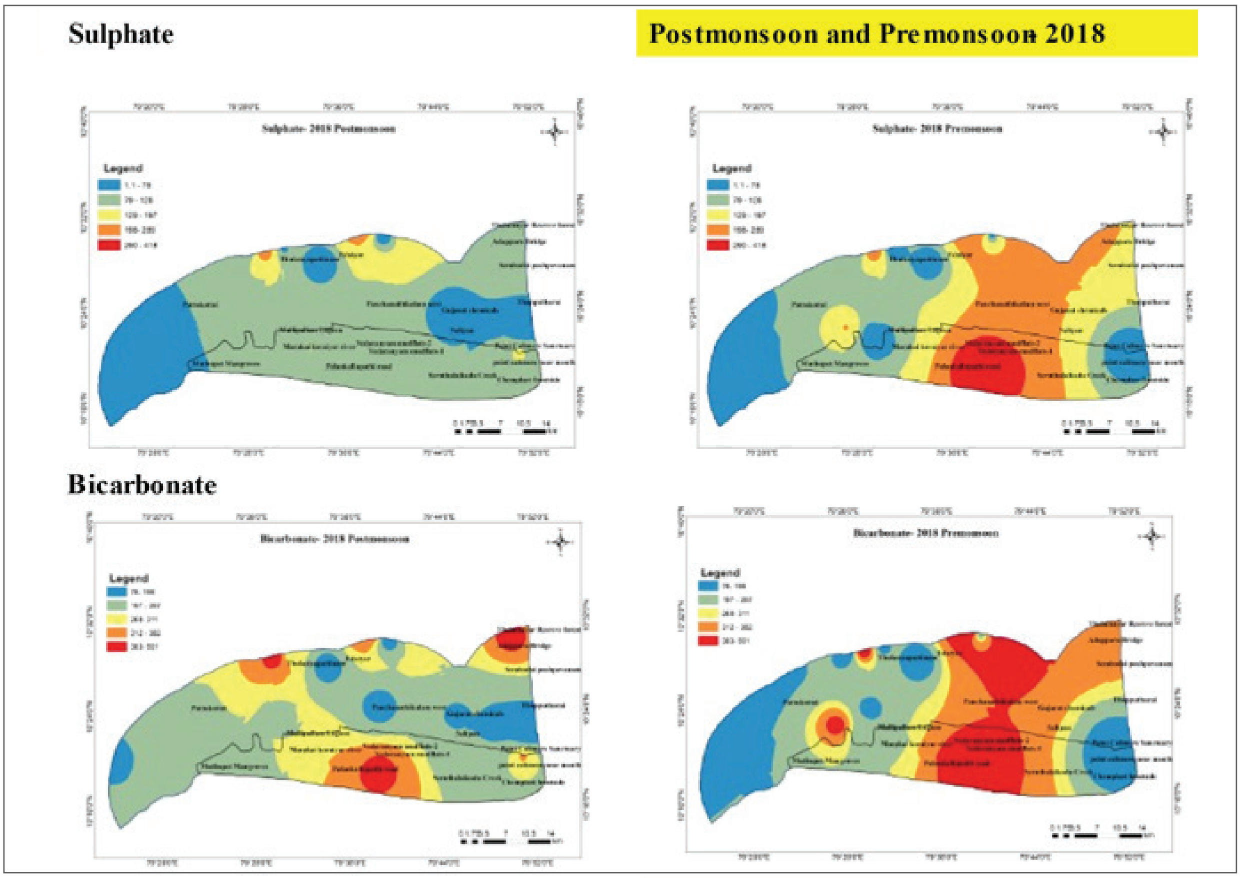


__Figure A-3- S__patial Distribution Map of Sulphate (mg/l) and Bicarbonate in Pre and Post Monsoon -2018

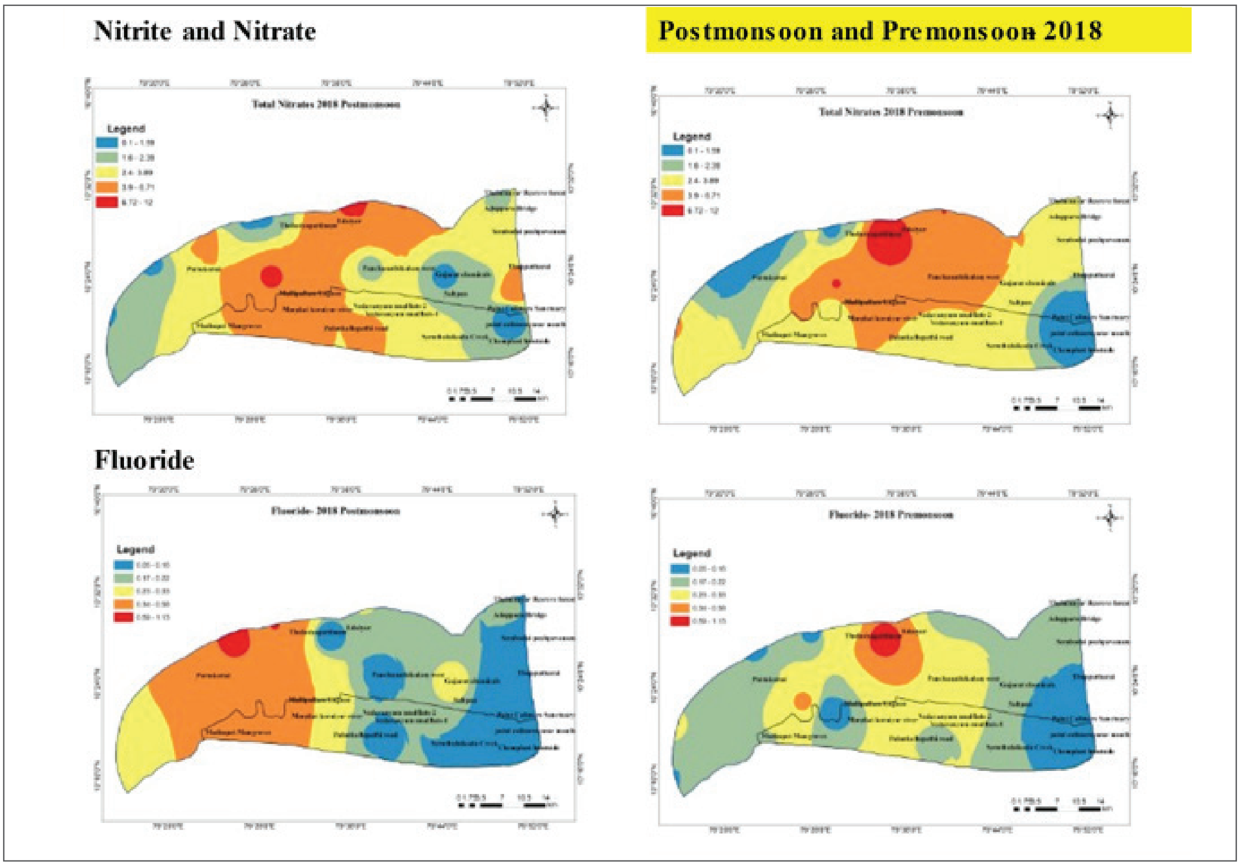


Figure A-4 - *Spatial Distribution Map of Nitrate, Nitrite (ppm) and Fluoride (ppm) in Pre and Post Monsoon -2018*

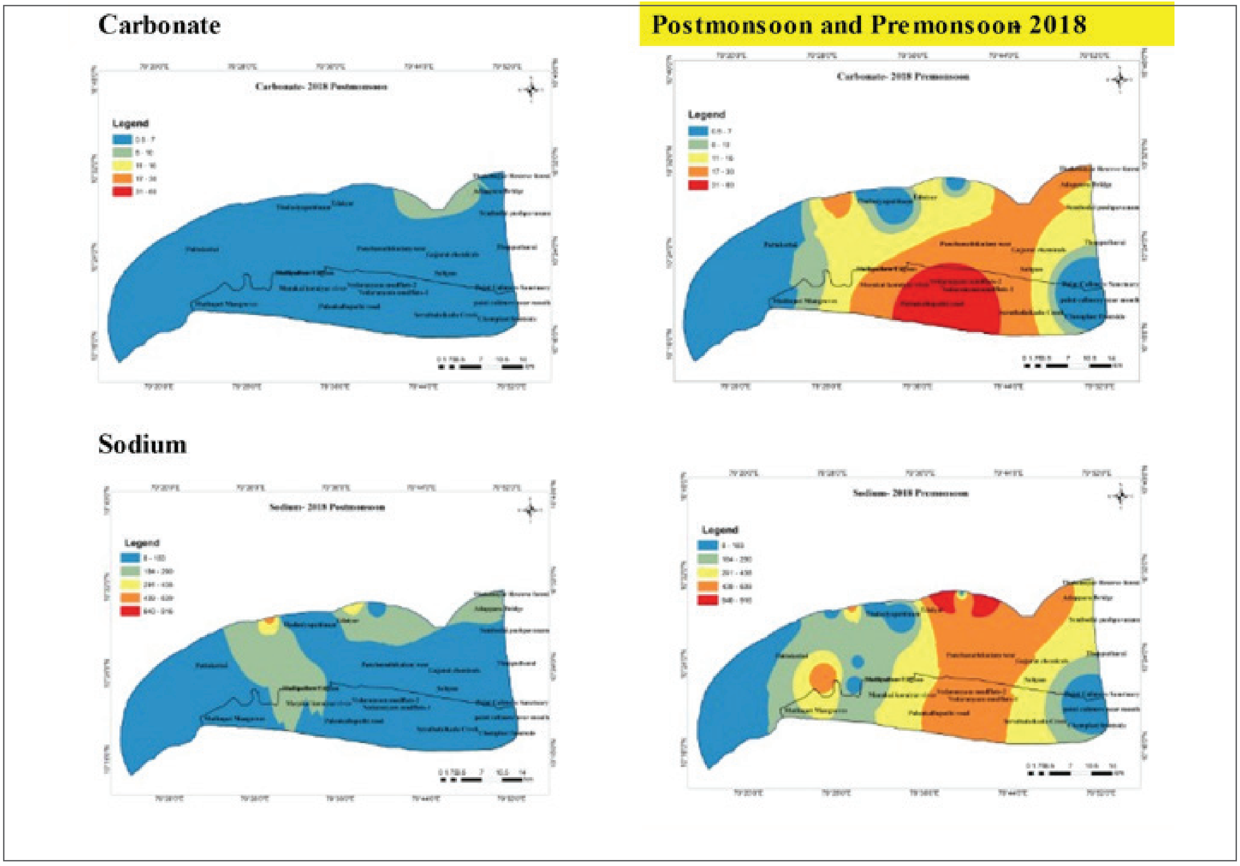


Figure A-5 -*Spatial Distribution Map of Sodium (ppm) and Carbonate (ppm) in Pre and Post Monsoon -2018*

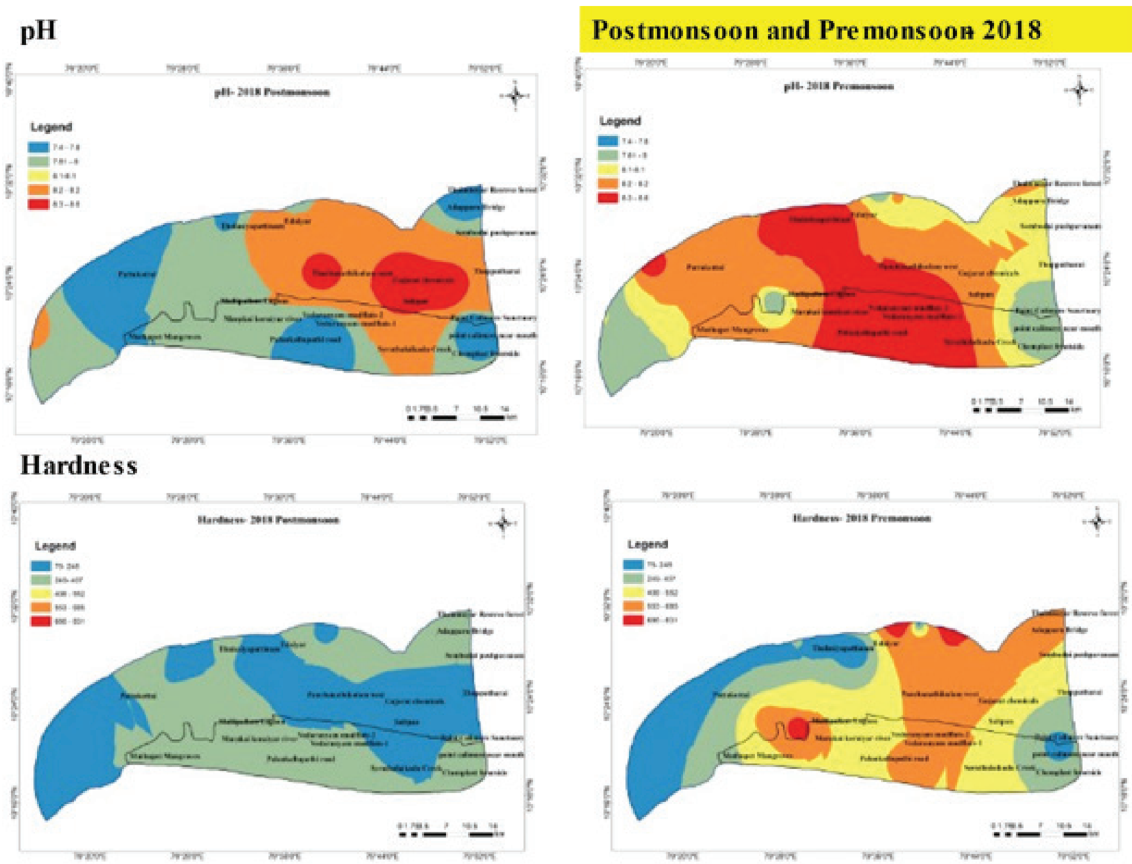


Figure A-6 -Spatial Distribution Map of pH and Hardness (mg/l) in Pre and Post Monsoon -2018

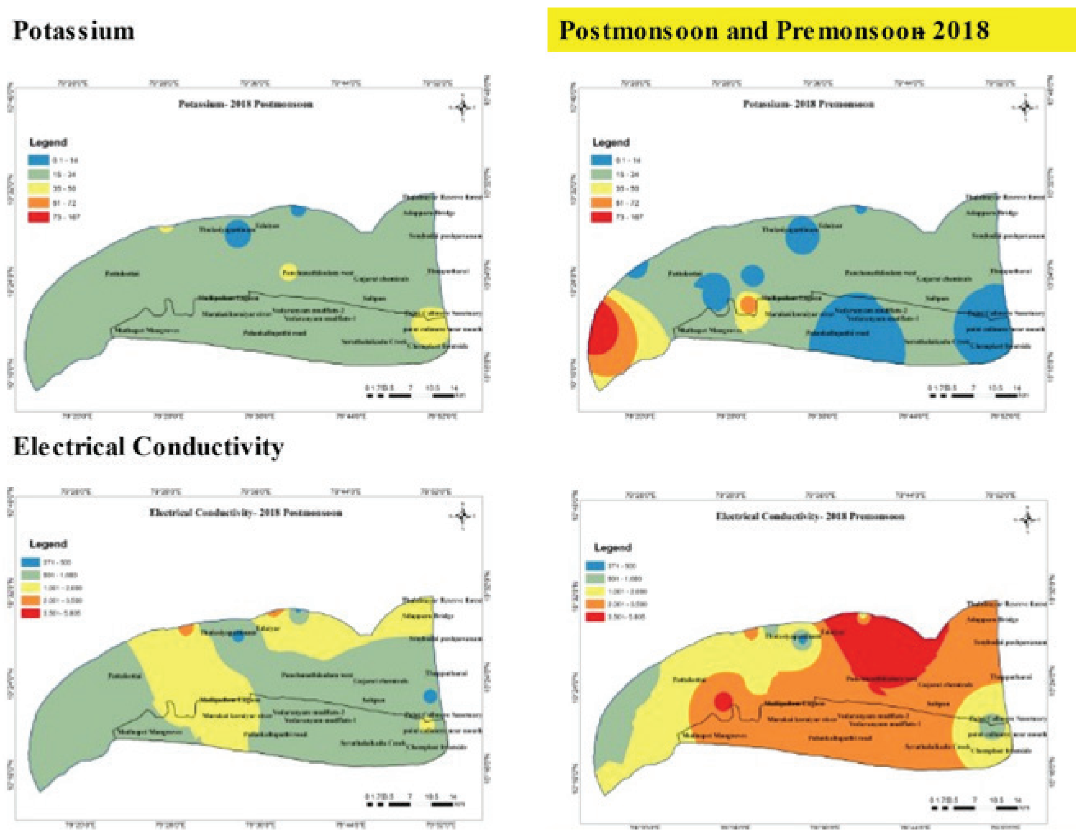


Fig A-7 -Spatial Distribution Map of Potassium (ppm) and Electrical Conductivity (mS) in Pre and Post Monsoon -2018

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