Assessment of Water Quality along the Coastal Areas of Kerala: A Study of the Tsunami Impact on Groundwater

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By

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Ph.D. thesis in the field of Environmental Chemistry

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Certificate

Certified that the work presented in this thesis entitled ***"Assessment of water quality along the coastal areas of Kerala: a study of the tsunami impact on ground water"*** *is a bonafide work done by* ***Mr. Jaison C A****, under my supervision and guidance in the School of Environmental Studies, Cochin University of science and Technology, Kochi-682 022 and that this work has not been included in any other thesis submitted previously for the award of any degree.*

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DECLARATION

I hereby declare that the work presented in this thesis entitled "**Assessment of water quality along the coastal areas of Kerala: a study of the tsunami impact on ground water**" is based on the original work done by me under the supervision of Dr. V Sivanandan Achari, Assistant Professor, School of Environmental Studies, Cochin University of science and Technology, Kochi-682 022 and has not been included in any other thesis submitted previously for the award of any degree.

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Preface

The study of tsunami coastal hazard had been very new to many of the researchers who ventured out to take part in rapid response studies to elucidate valuable and substantial inferences on the impact of tsunami on coastal environment. Dire need of primary data essential to correlate the post tsunami condition of a devastated region to what actually existed in time before the ocean hazard occurred had been the most difficult part of many of the successful research missions that followed.

Everywhere, on the coastal belt it is proved without doubt that the pristine ground water quality was severely deteriorated after the 26 December 2004 Indian Ocean Tsunami. But how far is more relevant, as it is decided by the so-called pre-tsunamic situation of the region. In water quality studies it is this reference finger print which earmarks regional ground water chemistry based on which the monthly variability could rationally be interpreted.

Alappad coast is the most affected region of Kerala, India by the 26 December 2004 tsunami event. The study of the ground water quality of the region in pre- and post-tsunamic situation has been identified as an essential aspect of tsunami impact on coastal environment. Lack of research on the impact of tsunami on ground water quality in the post-tsunamic situation had been a great limitation to arrive at a scientific judgment on its extent of quality damage. The study comprises the critical analysis of the ground water sources of the tsunami affected coastal regions of Kerala in the pre- and post-tsunami situation.

Water quality variation along the most severely affected Kollam, Alappuzha, Ernakulam coast of Kerala, has been studied just after the 26 December 2004 tsunami on temporal and spatial basis. The sea water inundation of the region ultimately damaged the balanced ecological system as evidenced by the loss of perennial fresh water plants and subsequent loss of the region’s drinking water sources. The data generated in this study form the most valuable base of the water quality profile of the region to identify the cause and reasons for the possible changes in future.

This study indicates that slight contamination by sea water has been inherently prevalent before the tsunami event in the Alappad region; due to the geographical features of the place – a narrow barrier islet fringed by Laccadive Sea and an estuarine arm of the Ashtamudy lake called T S canal. It is proved that the water in the region has originated from rainwater source subjected to 'mild contamination' and geologically subjected to reverse softening by the sediment layers characterized by a higher proportion of heavy mineral sands.

The physico-chemical and biological parameters of 42 ground water resources of the region were determined for duration of 12 months starting from the month of January 2005 to December 2005. Major parameters analyzed include pH, Conductivity, Redox potential, Turbidity, Alkalinity, Hardness, Total hardness, dissolved oxygen, Biochemical oxygen demand, Chloride, phosphate, Iron, sodium, potassium and Total coliform. A complete evaluation of the ground water quality of these 42 ground water sources has been done in December 2008 as a bench mark to serve as a basis for the evaluation/comparison of the water quality changes, this being essential for the understanding of the phenomena correctly and completely.

This Ph D thesis comprises the testing and evaluation of the facts: whether there is any significant difference in the water quality parameters under study between stations and between months in Tsunami Affected Dug Wells (TADW). Whether the selected water quality parameters vary significantly from BIS and WHO standards. Whether the water quality index (WQI) differ significantly between Tsunami Affected Dug Wells (TADW) and Bore Wells (BW). Whether there is any significant difference in the water quality parameters during December 2005 and December 2008. Is there any significant change in the Water Quality Parameters before 2001 and after tsunami (2005) in TADW.

Abbreviations

AL	-	Alkalinity
Alk	-	Alkalinity
AOC	-	Assimilative organic carbon
APHA	-	American public health association
AWDC	-	Affected well dewatered, cleaned
AWNDNC	-	Affected well not dewatered, not cleaned
BDOC	-	Biodegradable organic carbon
BIS	-	Bureau of Indian standards
BOD	-	Biochemical oxygen demand
BOM	-	Biodegradable organic matter
BW	-	Bore well
CGWB	-	Central ground water board
CH	-	Carbonate hardness
CI	-	Confidence interval
CMFRI	-	Central marine fisheries research institute
CMT	-	Centroid Moment Tensor
CW	-	Control well
D	-	Days
DGPS	-	Differential global positioning system
DO	-	Dissolved oxygen
DOC	-	Dissolved organic carbon
DST	-	Department of Science and Technology
EC	-	Electrical conductivity
EEC	-	European economic community
ESS	-	Extremely soft to soft
GIS	-	Geographic information system
GPS	-	Global positioning system
HIDZ	-	High inundated zone
HVH	-	Hard to very hard
IAP	-	Ion Activity Product
IRS-P6	-	Resourcesat-1
KSPCB	-	Kerala state pollution control board
KWA	-	Kerala water authority
LIDZ	-	Low inundated zone
MHH	-	Moderately hard to hard
MIDZ	-	Medium inundated zone
MSL	-	Mean sea level
NBOD	-	Nitrogenous biochemical oxygen demand

NCH	-	Non carbonate hardness
NSS	-	National service scheme
NTU	-	Nephelometric turbidity unit
RTKGPS	-	Real time kinematic global positioning system
SEARO	-	South east asia regional office- world health organization
SMH	-	Soft to moderately hard
SOP	-	Standard operating procedure
TADW	-	Tsunami affected dug well
TALK	-	Total Alkalinity
TDS	-	Total dissolved solids
TH	-	Total Hardness
THODU	-	Too hard for ordinary domestic use
UNEP	-	United Nations environment programs
USEPA	-	United states environmental protection agency
USSL	-	United States Salinity Laboratory
VHEH	-	Very hard to excessively hard
VHIDZ	-	Very high inundated zone
VLIDZ	-	Very low inundated zone
WHO	-	World health organization
WQI	-	Water quality index

Glossary of symbols

$\bar{x}$ - Mean
Ca - Calcium
$CaCO_3$ - Calcium Carbonate
Cd - Cadmium
Cl/Cl^- - Chloride ion
Co - Cobalt
Cr - Chromium
Cu - Copper
Eh - Redox Potential
F^- - Fluoride ion
Fe - Iron
K - Potassium
Mg - Magnesium
Mn - Manganese
n - Number of samples
Na - Sodium
Ni - Nickel
NO_3/NO_3^- - Nitrate ion
Pb - Lead
pE - Logarithm of electron concentration in a solution
PO_4^{3-}/PO_4 - Phosphate ion
S - Sulfur
SO_4/SO_4^{2-} - Sulfate ion
Zn - Zinc
μ - micro/Confidence Interval (CI)
σ - Standard Deviation

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Chapter 1

Introduction

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1.1 The 26 December 2004 Indian Ocean Tsunami

Seismological studies have revealed that the 26 December 2004 Sumatra-Andaman earthquake had been of devastating magnitude, next only to the great Chilean earthquake of 1960. Seismicity associated with thrust faulting along a 1200 km long fault line associated with the subduction of the Indian Plate under the Burma micro plate lead to the powerful displacement of huge columns of water, resulting in the generation of the devastating tsunami of 26 December 2004. Stein (Stein and Okal, 2005) and Sidao (Sidao et al., 2005) have determined the rupturing to have had an average duration of 500s. The average rupture speed was 2.5 km/s. The seismic moment has been estimated to be $1.0 \mathrm{x} 10^{30}$ dyne/cm (Moment Magnitude Mw = 9.3; Stein and Okal, 2005).

1. 1.1 The tsunami event

Indian Ocean tsunami occurred due to the earthquake on 26 December 2004 at 6:58:50 am (local time) with a magnitude of 9.3 in Ritcher scale. The epicenter of the quake was about 150 km off the coast of Sumatra island of Indonesia. This tsunami had disastrous effects in 18 countries on the rim of Indian Ocean (Figure 1.1)

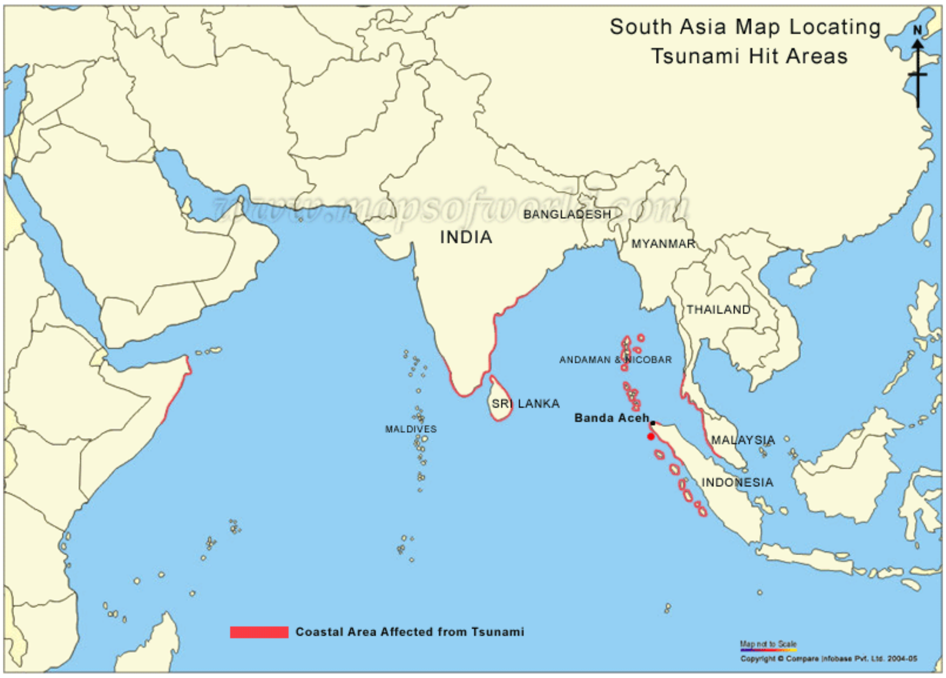

Figure 1.1: South Asia Map Locating Tsunami Areas

The epicenter was located at 3.298 N, 95.779 E with a shallow focal depth of about 33 km causing displacement of 1200 km of ocean floor for a depth of 30 m. The worst hit countries are Indonesia, Thailand, India, Srilanka, Maldives, Reunion Island (French), Seychelles. Madagascar, Mauritius, Somalia, Tanzania, Kenya, Oman, South Africa and Australia. In India alone the officially recorded death toll had been more than 10,000. In Kerala it numbers to 178 (Achari, 2005; Alex and Achari, 2005; Achari, 2008).

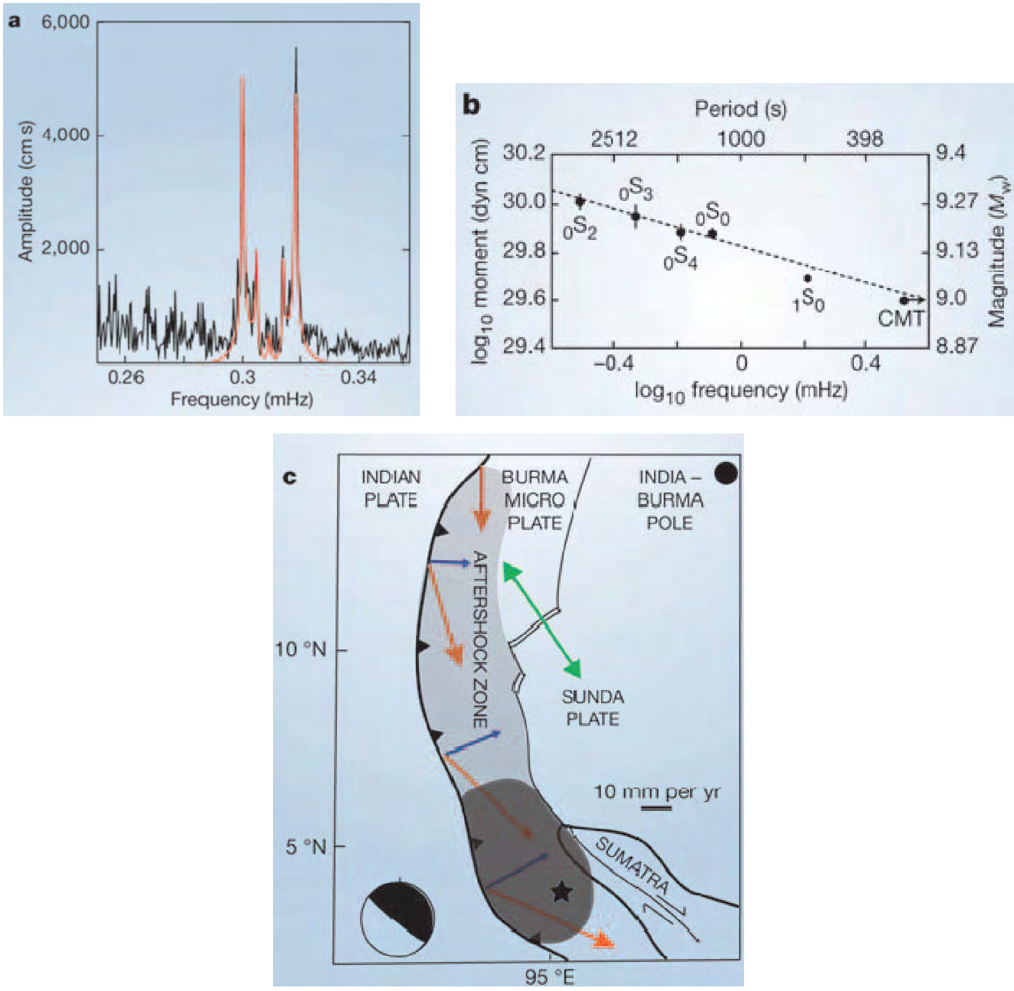

Figure 1.2: Features of the 2004 Sumatra–Andaman Earthquake (Stein and Okal, 2005)

The Figure 1.2 is the geophysical data of the 2004 Sumatra–Andaman Earthquake (as *reported by* Stein and Okal, 2005). *Figure 1.2a***,** observed (black) and predicted (red) amplitude spectrum for a $_0S2$ multiplet, showing the best-fitting seismic moment ($1.0x10^{30}$ dyn cm).

Figure 1.2b, Variation in seismic moment and moment magnitude, *M*w, with period. CMT (for Centroid-Moment Tensor project) represents the result from surface waves with periods below 300 s. *Figure 1.2c***,** Comparison of aftershock zone (greys) with minimum area of fast slip (dark grey; corresponding to one-third of rupture area), estimated from body waves, and the possible area of slow slip (light grey;

corresponding to the northern part of the fault area) inferred from normal modes. Star, earthquake epicentre. Arrows: total (red) and orthogonal (blue) convergence for an India–Burma Euler vector of (14.8°N, 99.8°N) 1.55° per million years; green, back-arc spreading; scale bar, 10 mm per year. Black and white disc is CMT focal mechanism.

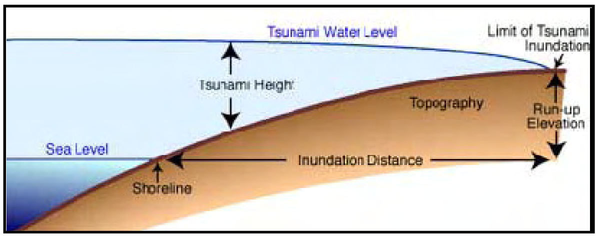

Figure 1.3: Inundation distances and un-up elevations

Burma micro plate is a sliver between the larger Indian and Sunda plates. Global positioning data had been used to correlate the motion of India (Sella et al., 2006) and Sunda (Chamot-Rooke and Le, 1999) plates with respect to Eurasia depicted in the above figure by back arc–spreading method (Curray et al., 1979; Bird, 2003). India-Burma pole is situated nearby the convergence direction- along the rupture zone and has highest incidence of strike-slip at the north end of the rupture.

In the final evaluation, **tsunami run up** is taken as a quantity to compute the intensity of tsunami waves. *It is the water's highest elevation at the maximum horizontal penetration.*

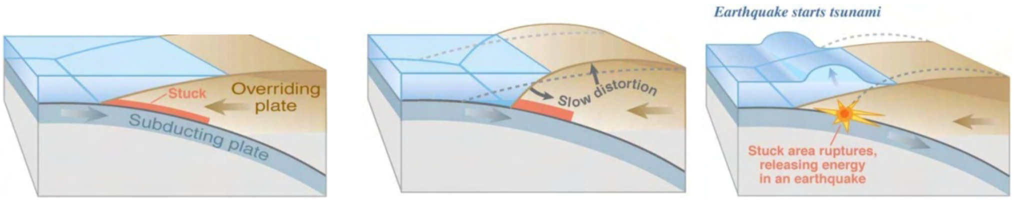

Figure 1.4: Movement or displacement of earth plates along a fracture line in seafloor causing the formation of tsunami wave.

Studies report that the run up has a direct relation to the fault slip because the run up typically does not exceed twice the fault slip (Okal and Synolakis, 2004). The run up had been 25-30 m in the near parts of Sumatra which itself confirms that the slip had been 12-15 m (Figure 1.3).

Inundation is the distance from the shoreline to the limit of tsunami penetration and run-up elevation is the elevation above sea level of the tsunami at the limit of penetration. **Inundation** is measured with respect to ground elevation and the regions are classified into Very high inundated zone (VHIDZ > 1200 m), High inundated zone (HIDZ > 801-1200 m), Medium inundated zone (MIDZ > 401-800 m), Low inundated zone (LIDZ > 100-400 m), Very low Inundated (VLIDZ <100 m). Most of the tsunami affected coastal zones of Kerala comes under the second lowest category of LIDZ > 100-400 m.

Satellite data put into simulation and modeling studies revealed that slow slip amplified the excitation of the tsunami. Here, the rupture started and propagated to northern side of Sumatra. The catastrophe on Indian and Srilankan coast had been due to the northward rupture of the fault zone (Stein and Okal, 2005) and tsunami amplitudes are largest when they are originated perpendicular to the fault.

Seismologically, these giant waves are originated as after effects of earthquakes triggered by the fault movement or displacement of earth plates along a fracture line on the seafloor under great depth (Figure 1.4).

1. 1.2 Plate and tectonic movement

Plate tectonics is the manifestation of the movement of the Earths' lithosphere which is broken up into seven major plates and a half a dozen minor ones over the fluid asthenosphere. The boundaries of these plates are the regions of '*fragmented stability'* and are known to exist as *divergent boundary, convergent and transform boundary*.

1. Divergent boundaries are *constructive in existence*: *leads to the formation of lithosphere along the ocean ridge.*
2. Convergent boundaries are *destructive in nature and subduction of plates occur.*
3. Transform (shear) boundaries are locations along which *one plate moves past the other*

All situations of disturbances in the plate boundary causes earthquake. ‘Activities occurred under sea floor always lead to the surge of water - *the ultimate cause for tsunami waves.* The wave travels with a speed of 700 km/h and above with a wavelength of 200 km (Baba, 2005). In the open sea the height of water column may be just 0.5 m average, making it difficult to recognize by seafarers and mariners of the ships. Hence, tsunami waves remain hidden in the deep sea and once it touches the shores the hidden ferocity is unraveled to kill and destroy all on the way!

At shallow and near shore areas the velocity reduces, thereby aggravating the momentum force that leads to piling up of water to emerge as jumbo waves, with an average height of 30 m (100 feet) and hits the land with accrued momentum force.

1.2 The tsunami Impact on Indian Coast

Many academic centers of India particularly Tamil Nadu state participated in the study of the “science of tsunami” and its indelible impact on coastal environments. To promote and chart out a scientific protocol and methodology to investigate tsunami phenomenon to scientists, a one week training program was organized (methodology for mapping of the sea water inundated areas during December, 2004 Tsunami) by DST.

Proven methodologies and tools like GPS, RTKGPS, remote sensing and GIS were largely used for preparing inundation maps. Elevation and extent of inundation was measured and gathered as primary data from field study. IRS-P6 data and GIS tools were used as support for preparing thematic and inundation maps. Mapping of extent of inundation was done using DGPS. However, the following features are identified for recording the *extent of inundation.* (1) marking of seawater level on the buildings, (2) extent to which washed material get deposited (3) wilting and degradation of vegetation by salinity hazard and (4) information provided by the affected people and public.

These researches were funded by the Department of Science and Technology Government of India, immediately after tsunami incident through the coordinated action of team of scientists. Later the outcome and the results were presented as individual research papers coast-wise in a valuable publication by Earth System Science, Department of Science and Technology, Government of India, New Delhi (Rajamanickam, 2006).

1.3 Ground Water Science, Water Quality and Tsunami

Ground water science is an emerging subject of importance the world over. Quality criteria become very stringent regarding collection, processing, storage and distribution of safe drinking water. Water chemistry is practiced by geologists, chemists and chemical engineers to attain the finest quality of the processed water and among geologists this subject is respectfully regarded as *inorganic water geochemistry*.

Environmental experts prefer to refer this systematic knowledge on water as Ground Water Chemistry (Hounslow, 1995). However, this subject is one which has received the most patronage, because of the realization that the survival of the modern civilization rests on the availability of safe drinking water.

Water Quality as a science is the practicing knowledge of inorganic geochemistry enriched by analytical science and sanitary engineering principles. Water is the resource material in all its forms, and it is holistically dealt with. Water- the natural inorganic material resource available in all geochemical spheres get replenished over millions of years in its natural aesthetic quality, but is exposed to numerable contaminants; both inorganic and organics. This thesis examines the effect on water quality subsequent to the tsunami event.

1.3.1 Ground Water Quality and Human Health

Presence of micro-pollutants and removal of their residuals is addressed everywhere by water specialists. The total carbon residuals are measured and expressed in the case of ground water contamination as Dissolved Organic Carbon [DOC] concentration (van der Helm, 2007). Many other names are very prevalent to term the carbon concentration of ground water. Assimilative Organic Carbon [AOC] and biodegradable organic carbon [BDOC] are the common references in the literature as they indicate the extent of undesirability. Bio-degradable Organic Matter [BOM] is another term that indicates the concentration of organic carbon contaminants. Designing and optimization of treatment plants equipped with ozone oxidation followed by filtration by carbon filter media is an active area of research engaged throughout the world.

1.3.2 Geochemical spheres

Various parts of the earth being studied are important in a greater perspective of ground water chemistry. The ***lithosphere*** (rocks), ***pedosphere*** (soils), ***biosphere*** (living organisms), ***atmosphere*** (air), ***hydrosphere*** (water), ***anthroposphere*** (man's effect on the spheres) are the common systems of the earth. The major and ultimate process occurring in these spheres are the *cyclic distribution of water* [hydrologic cycle] on the planet earth and the *rock cycle* [distribution of rocks].

Contamination of water itself indicates the mutual and perpetual interaction of all these spheres and fate of even the minutest of the pollutant fraction is being decided by the fluidity and permeability of the respective spheres. Geochemical spheres interact in various levels ever since the planet came to existence.

All the so-called instances of material (energy) interactions ultimately lead to the changes in ground water quality. Atmospheric carbon saturates ground water instantaneously which is decided by a constant pressure and temperature gradient as explained by Henry's law. The solubility of gases like H_2S, O_2 and Methane under natural conditions is decided by the same rule under normal atmosphere pressure gradient. All these are orchestrated by the proportion of free H^+ content described on logarithmic scale referred to as pH.

Form, texture, permeability and porosity of rock formations – *the aquifer characteristics* – have also to do with the quality of the ground water. Clay and other oxide minerals in the aquifers either retard or retain the chemical composition of the water it permits to pass through. Most instances this phenomenon is controlled by mass balance.

1.3.3 Water quality

Water quality – evaluation and optimization is the essential aspect of human health and it is a concern against diseases and mortality. Many excessive component in the ground water cause severe health threats; excessive ingestion of water having heavy metal ions [Cd, Ni and Pb] leads to many diseases and organ malfunctions. Radon is detected in ground waters of many regions of the world and residuals accumulate in the scales and deposits of the pipelines. This enrichment may cause the leaching of the deposit in a favorable condition decided by the water pH, ultimately reaching the distribution and consumption pathways.

Many of the drinking water companies processes raw water as a product by adopting softening procedures so that the so-called hardness may be too high or less. An average of 50 mg/ l water hardness is maintained as it is found to be ideal to human health. Urological malfunctions like Urolithiasis [incidence of kidney stone] is related to the biological build up of Ca- oxalate and Ca- phosphate.

Bureau of Indian Standards specifies 300 mg/l $CaCO_3$ as maximum total hardness of drinking water (BIS, 1999) beyond which adverse effects appear on domestic use. Necessarily a maximum of 0.3 mg/l of Fe is permitted as beyond this limit taste/ appearance are affected, has adverse effect on domestic uses and water supply structures, and promotes iron bacteria. WHO (WHO, 2004) specifies no minimum limit to hardness for drinking water. But it recommends a maximum of 0.2 mg/l of iron.

The study of the potential carcinogens in the hydrosphere requires massive analyses of ground water to deduce their active components. For example human cardiovascular functions and blood circulations are regulated by a concentration gradient decided by Ca and Mg ions. Ensuring of the quality of ground water is essential for the very human existence, specifically with respect to the maintenance of the groundwater sources. It is the need of the time to preserve the quality of the hydrosphere – the prime connector of all spheres.

1.3.4 Drinking Water: Quality and Global Crises

Depleted water sources and diminishing clean water supply due to lesser availability of preserved quality water sources are a great challenge of the world and moreover it is a global problem (Nwachcuku and Gerba, 2004; Shannon et al., 1994). The main cause is the increasing population and pollution of the hydrosphere. To overcome this crippling crises many missions are being planned that force the societies 'to redefine potable water sources to include the so-called the challenged supplies such as surface, brackish, produced, and recycled waste water'. Emerging water treatment technologies adopt many strategies to overcome the existing water stress situation starting with the identification of the raw water sources for better abstraction and exploitation.

1.4 Natural Disaster and Water Crises

Disasters and crises are asymmetrically correlated as it is known to the mankind throughout the history of civilizations as they bring pain and agony. Then what rationale connects natural disasters and water crises, could have been a prominent question.

The study on the interaction of geochemical spheres after a natural disaster remains a least followed scientific discipline. Distant disasters remain distant in our psyche. But most Indians know about earthquakes (especially people of Lathur, Utharkhand and Kutch) as many parts of India sit on earthquake-prone zones.

Coastal areas of the many Asian countries were damaged, scourging the human settlements, pinching the livelihood, damaging the dependable water sources, thereby depriving the population access to safe water for sustenance (Achari et al., 2007). Disasters deny the right of the living beings to sustenance; the coastal disasters take away all the physical essentialities for existence, including fresh drinking water.

1.5 26 December 2004 Indian Ocean tsunami impact on Kerala Coast

The coastal region (Figure 1.5) of Kerala from Alappad to Cherai (near Kochi) which was severely devastated by the tsunami is a fast developing area of the state. This stretch of the state is dotted with estuaries, lagoons, spits etc. with the Vembanad estuary being a prominent geomorphological feature.

This unique feature of the coastal belt draws much attention in the development efforts of the Government by building and making seaports, container terminals. Mooring buoyant jetties for oil transport and handling, shipping and navigation and indeed the promoting of canal and backwater tourism and housing urban development are the upcoming projects. The region is inherently subjected to geographic degradation both incidental and climatic triggered by monsoonal and wave activities. The technical viability of the choice of the respective projects rests on the expert opinion evolved out of the explorations already made.

The coastal areas particularly undergo a lot of environmental damage, being buffeted by storm waves during the monsoon, swells and strong longshore drift. This mechanism nevertheless enriches the shores of Alappad and Arattupuzha particularly in the form beach sand deposits. These mineral deposits are of strategic importance, and host thorium, cerium, titanium, as well as other rare earth elements. These black placer sand deposits provide the essential raw materials to the chemical processing and nuclear energy sectors of the country. Tsunami waves that struck Andaman Nicobar

Islands, coastal Tamil Nadu (Kanyakumari), rolled into the shores of Kerala at around 11.00 AM of the same day.

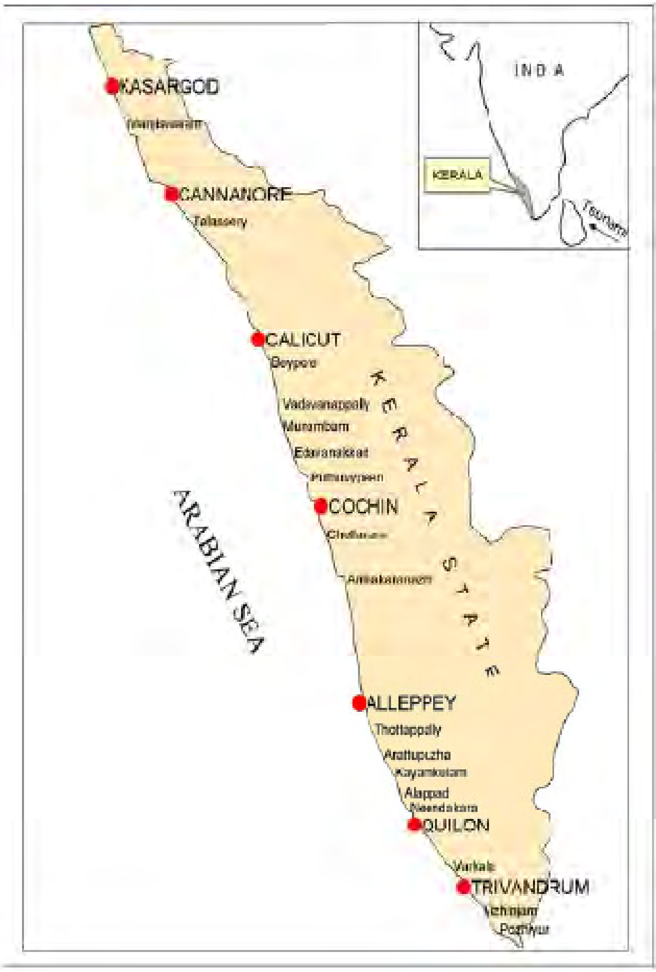

Figure 1.5: Map of Kerala coast

Fortunately coastal Kerala happened to be in the shadow zone of the tsunami waves. Impact had been very severe all along the entire coastal belt of Kerala but not as severe as that in Tamil Nadu. The severity had been maximum on either side of the Kayamkualm inlet: Alappad panchayath (south) or Arattupuzha panchayath (North). The run up and inundation along the coastal Kerala is given in the Table 1.1

Table 1.1: Tsunami striking time and salient features of the run-up along Kerala coast (Kurian et al., 2005)

Location	Run-up level (m)	Time of max. inundation (hrs)
Nandhi (Kasargode)	1.0	21:45
Chootad (Cannanore)	3.0-3.5	21:45
Dharmadam (Tellichery)	2.0-2.5	21:30
Calicut	1.5-2.0	23:30
Ponnani	0.5-1.0	12:00
Edavanakkadu (Kochi)	4.0-4.5	14:30
Andhakaranazhi	30.-3.5	14:00
Aleppey	2.5-3.0	13:00
Valiazhikal (Kayamkulam)	4.5-5.0	12:40
Azhikal	4.5-5.0	11:30
Thangasseri (Quilon)	2.5-3.0	14:00
Paravur	2.0-2.5	13:00
Vizhinjam (Thiruvananthapuram)	2.0-2.5	14:00

The run up levels are treated as an indicator of the extend of inundation and the magnitude of the devastation caused by the tsunami. The reported data (Kurian et al., 2006; Prakash et al., 2006) states that at Vizhinjam, in the south region of Kerala coast recorded a run up of 2.0 - 2.5 m maximum at local time 14.00 hr. Subsequent uprising of wave has been noted further north of the coast. Azheekal (Kollam) and Valiyazheekal (Alappuzha) on the either side of Kayamkulam inlet recorded highest run up of 4.5 to 5.0 m bringing maximum disaster in terms of human life and property loss.

Figure 1.6: The huge boulders of the sea wall were flung away by the tsunami

Figure 1.7: The islets of Alappad and Arattupuzha are made up of rich black sand deposits. It is evident that the sea wall is not a viable defense against the sea.

Coastal regions towards north of Kerala did not record much run up, except Edavanakkad-Cherai coast (Figure 1.6) where a run up equal to 4.0- 4.5m. This highest uprising after a gap area of more than 60 km beyond Kayamkulam inlet is treated as the *trough gap of the shadow tsunami*. The magnitude of the wave surge on Edavanakkad coast had been refluxed with enormous momentum.

Fortunately, the area being marshy with very few human settlements, not much mishap was recorded in terms of human life. Run up levels towards north of the Kerala coast after Edavanakkad had been very less. Nandhi (Kasargode) recorded the lowest inundation of 1.0 m.

1.5.1 Alappad Coast, Kerala, India

Most distinctive mayhem of the tsunami occurred on Alappad coast, particularly in wards I, II, III and IV on the southern edge of Kayamkulam lagoon. Debris of collapsed houses littered the coastal belt here. This is the location where the maximum devastation occurred: no doubt one can see and feel the impact on this strip of land and the destruction faced by traditional fishing community (Figure 1.7).

The extent of crop destruction initially did not draw much attention. Alappad and Arattupuzha have relatively higher numbers of houses; 5619 and 6755 (Census, 2001) respectively and the houses (as settlements) in the most damaged area are reported as

1589 and 1491 respectively. However, most of the houses are located at the apex of the ridge; at the area of slope divergences. Alappad coast is a narrow barrier island strip of width 250-500 m sandwiched between the sea and a canal called the *T.S. canal*. Many locations of the land have only a width of 50 m and are marshy areas supporting mangroves.

1.5.2 Arattupuzha Coast, Kerala, India

Arattupuzha is the extension of the barrier island on the north of Alappad coast. It is separated from Alappad by the inlet to the Kayamkulam lagoon. The coast has a width >500 m. At the time of the tsunami event the combined population of the panchayaths was 54,807 (Prakash et al., 2006) living in 12,374 households. (Figure 1.8)

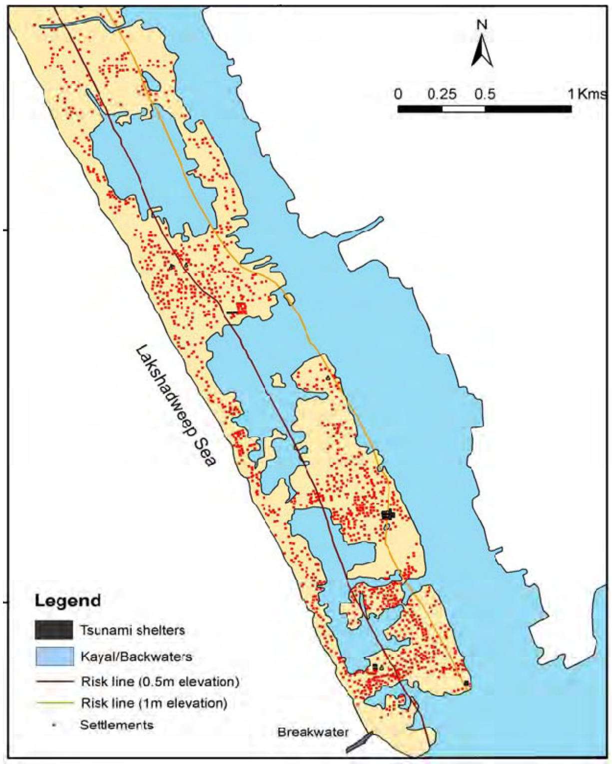

Figure 1.8: Settlement distribution of the Valiyazheekal sector, Arattupuzha

The tsunami rolled over the narrow strip of land, flushed the lagoon and finally returned to the sea. The lagoon acted as a funnel to collect and drain the *“back wash flood water”* to the sea. Hence, it saved the land and settlements further catastrophe. Total losses reported have been 178 lives and 4000 houses occupied by families. More than 3000 houses were damaged partially on the sides of the Kayamkulam lagoon in the two panchayaths (Figure 1.9, Figure 1.11). Many places landward near and above the shoreline were submerged with very thick black sand deposits with average depth of 1 m.

Figure 1.9: The mighty wave raged past the islets wiping out all manmade structures in the way

The extent of devastation and severity of wave impact is related to many factors. The geophysicists and geologists attribute its extent to sea water inundation, bathymetry convergence and other topographic conditions. The extent of run up and time of inundation was varied location wise. The inundation decreased northward beyond Kayamkulam lake (except Edavanakadu coast in Ernakulam District). The variability of the wave activity of the coastal hazard is attributed to the aggregate effect of many phenomena.

They are wave transference process; diffraction, reflection, and refraction coupled with the superimposition on high tides (Kurian et al., 2006). Furthermore, it rolled up the water column saturated with dense sandy sediments rich in heavy minerals. The momentum has been large enough to crush and crumble built-up structures, mainly houses.

This study has been limited to the stretch of coast which has severely experienced the impact and inundation starting from Alappad (Figure 1.10) to Cherai beach. The area covers nearly 150 km length in a coastal ridge line covering, Kollam, Allappuzha and Ernakulam districts.

The regions beyond Cherai north were not as much inundated as in the above regions and damage too was not high. One of the possible reasons had been the interaction of low tide waves with the tsunami waves. This part of the state experienced tsunami in the afternoon of the same day. However, the giant waves struck those areas in the midnight in resonance with the next cycle of high tides.

The reach and run up levels of the waves landward was different at place to place, which is decided by the variation of the beach profile and land pattern. Built up structures and crops inherently obstructed the upward movement of the waves as shield. Lagoons and their interconnected channels protected the flooding of hinterlands. Mechanically agitated sediments by scourge of the waves in the inner shelf too were transported to the barrier islands, deposited and identified as tsunami sediments.

Figure 1.10: The sea wall sinks and gives in to the persistent sorties of the waves and toe erosion. A view of Alappad beach

Everywhere the denser black sand deposit remains near to the coastal ridge deep into the regions of devastation whereas lighter quartz was mostly washed away. This was prominently seen on both Alappad and Arattupuzha regions.

All the major rivers of central Kerala, namely Chalakkudy puzha, Periyar, Muvattupuzha River, Meenachilar, Manimalayar, Pampa River and Achancoil River and lesser rivers like Keecheri, Karuvannur and Puzhackal discharge into the

Vembanad Lake. And the surrounding geological formations are maintained over the years by the sea and the fresh water contributions of the rivers. The provenance of the silt and sand are the charnockites and khondalites of the Western Ghats mountain ranges (Alex, 2005 and Achari, 2005).

The oceanic wave action and the unimpeded discharge of sediment load has resulted in the formation of a long sand bar from Kollam to Kodungalloor along with a large network of deltaic islets and lowlands in between braided streams. There are reasons enough to conclude that the seashore began along the western fringe of the midlands well before the emergence of the Vembanad Lake.

In Kuttanad region, thick layers of calcareous shells of extinct marine organisms are seen, that indicates a marine past of this region. Today the low lands and the catchments of the above seven rivers near to the shoreline are economically the most important region of Kerala. And this part of the state, over the past one hundred years or so, has undergone accelerated anthropogenic modifications.

The coastal strip of Kerala from Chavara to Cochin is environmentally a delicate and complex one. It consists of a long chain of barrier islets placed with a north-south orientation. The water bodies on the east of these sand bars have essentially estuarine characteristics, subject to the physico-chemical ministrations of the tidal pendulum. These shallow estuarine water bodies have suffered morphological and biogeochemical modification because of anthropogenic intervention in the form of social and economic activities.

Traditionally Keralites are not familiar to natural calamities except annual monsoonal floods. Kollam – Alappuzha coastal belt of Kerala is one of the most thickly populated regions in the country. The proximity to the sea, the relative ease for indulging in fishing operations and swift access to major urban centers of the state has apparently contributed to high population density in the region. But the morphological integrity of these very recent formations and the reliability of the fresh water reserves in the tertiary formations taunt the very philosophy of overpopulating these fragile lands.

The geographical setting of the sand bars is such that even without a tsunami, sea waves of less prominence also can potentially perpetrate grave damage to life and property in the region. Over the years the sea is steadily eroding its path east so much that the entire coastal strip has been humbled into a thin ridge of sand and alluvium.

Figure 1.11: Devastated Coast at the Kayamkulam Inlet (Prakash et al., 2006)

On the day when the sea is subsided to a treacherous calm and receded to unprecedented depths, curiosity moved the people to sea shore. It was nature's way of warning the tune of things to come. But, in the mind of the people it did not occur to hope that the sea was up to for a real mischief. In other words the people were least prepared to face a disaster as we could see from the shining faces of the jubilant mass gathered at the moment of tsunami as given in the photograph. (Figure 1.12, Figure 1.13, Figure 1.14)

Figure 1.12: The wrathful return of the sea; Cherai beach, Cochin on 26 December 2004 when the sea water came barging in (Achari, 2005).

Figure 1.13: The people could not read deep mood of receding sea. Tsunami event along Cherai beach, Cochin on 26 December 2004. The sea retreated before strike (Achari, 2005).

Figure 1.14: The tsunami water sweeps past the thickly populated sandbars Cherai beach, Cochin on 26 December 2004 (Achari, 2005).

In Kollam District alone the tsunami onslaught left 142 dead. A preliminary report prepared by the district authorities shows that 1254 persons were injured by the seismic waves, 1559 houses completely washed away and 926 houses partially damaged. Among those killed, 128 are from the Alappad village of Karunagappally taluk and the rest from Shakthikulangara and Kollam West in Kollam taluk. The district collector officially reported that 43 relief camps had been opened in the district to rehabilitate the affected people.

People of Kerala learned many lessons from Japan and other Pacific countries that are prone to tsunami. The problem of coastal Kerala is far more complex than learning to cope with an incident of tsunami. The strip of coastal land between Fort Cochin and

Chavara is particularly prone to continuous erosion. The aggressive swirl of waves scours and scoops from beneath and the wall in the course of time makes the stones of the seawall to sink. Sea walls and even mangroves are not potentially equipped to ward off tsunamis for all time, as tsunami waves can be as high as 10 meters. But experience on Tamilnadu coast, particularly Parankipettai showed that a man made mangrove by Annamalai University students and teachers near to the coast saved almost a village from total ruin by tsunami waves. At best they disperse the momentum of the speeding waves. Erecting a wall more than 10 meters high in the sea shore is impractical. Such walls will stand in the way of the retreating water after a tsunami-induced flood.

1.6 Coastal Kerala: Geology and Environmental Sensitivity

The coastal stretch described in addition to above is highly exploited for various developmental activities like habitat and human settlements (Figure 1.15), mineral processing and exploration, industrial and infrastructure development. In addition to prevailing coastal erosion, the threat due to inundation is more and is aggressive during monsoon season. The *changes* in the shoreline features marked by coastal and inland morphology over the years is a great concern of all as the state has a unique natural setting.

Figure 1.15: The coastal belt is steadily sinking across time- This house has evenly subsided to a depth of 20 cm during its 200 years of existence (Achari, 2005).

Kerala is physiographic divided into *highlands, midlands and coastal plains*. The coastal plain has an elevation of 0 to 8 m above mean sea level (Narayana and Priju, 2006). In many coastal areas the lateritic plateau soil structure extends up to shoreline. This is particularly observable in northern and southern coasts. Based on these observations geologists divide the shoreline and its related coastal plain into *(i) high coastal line or impermeable shoreline bordered landwards by a cliffed shoreline with or without a beach and a (ii) low coastal land or permeable shoreline, comprising a slanting plain* (Narayana and Priju, 2006).

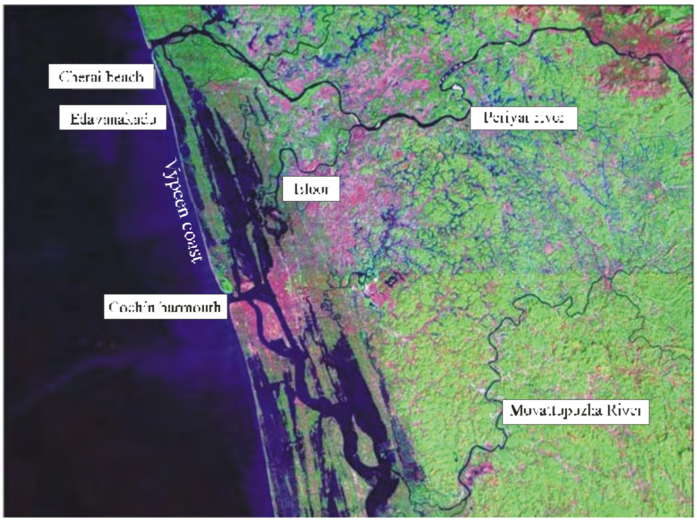

Figure 1.16: The satellite map of the 26 December 2004 tsunami affected study area on Cochin coast

The tsunami affected coastal stretches on which this research work mainly focused is a permeable shoreline. The coastal plain of Kerala generally has a width between 5 and 6 km in general except in Shertalai where it has a width of about 29 km. The coastal stretch extending from Alappad in south to Cherai beach in the north is dotted with backwater systems, lagoons, barriers, coastal alluvial deposits, and marshes.

Network of estuarine-lagoon arms of the Cochin backwaters extends almost entire length of this coastal stretch (Figure 1.16). The sampling stations of this study are located in the three adjacent districts of west coast of Kerala (Kollam, Alappuzha and Ernakulam districts). The region is ecologically most important as the major rivers of the state viz; Periyar, Pampa, Muvattupuzha, Meenachil, Manimala, Achankovil discharges to the Vembanad backwater-lagoon system prior to their merging to the sea. Any change in the surface and ground water quality and chemistry has a momentous impact on the biodiversity of the region as well as the economic stability of the state.

Petrography of the region consists of different formations as evidenced by the core profile. They are *(i) Holocene sediments, (ii) Tertiary sedimentary rocks, (iii) Laterites and (iv) Charnockites, granite gneiss, Khondalites – Precambrian crystalline rocks.* Narayana and Priju, (2006) report that sedimentary rock formations of Neogene and Quaternary periods cover Precambrian rocks in the study area. Marine rock structures of the region are constituted by Vaikom and Quilon formations. Non-marine formation is identified as the Warkalii beds. Laterite capping which is common to coastal shoreline is absent in the study area.

1.6.1 Coastal Kerala: Climate and Rainfall

The study area exhibits both dry and wet seasons decided by tropical monsoon climate. Dry and wet days are very common with intense pre-monsoonal showers as prelude to the onset of monsoon on June 1st of every year. October-December is almost dry. The diurnal temperatures range from *22°C—35°C*. Highest mercury rise is observed during March- May and they fall to minimum in December-January.

The region experiences annual mean relative humidity of 79-84% in mornings to 73-77% in the evening. Annual rainfall is between 2000-3000 mm and more than 60% of this is received during south west monsoon (June- September). Northwest monsoon showers contribute too little to 50 cm rain fall (October- December) average.

1.7 Profile of the tsunami affected study region

1.7.1 Beach Pofile

Alappad-Arattupuzha coast has been a scientifically explored and extensively studied coastal region particularly after the tsunami incidence (Kurian et al., 2005). Figure 1.17 is the location map and beach profile of the region.

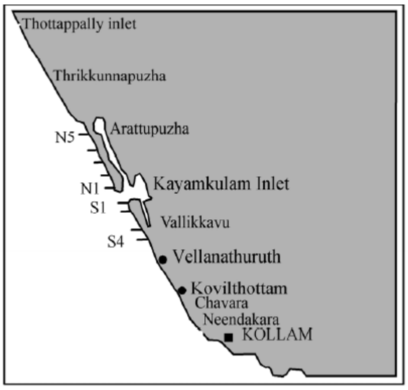

Figure 1.17: Location of beach and its profile

The region is subject to the extensive erosion/deposition as the sea – land interaction is very intensive, thereby many facts and realities of the nature have to be taken for granted. The post tsunami scenario of the region is well studied and reported by the above researchers and it gives lot of remarkable information on the impact of tsunami. In their critical evaluation of the coastal region, it has been found that the stations marked N_1 and N_2 north of Kayamkulam inlet along Arattupuzha coast (Valiyazheekal) noted an erosion amount to 53 m^3 and 16 m^3 respectively. Maximum erosion had taken place at station N_3 north of Kayamkulam inlet. Stations beyond that N_4 and N_5 showed much less erosion.

Alappad coast the southern part of Kayamkulam inlet experiences deposition instead of the attrition observed in north. The reports state that stations marked S_1 in the graph had a deposition of 91 m^3. The deposition decreases on moving further south beyond 200 m. Station S_2 recorded deposition of 38 m^3 of sand (Kurian et al., 2005).

At one kilometer towards south the extend of deposition is observed as 65 m^3 further south of this station only a small fractional deposition equal to 13 m^3 was noted. The beach deposition of these regions extends to Chavara. Industries like Indian Rare Earths Limited and Kerala Minerals and Metals Limited meet their raw material demands from the existing deposits. The region is ecologically and industrially important in many ways as it is the major enriched mineral depository of the country meeting the technical and strategic demands.

1.7.2 Sediment Character

Figure 1.18 is the bathymetric study profile of the region. After tsunami event showed a widening of the inner shelf (Kurian et al., 2005). The evaluation of the bathymetry data after tsunami with one already available on the region in 1987 noted that the existing bathymetry changed in the offshore. The above researchers confirmed that the changes which occurred beyond 10 m in the offshore correspond to the impact of the tsunami (Figure 1.19).

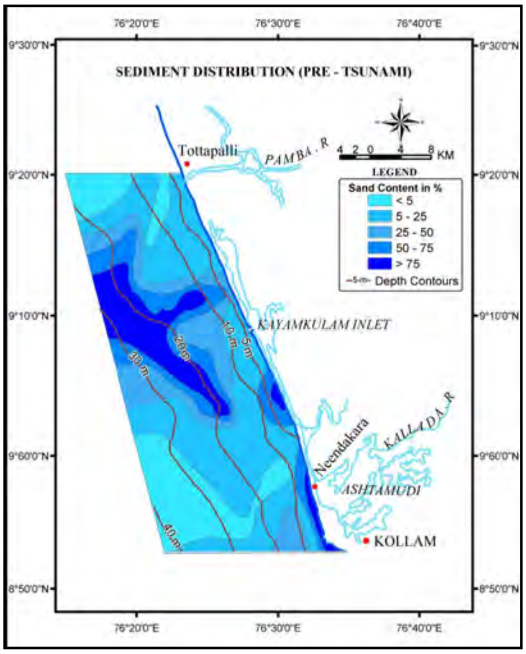

Figure: 1.18 The distribution of sand in the inner shelf during 1987.

This study confirmed that one of the geological impacts of tsunami has been the subsequent erosion of soil in the inner shelf of the coastal area. Quartz grain features of the sediments indicate that the sediments belong to the Holocene period (Prithviraj and Prakash, 1991).

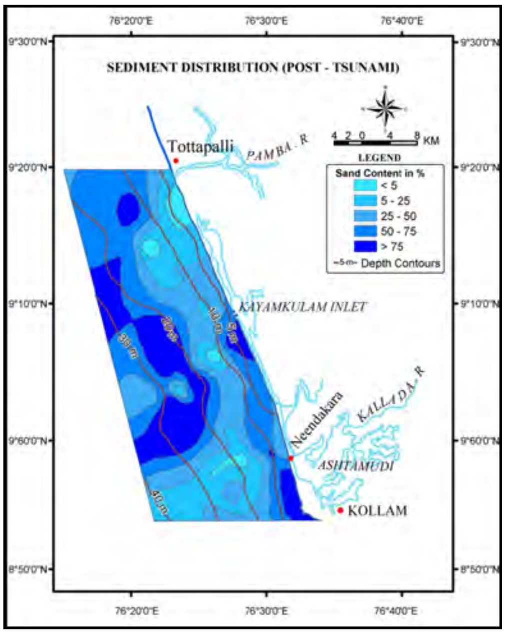

Figure1.19. The Distribution of Sand in the Inner shelf during 2005

Supporting conclusions are available on the basis of extensive research by many research teams. Analyzing sediment samples from the coastal area of Neendakara-Thottapally region researchers unraveled many striking facts. Finer sediments that constitute the major fraction have been taken away by tsunami waves.

Alappad-Arattupuzha exhibited the shoreward migration of sandy sediments in regions around Kayamkulam inlet. The monumental surge of the waves which measured average run up of 5 m in the region triggered huge extent of sediment transport. These waves took away the finer fraction of the sediments lifting the lighter quartz fraction to upper reaches of the barrier inlets.

1.8 Review of Literature

Indian Ocean Tsunami, widely referred as it originated and propagated there, destructively brought many short and long term impact on the coastal belt of India. East and south coast faced many direct and indirect after effects to be accounted as one of the most devastating earthquake borne coastal hazard second to none ever recorded in the recent history of the country. The tsunami waves brought about seawater invasion to coastline and caused very extensive seawater intrusion into groundwater (Achari, 2005; Achari et al., 2006a; Achari et al., 2007; Srinivaslu et al., 2008; Kitagawa et al., 2006; Sil and Freymueller, 2006).

Timely investigation by scientific groups documented enormous data on the impact of tsunami on various strata on the human environment. Most of them were precisely focused on the incidence of run up (Kurian et al., 2006), destructive aspect of tsunami (Achari et al., 2006c), trace metal enrichment (Srinivaslu et al., 2008), texture and mineralogy of placer deposits (Babu et al., 2007), ground water quality (Achari, 2005; Achari et al., 2006b; Perumal and Thamarai, 2007), salt and nutrient uptake behavior of tsunami inundated soils (Achari et al., 2007), effect of rainy season on the tsunami deposits (Szczucinski et al., 2007).

The scientific studies brought many publications that in fact strengthened the prominent literature regarding study of tsunami. Impact of the destructive giant waves on coastline topography, terrestrial ecology and human life (Narayana et al., 2005) are a few. The severity of the tsunami damage on the coastal flatland is decided by the beach run up height of the successive tsunami waves (waters highest elevation at the maximum horizontal penetration) and the extent of inundation (distance from the shoreline to the tsunami penetration limit). Long term evaluation and monitoring are required to decide activities to protect and preserve the quality groundwater (Ramasamy et al., 2006; Ramanmurthy et al., 2005; Oyedele and Momoh, 2009).

Many works on the medical, sociological, engineering, environmental and geological effects of tsunami are also reported from many parts of the world (Szczucinski et al., 2007; Satake et al., 2006; Morgan et al., 2006; Geoff et al., 2006; Ghobarah et al., 2006; Kench et al., 2006; Danielsen et al., 2005). Still the study of tsunami deposits and the leaching behavior of soil-bound contaminants under inherent condition and natural exposure is a subject of intensive research (Szczucinski et al., 2007; Babu et al., 2007; Srinivaslu et al., 2008).

Research on the geochemical and hydrological aspects of tsunami on coastal environment is very important in many ways (Rajamanickam, 2006). Deposits by tsunami waves from sea - the sediment layers lay on the coastal line and land areas brought many identifiable and prominent landmark changes on coastal geomorphology. This salty and mineral rich sediment layers spread on the inundated land buried deep the existing coastal terrain and augmented the secondary pollution (Szczucinski et al., 2007; Chaudhary and Gosh, 2006; Boszke et al., 2006) of the ground water. Many dug wells on the shoreline - the primary sources of the drinking water in the coastal Kerala had been contaminated and ultimately the population was denied of fresh water (Achari, 2005; Achari et al., 2007; Achari et al., 2006b) by the tsunami waves. Accumulated salt and marine ions brought damaged plants and especially affected the survival of fresh water plants (Achari, 2005).

In many places, the tsunami wave front reached more than 1.5 km inward in the land. In Kerala, the maximum run up of the tsunami wave was 4.5-5.0 m and occurred in Valiyazheekal and Azheekal (Prakash et al., 2006; Kurian et al., 2005), where the waves brought maximum devastation.

In India the maximum reach of inundation occurred at Colachel in Tamil Nadu (Chandrasekar et al., 2007). Everywhere, the inundated area was “blanketed” with salty sediments whose grain characteristics varied from region to region in several centimeter thicknesses (Szczucinski et al., 2007; Bishop et al., 2006). The thickness of silty sand and quartz sand blanketed the entire coast more than 500 m away from shoreline (Szczucinski et al., 2007). In Kerala coast, Alappad and Arattupuzha, the sediment blanket was consisting of finer quartz sand and coarser black sand minerals (Achari, 2005). Studies on the tsunami deposited sediments reveals that salty soil fractions are mostly saturated with high content of K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} as water soluble fractions). Acid leachable fractions of soil have high proportion of heavy metals ions of Cd^{2+}, Pb^{2+} , Hg^{2+} (Szczucinski et al., 2007). Metalloids and highly toxic organo mercury fractions are also not uncommon in isolated acid leachable fractions and their concentration remained high even after rainy season (Szczucinski et al., 2005 & 2007). Study of tsunami and tsunami deposits are important as a geological record in assessment of such hazard in a region. It may help to identify the recurrence of the event and vulnerable regions of inundation and sea water intrusion (Szczucinski et al., 2005 & 2007; Nanayama et al., 2003; Dawson et al., 2004).

Identification of paleo-tsunami deposits based on sediment chemistry and concentration of Na, S, Cl, Ca, and Mg is a common geographical diagnostic approach followed. Grain size distribution of tsunami deposits collected from paleo-tsunami regions is essential to calculate and interpret wave hydrodynamics and probable impact made (Szczucinski et al., 2007; Minoura et al., 1994; Chague-Goff and Goff, 1999; Chague-Goff et al., 1999; Goff et al., 2004.)

Dispersion of contaminants brought out by tsunami caused extensive changes in location wise in the respective tsunami affected regions; particularly their distribution of contaminant in the coastal hydrosphere (Achari, 2005). Presence and non uniform distribution in solution phase, saturated soil matrices and water flow regime influenced by weather condition catalyses long term repercussion on the ground water quality (Achari et al., 2006a; Achari et al., 2007; Ivahnenko et al., 2001) and its subsequent degradation.

One of the immediate adverse effects of tsunami had been contamination of existing freshwater sources pushing the survivors to the acute shortage of drinking water. The ocean surge subdued large land area spoiling immediate and available drinking water at sources. Subsequently, overburdened salinity of the surface-well water sources, flooded by seawater become heavily contaminated by undesirable components (Achari et al., 2007; Achari et al., 2006b; Tharnpoophasiam et al., 2006).

Fresh water churned with soil and mixed with potential foreign materials, salts, ions, organic molecules and micro organisms transported by tsunami waves. There are enough instances where tsunami waves degraded quality of drinking water. Over the days the damaged wells become a hamlet for vector breeding (Apiwathanasorn et al., 2005).

The importance of regular monitoring of water quality parameters is essential to redefine the permissible limit of many trace elements as observed by researchers.

Many metal contaminants like mercury, lead, cadmium and arsenic has potential health risk to children even during developing of human fetuses, once the mothers are ingested by ground water having these ions.

Precise knowledge on regional ground water quality and its chemistry in the background of tsunami event is essential to detect the chances of degradation and probable quality challenges. In this regard, a minor change in the content of a ground water component in a regular monitoring could lead in to rational analysis to judge upon causes and reasons. Researchers (Ivahnenko et al., 2001; Hamilton et al., 1993; Hounslow, 1995) meticulously highlight the importance and necessity of water quality data and art of interpretation. These works are regarded as a standard procedure of water analysis based on theory of ionic equilibrium. The result has to be useful and comparable over the so-called monitoring period of interest as well as in the retrospective studies.

In one of the water quality monitoring studies after tsunami event on Kerala coast brought many striking and delicate information on its direct impact on flora and fauna (Sam et al., 2006; Achari, 2005). Seawater brought by tsunami waves swept in through Thottapally barrage in Alappuzha mixed with fresh water that ultimately malnourished the paddy seedlings cultivation in a nearby agricultural research station. This had been a noted incidence of direct impact of tsunami on crops and response to tsunami water – one of the crop hazards reported from Kerala as a cited example (Sam et al., 2006).

Coastal Kerala had been seriously damaged by tsunami flood and domestic farming of major regional fresh water crops, banana, mango, jack tree, guava, and areca was quickly exposed to typical chloride toxicity (Achari et al., 2007). This could have been due to the accumulated salt concentration in rhizosphere that reversed the path of nutrient movement (Sam et al., 2006) in the plant.

Analysis of tsunami affected soil and water revealed high concentration of salt, the respective pH has been very alkaline. Data obtained with respect to a control sample selected from the same region exposed that samples (water and soil) directly affected by inundated tsunami water has high chloride content. Despite the raining season in the post tsunami period they have higher concentration of Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^- and SO_4^{2-} ions. This indicates the chance of yet another complex environmental situation brought by tsunami impact upon coastal environment. The slow dilution and percolation of the soil bound ions occurs in the eluting rain water front retaining a major proportion in the bound form. Released ions reaches to the freshwater sources, enough to cause subsequent dilution by steady ground water flow regime.

Sorption-evaporation-percolation of salt ions on soil matrices certainly enriched content of Na^+, K^+, Ca^{2+}, Mg^{2+}, and Cl^- in the terrestrial environment particularly in the post-tsunami lag phase. Acid leachable trace metals (Cr, Cu, Ni, Co, Pb, and Zn) too have been found contained in tsunami exposed soil. Uptake and exchange of ions have been related to the role acted by Fe-Mn oxyhydroxide (Perumal and Thamarai, 2007; Srinivaslu et al., 2008) a well-known ion facilitator material of soil.

This indicates that tsunami waves had been a harbinger of a rather extensive mass transfer process. Tsunami orchestrated mass transfer occurred as happens in an interphase phenomena leaving large ionic mass on land soil mass more and enough to change the chemosphere of the shoreline soil. Tsunami waves contained ionic mass is intermittently brought to the landward directions as if it occurs in a reactor system. In many instance of ocean driven coastal disasters, well water monitoring and evaluation in post event scenario revealed much insight into the reasons for a decline in ground water quality. A decrease in Ca/Mg ratio right after the event and slow replenishment to original pre-event values has been a noted phenomenon (Thomas et al., 2007). Imbalance in the ionic ratio controls the chances and the extent to which the environmental disaster occur. In all situations the physical existence of drinking water, wells, their structure, casing and or associated plumbing were damaged allowing salt water to flood badly (Thomas et al., 2007; Achari et al., 2006b).

Quality variation of ground water after an environmental disaster like tsunami is related to the natural recirculation of water as well as leaching of deposited minerals from soils and weathered rocks (Achari et al., 2007; Raju et al., 2009). The general approach followed to study the chemistry and hydro chemical nature of ground water is the evaluation of primary water quality parameters. Testing of the data by computing quality indices and ionic ratio calculations followed by simulating graphical forms in Hill-Piper-Trilinear Plot (Hill, 1940, Piper, 1944 and Piper, 1953) give many confirmatory inferences in water analytical science. Nevertheless it is done the prominent cations and anions and microorganisms otherwise determine the suitability of a ground water for many of the economic usage and human consumption without any quantifiable measure to judge upon.

Flooding by tsunami waves changes the natural quality of drinking water sources by disease causing microorganism leading to severe situations of acute diarrhea, cholera and serious infections (Tharnpoophasiam et al., 2006). The quality variability with respect to chemical components of ground water either due to peculiar terrestrial / coastal environment become a challenge to human health in the course of time.

Paired or values with weighing factor of individual parameters expressed as indices would give more insight into the water utility. Water quality indices reflect combined chemistry of the ions than singular/ paired ion chemistry (Prasad et al., 2009; Handa, 1965; Achari et al., 2007). Several methods and techniques are known available to interpret the acquired hydro chemical data to decide the potential utility of ground water (Hounslow, 1995; Handa, 1965; Kumaresan and Riyazuddin, 2006). Graphical simulation of the data simplifies the complexity of predicted hydrological interaction of ions. Hence the understanding of the interaction becomes easy and comprehensive (Prasad et al., 2009; Laluraj et al., 2005). Researchers (Hounslow, 1995; Kumaresan and Riyazuddin, 2006) in their similar works used many mathematical and graphical methods to interpret the groundwater data to decide upon ultimate use.

Hill-Piper diagrams (Hill, 1940, Piper, 1944 and Piper, 1953) are the common graphical simulation method used to classify ground water followed by many hydro chemists to present the individual behavior of water ions are, Collins bar diagram (Hem, 1985), Wilcox diagram of groundwater (Wilcox, 1985) and USSL (United States Salinity Laboratory) are the other well-accepted methods. Simulation of some these diagrams using primary data obtained on ground water of tsunami affected regions of the study area shown in the figure both in pre as well as post tsunami scenario is made to decide upon the further fate of the region's environmental quality. Recently many research initiatives aimed to evaluate the post-tsunami impact on coastal and marine environment is known (Srinivasa Kumar et al., 2012; Jha et al., 2011; Sharma and Bajpai, 2011; Patankar et al., 2012; Kocherla, 2012; Agoramoorthy, 2012; Patel and Agoramoorthy, 2012; Shibata et al., 2012).

This study specifically targeted to the overall water quality profile of the near and deep ground water sources that span the entire coastal belt of the three major districts of the state (Kollam, Alappuzha and Ernakulam) which are badly damaged. The data generated form the most valuable base with respect to the ground water quality to identify the cause and reasons for the possible changes in future due to any possible natural coastal hazard like tsunami.

1.9 Significance of the Study

This research work evaluates the influence of the physico-chemical and biological parameters of over 40 ground water resources of the region for 12 months starting from the month of January 2005 to December 2005. Major parameters analyzed include pH, Conductivity, Redox potential, Turbidity, Alkalinity, Hardness, Total hardness, dissolved oxygen, biochemical oxygen demand, Chloride, phosphates, Iron, sodium, potassium and Total coliform.

This study of the ground water quality variation of the severely affected water sources of the coastal regions of Kerala had been started immediately after the tsunami event on December 26, 2004. A complete evaluation of the ground water quality of the above stations has been done in January, 2008 as a bench mark to serve as a basis for the evaluation/ comparison of the water quality changes being essential for the understanding of the phenomena correctly and completely. Major results of the study are being presented in major six chapters with a short preface and broad introduction.

A detailed description of the specific protocols followed for the sampling and analytical chemistry followed, statistical tools used for the correlation of water quality parameters and evaluation of water quality index of the surface and deep ground waters of the tsunami affected study regions are given.

The preliminary reconnaissance survey has been carried out in the first week of January 2005, in order to chalk out a working and viable strategy for monitoring with first sampling. A few sites of regular spatial intervals were tentatively selected; samples were collected and analyzed to check the quality change. Thereafter, based on extensive field surveys the sampling stations for regular monthly water sampling were fixed. The fresh water dug well maintained outside the Cheriazheeckal Vadakkenada Bhagavathy Temple on Alappad coast was one location. Hindu temples have a custom of maintaining sacred wells near to the sanctum- sanctorium to draw the holy water for pooja and ritualistic practices, maintained protected in full sanctity mostly within temple compound. In this study the above mentioned temple well is well protected though it is very close to the shore. This well has a striking significance peculiar to the location where it is maintained. Though it is close to the tsunami affected region with same geo-morphological setting, it is not directly inundated by tsunami waves or its secondary impacts. The freshwater quality remained stable mostly in parallel with the pre-tsunamic conditions. This well was selected as the control station (marked as station 1 in Alappad coast). The entire stretch of the tsunami affected coastal area in Kerala, India has been hyphenated into four coastal regions with a total of 42 identified groundwater sources for regular monthly sampling and monitoring. This comprises

1. Alappad Coast in Kollam District, Kerala, India [22 km - with selected 11 stations]
2. Arattupuzha Coast in Kollam District, Kerala, India [18 km –with selected 11 stations]
3. Andhakaranazhy Coast in Alappuzha District, Kerala, India [12 km – with selected 10 stations]
4. Edavanakkad- Cherai Coast in Ernakulam District, Kerala, India [6 km of Edavanakkad- Cherai stretch–with 10 stations]

The ground water sources chosen for the present study have conspicuous and specific utility as a potential fresh water source. Each one has a definite water regime with a representative nature and some degree of specific economic utility. The data graphically presented in the following sections are experimental observations obtained after rigorous analyses of samples. These have meticulously been correlated to sift out the salient temporal and spatial tendencies characteristic of each water source. Standard methods (Clesceri et al., 1998) were systematically followed in each stage of analyses during sampling and preservation.

With four well-planned field trips per month, each station of the above strata singled out for the study is sampled in prominence. The locations chosen for the study, the sampling sites earmarked for each location and their respective serial numbers are well specified as a part of the robust protocol followed.

Ground water sample were collected from those marked station every month. Most of the water sources were dug well less than 2.0 M in depth and for uniformity samples are collected from the surface. In case of deep bore wells special standard method for deep ground water were strictly followed. It is assumed that vertical mixing in sampling sources is complete and the stratification is nonexistent in all stations.

Water Quality Index (WQI) has been evaluated according to a known standard procedure referred in literature (Pathfinder Science, 1988). This Index has been devised as a simple methodology to subject a water source to water quality ranking with the intention of its utility. Following the same procedure the water quality index of the tsunami affected ground water sources of the study area has been critically evaluated.

1.10 Aim and Scope of the Study

The main objectives of the study are:

i. To establish the temporal ground water quality variation profile after 26 December 2004 Indian Ocean tsunami event on coastal regions of Kerala within the local geo-physical constraints for a period starting just 7 days after tsunami to 1430 days.

ii. To study the variation of the ground water quality profile of the study area with respect to depth profile of ground water sources classified into three distinct strata; control well [CW], tsunami affected dug wells [TADW, average depth 6feet] and deep groundwater source- bore wells [BW, average depth 300feet]. Evaluation and critical analysis of prominent water quality parameters and their variability with respect to time and location.

iii. To come out with the statistical interpretation of the post tsunami water quality data of the region with respect to BIS and WHO standards. Also to pre-tsunamic situation with a baseline data of year 2001.

iv. To compute the monthly water quality index (WQI) of the region giving adequate weightage to significant quality parameters of the ground water with respect to specific depth profile and tsunami affected coastal region.

v. To consolidate a database, as elemental supporting material for further studies as a model for the study of coastal hazard and its consequences with respect to ground water quality.

vi. To study the ground water chemistry of the region in relation to the pre and post tsunami situation (after 26 December 2004 Tsunami).

vii. To classify the water types with respect to Hill-Piper Trilinear plots, hardness and salinity hazard values.

viii. To evaluate the overall water quality parameters of the tsunami-devastated coastal regions of the state.

ix. To come out with viable managerial options pertaining to rehabilitation and restoration of the fresh water sources of the tsunami affected coastal regions of the state.

The experimental methods and procedures followed for the evaluation of water quality parameters, the results and discussion on the major findings, inferences and further scope of the study are presented in the subsequent chapters.

1.11 Hypothesis

Hypothesis to be tested are,

i. Whether there is any significant difference in the water quality parameter under study between stations and between months in Tsunami Affected Dug Well (TADW).

ii. Whether the selected water quality parameters vary significantly from BIS and WHO standards.

iii. Whether the water quality parameters differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW).

iv. Whether the water quality index (WQI) differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW).

v. Whether there is any significant difference in the water quality parameters during December 2005 and December 2008.

vi. Is there any significant change in the water quality parameters before (2001) and after tsunami (2005) in TADW.

To test the hypothesis in (i), (iii) and (iv) listed above, the data collected for the study were subjected to statistical analysis using Two-Factor ANOVA. Wherever treatment effects were found to be significant, least significant difference (LSD) at 5% level were calculated to identify the significant treatment component.

For testing the hypothesis listed in (ii) and (v), students ‘t’ test was employed.

For testing hypothesis (vi), the mean of Water Quality Parameters in 2001 and 2005 in TADW are compared using independent student’s ‘t’ test.

1.12 Structure of the Thesis

Chapter 1 is a concise introduction of the thesis consisting of the impact of 26 December 2004 Indian Ocean Tsunami on Indian coast, run up and inundation profile of the entire severely affected regions. It comprises the background of the research study starting with the geographical importance of the coastal areas of Kerala with respect to geomorphology, bathymetry, coastal erosion, and coastal hazards including natural disasters. Geological significance of the soil formations in relation to ground water sources, ground water chemistry and ground water models: concepts and equations, consequence of tsunami impact on coastal areas of Kerala, extent of environmental damage and after effects, monitoring protocols for the present water quality studies, relevance of the current study, objectives of study and hypothesis form the major part of this chapter.

Chapter 2 mainly describes methodology followed for this research study. It includes materials and methods, instrumentation, the locations of the sampling stations and their significance, sampling protocols, standard operating procedures. Analytical chemistry and hydro analytical methods followed for the estimation of each parameter is briefly described. This is followed by a detailed description of the specific graphical, mathematical and statistical tools used for the correlation of water quality parameters including their intervariability and water quality index of the surface and deep ground waters of the tsunami affected study regions.

Chapter 3 comprises the results and discussion on the water quality parameters of the ground water sources of the Alappad region of the study area in a pre-tsunamic situation which existed in 2001 to draw insight into the gravity of the tsunami impact on the groundwater quality in the post tsunami time scale. Overall ground water quality profile of the regions is evaluated based on the data available including ionic ratio and Hill – Piper – Trilinear Plots. The results are very prominent and essential to the post tsunamic situations and its devastating impact on hydrochemical parameters. Chapter ends with a conclusion.

Chapter 4 elaborately discusses the results of the post tsunamic water quality of the ground water sources of the severely inundated Alappad region of the study area marked with highest run up level and inundation distance leading to devastating impact and damage to human lives. The tsunami impact on groundwater sources are extensively studied based on the data generated from the extensive field and laboratory studies of the water samples; control well (1nos), dug wells (7 nos), bore well (3 nos) is being presented under three distinct strata. Impact of tsunami on individual parameters is discussed with graphical interpretation of the results with suitable graphs and tables. Salinity hazard profile, variability of hardness, chloride ion impact, WQI and ionic ratio, Hill – Piper – Trilinear Plots are critically discussed to evolve out an inference with respect to the overall water quality of the region as well as the ground water quality of the TADW. The comparison of the water quality with respect to the sources is interpreted following *t* pooled test as statistical tool in regards to the nature of the source and strata. Chapter ends with a conclusion.

Chapter 5 consists of the graphical presentation of the data, logical interpretation of the results and discussion on the water quality parameters of the ground water sources of the other tsunami affected coastal areas of Kerala; Arattupuzha coast, Andhakaranazhy coast and Cherai Coast. The tsunami impact on groundwater sources are extensively studied based on the data generated from the extensive field and laboratory studies of the water samples; dug wells, bore wells is being presented under two distinct strata. Impact of tsunami on individual parameters is discussed with graphical interpretation of the results with suitable graphs and tables. Hill – Piper – Trilinear Plots are critically discussed to evolve out an inference with respect to the overall water quality of the region as well as the ground water quality of the TADW. The comparison of the water quality with respect to the sources is interpreted in regards to the nature of the source and strata. Chapter ends with a conclusion.

Chapter 6 summarizes the overall consolidation of the inferences gathered from the study. The interrelation of the prominent water quality parameters and critical analysis of the results for the occurrence of the specified changes on the quality of the ground water of the tsunami affected coastal area of the state, highly probable in the light of established theoretical and experimental facts. This Chapter ends with a conclusion.

The thesis ends with a concluding remarks and a discussion on the future scope of the study.

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Chapter 2

Materials and Methods

Contents

2.1 Tsunami affected study region

Three coastal segments along the Kerala coast, India were severely inundated by tsunami waves on the forenoon of 26 December 2004. The segments are Karunagapally (Kollam District) to Thottapally (Alappuzha District) that extent to a length of 37 km, Andhakaranazhy (Alappuzha District, 5 km) and Edavanakkadu to Cherai beach (Ernakulam District, 20 km). Tsunami struck the coastal areas of Kerala on December 26, 2004 at 12.45 pm, with a casualty of **172** and an estimated loss of property equal to Rs.**1358. 6 Cr** (Achari, 2005; Alex and Achari, 2005; Achari, 2008).

Alappad coast in Kollam District of Kerala in the south –west coast of India, 9^{o} 6' N 76^{o} 28' E (Figure 2. 1) is the area where most of the present work is concentrated as it is one of the most seriously affected regions of the Kerala cost with maximum human and economic loss. The area is a low-lying coastal plain having barrier island coast with a width about 50-200 m and elevation varying from 0.0 to 1.0 M above MSL. The entire barrier area close to the sea was inundated resulting in human loss and other property loss badly affecting agriculture due to seawater seepage and subsequent salt accumulation accelerated by summer evaporation.

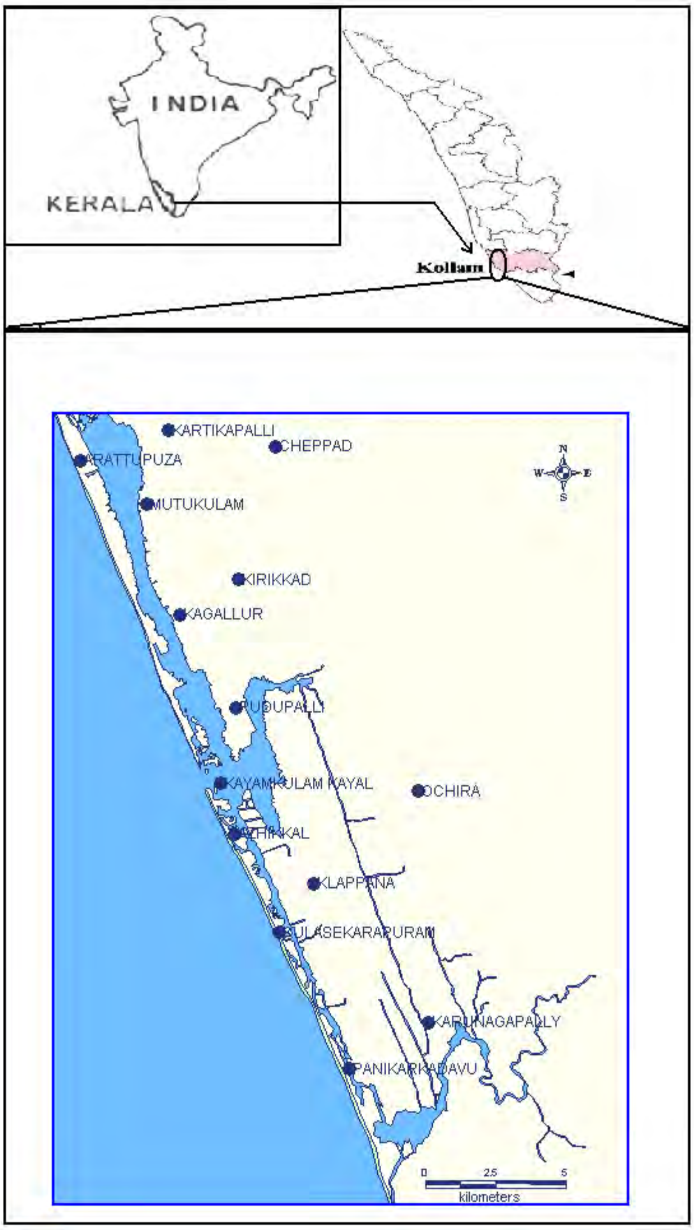

Figure 2.1: The location map of Alappad and Arattupuzha in Kollam-Alappuzha Coast, Kerala in **South of India.**

Based on the experience and observation made after the tsunami event the following hypothesis are proposed (i) with the first rains of the year after the tsunami event on 26 December 2004, the soil bound marine anions and cations leach down to the fresh water reserves or lens a feet down (to the perched aquifer) resulting in ground water contamination with dissolved inorganic and organic substances (ii) when the dry summer month's advance, salt swings back to the surface soil again by capillary rise (iii) the trapped salts will vertically oscillate between the perched ground water lens and the soil horizons for many years before being completely diffused away. Hence the deleterious repercussions of tsunami wave inundation are bound to last for a long time to come. (iv) the contamination of deep ground water aquifer (300 ft) the reserve depended by the coastal settlers are contaminated being both aquifers are well connected.

2.2 Monitoring Strategy and Sampling Protocol

Field sampling and monitoring the temporal water quality variation of the study area mentioned above started, immediately after the tsunami event on 26 December 2004. In the first week of January 2005, the team carried out the preliminary reconnaissance survey of the entire coastal stretch that faced maximum devastation, in order to chalk out a working and viable strategy as far as the monitoring program was concerned with first sampling. Identifying of a control well in the region had been the primary objective. This has to be one affected by tsunami waves in no way so that a baseline control could be ascertained to analyze the temporal and spatial variability of the water quality data. Sampling stations for regular monthly water sampling were fixed with respect to regular spatial intervals and samples were collected and analyzed. For this finalization extensive field surveys and consultations with the locals were made. The fresh water well outside the Cheriazheeckal Vadakkaenada Bhagavathy Temple in Alappad coast, which is close to the affected region and having very similar geo-morphological setting, was selected as the control well. (Figure 2.2)

The water sources chosen for the present study have conspicuous utility as a potential fresh water source, a definite water regime, a representative nature and some degree of economic utility. The data thereof have meticulously been tabulated to sift out secondary data and to distill out the salient temporal tendencies characteristic of each water source.

Standard methods (Clesceri et al., 1998) were followed in the full gamut of activities including sampling and analyses. Preservation of the samples was not required since all the unstable parameters were analyzed well within 3 hours of sampling. Hence the samples collected were not split nor were they subjected to pH control, chemical addition, refrigeration, filtration, freezing or bottling in amber colored or opaque containers. The sampling sites were less than three hours away from the laboratory.

Table 2.1: Water quality sampling stations representing various classes on tsunami Affected Alappad coast (Kollam) in 2005.

Station	Remarks	Location
1.Cheriyazheekal Vadakenada Bhagavathy Temple (outside)	Non affected well	09° 03’ 49N, 76° 29’ 47E
2. Vidyadharan- house owner	Affected well dewatered, cleaned.	09°0 3’ 04N, 76° 30’ 00E
3. Subhash –house owner	Affected well dewatered, cleaned.	09° 04’ 95N, 76° 29’ 69E
4. Parayakadavu Temple	Affected well dewatered, cleaned.	09° 05’ 23N, 76° 29’ 23E
5. Amrithapuri 600 feet well	Bore well	09° 05’ 23N, 76° 29’ 23E
6. Amrithapuri 300 feet well	Bore well	09° 05’ 24N, 76° 29’ 20E
7. Sraikadu Temple	Affected well not dewatered, not cleaned.	09° 05’ 32N, 76° 29’ 29E
8. Subrahamanya temple	Affected well dewatered, cleaned.	09° 06’ 54N, 76° 28’ 32E
9. Kurisady –public well	Dug well affected not cleaned	09° 07’ 78N, 76° 28’ 32E
10.Lakhmi-house owner	Affected well dewatered, cleaned.	09° 07’ 07N, 76° 28’ 32E
11.Pookottu temple 250feet well	Bore well (KWA) for local supply.	09° 07’ 07N, 76° 28’ 32E

The *chain–of-custody* report, as is required of a systematic sample analysis, is also not relevant in the present context as samples were collected, transported and analyzed by the self-same hands. With three field trips per month, each station singled out for the study is sampled every month. All samples were collected in the morning without fail. Mostly around 8.00a.m when photosynthetic activity is not yet established and ambient temperature has not reached its zenith.

The locations chosen for the study, the sampling sites earmarked for each location and then respective serial numbers are given hereunder in Table 2.1 to 2.5. White plastic cans of three-liter capacity where used as sample containers. The cans where thoroughly washed with dilute hydrochloric acid and then with distilled water. They were labeled indicating the name of the sampling site and the respective serial number. BOD bottles also undergo the same preliminaries.

Figure 2.2: The Control well Alappad coast close to Cheriyazheekal vadakenada Bhagavathy temple (A community well 50m from the sea but not directly affected by the tsunami on 26 December 2004

In the field diary the day and date of sampling and their respective serial numbers were entered well before the sampling trip was embarked upon. At the site, the time of sampling and the temperature of the sample taken were entered. Surface water sample was collected from the same site every month. All the water bodies covered were less than 1.5 m in depth and for uniformity samples are collected from the surface. It is assumed that vertical mixing is completed that stratification is non-existent.

Table 2.2: Water quality sampling stations representing various classes on tsunami Affected Arattupuzha coast (Alappuzha) in 2005

Station	Remarks	Location
1. Tsunami Pool-Valiyazheekal	Tsunami pool- depth 2 feet	09^{o} 08’ 25N, 76^{o} 27’ 43E
2. Thara- house owner	Groundwater supplied	09^{o} 08’26N, 76^{o} 27’ 40E
3. Bore well 250 feet (pump house)	Bore well (KWA) for local supply	09^{o} 08’ 32N, 76^{o} 28’ 02E
4. Subrahmanya Swami temple	Dug well affected and cleaned	09^{o} 08’ 35N, 76^{o}27’ 47E
5. Tsunami Pool-Tharayilkadavu	Tsunami pool- depth 2 feet	09^{o} 09’ 35N, 76^{o}27’ 12E
6. Kuriappassery Temple	Dug well affected not cleaned	09^{o} 09’ 41N, 76^{o} 27’17E
7. Bore well 250feet(KWA)	Ground water at source	09^{o} 09’ 41N, 76^{o} 27’ 17E
8. Panakal Devi Temple	Dug well affected and cleaned	09^{o} 09’ 56N, 76^{o}27’ 11E
9. Bore well 250 feet Ramanchery	Ground water at source(KWA)	09^{o} 10’ 37N, 76^{o} 26’ 42E
10.Manoj-house water	Dug well affected not cleaned	09^{o} 10’ 43N, 76^{o} 26’ 40E
11.Bhaskaran-house owner	Dug well affected and cleaned	09^{o} 11’ 02N, 76^{o} 26’32E

Table 2.3: Water quality sampling stations representing various classes on Tsunami affected Andhakaranazhy coast (Alappuzha) in 2005.

Station	Remarks	Location
1. Dug well-canal side	Dug well Affected, not cleaned	09^{o} 44’ 50N, 76^{o} 17’ 07E
2. Mariamma-house owner	Dug well Affected and cleaned	09^{o} 44’ 50N, 76^{o} 17’ 05E
3. Maniyan- house owner -	Dug well Affected and cleaned	09^{o} 44’ 48N, 76^{o} 17’ 04E
4. James- house owner	Dug well Affected and cleaned	09^{o} 44’ 37N, 76^{o} 17’ 08E
5. Pius- house owner	Dug well Affected and cleaned	09^{o} 44’ 37N, 76^{o} 17’ 07E
6. Sebastian- house owner	Tube well – 6 feet depth	09^{o} 44’ 35N, 76^{o} 17’ 07E
7. Devdas- house owner	Tube well – 5 feet depth	09^{o} 44’ 35N, 76^{o} 17’ 07E
8. Babu- house owner	Open Community Pond affected-	09^{o} 44’ 36N, 76^{o} 17’ 08E
9. Purushothaman- house owner	Dug well Affected and cleaned	09^{o} 45’ 25N, 76^{o} 17’ 00E
10.George- house owner	Dug well Affected and cleaned	09^{o} 45’ 09N, 76^{o} 17’ 03E

Table 2.4: Water quality-sampling stations on tsunami affected Edavanakadu Coast (Cochin) in 2005.

Station	Remarks	Location
1.Puthenkadappuram1	Open pond-between sea and backwater	10^{o} 05’ 13N, 76^{o} 11’ 33E
2.Puthenkadappuram2	Open pond- between sea and backwater	10^{o} 05’ 25N, 76^{o} 11’ 31E
3.Edavanakkadu South	Open pond- between sea and backwater	10^{o} 04’ 20N, 76^{o} 11’ 50E
4.Ambrose-house owner	Not affected open cut well -control	10^{o} 04’ 41N, 76^{o} 12’ 30E

Table 2.5: Water quality sampling stations representing various classes on Tsunami Affected Cherai coast (Cochin) in 2005.

Station	Remarks	Location
1. Francis- house owner	Dug well Affected and cleaned	10^o 08’ 24N, 76^o 10’ 46E
2. Varghese- house owner	Dug well Affected and cleaned	10^o 08’ 40N, 76^o 10’ 40E
3. Rosamma- house owner	Dug well Affected and cleaned	10^o 09’ 06N, 76^o 10’ 32E
4. RosammaTube well- house owner	Tube well-5 feet depth	10^o 08’ 06N, 76^o 10’ 32E
5. Varghese Madavana- house owner	Dug well Affected not cleaned	10^o 08’ 09N, 76^o 10’ 50E
6. Anandhan- house owner	Dug well Affected and cleaned well	10^o 08’ 24N, 76^o 10’ 52E

The grab sampler and the containers were rinsed thrice with the sample and the DO was fixed *in situ*. Bacteriological sampling bottles were opened under water. On every field trip, the conspicuous visual features observed were noted, especially the status of floating vegetation, color variations, cases of fish kill, construction/ destruction of temporary bunds, evolution of H_2S and presence of mosquito larvae etc.

Once back in the laboratory, where reagents had in advance been prepared and the instruments calibrated, the analyses were carried out immediately.

2.3 Laboratory quality control checks

The validity of any monitoring program depends on the quality of monitoring data generated. To ensure the quality of data the following quality control aspects were ensured. To prevent any deviation in analytical procedures a document on standard operating procedure (SOP) was compiled for this tsunami water quality-monitoring program.

Strict quality assurance procedures for data entry were routinely followed in all sampling events. Any changes made to data on bench sheets were initialed by the analyst. Analysts reviewed the raw data for outliers and questionable entries, if any, were immediately verified. Final data were recorded on a master data book and thereafter, fed to the computer.

The distance between two consecutive sampling sites, as a general rule, was fixed to be 1km. However, accessibility and the nature of the site were the deciding factors in the flexible rule. Field trips were undertaken in the middle of every month and this rhythm remained unaltered, all through the sampling year. The parameters monitored were pH, Eh, Alkalinity, Electrical Conductivity, Turbidity DO, BOD, Chloride, Total Hardness, Calcium Hardness, Phosphate, Sulfate, Total iron, and Nitrate.

pH was chosen as a regular parameter to be monitored because it is indicative of the degree of the saline water intrusion, bio-geochemical processes and contamination. Fresh water is generally acidic where as seawater is alkaline. Thus the pH variation around the year, covering all seasons, was expected to be revealing. *Alkalinity, conductivity, chloride, hardness and sulphate* are directly related to salinity intrusion. When salinity starts picking up, all the above parameters show a rising tendency, unless some other chemical sub-routes are involved. Hence, the rise and fall could be in phase with the migration of salinity. This possibility was explored by monitoring the above parameters.

Nitrate and phosphate are the essential plant nutrients and their ratio is indicative of sewage contamination. Increased pH and the intrusion of marine cations could lead to the flocculation of phosphate. Nitrate is a very unstable component in an oxygen-depleted aquatic ecosystem and hence, the concentration of nitrate and DO are complimentary. In the absence of DO, the oxygen-demanding wastes reduce nitrate. Solubility of iron is directly related to pH and DO. Iron is immediately precipitated to the sediments by hydrogen sulfide in anoxic conditions. On interaction with alkaline marine water, Fe was expected to be removed from the water column. DO and BOD are the most important parameters required to define the quality of a water body. Percentage saturation of DO is a direct measure of the purity of water.

2.4 Methods

2.4.1 Water Quality Analysis; Methods Followed

pH value (Method: 4500 $H^{+:}$ *Clesceri et al., 1998*): pH measurements are made with a digital pH meter (Systronics 1011 model).*Electrical conductivity (*Method: 2510b: *Clesceri et al., 1998*): The electrical conductivity of the water samples were measured using Digital conductivity meter (Century CC 601- P N- model). To calibrate and check the instrument, the cell constant is measured from time to time using standard KCl. *Hardness (*Method: *2340 C EDTA Titrimetric Method : Clesceri et al., 1998). Water Hardness:* The complexometric method using EDTA was used for the determination of Ca and Mg ions present in the water samples. The titration of the water using Eriochrome Black -T indicator was followed to determine Total hardness, and murexide indicator (ammonium purpurate- this indicator changes from pink to purple at the end point) to determine Calcium and Magnesium hardness. *Turbidity* (Method: 2130B; Nephelometric Method, *Clesceri et al., 1998*). *Standard Nephelometric Method* using formazin suspension (hydrazine sulphate and hexamine mixture) as standard was followed to measure the turbidity in NTU using single beam turbidimeter. Nepheloturbidimeter: 131 SYSTRONICS make (Range: 1 to 1000NTU) was used to measure the light scattered measured in turbidity unit. *Alkalinity* (Method: 2320B; Titration Method, *Clesceri et al., 1998*). Alkalinity of water (is a measure of titrable bases) is determined by acid titration using mixed indicator (Bromocresol green and methyl red) as a measure of total titrable bases. *Dissolved Oxygen* (Method: 4500-O C; Azide Modification Method, *Clesceri et al., 1998*). Dissolved Oxygen Content of the water has been determined following the above method most suitable for water analyses. *Total Iron* (Method: 3500 Fe-B; Phenanthroline Method, *Clesceri et al., 1998*). Iron present in the ground water samples were analysed forming into the Fe- phenanthroline chelate – orange red complex spectrophotometrically measured at 510nm. Water is first treated with acid – hydroxylamine and treated with *1-10, Phenanthroline* to make any iron present into the dissolved form. *Chloride* (Method: 4500 Cl^- B; Argentometric method, *Clesceri et al., 1998*). The Chloride content of the water samples were analyzed by argentometric method were the titration of water against with $AgNO_3$ will precipitate out AgCl fully before the red coloured $Ag_2(CrO_4)$ reacts. This could indicate the completion of the titration procedure. *Biochemical Oxygen Demand* (Method: 5210 B; 5- Day BOD Test, *Clesceri et al., 1998*). BOD determination was made for the each water samples by incubating under thermostatically controlled condition for five days. *Nitrate*: (Method:

4500 NO_3^- E; Cadmium Reduction Method, *Clesceri et al., 1998*). Dissolved nitrate present in the water samples were determined quantitatively by reducing to nitrite by passing through a packed tubular reactor containing cadmium filings treated with copper sulphate. The nitrite thus produced is determined by diazotizing with sulfanilamide and coupling with N- (1-naphthyl) - ethylene diamine to form a highly colored azo dye which is quantitatively measured colourimetrically as per the above cited standard method. *Sulphate* (Method: 4500-SO_4^{2-} E; Turbidimetric Method, *Clesceri et al., 1998*). Ground water samples containing sulphate has been determined by precipitating in acetic acid medium in presence of barium chloride as uniform crystals of sulphate get measured photometrically and the results are extracted against a standard calibration curve. *Phosphate* (Method: 4500-P E; Ascorbic Acid Method, *Clesceri et al., 1998*). Spectrophotometric method is followed for measuring orthophosphate content of the ground water where water forms heteropoly acid-phosphomolybdic acid that is insitu reduced to intensely coloured molybdenum blue by ascorbic acid. *Enzyme Substrate Coliform Test* (Method: 9223 B; Enzyme Substrate Test, *Clesceri et al., 1998*). Delayed – Incubation Total Coliform Procedure was followed to determine total coli form content of the water samples. Because, most of the time the sampling location was away from the laboratory hence the time lag between collection, transportation and analyses was not avoidable at any instance of sampling.

2.4.2 Water Quality Index (WQI)

Many water quality-monitoring agencies across the world have introduced water quality indices to indicate the overall quality of the water body imparting appropriate weightage to specific water quality parameters (Figure 2.3a & 2.3b). Many such calculations are based on the frequency of temporal quality infringement events.

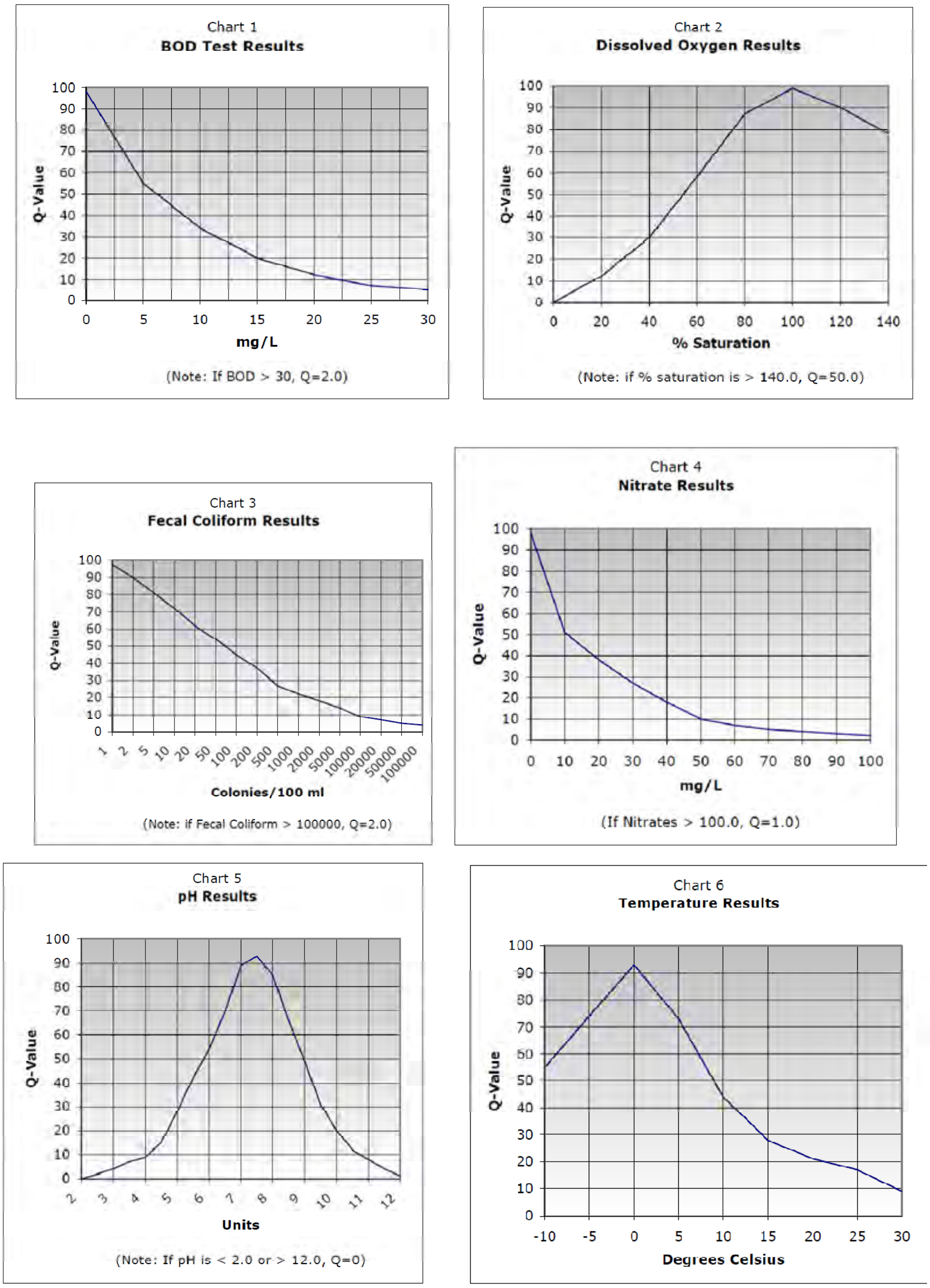

Figure 2.3a: Water Quality Index (WQI) Charts (Pathfinder science, 1988)

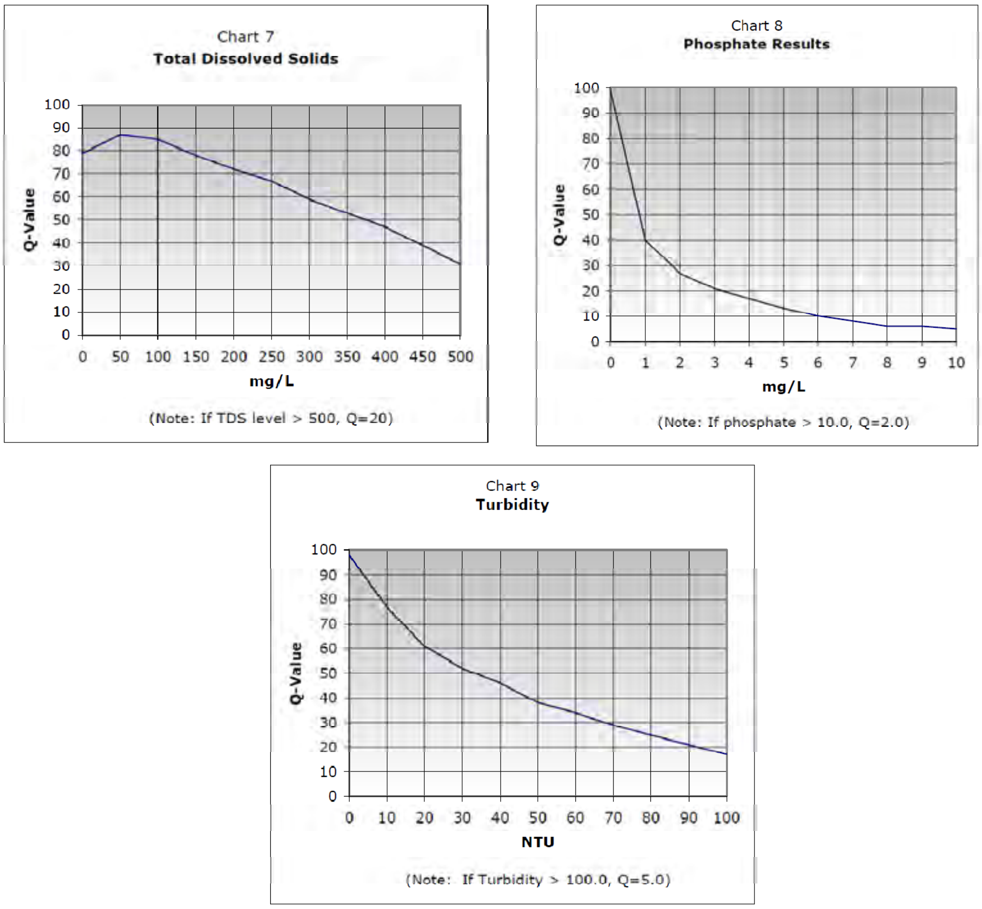

Figure 2.3b: Water Quality Index (WQI) Charts (Pathfinder science, 1988)

Table 2.6: The scheme for calculating water quality index

Parameter	Test results	Q-value (From graphs)	Weighing factor	Total
BOD	mg/L		0.11	
DO	% Saturation		0.17	
Nitrates	mg/L		0.10	
E. Coli. form	Colonies/100ml		0.16	
pH			0.11	
Temperature			0.10	
TDS	mg/L		0.07	
Phosphate (T)	mg/L		0.10	
Turbidity	NTU		0.08	

United States Department of Education and Technology Innovation (Pathfinder Science, 1988) has devised a simple methodology to subject the water bodies to water quality ranking reflecting the utility of the same. Based on the same procedure the water quality index of the tidal canals during the fresh water phases is tabulated. The worksheet for the calculation of WQI is provided in http://pathfinder science/stream/forms/WQI_worksheet.pdf. (Table 2.6).

The Water Quality Index uses a scale from 0 to 100 to rate the quality of the water, with 100 being the highest possible score that represents **excellent quality water**. (Table 2.7) Once the overall WQI score is known, it can be compared against the following scale to determine how healthy the water is on a given day.

Table 2.7: Water Quality Index Scale

WQI Quality Scale	
91-100:	Excellent water quality
71-90:	Good water quality
51-70:	Medium or average water quality
26-50:	Fair water quality
0-25:	Poor water quality

Water supplies with ratings falling in the good or excellent range would able to support a high diversity of aquatic life. In addition, the water would also be suitable for all forms of recreation, including those involving direct contact with the water. Water supplies achieving only an average rating generally have less diversity of aquatic organisms and frequently have increased algal growth.

Water supplies falling into the fair range are only able to support a low diversity of aquatic life and are probably experiencing problems with pollution. Water supplies that fall into the poor category may only be able to support a limited number of aquatic life forms, and it is expected that these waters have abundant quality problems. A water supply with a poor quality rating would not normally be considered acceptable for activities involving direct contact with the water, such as swimming.

2.4.3 Standard Operating Procedure

2.4.3.1 Analytical Procedures

Standard analytical procedures and those reported in the literature are followed for the analysis and interpretation of the test results (Clesceri et al., 1998; Hounslow, 1995; Svehla, 1996; Alex, 2005; Harris, 2006)

2.4.3.2 Chemicals

Unless otherwise specified, the chemicals used where of reagent grade/ Minimum assay 98% (Merck/Qualigens).

2.4.3.3 Instruments

Spectrophotometer	:	The spectrophotometer used was of Varian make Carry 50 Probe UV-Visible Spectrophotometer.
Analytical Balance	**:**	All reagents were weighed on Sartorius BP211d digital weighing device (Maximum 210 g, d = 0.0001 mg).
Glass wares	:	Glassware used was of Borosil/ Magnum make.

2.5 Piper Diagrams

2.5.1 Piper Chart: Evaluation of Chemical Trends of Ground water

Chemical trends or behavior of ground water is commonly interpreted based on graphical simulations or plots made individually either in the form of *x-y plot* or *triangular* diagrams. In the conventional two dimensional *x-y* plots only individual analysis are marked and trends are interpreted as an expression of the solution behavior. Each graph of the trilinear is a singular representation of ionic character and fate under a set of specific conditions.

To study ground water chemistry, only major components of the water are generally plotted. Amongst them concentration of $\mathrm{Na^+}\left(+\mathrm{K^+}\right)$, $\mathrm{Ca^{2+}}$, $\mathrm{Mg^{2+}}$, $\mathrm{Cl^-}$, $\mathrm{SO_4^{2-}}$, and $\mathrm{HCO_3^-}\left(\mathrm{CO_3^{2-}}\right)$ are generally represented.

In real trends plotting, individual data are used based on unique analysis and shapes are interpreted. In chemical trend plots all analytical observations are presented as points in one diagram.

2.5.2 Piper Plots

It is a graphical method and a very complex way of presenting data in water quality studies (Hounslow, 1995).

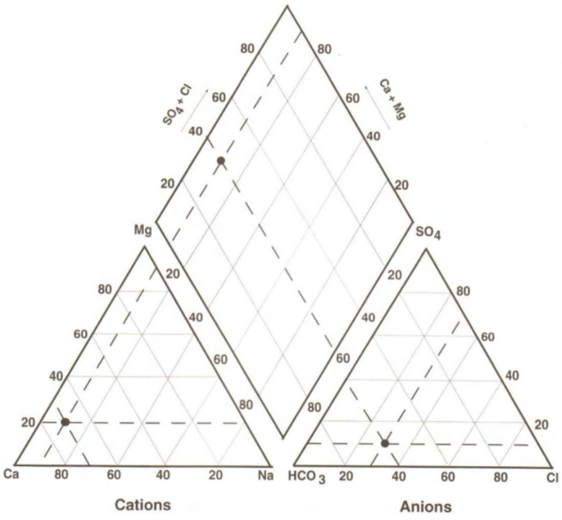

Figure 2.4: Piper triangular graph (Hounslow, 1995)

The limitations on plotting two variables in a single triangular graph can be overcome by plotting cations and anions separately on adjacent triangles (Figure 2.4). They can be favorably arranged to make the interpretation properly simple (Hounslow, 1995). Despite the easiness favorably making the inferences very elusive, the graph plots only ratios making the dilution factor exclusive.

2.5.3 Significance of Piper Diagrams

Piper diagrams (Piper, 1944) are a construct of two triangles that are supposed to share a common base line and each side are separated by an angular distance of 60º apart. The two are interlocked by a diamond cut design shaped graph to contain reported values of the data (ionic concentrations) as circles. The area of this graph is proportional to TDS.

The data position on Piper diagrams *are really finger print information to reach tentative conclusions; origin of the water and its character in particular*. Basically, Piper diagrams provide very valuable knowledge on *the water type, precipitation or solution behavior, mixing character and ion exchange phenomena.*

2.5.4 Classification of water types

The diamond shape of the Piper diagram and its four corners are indicative of nature of the water type as shown in the model graph (Figure 2.5)

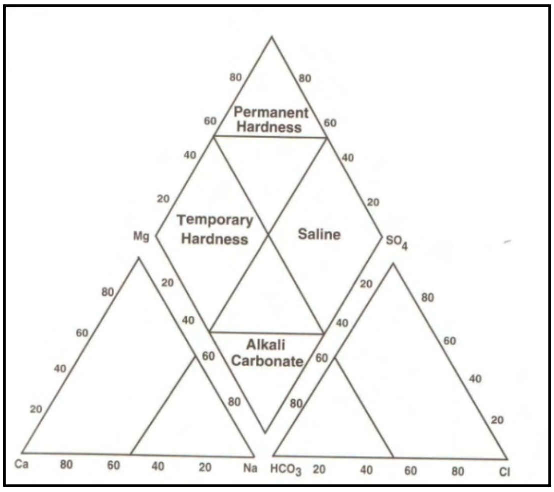

Figure 2.5:-Water type classification as per diamond portion of Piper diagram

According to Piper water belongs to mainly four different water types based on their positions near the corners of the diamond.

i. Permanent hardness: Water with plot data at top of the diamond, i.e. high in both $\left[Ca^{2+} + Mg^{2+}\right]$ and $\left[Cl^{-} + SO_4^{2-}\right]$ ions indicates character of *permanent hardness.*

ii. Temporary hardness: Water with plot values at left corners of the diamond has character of *temporary hardness*. Ions $\left[Ca^{2+} + Mg^{2+} \text{and } HCO_3^{-}\right]$ are prominent.

iii. Hardness due to soft-ions: Water with plot data at lower corner of the diamond has hardness due to soft ions due to alkali carbonates $\left[Na^{+} + K^{+}\right]$ and $\left[HCO_3^{-} + CO_3^{2-}\right]$ ions.

iv. Hardness due to saline ions: water with plot data at right corners are classified as *saline*: $\left[\mathrm{Na}^{+}+\mathrm{K}^{+}\right]$ and $\left[\mathrm{Cl}^{-}+\mathrm{SO}_4^{2-}\right]$ ions are prominent.

2.5.5 Precipitation or Solution

This character can be easily identified when a Piper diagram constructed based on observed analytical results has data / plots on a straight line and there on extrapolation passes through the corner of either or both triangles. The specific component expressed on the corner of triangle is naturally added or removed from water/solution. This feature is present in Figure 2.6.

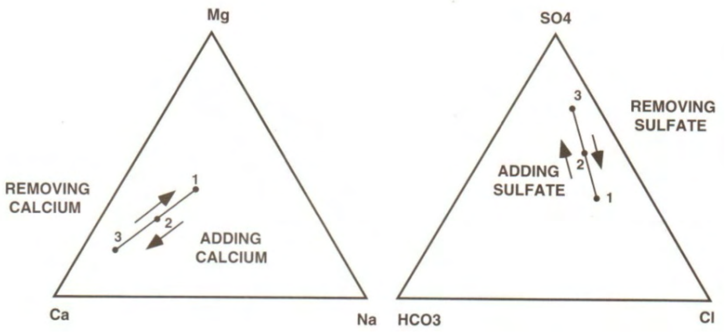

Figure 2.6: Precipitation and solution of ions on Piper diagram; dissolution of Gypsum

This feature is quite common in water systems where scales are formed. Deposits are calcite [$CaCO_3$] and gypsum [$CaSO_4$] could precipitate (deposit) or dissolve (solution) as per the nature of ionic equilibrium decided by saturation index (Faust and Ali, 1998)

There are plots with this peculiar feature indicating the addition of Ca^{2+} and SO_4^{2-} together and simultaneous dissolution of $CaSO_4$ into water. This is regarded as the dissolution of gypsum (anhydrite) leading to enhanced TDS. Generally, the removal (scale forming) process is being initiated in water under constant TDS. The scale formation is a process accompanied by the addition of complementary ions (by dissolution). Under this condition of removal the TDS remains constant as it is observed at the instance of ion exchange. Hydrochemical aqueous system always favors the existence of an equilibrium TDS value.

2.5.6 Mixing

The mixing behavior of water and its gross character is observable from Piper plots. The data points of water 1 and water 2 and resulting mixed water lie on a straight line joining the two end members. The relative proportion of each member ion in the water mix is inversely proportional to the distance of the mixture from that member ion. The closeness of the end member position to the mixture is an indication of the higher proportion of that ion in the mixture.

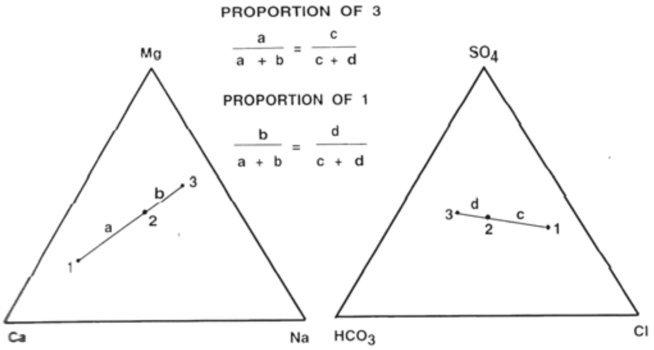

Figure 2.7: Mixing of two waters on Piper diagram

It is well known that there is seldom chance for material exchange in a mixing process. As there is no phase is either added or removed. Mixture exhibits truly the same proportion between end members on all both triangles and diamonds. The example is given in (Figure 2.8 & 2.9)

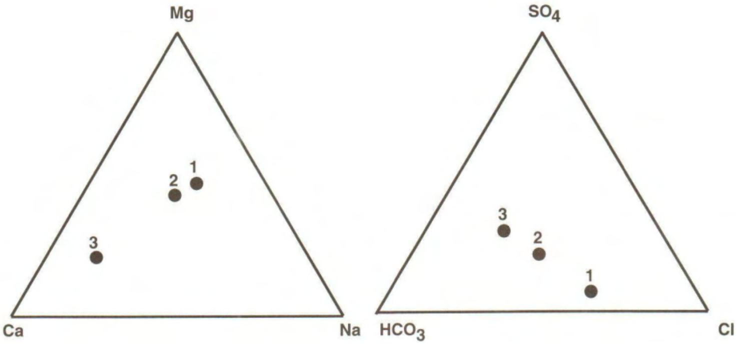

Figure 2.8: Interpretation of Piper diagrams for mixing of two waters with different compositions

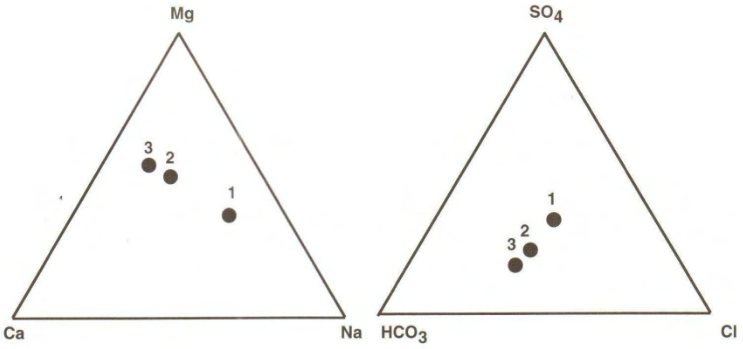

Figure 2.9: Interpretation of Piper diagrams for mixing of two waters with different compositions

2.5.7 Calculation

The proportion of end member1 equals the distance on the diagram from that end member to the mixture composition marked 2 to the total distance from end member 1 to end member 3 (Figure 2.7).

If 'a' is the distance from the end member 1 to the mixture composition and 'b' is the distance from the mixture to the end member 3, then

$$\text{The proportion of the end member 1,} = \frac{b}{(a+b)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

$$\text{The proportion of the end member 3, } = \frac{a}{(a+b)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

In water many instance of replacement of Ca^{2+} and Mg^{2+} occurs by sodium ions. This is distinctively marked on Piper diagram as a trend; slightly curved straight line run or lies parallel or opposite to the magnesium corner. The curve may usually point to sodium apex. This indicates a situation where more Ca^{2+} is exchanged than Mg^{2+}. The anion triangle does not exhibit any peculiar change, i.e. during exchange process in water no anion being added or removed. This phenomena is presented in detail in the section 2.5.9.

2.5.8 Ground Water Chemical Reactions

The infiltration of water or ground water 'down gradient' in an aquifer cause to dissolve many of the minerals that ultimately enhances the TDS of water. This effect is most prominent in *sedimentary rocks* as it contains many water soluble minerals, as *gypsum, anhydrite or halite.* This *in situ* contact of confined water with distinct aquifer enhances the solution of mineral ions, leads to the variation in water composition. This change happens in many ways.

a) Progressive dissolution of homogenous aquifer
b) Chemical reactions of water with heterogeneous aquifer forms
c) Deoxigenation by dissolved oxygen with bound organic aquifer carbon
d) Underground infiltration of water and subsequent contamination from other source
e) Upward leakage from underlying aquifers

Specific phenomena are also responsible for the variation of groundwater quality. They are known as the following

Dissolution: Down to depth the TDS value of ground water increases, may be due to the uncontrolled dissolution of minerals. Dissolution is a common phenomena in sedimentary rocks as it contains many highly soluble minerals viz: anhydrite, gypsum or halite, so-called progressive dissolution of carbonate rock is, limited because of the reduced concentration of dissolved CO_2 to have an acidic pH

2.5.9 Ion Exchange

Water confined to aquifer with composition of montmorillonite clay exchanges Ca^{2+}, Mg^{2+} for Na^{+} ions. In such situation water gets softened and concentration of Na^{+} that often exceeds Cl^{-}. If the exchanged Ca^{2+} is sourced from gypsum minerals then $Ca^{2+}/(Ca^{2+}+SO_4^{2-})$ may be less than 0.5 in many instances. The ion exchange phenomena is written as

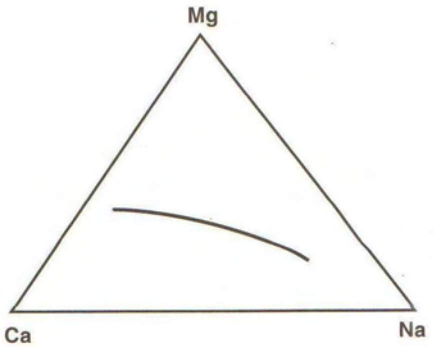

Figure 2.10: Piper plot for typical ion exchange process

Exchange occurs as; $Na_2 - Clay + Ca^{2+} \rightarrow 2Na^{+} + Ca - Clay$ 2.3

Being the ion exchange phenomena progressively decreases Mg^{2+} ion with an instant increase of Na^{+}, the piper graph has a distinct behavior (Figure 2.10). The plot starts with a line parallel to constant magnesium and then curved down towards Na apex. It explain situation of exchange of more Ca^{2+} than Mg^{2+}. In the case of ion exchange the ratio is $Na / (Na + Cl)$ >0.5 in meq/l.

2.5.10 Mineralogy Variation

The chemical nature of water especially contained to aquifer and deep bore well water often vary according to the mineral heterogeneity of the respective aquifers. Different carbonate minerals and fractions rich in gypsum (anhydrite) constitute *limestone aquifer*. Cements (calcium or magnesium alumina silicates) form the major compositional part of sand stone aquifer. Pyrites (FeS_2), a known source of Fe in ground water is not homogeneously distributed in aquifer. Presence of ions and their species behaviors are the indicator evidence to formulate the true mechanism of the movement of water column in an aquifer.

2.5.11 Reverse Ion Exchange

Many incidents of terrestrial contamination under circumstances of inundation by sea water (or water rich in sodium) accelerates the exchange of Ca^{2+} with clay especially montmorillonite by Na^+ ions. This phenomena occurred in ground water is referred as *reverse ion exchange*. This happens in water with higher Na^+ content. The final ground water may contain more Ca (and often Mg) subsequently decreased concentration of Na^+. Calcium binds almost reversibly than $Mg^{2+.}$ Results are being expressed in *meq/L*.

Ratio of Na / Cl of <1 often <<<1 as reported by Hounslow (1995).

$$2Na^+ + Ca - Clay \rightarrow Na - Clay + Ca^{2+} \quad ....2.4$$

Once, all Ca^{2+} ions are removed by exchange, the process become complete. This behavior detected in the solution front of the seawater encroachment into a fresh water aquifer. There are cases, where Mg is exchanged than Ca in clay matrices where Ca^{2+} will be high in the water. This finally enhances $CaCl_2$ content in the so-called leading edge of a brine contamination or sea water inundation.

2.5.12 Sulfate Reduction Mechanism

It is a common process occurring in ground water aquifers. Bio-geo chemical degradation of SO_4^{2-} ions by micro organisms is a well known kinetics that leads to the formation of H_2S and HCO_3^- in carbohydrate metabolism.

$$C_6H_{12}O_6 + 3SO_4^{2-} \rightarrow 6HCO_3^- + 3H_2S \quad ....2.5$$

The evolution of H_2S gas is realized by its smell and has high HCO_3^- content of the water. Many ground waters have a low SO_4^{2-} content; as it undergoes the above transformation.

2.5.13 Pyrite Oxidation

Common source of SO_4^{2-} ions in water is the result of microbial degradation of pyrite. Water having no bicarbonate concentration realistically shows the condition for oxidation of pyrite to sulfuric acid in low acid pH with high SO_4^{2-} / Cl^- ratio recognized as an indication of the process. Presence of CO_3^{2-} in such water may lead to very confusing situation to identify the chance for pyrite oxidation and the possible neutralization of carbonate by the dissolving gypsum. Oxygen is essential for this type of mineral oxidation.

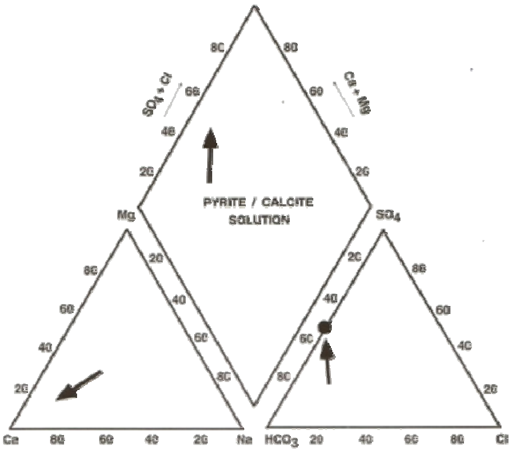

Figure 2.11: Pyrite oxidation and neutralization by calcite

Pyrite oxidation occurs under excess oxygen bringing out the product ferric hydroxide. The iron fraction Fe^{3+} remain in an excessive acid pH. It may remain in acid medium to the form of stabilized ferrous ions at low pH in the subsequent anoxic conditions.

$$FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + SO_4^{2-} + 4H^+ \quad ....2.6$$

$$2CaCO_3 + 4H^+ \rightarrow 2Ca^{2+} + 2H_2O + 2CO_2 \quad ....2.7$$

Solution of CO_2 make the medium more acidic, accelerates dissolution of carbonates as

$$2CaCO_3 + 2H_2O + 2CO_2 \rightarrow 2Ca^{2+} + 4HCO_3^- \quad ....2.8$$

Hence, the overall representative equation for pyrite oxidation is

$$FeS_2 + 3.75O_2 + 3.5H_2O + 4CaCO_3 \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4Ca^{2+} + 4HCO_3^- \quad ....2.9$$

The Piper diagram for a pyrite oxidation mechanism is shown as in the Figure with 1:1 $HCO_3^-: SO_4^{2-}$ side than forwards the sulfate corner Figure 2.11 is an example for pyrite oxidation

2.5.14 Calcite Precipitation

Water has a tendency to deposit or dissolve scale forming substance with respect to an inert or reactive surface. Among these, calcite $CaCO_3$ is the common mineral deposits formed from water. Chemistry of scale formation on the surface of the piping materials, cement pipes and other surfaces has been extensively studied (Faust and Ali, 1998). Calcite precipitation mechanism in marine and non-marine (as spring deposit) aquatic environment is well known in literature could be successfully related to ground water science. Nevertheless to say the basic mechanism in all situations is the deposition of calcite $\left(CaCO_3\right)$ as a heterogeneous mineral mass. $CaCO_3$ deposits are common to happen in aquifer as incidence of ground water interaction with mineral constituents. In water treatment and supply systems it stimulates intensive thoughts because the corrosion control is related to scale formation decided by the aggressiveness of the water reported in terms of saturation index (SI).

The calcite scale deposition process is represented as

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \text{ [calcite]} \qquad \text{..} 2.10$$

and $CaCO_3$ will precipitate when,

$$\frac{\left[Ca^{2+}\right]\left[CO_3^{2-}\right]}{K_s} > 1 \qquad \text{..} 2.11$$

K_s is the solubility product for calcite. The precipitation of $CaCO_3$ is solely determined by the conditions that decide (1) when the ionic concentrations of Ca^{2+} and CO_3^- is increased so that K_s is exceeded considerably either by super saturation enhanced by warming, increased salinity, pressure reduction and loss of carbon dioxide. Other aggregate causes are pressure reduction, increased salinity (evaporation), decreased salinity due to mixing of waters. Loss of CO_2 by degassing effect or photosynthetic extraction are the other known causes for calcite precipitation

Hardness of water due to both Ca^{2+}/Mg^{2+}or its absence in the tsunami affected water sources in the summer months (Jan-May) continued to be the overall effects of these onsite phenomena in the present study.

Table 2.8: Nonmixing Trend on Piper Diagrams

First Triangle	Second Triangle	Interpretation
→ Ca apex	→ HCO_3 apex	Calcite solution
	→ SO_4 apex	Gypsum solution
	→ 1:1 HCO_3:SO_4	Pyrite oxidation and calcite solution or calcite and gypsum solution
	→ Cl apex	Reverse softening (brine contamination)
→ Na apex	→ HCO_3 apex	Albite solution or calcite solution and ion exchange
	→ SO_4 apex	Gypsum solution and ion exchange
	→ Cl apex	Halite solution no change ion exchange
→ Mg apex	→ HCO_3apex	Ferromagnesian silicate solution(Mg often > Ca)
→ HCO_3 apex	→ Ca apex	Calcite solution
	→ Na apex	Albite solution or calcite solution and ion exchange
	→ Mg apex	Ferromagnesian silicate solution(Mg often > Ca)
	→ Ca-Mg side	Calcite-dolomite solution
→ SO_4 apex	→ Ca apex	Gypsum solution
	→ Na apex	Gypsum solution and ion exchange
	→ 1:1Ca:Mg	Dedolomitisation parallels Ca-Mg side & (Ca > Mg)
→ Cl apex	→ Ca apex	Reverse softening (brine contamination)
	→ Na apex	Halite solution

The change in the overall solution chemistry of the water sampled from the region has to be interpreted on the basis of the probable mineralization mechanism (Table 2.8). Hounslow (1995) enumerates the effective causes leading to scale formation by water / solution of $CaCO_3$ calcite in ground water under following conditions.

a) When concentration of both constituents (Ca^{2+} and CO_3^{2-}) is increased, as if by evaporation and other factors mentioned (Bricker, 1971). Deposits from surface water by evaporation are of this type.

b) When the solubility product which is a function of temperature. Warming by insolation or by geothermal heating can enhance this situation.

c) Changing the ionic strength of the solution by increasing the ion activity product. Likely mixing of low-and high – salinity waters. An increase in ionic strength causes a decrease in the activity coefficients and increases calcite solubility (Dreybrodt, 1988).

d) By increasing Ca^{2+} ion concentration for example, by dissolving another soluble calcium mineral such as gypsum (common ion effect). This process is *called dedolomitization*.

e) By increasing the CO_3^{2-} concentration. Usually this can be done by decreasing the CO_2 content of the water. Increasing of the bicarbonate content could do the same effect. The reaction is

$$CaCO_3 + 2H_2O + CO_2 \Leftrightarrow Ca^{2+} + 2HCO_3^- \quad \text{.. 2.12}$$

Increasing carbonate concentration may result from (Hounslow, 1995)

i. Decreased pressure, for example, spring depositing travertine, or cave deposits.

ii. Photosynthesis, for example, algal deposits in lakes.

iii. Adding HCO_3^-, such as through sulfate reduction (Berner, 1971). This researcher proposed that the bacterial process of sulfate reduction can result in the formation of excess HCO_3^-, which may cause the precipitation of $CaCO_3$ in marine sediments pore waters. He summarizes the reaction as:

$$SO_4^{2-} + 2CH_2O \rightarrow 2HCO_3^- + H_2S_{(aq)} \quad \text{.. 2.13}$$

$$2HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + CO_{2(aq)} + H_2O \quad \text{.................................... 2.14}$$

There are occasions where Ca^{2+} concentration is being compensates in alternate ways. A concurrent carbonate dissolution-precipitation reaction whereby magnesium calcite is dissolved is known example (Chapelle, 1983, Hounslow, 1995). Calcite is precipitated to account for secondary calcite cementation as given in the following equations

$$\left(Ca_{1-x}Mg_x\right)CO_3 + H_2O + CO_2 \Rightarrow \left(1-x\right)Ca^{2+} + xMg^{2+} + 2HCO_3^- \text{ ....2.15}$$

$$Ca^{2+} + 2HCO_3^- \Leftrightarrow CaCO_3 + H_2O + CO_2 \text{ ....2.16}$$

2.5.15 Saturation index and calcite deposition

Saturation index for water with calcite precipitation is found to have a value close to zero where an equilibrium condition is maintained for a Langelier Saturation Index (LSI = 0). In many cases it is observed that the ground water with this situation have constant HCO_3^- and pH. There are instances where, magnesium calcite being dissolved to have x = 0.1, and if it is a dolomitic formation x = 0.5.

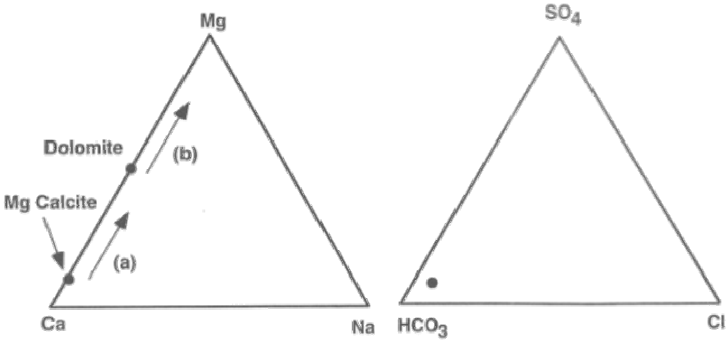

Figure 2.12: Calcite Precipitation

Here, the dissolution of dolomite rises the Mg^{2+} content and enhances it to an exceeding level more of Ca^{2+} ($Mg^{2+} > Ca^{2+}$). Studies (Hem, 1985) reported that a water with $Mg^{2+} > Ca^{2+}$ has origin from a dolomite derived water. If the saturation index (SI) for the reported water has been +1.58, is an indication of the over saturation of the water with respect to dolomite (Hounslow, 1995). Deposition of calcite leads to higher concentration of Mg^{2+} generally referred as magnesium water. Many researchers reported that water with high Mg^{2+} ions have Cl^- or $Cl^- + SO_4^{2-}$ as major anions (Hounslow, 1995).

The major difference between surface and ground water situation is that in surface water, being it is an open system HCO_3^- decreases in the piper diagram. In ground water bicarbonates remain constant because it is a closed system. A piper diagram for dolomite and Mg-calcite deposits are given in Figure 2.12 as after Mg calcite solution (b) after dolomite solution.

2.5.16 Dedolomitisation

Dedolomitisation is a geochemical process by which $CaMg(CO_3)_2$, the so-called calcium magnesium carbonate is being replaced by Ca^{2+} ions, $CaMg(CO_3)_2 \rightarrow 2CaCO_3 + Mg^{2+}$.

Dolomite (calcium magnesium carbonate $CaMg(CO_3)_2$ has a rhombohedral structure can undergo replacement by calcite $CaCO_3$ by lattice substitution (Evamy, 1967, Hounslow, 1995). Dolomitisation occurs as a result of four distinct processes, evidenced by Back et al. (1983) and Hounslow, (1995). These workers identified the process is the outcome of following four process (a) Dissolution of calcite (b) Dissolution of dolomite(c) Dissolution of gypsum (d) Precipitation of calcite.

Calcium ions released from gypsum have been used for the formation and deposition of calcite by common ion effect. Besides, the $CaCO_3$ genesis deplete the pH that itself causes dissolution of dolomite commonly this chemical reaction is most favored by an ionic ratio of Ca^{2+}/Mg^{2+} ratio >1 for the water saturated by a low pCO_2 and temperature <50ºC. At all favorable situation a high Ca^{2+}/Mg^{2+} ratio accelerates the dedolomitisation because the dissolution of gypsum or anhydrite enhances the ionic ratio. However, the presence of calcium sulfate and high pCO_2 has a very little influence to induce dedolomitisation.

Dedolomitisation is a chain of activities directly related to the dissolution of dolomite and gypsum and subsequent precipitation of calcite. Visibly, Ca^{2+} / Mg^{2+} ratio will increase towards 1.0 and subsequently the sulfate content increases. The piper diagram of dedolomitisation is shown figure reported by Hounslow, 1995. An interesting finding is that the process of dedolomitisation occurs by a molar ratio of $\left[Ca^{2+} + Mg^{2+}\right] / SO_4^{2-}$ approaching ≈ 1.0 (Richter and Kreitler, 1986 & Hounslow, 1995).

2.6 Sodium Adsorption Ratio (SAR)

The SAR of water is defined as

$$\frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad \text{..2.17}$$

Where the ion concentration are expressed in meq/l. SAR measures the degree to which sodium in irrigation water replaces the adsorbed (Ca^{2+} + Mg^{2+}) in the soil clays and thus damages the soil structure. Irrigation waters are usually classified in terms of salinity hazard (conductivity or TDS) and sodium hazard (SAR). Figure 2.13 is the SAR conductivity plot where the salinity hazard dividing point are 250, 750 and 2250 µmhos, resulting in four categories:

a) <250 µmho- Low-salinity water [C1],

b) 250-750 µmho- Medium-salinity water [C2],

c) 750-2250 µmho- High- salinity water [C3]

d) >2250 µmho - Very high- salinity [C4].

The sodium hazard is a function of both SAR and salinity. The dividing lines are

$$S = 43.85 - 8.87 \log C$$

$$S = 31.31 - 6.66 \log C$$

$$S = 18.87 - 4.44 \log C$$

Where S is the SAR and C is the conductivity. The resulting four categories are

S1 - Low-sodium water
S2 - Medium-sodium water
S3 - High-sodium water
S4 - Very high-sodium water

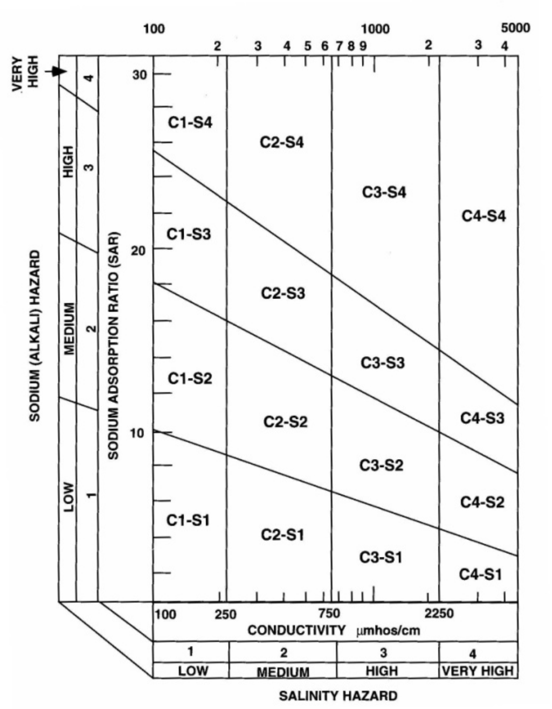

Figure 2.13: SAR conductivity plot (Hounslow, 1995)

2.7 Langelier Saturation Index

Hounslow (1995) describes that "when a mineral is dissolved in water the cations and anions of which it is composed will attain a specific concentration. Their sum essentially equals the solubility of that mineral". The mathematical product of these concentrations is given the name solubility product K_{sat}.

In any solution where the concentration of these ions known, their product may be calculated. This number is called the ion activity product (IAP). The number so obtained may be compared to the solubility product of a mineral of interest. The comparison takes the form of a log of the ratio, which is called the saturation index (SI), namely:

$$\text{Saturation Index (SI)} = \log\frac{\text{IAP}}{K_{sat}} \quad \text{......................................2.18}$$

If the SI equals zero, that is, IAP $= K_{sat}$, when the water is just saturated with the mineral phase in question. If SI is positive, OR IAP $> K_{sat}$, then the water is oversaturated with respect to the mineral phase in question and will tend to precipitate. If SI is negative or IAP < K_{sat}, then the water is under saturated with respect to the mineral phase in question and will tend to dissolve more of the mineral if it is present. The mineral whose SI is most commonly required is calcite ($CaCO_3$). When Calcite is in equilibrium with water the solubility product of the Ca^{2+} and CO_3^{2-} ions in solution is expressed by their product $[Ca^{2+}][CO_3^{2-}] = K_{sat}$ for calcite = $K_{c.}$

Any solution that contains Ca^{2+} and CO_3^{2-} will have an IAP = $[Ca^{2+}]\,[CO_3^{2-}]$ from solution. In this case of calcite the SI may expressed in a different manner. It may be written as

$$SI = pH_{\text{of solution}} - pH_{\text{at which calcite precipitates}}. \quad \text{...2.19}$$

When written in this form the SI is usually known as the "Langelier index".

If the Langelier index is positive [LSI= +ve], the solution is oversaturated with respect to calcite (*chance for scale formation*) and if it is negative [LSI = - ve] it is under saturated with respect to calcite (*chance for corrosion)*. Condition of stable ionic equilibrium is maintained if the index [LSI = 0] is zero (Faust and Ali, 1998).

2.7.1 Indices of Corrosion

Any change in the quality of water by the influx of materials that alter the TDS will accelerate the electrochemical corrosion of metallic plumbing materials by a complex process. This requires the need of a method (index) whereby the incidence of corrosion can be predicted incorporating chemical and physical factors: *dissolved oxygen, pH, alkalinity, calcium, magnesium, particulates, organic compounds, buffer* *intensity, reducible metallic ions, total dissolved solids, such anions as chloride, sulfate, phosphate, silicate, biological factors and temperature.* Many indices known as Aggressiveness indices, Langelier indices, Riznar's Indices, Caldwell – Lawrence indices are available that have had their own success and limitations in the prediction of corrosion by water.

2.8 Tsunami Impact on Saturation Index

Chemical indices indicate the corrosiveness of raw and finished water to metallic pipes. For the most part, they are derived from chemical equilibrium equations for the $CaCO_{3(s)}$ system decided by pH, hardness and alkalinity. These indices are related to some symptom of corrosion, i.e., *red water* complaints due to the presence of iron by-products. Langelier developed a saturation index (LSI) for corrosion protection by a thin film of $CaCO_{3(s)}$ on the interior walls of pipes. This index is calculated from readily obtainable analytical data and indicates the tendency of natural or finished water either to deposit or dissolve calcium carbonate. When pH_{ac} is less than pH_s, negative LSI value is obtained, and the water tends to be corrosive. When the pH_{ac} is greater than the pH_s, positive LSI values are obtained, and the water tends to be $CaCO_{3(s)}$ scale forming. When the LSI value is 0 the water is in equilibrium with respect to calcium and bicarbonate ions. Occasionally there is a need to correct alkalinity due to carbonate above a pH_{ac} of 9.5 and hydroxyl ions above a pH_{ac} of 10.5. A definition of total alkalinity (TALK) in waters where the carbonate predominates is: $[TALK] = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+]$

2.9 Statistical Analyses

The study is presented to determine the impact of tsunami on the ground water quality of tsunami affected coastal areas of Kerala such that it is pertinent to evaluate the variation of the parameters with respect to different strata of the samples analyzed either as a matter of depth of the aquifer based on shallow dug well or deep bore well sources or the locations. To ensure the confidence level for 95% level of significance, two sets of data consisting of n_1 and n_2 measurements (with averages x_1 and x_2) whose t value is calculated using the formula,

$$t = \overline{x_1} - \overline{x_2} \Big/ s_{pooled} \sqrt{\frac{n_1 n_2}{n_1 + n_2}} \quad \text{..2.20}$$

$$s_{pooled} = \sqrt{\frac{s_1^2 (n_1 - 1) + s_2^2 (n_2 - 1)}{n_1 + n_2 - 2}} \quad \text{..2.21}$$

$$t_{calculated} = \frac{\left|\overline{x}_1 - \overline{x}_2\right|}{\sqrt{s_1^2 / n_1 + s_2^2 / n_2}} \quad \text{..2.22}$$

$$\text{Degrees of freedom} = \left\{ \frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\left(\frac{\left(s_1^2/n_1\right)^2}{n_1 + 1} + \frac{\left(s_2^2/n_2\right)^2}{n_2 + 1} \right)} \right\} - 2 \quad \text{......................2.23}$$

S_{pooled} is a pooled standard deviation making use of both sets of data. The value of t calculated and given in the above table is compared with standard value of student's t for n_1+n_2-2 degrees of freedom. If the calculated t is greater than the tabulated t at the 95% confidence level, the two results are considered to be different. If population standard deviation is different for both the set of measurement, and then we use the equations (Harris, 2006). To test the hypothesis of this research study two factor ANOVA, students t test, independent students t test are extensively used (Montgomery, 2009).

Conclusions

The significance of the study area selected, protocols followed for the sampling and analysis of the groundwater samples from the tsunami affected area, the relevance of the prominent water quality parameters selected to evaluate the impact of tsunami, theory, kinetics, and statistical methods followed in this extensive, exclusive research study are scientifically presented through the sections placed above. The results, outcome and inference are presented in the following chapters.

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Chapter 3

Pre-tsunami Water Quality Of Coastal Kerala: A Critical Evaluation

Contents

3.1 Introduction

Post-tsunami study of ground water quality along the coastal areas of India after 26 December 2004 tsunami had a serious thought of research initiated by many researchers (Achari, 2005). It has been very essential to have baseline data to identify zones of rapid ecological damage prone to such future ocean disasters. Ground water quality deterioration, the extent of dilution and replenishment of water in the post-tsunami situation are the basic motivation of many such studies (Rajamanickam, 2006).

Many studies on ground water quality variation after tsunami disaster is related to the natural recirculation of water and leaching of deposited minerals from soils and weathered rocks (Achari, 2005; Achari et al., 2007; Achari, 2008; Raju et al., 2009). The general approach to study the chemistry and hydrochemical nature of ground water is the evaluation of primary water quality parameters and testing of the data in trilinear diagrams perceived by Hill and Piper generally known as Hill-Piper-Trilinear Plot (Hill, 1940, Piper, 1944 and Piper, 1953). The prominent cations and anions and microorganisms determine the suitability of a ground water for human consumption.

Flooding by tsunami waves changes the natural quality of drinking water sources through disease causing microorganism but do not produce any distinguishable taste or odor, if it is ingested would lead to severe situations of acute diarrhea, cholera and serious infections (Tharnpoophasiam et al., 2006). The incidence of variability with respect to chemical components of ground water either due to peculiar terrestrial / coastal environment become a challenge to human health in the course of time. In Kerala data in crude form is available with many monitoring agencies but not statistically evaluated to refine out the inference on a time scale.

3.2 Significance of Pre-tsunamic Water Quality

The need of a refined water quality index profile specific to coastal region lacked in reality enough to formulate the baseline situation prior to the tsunami event. In this circumstance we make an attempt to come up with a set of reliable inferences to the true behavior of the ground water in a pre-tsunamic period in full conformity with the set of data already available (Achari, 2005; Achari et al., 2007 & Achari et al., 2006b)

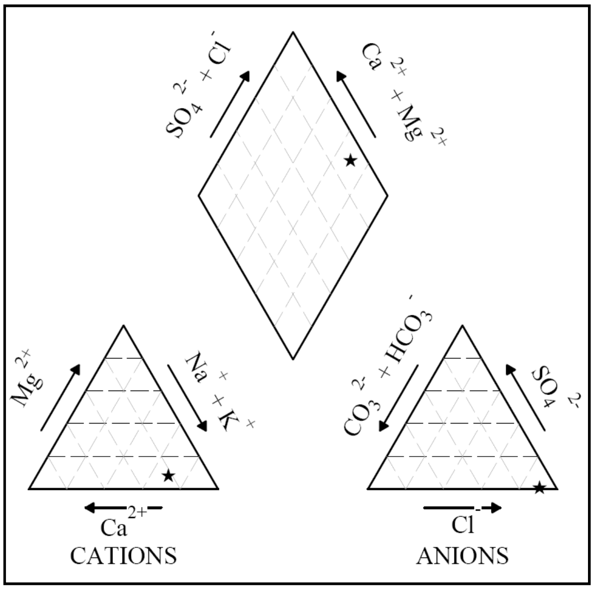

Figure 3.1: Hill Piper- Trilinear diagrams of the water sampled from control well (station 1, Alappad coast in April 2001 represents the pre-tsunami situation). Station is a control well not affected directly by tsunami waves on 26 December, 2004

Table 31: Base line water quality data of Alappad coast prior to 26 December 2004.

No.*	pH	EC *mS/ cm*	TH mg $CaCO_3$/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	CO_3 mg/l	HCO_3 mg/l	SO_4 mg/l	Cl mg/l	F mg/l
1.	6.8	0.353	44	13	2.9	42	8.1	0	9.8	0.7	58	0.08
2.	7.5	0.356	66	13	8.3	41	0.6	0	34	34	64	0.1
3.	8.2	0.466	152	52	5.4	27	14	-	127	47	60	0.07
4.	8.0	0.280	56	14	4.9	11	25	2.6	-	20	31	0.09
5.	7.5	0.307	22	4.8	2.4	46	2.5	0	0	0.5	70	0.08
$\overline{x} \pm \sigma$	7.5±0.5	0.352±0.071	68±50	19±19	4.8±2.3	33±14	10.0± 9.9	0.5±1.2	34.2± 53.7	20.4± 20.5	57±15	0.08± 0.01
$\overline{x} \pm \frac{t\sigma}{\sqrt{n}}$	7.6±0.1	0.352±0.018	68±13	19±4.8	4.8±0.6	33±4	10.0±2.5	0.5±0.3	34.2±13.8	20.4±5.3	57±3.9	0.08± 0.003
CI(μ)	7.5-7.7	0.334-0.370	55-81	14.2-23.8	4.2-5.4	29-37	75.-12.5	0.2-0.8	20.4-48.0	15.1-25.7	53.1-60.9	0.077-0.083

*Source: Central Ground Water Board (year 2001), Government of India, Thiruvananthapuram (Achari, 2006). Station 1 (•) is the control well, stations 2 (★), 3 (■) & 4 (▲) are shallow dug wells. Station 5(▼) is the deep bore well. All stations except 1&4 were later inundated by tsunami waves on 26December, 2004. The respective markings are followed in the Piper plots for identification.

Chemical trends or behavior of ground water is commonly interpreted based on graphical simulations or plots made individually either in the form of x-y plot or triangular diagrams. In the conventional two dimensional *x-y* plots only individual analysis are marked and trends are interpreted as an expression of the solution behavior. Each graph of the trilinear is a singular representation of ionic character and fate under a set of specific conditions. To study ground water chemistry, only major components of the water are generally plotted. Amongst them concentration of $Na^{+}\left(+K^{+}\right)$, Ca^{2+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, and $HCO_3^{-}\left(CO_3^{2-}\right)$ are generally represented. In real trends plotting, individual data are used based on unique analysis and shapes are interpreted. In chemical trend plots all analytical observations are presented as points in one diagram.

The data given in the Table 3.1 is the gross composition of the ground water quality parameter of the Alappad – Arattupuzha region in the year 2001 and the sources are mainly dug wells (mean depth 2.0m) except the station No.4 which is a deep bore well with (depth 75.0m). Pertinent parameters given are mean ($\bar{x} \pm \sigma$) of the five determinations such that these values pH (7.6±0.1), EC mS*/cm* (0.352±0.018), TH mg $CaCO_3$/l (68±13), Ca mg/l (19±4.8), Mg mg/l (4.8±0.6), Na mg/l (33±4), K mg/l (10.0±2.5), CO_3 mg/l (0.5±0.3), HCO_3 mg/l (34.2± 13.8), SO_4 mg/l (20.4±5.3), Cl mg/l (57±3.9), F mg/l (0.08±0.03). This basic datum is used to evaluate the hydrochemical behavior of the regions ground water quality.

3.2.1 Sodium - Chloride Ratio

The brackish nature of ground water may be due to Cl^{-} ions or metals combined directly with chloride. Though threshold level of chloride in drinking water is 250-500 mg/L, and even a higher level of 1500mg/L is not harmful for healthy consumers. The chloride content on taking as a ratio with sum of anions give an indication of source of the water; whether seawater or brine or evaporate, rain water or rock weathering.

In the pre-tsunami situation the mean ($Na^{+}/Na^{+}+Cl^{-}$) for the known five stations consisting of so-called control dug well (station 1) of the succeeding studies, common dug wells (2, 3 &5) which later underwent tsunami devastation were found extensively degraded by inundation and a representative deep ground water source marked as station 4 (bore well depth 75.0m) has a ratio of 0.47. This indicates the water is of unfiltered rainwater origin.

Table 3.2: Na^+ / Cl^- ionic ratio and probable inferences regarding ground water quality of a tsunami devastated region (situation existed before 26 December, 2004)

Station	EC µmho/cm	TDS ppm	$\frac{Na}{Na+Cl}$	$\frac{Na}{Cl}$	Remark	Inference*
1	352	194.2	0.52	1.12	Dug well	Ion exchange
2	356	195.8	0.49	0.99	Dug well	Reverse ion exchange and sea water
3	466	256.3	0.41	0.69	Dug well	Reverse ion exchange
4	280	154.0	0.36	0.55	Bore well	Reverse ion exchange
5	307	169.0	0.50	1.00	Dug well	Ion exchange
$\overline{x}$	352	193.6	0.47	0.89	Mean	Reverse ion exchange in presence of sea water

* $Na^+ / Na^+ + Cl^-$ >0.50 (ion exchange) and Na^+ / Cl^- <1.0 (reverse ion exchange) as reported by Hounslow (1995)

The deep ground water has the lowest ratio of 0.36 is having entirely a different character than the dug well source water. Since the ratio ranges between 0.36-0.52 band, and it does cross the limit of 0.5 only on a single occasion either we could confirm that the ground water has an inherent existence originated from rain water over a period of time probably of millions of years. To confirm whether sources are contaminated by the seawater because of the closeness of the sea and if it is replenished by any geochemical mechanisms, more data treatment is distinctly necessitated.

The condition of the reverse softening might had been prevailing inherently in the region even before the tsunami incidence evidenced by $Na^+ / Na^+ + Cl^-$<0.5 prominent for ion exchange. Though the above ratio in all cases is less than 0.5 (ideal for rain water), significantly this indicates the deep ground water is geologically originated from the regions ground water.

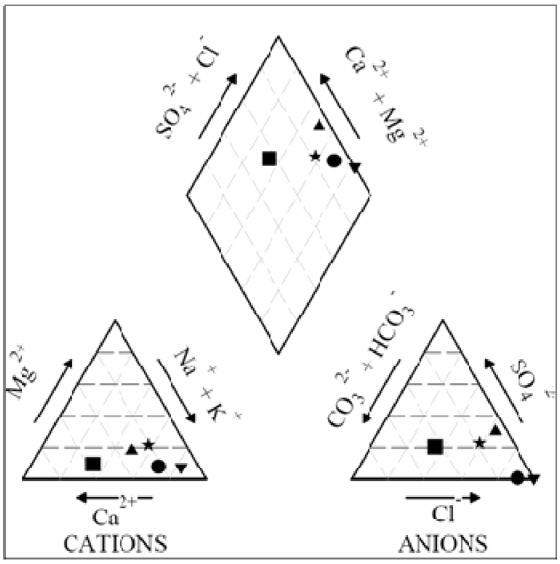

Figure 3.2: Hill Piper Trilinear diagrams of the Alappad coast in April 2001 (Represent the station wise pre-tsunami situation of the region). Station 1 (●) is the control well, stations 2 (★), 3 (■) & 4 (▲) are shallow dug wells. Station 5(▼) is the deep bore well. All stations except 1&4 were later inundated by tsunami waves on 26 December, 2004.

The Piper diagrams for the water (Figure 3.1 & Figure 3.3) reveal that the data are pointing towards the Na^+ apex in the cation triangle. The data on the anion triangle also have the feature of orienting towards Cl^- apex, a clear indication of NaCl contamination. The possibility is greater as the location is a barrier islet, sandwiched by Laccadive Sea and an extension of estuarine arm influenced by tidal fluctuations. Mean $Na^+ / Na^+ + Cl^-$ ratio for five determinations is 0.47(<0.5) suggesting the source of contamination to be seawater.

In the present study this is found to be true as Na/Cl (meq/L) has been 0.89 (<1.0) means the intruded sodium is being exchanged with bound calcium. The water though is originated from accrued rainwater percolating through the fine grain of heavy mineral sands in combination with quartz, clay and carbonate mineral is subjected to seawater contamination by intense tidal influences. Stations are the dug wells, shallow in form less than 2 m depth, the clay matter of the soil exchange the available Ca^{2+} by reverse ion exchange process such that the water retains its ionic balance by a natural process so that the marked quality variations are limited. Quality of the ground water in this small island is of highest grade on evaluation based on the above said protocol. This may be one of the reason that the area is thickly populated though it is geographically not conducive for safe living other than for fishing.

The original mean water quality of the Alappad coast in 2001 can be taken as a representative pre-tsunami profile of the ground water. The analysis of the data shows that quality of the ground water in this small speck of land is of highest grade slightly contaminated by seawater. The extra addition of ions by infiltrating seawater is encountered by reverse ion exchange behavior of soil structure where Na^{+} ions are exchanged by bound Ca^{2+}.

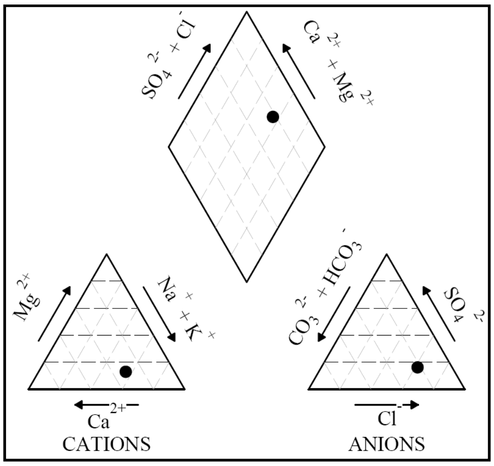

Figure 3.3: Hill Piper Trilinear diagrams of the Alappad coast in April 2001 represent the pretsunami situation of the region. Mean of the respective data for stations 1 (●) 2 (★), 3 (■), 4(▲) & 5(▼) (Figure 3.2) are plotted in a single graph.

Data analyzed for the gross composition of the ground water quality parameter of the Alappad – Arattupuzha region are mostly represented by groundwater sampled from dug wells (mean depth 2.0m) except the station No.4 which is a deep bore well with (depth 75.0m). There is more than 95% chance that the true value of the representative parameters lies in the confidence interval; pH (7.5-7.7), EC (0.334-0.370) mS*/cm*, TH (55-81) mg $CaCO_3$/l, Ca (14.2-23.8) mg/l, Mg (4.2-5.4) mg/l, Na (29-37) mg/l, K (7.5-12.5) mg/l, CO_3 (0.2-0.3) mg/l, HCO_3 (20.4-48.0) mg/l, SO_4 (15.1-25.7) mg/l, Cl (53.1-60.9) mg/l, F (0.077-0.083) mg/l.

Conclusions

Everywhere, on coastal belt it is proved without doubt that the pristine ground water quality after tsunami has been severely deteriorated. But how far is more relevant as it is decided by the so-called pre-tsunamic situation of the region. In water quality studies a reference finger print that ear mark a region’s ground water quality existed is most important and based on that the monthly variability in the post tsunami period could be significantly interpreted. The pre- tsunamic evaluation can be of very useful in two ways; (1) To have a picture of the hydrochemical behavior of the regions ground water quality existed (2) as a reference point to quantify the impact of 26 December 2004 Indian Ocean tsunami on the groundwater chemistry of the region in the post tsunami studies. This part of the work tries to bring to the limelight some valuable findings as a prologue to the succeeding similar works.

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Chapter 4

Post-Tsunami Ground Water of Alappad Coast

Contents

4.1 Introduction

It is a known fact that water quality of the tsunami affected coastal region of Kerala, India, were deteriorated after the excruciating tsunami event of 26 December 2004 (Achari, 2005; Achari et al., 2006b; Achari, 2008) through a chain of ecological devastation caused by the inundation by tsunami waves creating geomorphologic changes in the shoreline features as well as in the coastal flat land. The invading seawater substantially altered the ground water chemistry of the region. It is certainly a known matter of concern that, the ground water is immediately and directly influenced by climatic and other external factors.

This is primarily because of the extremely high permeability of the sandy soil and the perched sub surface nature of the water body. Figure 4.1 shows the locations of the sampling stations in the tsunami affected Alappad coast, Kerala, India. The seawater emerged in devastating formations, hurled and piled up with organic debris and other externalities were washed out and deposited in the natural depressions, swamps and marshes of the otherwise flat land. In the course of time the undesirable material components could have been degraded and leached out to reach the ground water.

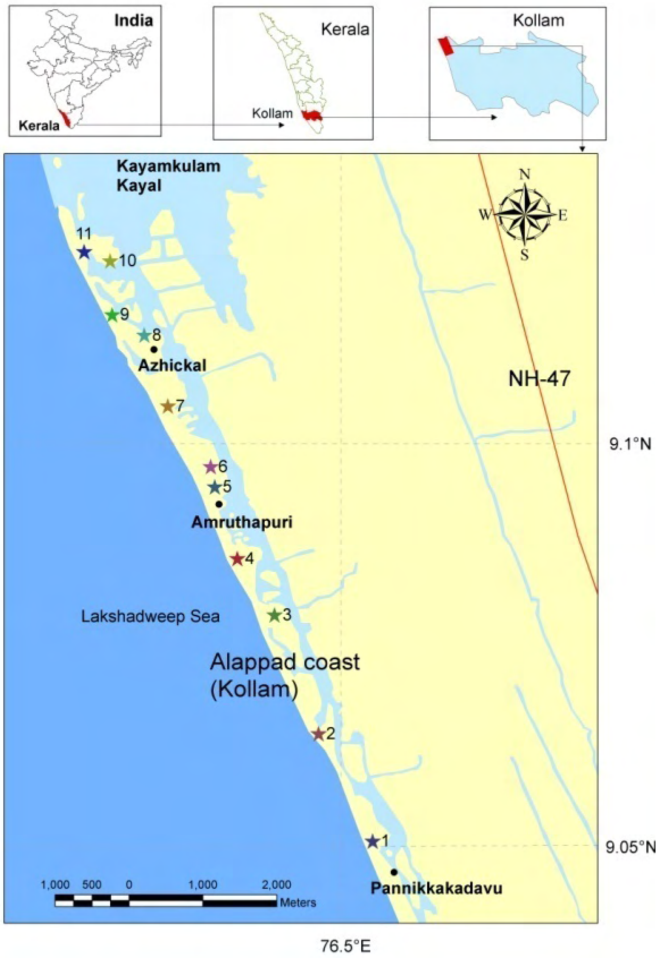

Figure 4.1: Location map of the study area and sampling stations of Alappad coast, Kerala, India

The earlier reported studies eloquently corroborate the biogeochemical changes brought about in the coastal environments as a severe outcome of sea water inundation by tsunami waves (Achari, 2005; Ramesh et al., 2006; Achari et al., 2007; Achari et al., 2006b; Kaystrenko, 2010; Ren et al., 2010; Wong et al., 2010; Walker, 2010; Srinivasa Kumar et al., 2012; Jha et al., 2011; Sharma and Bajpai, 2011; Patankar et al., 2012; Kocherla, 2012; Agoramoorthy, 2012; Patel and Agoramoorthy, 2012; Shibata et al., 2012).

The study taken up under this chapter elaborately discusses the major findings arrived on the basis of primary data obtained as outcome of years of long painstakingly rigorous analytical determinations made on hundreds of samples collected from the study area; Alappad coast, Kerala, India. The major sampling stations and their location-wise character are well marked as given in the Table 4.1

Table 4.1: Water quality sampling stations representing various classes on tsunami affected Alappad coast (Kollam) in 2005.

Station	Remarks*	Location
1.Cheriyazheekal Vadakenada Bhagavathy Temple (outside)	Non affected well -Control well [CW]	09^{o} 03’ 49N, 76^{o} 29’ 47E
2. Vidyadharan- house owner	Affected well dewatered, cleaned[AWDC]	09^{o}0 3’ 04N, 76^{o} 30’ 00E
3. Subhash –house owner	Affected well dewatered, cleaned[AWDC]	09^{o} 04’ 95N, 76^{o} 29’ 69E
4. Parayakadavu Temple	Affected well dewatered, cleaned[AWDC]	09^{o} 05’ 23N, 76^{o} 29’ 23E
5. Amrithapuri 600 feet well	Bore well [BW]	09^{o} 05’ 23N, 76^{o} 29’ 23E
6. Amrithapuri 300 feet well	Bore well [BW]	09^{o} 05’ 24N, 76^{o} 29’ 20E
7. Sraikadu Temple	Affected well not dewatered, not cleaned[AWNDNC]	09^{o} 05’ 32N, 76^{o} 29’ 29E
8. Subrahamanya temple	Affected well dewatered, cleaned[AWDC]	09^{o} 06’ 54N, 76^{o} 28’ 32E
9. Kurisady –public well	Affected well not dewatered not cleaned [AWNDNC]	09^{o} 07’ 78N, 76^{o} 28’ 32E
10.Lakhmi-house owner	Affected well not dewatered not cleaned [AWNDNC]	09^{o} 07’ 07N, 76^{o} 28’ 32E
11.Pookottu temple 250feet well	Bore well (KWA) for local supply[BW]	09^{o} 07’ 07N, 76^{o} 28’ 32E

* Tsunami affected dug well (TADW) = [AWDC] + [AWNDNC]

The work presented in the following session of the thesis comprises the major results and discussions on the water quality parameters of the ground water sources of the Alappad region; the specific study area and their ground water chemistry. The original data obtained from the extensive chemical analyses and laboratory studies of samples selected from water sources are promptly placed in three distinct strata; control well (1nos), dug wells (7 nos), bore well (3 nos) are being systematically presented. The comparison of the water chemistry behavior with respect to the sources is interpreted literally following standard methods and statistical tools. The water sources chosen for the present study have conspicuous utility as a potential fresh water source, a definite water regime, a representative nature and some degree of economic utility in a geographically sensitive area.

4.2 Pre-tsunami Water Quality of the Alappad coast, Kerala, India

The base line data indicate (Table 3.1) the waters of the affected coastal region are not hard even in the zenith of the dry summer. Other parameters too indicate that the ground water is indisputably fresh and is within the narrow permissible limit; for safe drinking water status. It justifiably conforms to the BIS standard for the many parameters (TH <300mg/L $CaCO_3$). But samples 2, 3 and 4 shows that sulphate has entered the system to such a level quite unbecoming of a fresh water source. However, the desire limit for the sulphate is quite above (< 200 mg/l desired) the known. Yet high sulphate levels signify the existing of an oxidizing aquatic environment with sufficient dissolved oxygen concentration. Water quality parameters are comfortably below the desirable levels of the BIS guidelines, hence it is established that the ground water of this region was of fairly good quality by source itself.

The early and available water quality parameters of the region (the so-called pre-tsunami data in this thesis) show that the ground water was not hard before the event. Analysis of the available data make to believe that the SO_4^{2-} content of the water is almost or greater than half of the chloride content, causing the oxidative transformation of S to SO_4^{2-}. Interestingly, the Ca^{2+} content significantly exceeds Mg^{2+} in the entire ground water regime. However, the ionic content quantified as mean is found to be SO_4^{2-} (20.4±20.5), Ca^{2+} (19±19), Mg^{2+} (4.8±2.3) and Cl^- (57±15) mg/l respectively. The TH (68±50), CaH (19±19), Na^+ (33±14), K^+ (10±10), CO_3^{2-}(0.5±1.2), HCO_3^- (34.2±53.7) and F^-(0.08±0.01) mg/l indicates the entire section has a fluctuating water chemistry with standard deviation greatly more or equal to the observed mean for a single event of sampling done in March 2001, a time almost three years before the tsunami. Hence referred as the so-called pre-tsunamic ground water quality of the study region.

On analysis the above data individually to obtain the solution features of the ground water in Hill-Piper-Trilinear plots, the distinct behavior of the aquifer in each location had been specific. Though sampling stations have an average spatial separation of one kilometer in the narrow islet barrier, the water of station 1(regarded as the control station of the study throughout) is chemically having some connection to saline water. This may be due to the closeness of the well situated very near to the shore. Water of stations 2 and 4 is of shale in origin and water of station 3 is of temporarily hardiness type. Cation triangle data has a moving tendency towards Na^+ and anion has a trend towards Cl^- apex.

The average water quality trilinear plot reveals that water is having an origin from shale based aquifer with a Na^+ and Cl^- apex. The Na^+/ Na^++ Cl^- ratio equal 0. 47(<0.5) confirms that water is of halite origin but originally contaminated by Na^+ Cl^- source either mixing with saline ground water or seawater. In addition to this there are active hydro chemical mechanisms prominently add enough Ca^{2+} ions either by dissolving gypsum or anhydrite into the system evidence by a high ratio of Ca^{2+} / Mg^{2+} (>1.0).

4.3 Post Tsunami Water Quality of the Alappad coast, Kerala, India

4.3.1 pH

The region marked with a pH of 7.6±*0.1* with CI of 7.5-7.7 at 95% significant level before the tsunami drastically changed to value of 7.8 just after the seventh day of the disaster in January, 2005. Most of the directly affected dug wells have a pH 7.8±*0.5* by this time showing not much damaging behavior initially, drastically changes to pH 8.2±*0.7* by a time of 30 days in February, 2005. The deep bore wells which have a normal pH of 7.5 in the before tsunami situation changed to 8.3±0.3 with a marked change in this period of one month. This indicates that the sources are drastically put into stressful situation by inundation. But the annual average of pH for the determinations consisting 12 month data for the 10 ground water sources of the three strata (given in the Table 4.15) shows that dug wells who are devastatingly spoiled by tsunami inundation have an average pH of 7.7±*0.1* while control well (pH 7.5±*0.5*) and deep bore wells (pH 7.2±*0.1*) have the same range of H^+ activity. The region has a pH of 7.6±0.2 in the year 2005 with CI of 7.4-7.8 at 95% significance

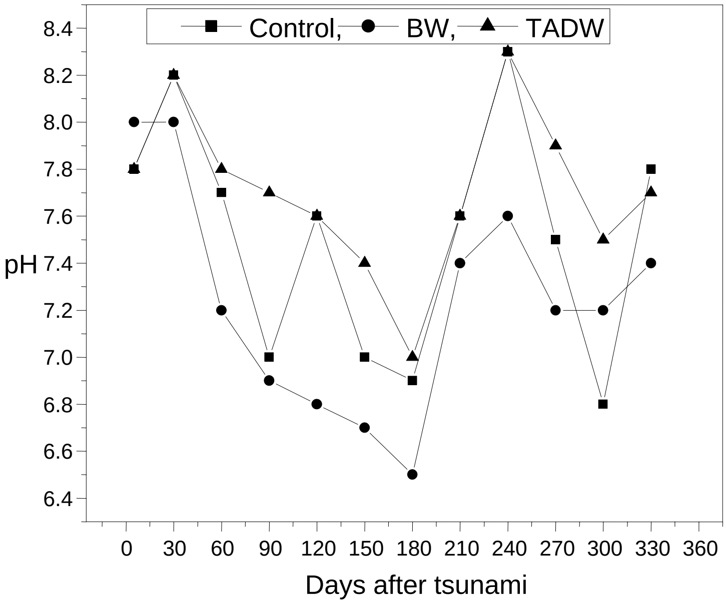

Figure 4.2: Temporal and spatial variation of pH at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Stations 1(■) is the control well [CW]; stations (●) is [BW] and (▲) tsunami affected dug wells [TADW] badly inundated; Post tsunamic studies.

After 1430 days (in December, 2008) the region have been put into highly replenishing situations as revealed by respective mean pH measured of control well (7.7), tsunami affected dug wells (7.4 ±0.4) and deep bore wells have been (7.1±0.1*);* all are attained to a realistically ideal situation. However, the overall pH of the region after tsunami event after this period (by December, 2008) has been 7.4±0.2 within in a CI of 7.2-7.6 at 95 % level of significance on averaging the above three strata of sampling stations. In the time before the tsunami (pre-tsunamic situation) the region's water has a normal behavior with pH 7.6 ±0.1 with CI of 7.5-7.7 (with µ 7.5 -7.7). After 4 year (1430 days in December 2008) the pH of the region is existing with CI of 7.4±0.2 (with µ 7.2-7.6) for the same degrees of freedom. Study of pH alone couldn't be taken for rightly jumping to any of the conclusions as many other prime parameters has to be scientifically evaluated to judge upon the regions ground water chemistry after the tsunami devastation. Rapid change in quality of the ground water followed by slow replenishment nurtured the barrier islets in the post tsunamic period. (Figure: 4.2)

4.3.2 Electrical conductivity

The conductivity of ground water of the Alappad region before tsunami had been 0.352±0.018 *mS/cm* within a range 0.334-0.370 at 95% of confidence interval. Figure 4.3 shows the variation of electrical conductivity of water at various stations everywhere trend is higher than the pre-tsunami value. Station (7) (9) and (10) in the graph had a very much high value visibly distinguished from other ground water sources and the trend remains pertinent over the months till July 2005 (180 days).

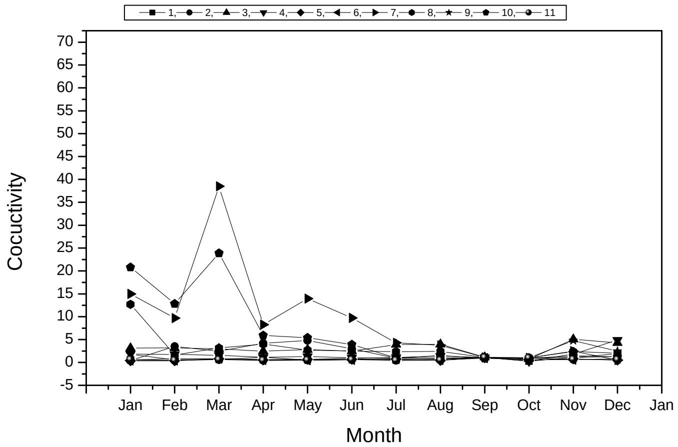

Figure 4.3: Temporal and spatial variation of conductivity at various Sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(▶), 8 (⬢), 9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(♦) 6 (◀) &11(●) are deep bore wells [BW]; Post tsunamic studies.

Afterwards the ground water has a constant conductivity profile towards reaching a uniform level. The above stations are strongly a tsunami devastated and temple well (station 7) and household wells (station 9&10) are not either cleaned or dewatered. All other wells had a comparatively very low electrical conductivity being they are all well cared after tsunami event but maintains almost uniformity in conductivity for as long as a period of 240 days (September 2005) to attain a stable and uniform value. However a continuous replenishment occurs by 270 days (October 2005) to attain the minimum in the graph. Both south west and north west monsoonal dilutions played their role very well to dilute away the tsunami brought additional TDS load.

Another fact notices is that the control well had EC of 0.57 just after tsunami event and always maintained a uniform character with $\overline{x}$(EC) = 0.84±0.4 throughout the year from the day of first sampling after tsunami to 330 days (December 2005) which is quite high compared to the pre-tsunami data of $\overline{x}$(EC) = 0.352± 0.018. All tsunami affected dug wells showed $\overline{x}$(EC) = 3.84± 1.57 *mS/cm* a high value with confidence interval range 2.27- 5.41 *mS/cm*. However, the deep ground water sampled from three bore well stations having depth 250 feet has $\overline{x}$(EC) = 0.62±0.3 *mS/cm*. Time brought remarkable change in conductivity as released by data obtained for December 2008 sampling (after 1430 days). Conductivity becomes respectfully favorable with observed value of 0.3 *mS/cm* for control well, indicating an agreement to the pre-tsunami value of 0.35 ±0.018, and $\overline{x}$(EC) = 0.9± 1.16 *mS/cm* for tsunami affected dug wells showing slow swing to normal behavior even after four years. However the deep ground water maintained it pristine character with value of $\overline{x}$(EC) = 0.23± 0.06 *mS/cm* after 1430 days of tsunami event. Conductance studies strongly indicate that irrespective of the form and character all ground water sources; were subjected to quality variation by tsunami waves in Alappad barrier island.

4.3.3 Redox Potential

pH-pE diagrams are useful to draw conclusion on systems where the transition of species occurs with respect to pH and pE values. In water with Fe ions water is oxidized if pE >13.0 and is in reduced form if pE < 13.0. In general pE varies with pH three times of its values by the equation $pE = 21.41-3pH$.

Figure 4.4 shows the variation of Eh of ground waters of tsunami affected Alappad coast at temporal and spatial distributions. It is clear that Eh is negative to most samples except station 2 and 3 (tsunami affected and cleaned wells) and bore well source of depth (600 feet). They have an Eh more on the positive side on just after tsunami event and remains as such for more than 30 days may be due to cleaning and dewatering. Water of these stations exist in oxidized form by virtue its constituents. All others [AWNDNC] mostly tsunami affected dug wells not cleaned the Eh is more negative; indicate the water is inherent in reducing environment.

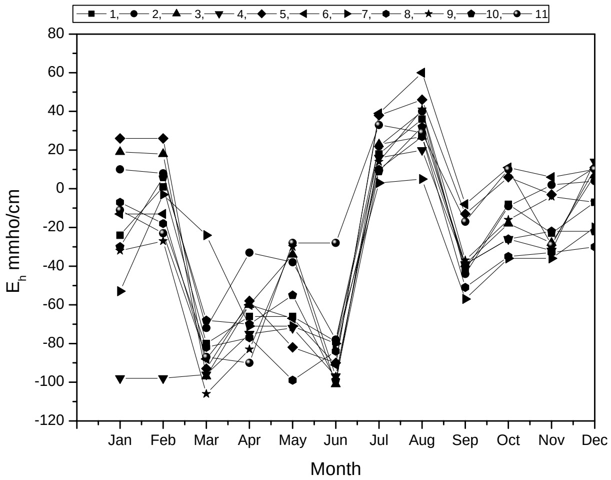

Figure 4.4: Temporal and spatial variation of redox potential at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆),3(▲), 4 (▼), 7(▶), 8 (⬣), 9(★) & 10(⬟) are tsunami affecteddug wells [TADW] badly inundated and stations 5(♦) 6 (◀) &11(◖) are deep bore wells [BW]; Post tsunamic studies.

Station (7) a temple well (not cleaned) has the highest of the Eh = -0.57mv comes to a stable range after 30 days of the incident by February, 2005. Hereafter, the all water sources sink into a highly reducing environment by 60 days of tsunami (by March 2005) irrespective of their nature either the category of control well, dug well or bore well sources. All retains the reducing situation for another 90 days (till June 2005). Once the monsoon started reduction potential rapidly rise to the positive side indicate the rapid oxidation of the constituents by dissolved oxygen rich rain water by a gap of exactly 120 days since tsunami event.

Eventually the tsunami brought the ground water of the region rigorously into a reducing situation quickly within few days. Stabilization of species occurs ever a gap of 120 days and shift to a highly oxidizing environment has been very fast with the monsoonal dilution. The respective reduction potential ($\overline{\mathrm{x}}$) prior to tsunami is not known but it has been noted that regions water has a reduction potential ($\overline{\mathrm{x}}$) = -17±15 just after the event in January 2005, and it goes straight up to -80±38 by June 2005 (within 150 days) rapidly attains as oxidative environment within next 30 days by July 2005 marked by +23±3mv. Further shift to moderately reducing situation occurs with +

33±3 by 230 days (September 2005). Here after, the ground water sustains a stable redox situation with slightly reducing tendency by all samples. A high peak area at August 2005 (by 150 days) indicates the oxidation of water is more prominent this time by the influx of fresh water by the regional discharge. By September it varies as monsoon weakens rapidly the system faces an oxygen limiting situation, water sinks to reducing condition.

4.3.4 Dissolved Oxygen

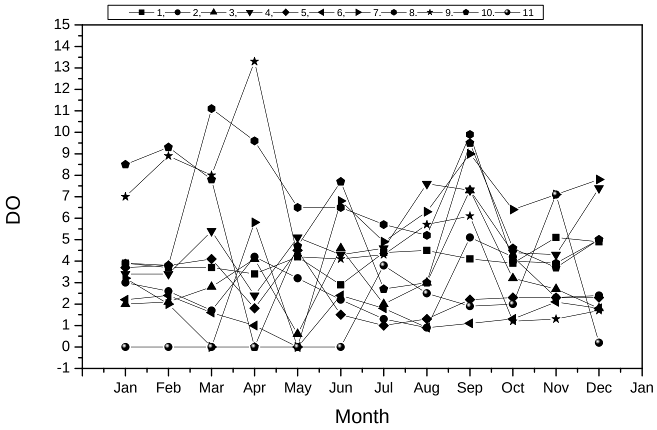

Figure 4.5: Temporal and spatial variation of Dissolved Oxygen (DO mg/l) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(▶), 8 (⬣), 9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(⧫) 6 (◀) &11(◐) are deep bore wells [BW]; Post tsunamic studies.

The dissolved oxygen content of the ground water of the Alappad region prior to tsunami has not been known to have a glimpse of the baseline situation. The post tsunami behavior of the region is statistically evaluated out of the data collected and graphically plotted in the Figure 4.5. It shows that all ground water samples have a dissolved oxygen range from 2.0 to 10.0 mg/L after tsunami event (after 7 days). Clustering of the data to the range of 2.0 to 4.0 mg/L is prominent in the graph except for 9 (dug well not cleaned) and 10 (house dug well not cleaned).

These two stations behave alike though their situations are quite contrary. Both wells are situated on the side of the lagoon on the eastern side of the islet, might have subjected to dilution by the influx of fresh water gradient. This odd behavior is prominent till 90 days of duration (April 2005). However all other dug wells and bore wells maintained the stable shape in dissolved oxygen content irrespective of their nature and damage implied by tsunami waves and replenishment through human intervention by dewatering and cleaning till a period of 150- 240 days (June 2005-September 2005) after tsunami event. By 240 days the dissolved oxygen of some of the tsunami affected drinking water sources attained maximum of 10.0 mg/L (stations 7, 8 and 10). Because the dilution by rain water oxygenate the surface ground water and by the time most of the organic carbon sources might have been either stabilized or degraded. Hence water becomes moderately saturated by dissolved oxygen.

The control well [CW] just after the tsunami event has a DO of 3.9 mg/l and tsunami affected dug wells [TADW] has a DO of 4.4±2.4 mg/l where as the bore wells [BW] has a DO of 2.9 ± 1.9 mg/l. Oxygen is a common redox element (O_2/H_2O) in natural waters. It maintains a range of 8-10 mg/l in well aerated waters (Hounslow, 1995).

Organic carbon compounds deplete the dissolved oxygen content of a water body and re-aeration regulates the condition of saturation. Depletion of dissolved oxygen by redox mechanism makes water anaerobic. Spread of the data in the graph as well as the monthly mean distribution of the DO content shows little variability across all strata of ground water source throughout the year following the tsunami incident. Even in the month of July (180 days) once monsoon become prominent, the DO remains almost stable with 4.4 mg/l, 3.6 ± 1.6 mg/l and 2.2 ± 1.4 mg/l for the above strata of the fresh water sources. After the twelve consecutive measurement of the data for the sample for the respective strata of sources; the so-called annual mean DO for the control well [$\bar{x}$ DO-CW] is 4.1± 0.6 mg/L, [$\bar{x}$ DO- TADW] is 4.6± 0.7 mg/L where as the deep ground water maintain [$\bar{x}$ DO –BW] is 1.9± 0.5 mg/L.

These quantities are the outcome of natural self-purification behavior of the tsunami devastated ground water sources that took a time of 330 days. By 2008 (After 1430 days) the respective strata of drinking water sources shows that [$\bar{x}$ DO-CW] is 4.5 mg/L, [$\bar{x}$ DO- TADW] is 6.8± 3.4 mg/L where as the deep ground water maintain [$\bar{x}$ DO –BW] is 2.3± 1.4 mg/L. Tsunami affected dug well sources with ($\bar{x}$ DO) attains a near to saturation condition of 6.8±3.4 mg/L with range 3.4 to 10.2 mg/L over a long time of 1430 days indicating sources were in a stage of oxygen sink after tsunami event due excessive pollutional load by giant waves.

Long period of exposure brought profound oxygenation of the ground water irrespective of the devastation supported by subsequent cleaning intervention. Control well too has registered a reasonable change with DO (4.5 mg/L) by this time. Deep ground water retained a stable character with observed as $\bar{x}$= 2.3±1.4 mg/L or (0.9-3.7 mg/L).

4.3.5 Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) of the tsunami affected ground water is regarded as the milligram of oxygen consumed by the organic compounds per liter of water for its degradation over a period of 5 days. In natural water oxygen is used up for the oxidation of ammonia (nitrification) is called nitrogenous BOD or NBOD in addition to usual carbonaceous BOD or CBOD keeping the fact that it is not easy to regard the exact composition of organic matter in ground waters after a geological disaster like tsunami. There exists need of rational to avoid strenuous efforts to find exact composition of organic matter and the computation of the stoichiometry. As a direct determination program BOD, its proportional to the organic carbon content of water measured by a TOC analyzer is a rather simple and accepted method [$L_0 = r_{oc}C_{org}$; C_{org} is organic carbon content of the water (mg C/l) and r_{oc} is the ratio of mass of oxygen consumed per mass of carbon assimilated evaluated as 2.67mgO/mgC (Chapra, 1997)]

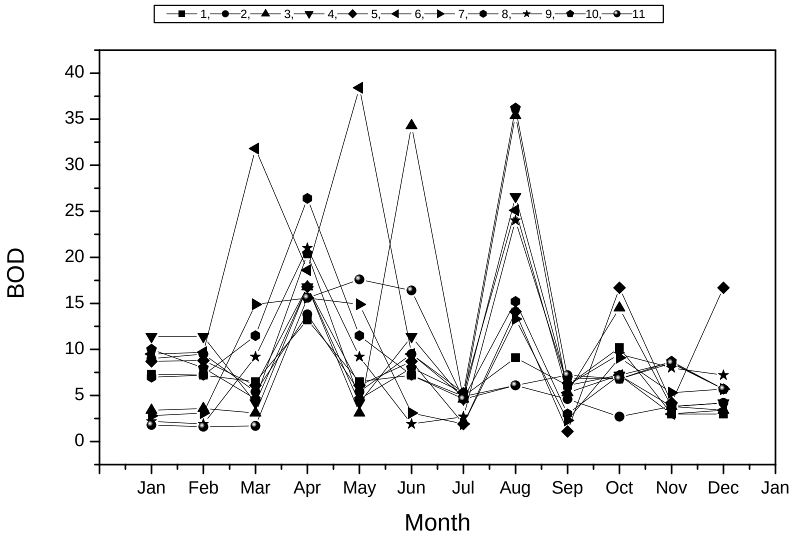

Figure 4.6: Temporal and spatial variation of Biochemical Oxygen Demand (BOD mg/l) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(►), 8 (⬢), 9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(♦) 6 (◄) &11(◐) are deep bore wells [BW]; Post tsunamic studies.

Graphical plot of variation of biochemical oxygen demand is given in Figure 4.6. BOD level has been less than 10.3 mg/l in case of tsunami devastated stations just after event 6.5±3.8mg/l whereas the control well has 7.3 and deep bore wells have 6.7±4.2 mg/l. All stations maintained a stable level of BOD profile till March 2005 over a period of 60 days except for station No.6 (A bore well with 600 feet) and a slight higher level for wells not cleaned and flushed (stations 7, 9 and 10). May be the immediate flushing and caring by the people have made the water more fresh in existence for timely being.

The low but stable BOD of the ground water shows the hindered accumulation of organic waste by dug wells even after it were being cared for. The deep ground water registered a lower $\bar{x}$ (BOD) = 6.7±4.4 mg/L for 30 day sampling after tsunami event indicates somehow these sources are not well protected in the region though casing are there in existence once they were drilled. The consistency with a low BOD level maintained by deep ground water is against the belief that it is no way contaminated. A rapid rise observed in BOD for all stations irrespective of their profile by April 2005 (90 days after tsunami event) with $\overline{x}$ (BOD) 18.7±4.2 mg/l for [TADW]and $\overline{x}$ (BOD) 17.0±1.5 mg/L for [BW] with highest BOD 13.2mg/l for CW.

This is quite, contrary to expectation as whatever be the cause either diluted by summer showers or other hydro geological aspects uniformly affected the quality of ground water. The depth profile is distinguishably varied over many times even then the BOD change noted is almost the same pattern. The accumulation of organic waste picked up by rain water caused by the natural degradation sprouted the BOD to such a level, with large marginal differences. The high BOD for deep ground waters may be of over contamination of SO_3^{2-}, S^{2-} or N by ground water. Because the BOD is a measure of oxygen equivalence consumed mainly for organic molecules in most cases, but exceptions are very common if these mentioned ions also exist (Hounslow, 1995).

By May, 120 days after the first sampling BOD content decline to 7.6±4.4 mg/L for surface ground waters (dug wells) and reaches to the minimum of 4.1±1.3 mg/L by July 2005 (after 180 days). However, deep ground water and shallow ground water shows marked difference in their peak values. In the case of BW BOD 6.7 ± 4.2 mg/l after the tsunami event progressively enhanced over time till June 2005 (after 150 days) with a value of 60.7±89.4 mg/l within a range of 0.0-150.1 mg/l. Tsunami affected dug wells having mostly shallow ground water profile has the higher BOD of 22.4±11.4mg/L (11.0 33.8 mg/L range) by August 2005 (210 days) in the same region may be due to the successive cleaning and dewatering by the affected people. In between these, many ups and downs are found among the strata of tsunami affected dug wells. However, BOD declines for all strata of sampling station till 330 days of sampling. A high BOD level for all stations irrespective of the geographical feature after May 2005 indicates the monsoonal discharge badly supplies nutrients and organic wastes to ground waters of the region to decline the quality of water.

The progressive degradation of the deep ground water quality in tune with affected dug wells indicate a serious question that the deep ground water too contaminated as the data processed for stations 5,6 and 11 indicates for the deep ground water of the region.

Nevertheless to say that the average BOD of the ground water with respect to [TADW] 9.0±1.6 mg/l (range 7.4-10.6 mg/L) is not much different from that of deep ground water sampled (BW) 14.4±7.8 mg/L (6.6-22.2 mg/l). The control well has the lowest BOD level in the group 7±3 mg/l goes well with thought to be safe supplied and consumed by all without proper treatment.

The result indicates the ground water mined from deep aquifer is more polluted than the shallow ground water sources; seriously tsunami affected dug wells of the region. In this respect this study throws light on the gravity of the situation of the region against all prevailing odds. Deep ground water mined from BW of a tsunami devastated region is more polluted than the shallow dug wells because they are holistically preserved by the affected people neglecting their total loss. The control well maintained a very steady profile with annual mean of 7.0±3.0 mg/L (4.0 – 10.0 mg/L). But the replenishment occurred over the years (by 2008) as it is revealed that BW has 9.6±5.8 mg/L (3.8-15.4 mg/L) where as the shallow ground water is resistant to retain the pristine behavior as revealed by its high BOD mean $\overline{x}$ (10.0±5.0 mg/l) with range 5.0 – 15.0mg/l though the control well become normal with stable $\overline{x}$(BOD) = 4.8±0 mg/l. The over pumping of deep ground water BW after the devastating event to meet the abject shortage of drinking water for a vast region from available 2-3 bore wells leads to excessive percolation of inundated wastewater in to them through highly corroded metal casings. Evaluation of the aggressiveness index of the ground water will provide more insight into this proposition.

4.3.6 Sulphate

Hydrochemical behavior of SO_4^{2-} ions in the tsunami affected zone behave in a rather complex way. In first sampling (7D) SO_4^{2-} levels of the stations were shown a very staggered feature that all TADW has shown a high SO_4^{2-} range (89 ± 65), where as deep ground water has a lower SO_4^{2-} level (6± 6). The feature exhibited by figure indicates a high level of SO_4^{2-} for stations 7,8 and 10 all are directly tsunami affected dug well but not (7 &10) are not at all cleaned or dewatered.

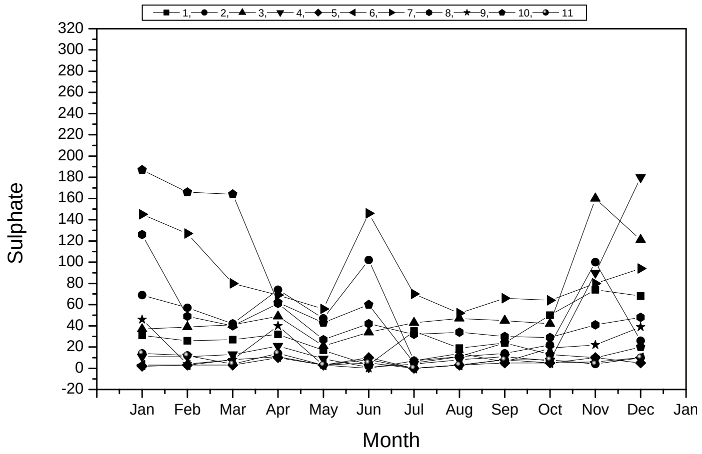

Figure 4.7: Temporal and spatial variation of sulphate (SO_4^{2-} mg/l) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(►), 8 (⬢), 9(★) & 10(⬟) are tsunami affected dug wells [TADW]badly inundated and stations 5(♦) 6 (◄) &11(⬟) are deep Bore wells [BW]; Post tsunamic studies.

They maintain this high level of gross SO_4^{2-}content for over a period of 90 days (till April 2005) such that the overall contribution varies (89 ± 65) for January 2005 (first 7D), (65 ± 60) for February 2005 (30 D, days after first sampling) and (55 ± 53) for March (60 days after first sampling), April 05 (90 days) with 54±19 mg/l. By May 2005 (120 days after first sampling) more consistency is being achieved by the ground water of the region as sum of the three strata of sources such that $\overline{x}$ (SO_4^{2-}) for (TADW) is (29 ± 20). The control well has a declining feature over this time moving from 31mg/l to 3mg/l by 50 days (June 05). However, TADW and CW approach a minimum within 120days rather rapid stabilization.

High sulphate level for TADW in the initial stages after tsunami event indicates oxygen limitation situation in most of the uncared sampling stations though those wells were not cleaned and attended in person is having stabilized values. Unattended wells seriously faced the very reducing environment as they are mostly contaminated in the beginning. Consequently SO_4^{2-} gets reduced by organic carbon sources to H_2S subsequently influencing pyrite formation by the dissolved iron.

$$2C + SO_4^{2-} + 2H_2O \rightleftharpoons H_2S + 2HCO_3^- \quad \text{....................4.1}$$

$$Fe^{2+} \rightarrow FeS_2 \quad \text{..4.2}$$

This is a slow geochemical redox process which took enough time as is evident from the graph that is stable and dip values reach 29±20 mg/l by May 2005 (120 days). Every time the dug wells were cleaned to achieve this acceptable position. Ground waters have a steady profile throughout the year. The uneven behavior of the ground water sources directly affected by tsunami event is evident in January 2005 (150 days data) as the elution of bound SO_4^{2-} by soil grains enhances the input especially the surrounding areas of the worsely affected ground water sources. After this period SO_4^{2-} level maintains a stable profile well over a period of July 2005 (180 days) till October 2005 (270 days). Afterwards the affected wells behave a mirroring tendency exactly matching to their behavior actually observed first after the tsunami event almost 360 days before. This is observed on comparing the data of January 2005 (first sampling) gross value for TADW $\overline{x}$ (SO_4^{2-}) = (89± 65) and December 2005 (330 day sampling result $\overline{x}$ (SO_4^{2-}) = (75 ± 52).

The overall SO_4^{2-} concentration as a mean of 11 samples for Jan 05 (7D) has been 42±22 and December 05(330D) was 50 ±17 mg/l. However the annual mean for the 12 sampling event for the above eleven stations have been 36±18 mg/l with CI of 18-54 mg/l for n=132. By December 2008 (1430D) the sulphate content of the region attains a mean of 17±15mg/l n=12 with CI of 2-32 at 95% level of significance.

The stable profile of SO_4^{2-} beyond 180 days sampling indicates a residual quantity of (SO_4^{2-}) only remains as mostly converted into H_2S in mean time. This observation is prominent as the Fe concentration also stable in the respective graph. Because Fe^{2+} too get reduced to FeS_2 in such a reducing environment orchestrated by SO_4^{2-} reduction mechanism as revealed by the equation ($Fe \rightarrow FeS_2$). The variation of sulfate is graphically represented in Figure 4.7.

4.3.7 Iron

As mentioned in the section of SO_4^{2-}, the content of Fe^{2+} in ground water is largely controlled by the availability of O_2; decided either in aerobic or anaerobic situation or reducing environment with H_2S. In most waters with H_2S, Fe^{2+} is removed by precipitation as pyrite (FeS_2) called marcasite (Hounslow, 1995).

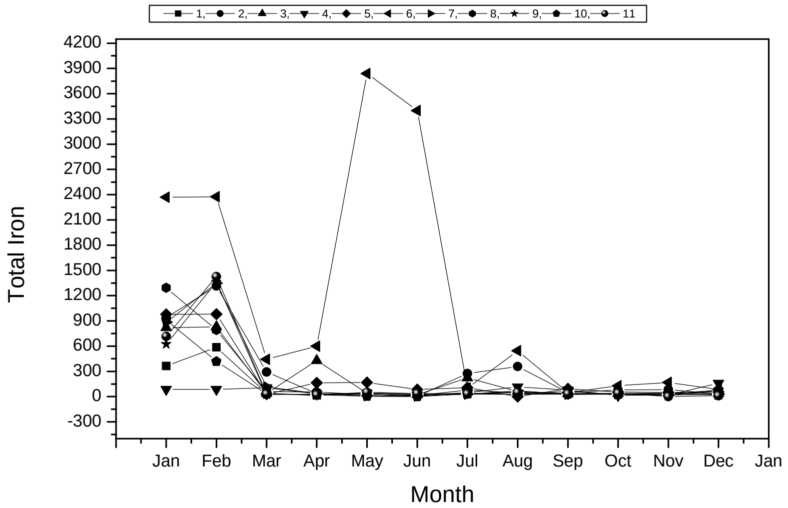

Figure 4.8: Temporal and spatial variation of Iron (Fe) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(▶), 8 (⬢), 9(★) & 10(⬟) are tsunami affected dug wells [TADW]badly inundated and stations 5(⧫) 6 (◀) &11(⬣) are deep Bore wells [BW]; Post tsunamic studies. Concentration of Fe (μ g/l).

In circumstances where HCO_3^- concentration is less than 61.0 mg/L, Fe concentration would go up to 50mg/L from the normal expected range of 1-10 mg/L for moderately reduced anaerobic waters. Fe content of the ground waters of the tsunami affected region shows a very similar profile followed by SO_4^{2-}, a higher but favorable within the permissible range (3.0 mg/l) during the aftermath of the tsunami event which suddenly falls by a slow and steady level after 30 days.

Afterwards, irrespective of the identity of the sampling sources consistency is maintained throughout the year as revealed by the Figure 4.8. The high level of iron is mostly contributed by a deep ground water source (station 6) of deep bore well BW

600 feet and the (TADW) too have a high proportion of Fe that slowly get converted to SO_4^{2-} over the month's time by a concerted mechanism favored by a very strong reducing Eh environment with SO_4^{2-} reduction and methanation (Hounslow, 1995).

A stable and minimum is observed by June 2005 after 150 days of the first sampling in the data profile. A stable and minimum in the graph is observed by June 05 (150 D) of the first sampling in the data profile. The three distinguished strata of the wells have a high incidence of Fe content in Jan 05 (7D) such that CW has 363 μ g/l, TADW has 794±370 μ g/l and BW has 2355±889 μ g/l shows that the Fe content of the sources are very high. After 30 days the highest recorded maximum respectively of CW (587 μ g/l) TADW (879±499 μ g/l) and BW (1594±713) μ g/l has been noted. Since we are not having a known pre-tsunamic value of the region with respect to the Fe content it is very pertinent of accept that the tsunami impact strongly affected the hydro geochemistry of the ground water sources. One of the major observations has been that CW attains the stable Fe profile of 14 μ g/l by 90 days (April 05) after tsunami whereas the TADW reaches to the minimum of 11±8 μ g/l by 150 days only due to monsoonal dilution in June 05. The bore wells have the minimum of Fe content only after 240 days (Sept05). However by 330 days (Dec 05) after tsunami event the iron content of the respective strata has been CW 18 μ g/l, TADW 109 ±59 μ g/l and BW 50±37 μ g/l, mostly disappeared due to oxidative hydrolyses initiated by natural aeration and pH. Annual mean of the Fe content strata wise has been CW 104±180 μ g/l, 19 μ 0±59 mg/l and 537 ± 262 μ g/l. The overall Fe content of the region in a post tsunamic situation consisting the mean of 11 sampling stations over 12 sampling event has been evaluated as 280±210mg/l with CI of 70-480 μ g/l for a 95.5% level of confidence. Variation of iron represented graphically in Figure 4.8.

More insight into this mechanism could be gathered on analysis the respective Hill–Piper-Trilinear diagram meant for pyrite oxidation and neutralization by calcite.

4.3.8 Phosphate

By no way phosphate is regarded as a major constituent of ground water being its usual level make in chance to be positioned one among the trace constituent (<0.1 mg/l; Hounslow, 1995)

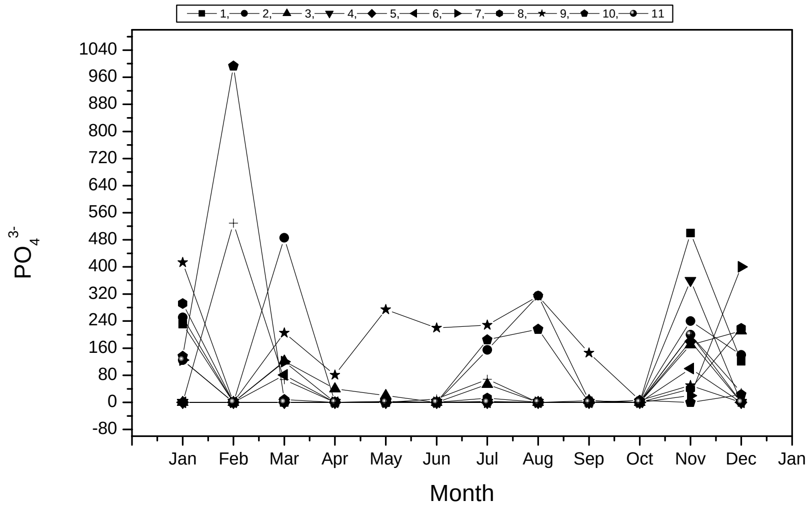

Figure 4.9: Temporal and spatial variation of Phosphate (PO_4^{3-}) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(▶), 8 (✸), 9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(♦) 6 (◀) &11(⬟) are deep bore wells [BW]; Post tsunamic studies. Concentration of (PO_4^{3-}) (µg/l).

Nevertheless this constituent forms an important weighing factor in gross computing of Water Quality Index (WQI).

Variation of PO_4^{3-}shown in the Figure 4.9 reflects the fate of these ions in the region ground water after the tsunami impact. Graphically the trend is more matching with that of NO_3^- in features not in magnitude, may be both are macronucleus and their solution concentration inseparably connected to biological activity of the system. Just after the tsunami event the PO_4^{3-} level is more quantified as $\overline{x}(PO_4^{3-})$ 0.174±0.153 mg/L for the tsunami affected wells (TADW) being the control well has 0.231mg/L. The deep ground water too seem to be contributing PO_4^{3-} level by $\overline{x}(PO_4^{3-})$ =

0.42±0.72 mg/L. This indicates the logic of choosing PO_4^{3-} a prominent factor as it here act as a minor constituent (0.01-10mg/L).

Tsunami brought a well-defined phosphate regime in the regional water quality by its never ending presence for many years since the tsunami event. The content dwindle to the minimum level after 90 days (April 2005) with $\overline{x}(PO_4^{3-})$ = 0.42±0.32 mg/L where both control well and deep groundwater sources registered a zero PO_4^{3-} value. Further it gains to maximum by 210 day (August, 2005) with $\overline{x}(PO_4^{3-})$ = 0.121±0.154 mg/L for TADW, still with a zero level for control well and BW sources. It further unequivocally falls to minimum $\overline{x}(PO_4^{3-})$ =0.002±0.003 mg/L by 270 days (October, 2005) after tsunami for all tsunami affected dug wells (TADW) further rises to a maximum once the full circle is about to complete in the twelfth sampling by 330 days with $\overline{x}(PO_4^{3-})$ = 0.142±0.148 mg/L for TADW and a $\overline{x}(PO_4^{3-})$ of 0.121 mg/L for control well. On comparing the first and last sampling events the PO_4^{3-} level declined from 0.174±0.153 mg/L to 0.142±0.148mg/L for TADW over year, passing through a set of natural conditions. However, the last sampling after fourth year of the tsunami devastation by (1430 days) December 2008 has $\overline{x}(PO_4^{3-})$ =0.080±0.047 mg/L for TADW with a $\overline{x}(PO_4^{3-})$ = 0.260 mg/L for control well and 0.079±0.108 mg/L. Since the pre-tsunami data is not available with respect to PO_4^{3-} it is not at all rational to make any impartial judgment whither tsunami brought a direct impact on PO_4^{3-} level of the regions ground water. Ever since, it is most conclusive based on the data gathered that PO_4^{3-} has an irregular pulse in defining water quality of the region.

4.3.9 Nitrate

The common perception on Nitrate level in drinking water sources is mainly due to contamination from intensive agriculture practices, which lead to changes in the drainage pattern of steep terrains. Traces of nitrate in dug wells in a tsunami devastated region may arise from the altered drainage channels. Subsequent sewage effluent contains NO_3^- ions enough to contaminate the shallow drinking water sources leads to an oscillating quality behavior of the shallow ground water. Higher level of nitrogen is severely troublesome to infants.

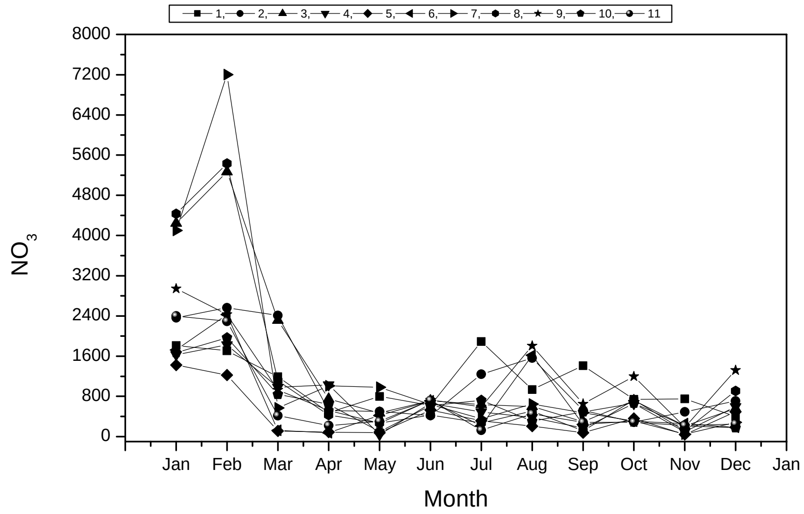

Figure 4.10: Temporal and spatial variation of Nitrate (NO_3^-) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(►), 8 (⬣), 9(★) & 10(⬟) are tsunami affected dug wells [TADW]badly inundated and stations 5(♦) 6 (◄) &11(◖) are deep bore wells [BW]; Post tsunamic studies. Concentration of (NO_3^-) (µg/l).

Infants do not have enough micro flora (normal bacterial flora) in their intestine unable to deal with ‘nitrates’ of drinking water consumed. Any drink or milk (contaminated with a nitrate of 10-20 mg/L) consumed by a baby of this age causes nitrite to get absorbed in the blood preventing oxygen binding to cause life challenging situation of methaemoglobinaemia (called blue baby disease). High concentration of nitrate in drinking water sources cause many health related problems characteristic of the drinking water as per the state guideline limits to a value of 45.0 mg/L and for drinking water sources without conventional treatment but after disinfection with 20.0 mg/L. In natural environment, particularly aerobic process, obligate aerobics survives using oxygen as the electron accepter. Ultimately hydrogen atoms from the organic compounds end up in forming water combining with reduced oxygen. Against these obligate anaerobes depends oxygen containing inorganic compounds such as nitrates and sulphates. Nitrates are reduced to ammonia (NH_3) and sulphate to hydrogen sulphide (H_2S). Nitrate is more preferred by microorganisms, so the process is more common in natural environment.

Nitrate profile of the region ($\overline{x}$) first after the tsunami event (January, 2005) is observed as 1.812 mg/L for control wells, 3.06±1.22 mg/L for TADW and 1.85±0.50 mg/L for deep bore well ground water sources. In next 30 days (February, 2005) the $\overline{x}(NO_3^-)$ has change to 1.71 mg/L, 3.81±2.12 mg/L and 1.98±0.66 mg/L respectively for the stations with a marked jump for affected dug wells and deep bore well stations. There after a marked is prominent for all stations during the sampling period spanning over one year after the tsunami incident. The Annual average with respective the source strata is 1.06± 0.53 mg/L for control well, 1.09±0.23 mg/L for TADW and 0.59±0.098 mg/L for deep bore well samples. However, the overall mean NO_3^- level of the region remains to be (0.96±0.22) mg/l in the post tsunami year with CI of 0.74-1.18mg/l at 95% level of significance (n=132). The variation of nitrate given in Figure 4.10.

Analysis of the data for the year 2008 exhibits a rather complex situation. The control dug well has NO_3^- (0.144 mg/L), while TADW have 1.61±0.89 mg/l where as deep ground water has 2.27±0.67 mg/L. The overall NO_3^- level of the region after four years is $\overline{x}$(1.65 ±0.65) mg/l for n = 12 with CI of 1.01 – 2.29 at 955 level of significance. The high NO_3^- level after tsunami event may be due to the prevailing oxidative environment of the ground waters as evidenced by Eh profile in the figure. The water has a stable oxidized state whole NO_3^- is preserved as such by stabilization. The situation persists for another 30 days till (February, 2005), here after water shifts to reductive environment, where NO_3^- is utilized by the oblate anaerobic microbes targeting NO_3^- as an electron acceptor to convert organically bond hydrogen atoms to NH_3.

4.3.10 Alkalinity

In post-tsunamic situation alkalinity is being regarded as a measure of buffering capacity of ground water of the tsunami affected region to effect the neutralization of acid or H^+. HCO_3^- and CO_3^{2-} produced by the dissolution of atmospheric CO_2 or from $CaCO_3$ can grab H^+ entered into the system by geological route. According to Vesilind and Morgan (2004) the alkalinity equilibrium

Alkalinity (mol/L) = $[HCO_3^-]+[2CO_3^{2-}]+[OH^-]-[H^+]$ 4.3

Alkalinity (meq/L)= $[HCO_3^-]+CO_3^{2-}+[OH^-]-[H^+]$ 4.4

At pH<8.3, alkalinity exists as HCO_3^- but near to pH = 7.0, $[H^+]\approx[OH^-]$ 4.5

For potable water in reality alkalinity means [HCO_3^-] content of water. Alkalinity has a remarkable effect on total hardness. If the alkalinity is less than the total hardness (TH), then alkalinity equals to carbonate hardness. At conditions, alkalinity becomes more than TH, then CO_3^{2-} hardness would be equal to total hardness. Provided, it is known fact that carbonate hardness never be greater than the TH.

Alkalinity profile of the region show a steady trend as revealed by the feature of the graph shown in Figure 4. 11. However, the TADW sources have a high alkalinity value compared to control and deep ground water through out. After the tsunami event (7D) affected dug wells TADW has $\overline{x}$(Alk) of 344±258 mg/L, $\overline{x}$(Alk) of 200±43 for deep ground water and $\overline{x}$(Alk) 88.0 mg/L for control well. Not much swing is observed except for the station (7), an extensively devastated dug well, that too placed close to the canal arm of the estuary.

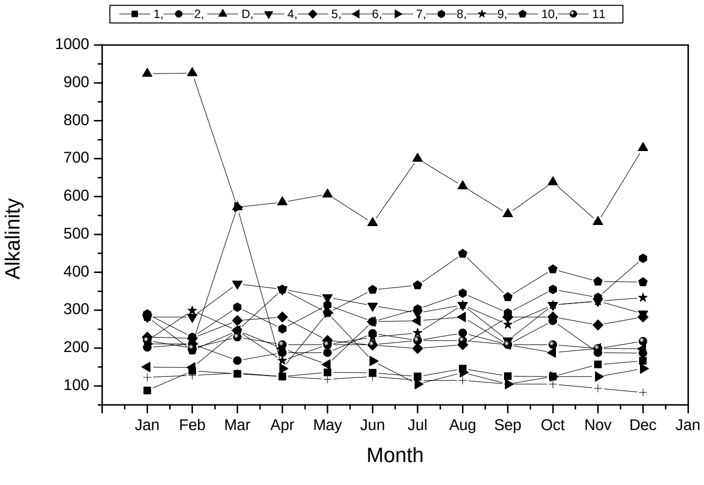

Figure 4.11: Temporal and spatial variation of Alakalinity at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲), 4 (▼), 7(►), 8 (⬢), 9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(♦) 6 (◄) &11(●) are deep Bore wells [BW]; Post tsunamic studies. Concentration of alkalinity as$CaCO_3$ (mg/l).

Observations reveal that the highest level observed in August, 2005 (after 210 day of first sampling) may be interfered by many events due to monsoon and related hydro-geological situations with $\overline{x}$(Alk) = 346±157 mg/L for TADW 237±39 mg/L for (BW) and 146 mg/L for control; are indicative of less fluctuations. Figure 4.11 shows the variation of alkalinity.

On completion of almost one year cycle (i.e. 330 day data) the respective value remains as 357±193 mg/L (TADW), 233±44 mg/L (BW) and 166 mg/L for this parameter. It is certain that annual mean of alkalinity of the region could be regarded as overall alkalinity would be 326±51 mg/L, 223±11 mg/L and 133±51 mg/L for the strata of TADW, BW and C-control sources respectively. Incessant dilution over the years made the water thin with HCO_3^- content. This is most lucidly observed by their low concentration HCO_3^- measured as alkalinity in December 2008; 33±11 mg/L, 27±6 mg/L and 20±19 mg/L for the strata of TADW, BW and control sources respectively

4.3.11 Hardness

Hardness profile of the groundwater in the tsunami affected region is mainly contributed by the multivalent cations Ca^{2+}, Mg^{2+} and Fe^{2+} ions picked up by water from rock and mineral sources. They are not at all a challenge to the health. Though the above ions are the contributing largest towards the TH, Fe^{2+}/ Fe^{2+}, Mn^{2+}, Sr^{2+}, Al^{3+} are too common in ground waters. However, TH is regarded as

$$TH = \Sigma \text{ multivalent cation} \cong Ca^{2+} + Mg^{2+} \ldots\ldots\ldots\ldots 4.6$$

Total hardness (TH) is a sum of two components: Carbonate hardness (CH) known as temporary hardness and noncarbonated hardness known as permanent hardness [ie; TH = CH + NCH] , CH being the contribution of CO_3^{2-} and HCO_3^- the so-called scale forming part. NCH is the contribution of all other anions. CH is always regarded as the less contribution measured as alkalinity (AL) or in certain occasions equal to total hardness (TH). The non carbonate hardness (NCH) is the difference. In circumstances where the alkalinity becomes equal or greater than TH the NCH becomes zero as much as related that all the hardness ions are related to alkalinity. Every time the system adjusts to balance such that sum of carbonate (CH) and non carbonate hardness (NCH) cannot be greater than TH (Vesilind and Morgan, 2004 & Tebbut, 1998). Water hardness classification is given in table 4.2.

Table 4.2: Water Hardness Classification (Vesilind and Morgan, 2004)

Classification	Hardness (mg/l)	Hardness (mg/l) $CaCO_3$
1.Extremely soft to soft [ESS]	0 - 0.9	0 - 45
2.Soft to moderately hard [SMH]	0.9 - 1.8	46 - 90
3.Moderately hard to hard [MHH]	1.8 - 2.6	91 - 130
4.Hard to very hard [HVH]	2.6 - 3.4	131 - 170
5.Very hard to excessively hard [VHEH]	3.4 - 5.0	171 - 250
6.Too hard for ordinary domestic use [THODU]	> 5.0	> 250

In the hardness – alkalinity relationship alkalinity may be less than the total hardness. It is well established that if the alkalinity is less than total hardness, then alkalinity equals temporary hardness. Also under situations where alkalinity is greater than total hardness then all the hardness is regarded as temporary. In short we can summarize that the Alkalinity is known as the exact measure of the difference in total hardness minus permanent hardness.

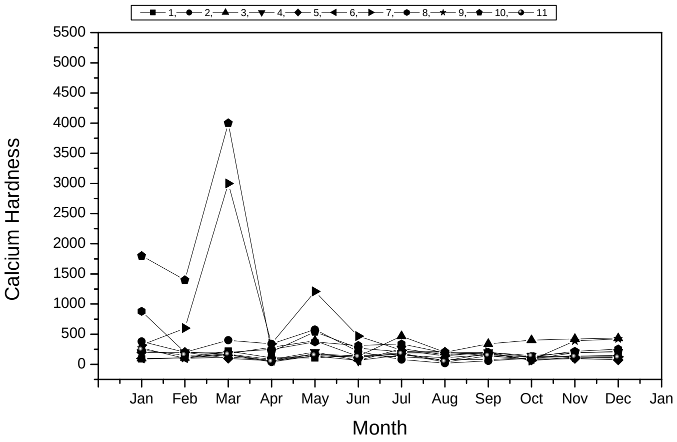

Figure 4.12: Temporal and spatial variation of Calcium Hardness at Various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆),3(▲),4 (▼),7(►), 8(✸), 9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(⧫) 6 (◄) & 11(⬟) are deep bore wells [BW]; Post tsunamic studies. Concentration of Calcium Hardness as $CaCO_3$ (mg/l).

All sampling points all across the sampling period were hard (Figures 4.12). It is to be assumed that calcareous materials from the soil keep leaching into the water body after the seawater influx. High levels of alkalinity also corroborate this fact. The backwater shows sharp and spectacular fluctuation in hardness indicating substantial variation in mixing ratios. It is worth mentioning that the base line data showed that the water of this region was not hard. Hence, one of the standing impacts of the tsunami event was imparting the waters hard, thereby demoting the water sources in utility.

Figure 4.13 shows the total hardness (TH) profile of water in the post tsunamic period where control well has 125mg/l $CaCO_3$ after 7D the tsunami event occurred. It slowly rises to 135mg/l (30D), 250mg/l (60D) in the following time scale to a maximum within 60 days afterwards decline to 225 mg/l (90D). This could be due to the overall diffusion of the Ca^{2+} and Mg^{2+} ions from the soil regime those where badly exposed to tsunami wave interactions.

Tsunami affected dug wells badly inundated [TADW] have a high hardness of 1045±794 mg/l (7D) just after the tsunami event. The deep bore wells have on the same instant has total hardness equal to 252±123mg/l $CaCO_3$. But this is followed by a dip in the both cases after 30 days with 644±644 mg/l for TADW and 200±55mg/l for BW. Afterwards the TH shoots up to as far as 1604±167mg/l (60D) for TADW and 500±100 mg/l (60D) for BW. As regards to TH the three sampling strata either control well (CW), tsunami affected dug well stations TADW or the deep bore well stations (BW) all have downward swing during the initial period and thereafter, the stable feature is maintained.

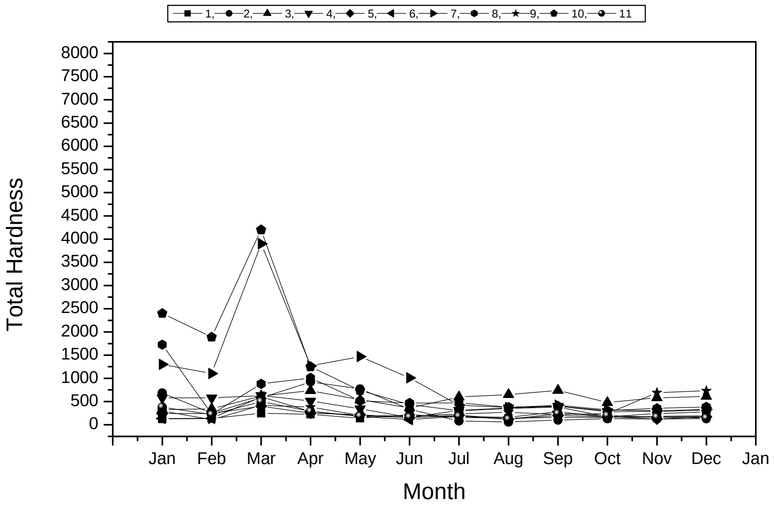

Figure 4.13: Temporal and spatial variation of Total Hardness at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆),3(▲),4 (▼),7(▶), 8(✸),9(★) & 10(⬟) are tsunami affected dug wells [TADW]badly inundated and stations 5(⧫) 6 (◀) & 11(⬣) are deep bore wells [BW]; Post tsunamic studies. Concentration of Total Hardness as $CaCO_3$ (mg/l).

The water hardness classification (CW) has a hardness status of moderately hard to hard [MHH] with 125mg/l $CaCO_3$ moves to the region of very hard to excessively hard [VHEH] by 90 days with TH ranging 171-250 mg/l. The fact that the region has a $\bar{x}$ (TH) = 174 ± 40 mg/l for the annual mean clearly reminisces that the inherent behavior of the region is prone to water with nature of [VHEH]. By 2008 after 1430 days the character became moderately hard to hard [MHH; range 91-130mg/l $CaCO_3$] with 101 mg/l $CaCO_3$, the source regained the original character over the period of time.

Throughout the sampling sessions the strata of tsunami affected dug wells [TADW] have a TH position unaltered from the robust class - too hard for ordinary domestic use [THODU; with > 250mg/ l] with observed mean $\bar{x}$(TH for TADW) = 613 ± 175 mg/l $CaCO_3$. The initial TH 1045 ± 794 mg/l $CaCO_3$ just after the tsunami event (7D) becomes 397 ± 206 mg/l $CaCO_3$ after almost completing one year (330D) indicates marked change in the ionic chemistry and balance such that hardness is subjected to many a number of metamorphoses. However the respective alkalinity measured are lower in every sampling event and a close examination for the comparison can be paralleled; the initial AL 344 ±258 mg/l $CaCO_3$ just after the tsunami event (7D) becomes AL 357 ± 193 mg/l $CaCO_3$ after almost completing one year (330D) with $\bar{x}$ (AL for TADW) = 326 ± 51 mg/l $CaCO_3$, a stable structure is retained. The data of TH and AL after 1430 D by December 2008 has the following values; TH 185±106 mg/l $CaCO_3$ for AL 33 ± 11mg/l $CaCO_3$ all occasions alkalinity is less to the TH for the strata of tsunami affected dug wells (TADW). Comparison of TH, AL, TeH & PeH in mg/l $CaCO_3$ for the control well (CW) given in Table 4.3.

One-to-one extrapolation of the new findings to the pre-tsunamic situation that existed in the region in 2001 with TH 68±50 mg/l $CaCO_3$ with AL 34.7 mg/l $CaCO_3$. Further it is seen that 33.4 mg/l $CaCO_3$ comes from the contribution of permanent hardness. The meaning and metrics of TH and AL in the above strata further indicates that the lower measure of AL with a steady profile throughout being a sign of prominent temporary hardness due to HCO_3^- and CO_3^{2-} and the difference TH- AL is the measure of permanent hardness.

Table 4.3: Comparison of TH, AL, TeH & PeH in mg/l $CaCO_3$ for the control well (CW)

Period	Day	TH	AL	TeH Mg/l	TeH %	PeH Mg/l	PeH %	Inference
Jan 05	07D	125	88	88	70.4	37	29.6	MHH
Feb05	30D	135	140	140	103.7	-5	0	HVH
Mar05	60D	250	132	132	52.8	118	47.2	THODU
Apr05	90D	225	125	125	55.5	100	44.4	VHEH
May05	120D	140	136	136	97.1	4	2.9	HVH
Jun05	150D	218	135	135	61.9	83	38.1	VHEH
Jul05	180D	156	125	125	80.1	31	19.9	HVH
Aug05	210D	140	146	146	104.2	-6	0	HVH
Sep05	240D	160	126	126	78.8	34	21.3	HVH
Oct05	270D	160	125	125	78.1	35	21.8	HVH
Nov05	300D	181	157	157	86.7	24	13.3	VHEH
Dec05	330D	197	166	166	84.2	31	15.7	VHEH
$\bar{X}\pm\sigma$	Mean	174±40	133±19	133±19				
CI		134-214	114-152	114-152				
Dec08	1430D	101	20	20	19.8	81	80.1	MHH

The classification of source water with respect to strata finds that the control well is very much distinct in its shape though located in the tsunami affected region with pertinent character. It is having the persistent temporary hardness over the sampling period mostly the HVH (hard to very hard) category. TH rarely crosses > 250 mg/l only one event after 60Day after tsunami shifting the source to THODU (too hard for ordinary domestic use) position. Comparison of TH, AL, TEH & PEH in mg/l $CaCO_3$ for the Tsunami Affected Dug Wells (TADW) given in Table 4.4.

The TADW (Tsunami affected dug wells) have drastic change in the character as revealed by the data shown in the table. Entire sources have a drastic shift with respect to the baseline control well and all belong to the category of THODU with marked proportion of permanent hardness ions. Regions water with the TeH 70.4% (PeH 29.6%) has rapidly changed to TeH 32.9% (PeH 67.1%) by the sudden inundation by giant tsunami waves. Comparison of TH, AL, TEH & PEH in mg/l $CaCO_3$ for the Deep Bore well (BW) given in Table 4.5.

Table 4.4: Comparison of TH, AL, TEH & PEH in mg/l $CaCO_3$ for the Tsunami Affected Dug Wells (TADW).

Period	Day	TH	AL	TEH Mg/l	TEH %	PEH Mg/l	PEH %	Inference
Jan 05	07D	1045±794	344±258	344±258	32.9	701	67.1	THODU
Feb05	30D	644±642	336±263	336±263	52.2	308	47.8	THODU
Mar05	60D	1604±1678	354±161	354±161	22.1	1250	77.9	THODU
Apr05	90D	869±345	292±155	292±155	33.6	577	66.4	THODU
May05	120D	654±412	320±137	320±137	48.9	334	51.1	THODU
Jun05	150D	422±284	300±118	300±118	71.1	122	28.9	THODU
Jul05	180D	345±168	318±187	318±187	92.2	27	7.8	THODU
Aug05	210D	349±174	346±157	346±157	99.1	3	0.008	THODU
Sep05	240D	380±198	283±140	283±140	74.5	97	25.5	THODU
Oct05	270D	275±114	346±156	346±156	125	-71	0	THODU
Nov05	300D	370±198	315±132	315±132	85.1	55	14.9	THODU
Dec05	330D	397±206	357±193	357±193	89.9	40	10.1	THODU
$\bar{X} \pm \sigma$	Mean	613±175	326±51	326±51	53.2	287	46.8	THODU
CI		438-788	22-44	22-44				
Dec08	1430D	185±106	33±11	33±11	17.8	152	82.2	THODU

Table 4.5: Comparison of TH, AL, TEH & PEH in mg/l $CaCO_3$ for the Deep Bore well (BW)

Period	Day	TH	AL	TEH Mg/l	TEH %	PEH Mg/l	PEH %	Inference
Jan 05	07D	252±123	200±43	200±43	79.4	52	20.6	THODU
Feb05	30D	200±55	192±39	192±39	96	8	4	VHEH
Mar05	60D	500±100	249±22	249±22	49.8	251	50.2	THODU
Apr05	90D	277±23	230±45	230±45	83	47	17	THODU
May05	120D	192±19	195±34	195±34	101.6	-3	0	VHEH
Jun05	150D	143±27	229±36	229±36	160.1	-86	0	HVH
Jul05	180D	191±15	230±38	230±38	120.4	-39	0	VHEH
Aug05	210D	133±23	237±39	237±39	178.2	-104	0	HVH
Sep05	240D	240±40	233±42	233±42	97.1	7	2.9	VHEH
Oct05	270D	178±20	226±49	226±49	127	-48	0	VHEH
Nov05	300D	152±23	220±36	220±36	144.7	-68	0	HVH
Dec05	330D	165±15	233±44	233±44	141.2	-68	0	HVH
$\overline{X}\pm\sigma$	Mean	219±15	223±11	223±11	101.8	-4	0	VHEH
CI		438-788	212-234	212-234				
Dec08	1430D	108±18	27±6	27±6	25	81	75	MHH

The deep ground water has a prominently pristine character though it crosses the THODU limit at three occasions water is soft in most occasion with a greater contribution of carbonate and bicarbonate ions. The proportion of hardness marked by TeH 79.4% (PeH 20.6%) indicated the deep groundwater sources are in no way devastated by the direct impact of tsunami waves. Every occasion, the data of 210 Day has a zero PeH with highest proportion of TeH; supports the influence of rainwater on groundwater changing the hydrous chemistry causing marked shift in the ion balance.

4.3.12 Sodium

Sodium content of water is most important in describing the quality of a ground water source particularly for domestic consumption. SAR the so-called sodium absorption ratio is a prominent parameter in deciding the specific irrigational applications. In the present study the primary source of sodium and chloride is directly by the tsunami waves in the TADW strata, the core monitoring stations.

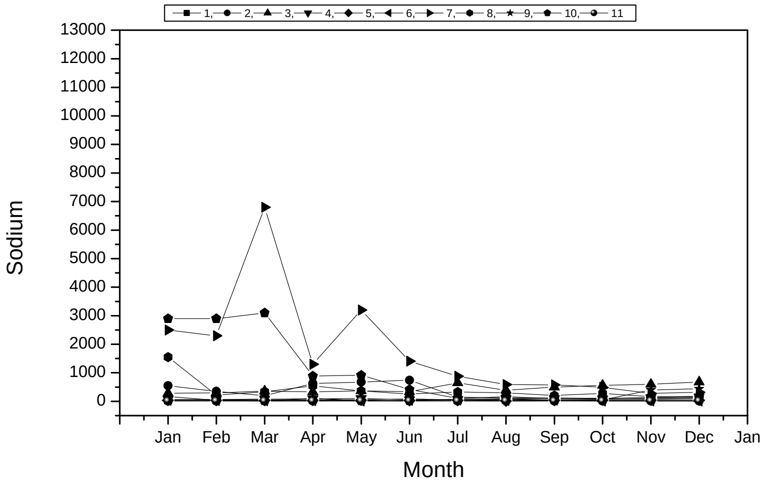

Figure 4.14: Temporal and spatial variation of Sodium at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆),3(▲),4 (▼),7(▶), 8(⬢),9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(⧫) 6 (◀) & 11(⬟) are deep bore wells [BW]; Post tsunamic studies. Concentration of Sodium (mg/l).

While the CW &BW sources have the Na geographical sources / by dilution augmented by rainfall. Sodium effect on ground water is usually expressed in terms of SAR (sodium absorption ratio) to quantify the hydro chemical behavior of water **(**SAR = $Na^+/\sqrt{Ca^{2+}+Mg^{2+}/2}$). SAR of water indicates degree to which Na of water (particularly irrigation water) replaces the adsorbed [Ca^{2+}+Mg^{2+}] in the soil clay structure leading to the enhanced damage of the soil. Salinity hazard (conductivity or TDS) and sodium hazard (SAR) are the prominent characters of irrigation waters.

Graphical feature of Na^+ shown in the Figure 4.14 reflects the fate of sodium ions in the ground water after the tsunami impact. Graphically the trend is more matching with that of conductivity in features but not in magnitude. Just after the tsunami event the level of Na^+ is more quantified as $\overline{x}$(Na^+) 1147±1174 mg/L for the tsunami affected wells (TADW) being the control well have 42mg/L. The deep ground water too seem to be contributing Na^+ level by $\overline{x}$(Na^+) = 27±14 mg/L. This indicates the logic of choosing Na^+ a prominent factor as it here act as a major constituent (> 5mg/L). By

March 2005 (60Day) the tsunami affected dug wells showed highest Na content of 1556±2556 mg/l.

Tsunami brought a well-defined sodium regime in the regional water quality by its never ending presence for many years since the tsunami event. The content dwindle to the minimum level after 90 days (April 2005) with $\overline{\mathrm{x}}(\mathrm{Na}^+)$ = 557±434 mg/L where both control well and deep groundwater sources registered a steady Na^+ regime. Further it exhibits a declining feature over the time after 150D (463±482 mg/l; June 2005) to minimum by 240 day (September, 2005) with $\overline{\mathrm{x}}(\mathrm{Na}^+)$ = 238±213mg/l for TADW, still with a stable Na^+ level BW sources. Na content unequivocally falls to $\overline{\mathrm{x}}$ (Na^+) = 294±204 mg/L once the full circle is about to complete in the twelfth sampling by 330 days (December, 2005) though after 7D it has been 1147±1174mg/l for all tsunami affected dug wells (TADW). Summation of Na content of ground water sources of severely tsunami affected Alappad coast given in Table 4.6.

Table 4.6: Summation of Na content of ground water sources of severely tsunami affected Alappad coast of Kerala, India

Strata	n		3 Jan 2005 (7 Days)	3 July 2005 (180 Days)	3 Dec 2005 (330 Days)	Annual Mean (2005) N=12	Dec 2008 (1430 Days)
Control Well (CW)	1	$\bar{x} \pm \sigma$	42±0	46±0	90±0	62±16	40±0
		μ				62±11	
		CI				51-73	
Tsunami Affected Dug Well (TADW)	5	$\bar{x} \pm \sigma$	1147±1174	323±321	294±204	585±280	115±127
		μ	1147±837	323±229	294±146	585±200	115±91
		CI	310-1984	94-552	148-440	385-785	24-206
Deep Bore well Ground Water (BW)	4	$\bar{x} \pm \sigma$	27±14	31±18	22±17	24±4	41±23
		μ	27±26	31±33	22±31	24±7	41±42
		CI	1-53	2-64	9-53	17-31	1-83
Mean	**10**	$\bar{x} \pm \sigma$	**741±747**	**218±204**	**201±130**	**385±178**	**88±81**
		μ	**741±502**	**218±137**	**201±87**	**385±120**	**88±54**
		CI	**239-1243**	**81-355**	**114-288**	**265-505**	**34-142**

The control well exhibited a distinct feature that Na^+ though registered 42 mg/l just after the tsunami event further slowly but steadily rises over the time as in the form of exponential growth profile. This suggests that the surrounding environment is acting as a source to add Na to the control well region though the location is no way exposed to direct hit- impact of tsunami waves. On comparing the first and last sampling events for control well the Na^+ level increased from 42 mg/L steadily to 90mg/L over the year, passing through a set of natural conditions.

Annual mean of the Na^+ content of strata has been found that $\overline{x}(Na^+)$ =585±280 mg/L for TADW with a $\overline{x}$ (Na^+) = 62±16 mg/L for control well and 24±4 mg/L for deep bore wells. However, the last sampling after fourth year of the tsunami devastation by December 2008 (by 1430 days) has $\overline{x}(Na^+)$ =115±127 mg/L for TADW with a $\overline{x}$ (Na^+) = 40 mg/L for control well and 41±23 mg/L. Since the pre-tsunami data is available with respect to Na^+ it is rational to make impartial judgment whither tsunami brought a direct impact on Na^+ level of the regions ground water (Table 3.1). Pre-tsunamic Na content of the region has been found to be $\overline{x}(Na^+)$ =33±4 mg/L (CI; 29-37 mg/l) for n=5 with four shallow dug wells and a single deep bore well (BW). However the Na data of the monitored shallow dug wells has been in the range of 11-42mg/l below the permissible limit. BW too has a Na content of 46 mg/l it has been safe to any more Na contamination as of the so-called pre-tsunamic situation. Ever since, it is most conclusive based on the data gathered that Na^+ brought by tsunami waves has a regular pulse in defining water quality of the region in the post tsunamic situation to bring about drastic changes in chemistry of the water and the regions environmental quality.

4.3.13 Potassium

The Figure 4.15 shows the fate of potassium ions in the ground water after the tsunami impact on the water sources of the Alappad coast study region. Graphically the trend is more matching with that of sodium in features definitely not in magnitude. Just after the tsunami event the level of K^+ is more quantified as $\overline{x}(K^+)$ 34±32 mg/L for the tsunami affected wells (TADW) being the control well have 9mg/L. The deep ground water too seem to be contributing K^+ level by $\overline{x}(K^+)$ = 7±3 mg/L. This indicates the logic of choosing K^+ a prominent factor as it here act as a minor constituent (0.01-10mg/L). By (60Day) March 2005 the tsunami affected dug wells showed highest K^+ (51 ± 84mg/l) where as the Na content of water this time too is recorded maximum 1556±2556 mg/l. Afterwards the K^+ content of the tsunami affected dug well strata shows a decline in concentration with a minimum of 12±12mg/l in 180 day sampling (July 2005).

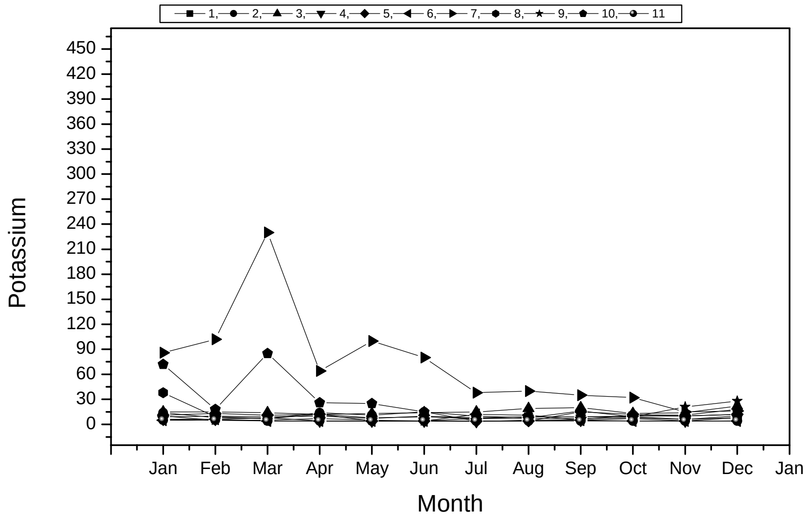

Figure 4.15: Temporal and spatial variation of Potassium at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆),3(▲),4 (▼),7(▶), 8(✱),9(★) & 10(⬟) are tsunami affected dug wells [TADW] badly inundated and stations 5(♦) 6 (◀) & 11(●) are deep bore wells [BW]; Post tsunamic studies. Concentration of Potassium (mg/l).

Tsunami brought a well-defined potassium regime in the regional water quality by its never ending presence for many years since the tsunami event but the amount is less compared to Na. The content dwindles to the minimum level after 60 days (March 2005) with $\overline{x}(K^+)$ from 51±84 to 20± 21mg/L. Whereas both control well and deep groundwater sources registered a steady K^+ regime ranges from 7-12mg/l for control well. Further it exhibits a declining feature over the time after 180D (12±12 mg/l; July 2005) to minimum by 300 day (November, 2005) with $\overline{x}(K^+)$ = 11±16mg/l for TADW, still with a stable K^+ level for BW sources that ranges from 4-8mg/l. K^+ content unequivocally falls to $\overline{x}(K^+)$ = 16±18 mg/L once the full circle is about to complete in the twelfth sampling by 330 days (December, 2005) though after 7D it has been 34±32mg/l for all tsunami affected dug wells (TADW).

Annual mean of the K^+ content of strata has been found that $\overline{x}(K^+)$ =21±9 mg/L for TADW with a $\overline{x}$ (K^+) = 6 mg/L for control well and 10±10 mg/L for deep bore wells. However, the last sampling after fourth year of the tsunami devastation by December 2008 (by 1430 days) has $\overline{x}(K^+)$ =7±6 mg/L for TADW with a $\overline{x}$ (K^+) = 6 mg/L for control well and 10±10 mg/L for the deep bore wells. Since the pre-tsunami data is available with respect to year 2001 (Table 3.1) K^+ of the region is 10±2.5mg/l (CI 7.5 - 12.5) it is rational to think that all the tsunami affected shallow dug wells have tremendous change in the quality by inundation by seawater at all rational to make any impartial judgment whither tsunami brought a direct impact on K^+ level of the regions ground water. Ever since, it is most conclusive based on the data gathered that K^+ has a regular pulse in defining water quality of the region in the post tsunamic situation.

4.3.14 Chloride

The brackish taste of ground water is due to the Cl^- ions or metals combined directly with chloride. Threshold level of chloride in drinking water is 250-500 mg/l and even a high level of 1500 mg/l is not harmful for healthy consumers if there is no alternative sources available. The excess chloride content of the shallow dug wells of the region originates from the inundating giant waves. WHO guidelines suggest that excessive chloride concentrations increase rates of corrosion of metals in the distribution system, depending on the alkalinity of the water leading to a series of issues. This ultimately leads to increased nature of metal pick up concentrations in the supply, like many components of water. However, they propose the fact that chloride concentrations in excess of about 250 mg/liter can give rise to detectable taste in water.

No health-based guideline value is proposed for chloride in drinking-water by the WHO, BIS & KSPCB also very much certain in their directions fixing 250mg/l as the threshold limit. The latest WHO guidelines state that high concentrations of chloride give a salty taste to water and beverages. Taste thresholds for the chloride anion depend on the associated cation and are in the range of 200–300 mg/L for sodium, potassium and calcium chloride (WHO, 2004). Variation of Chloride is represented in Figure 4.16.

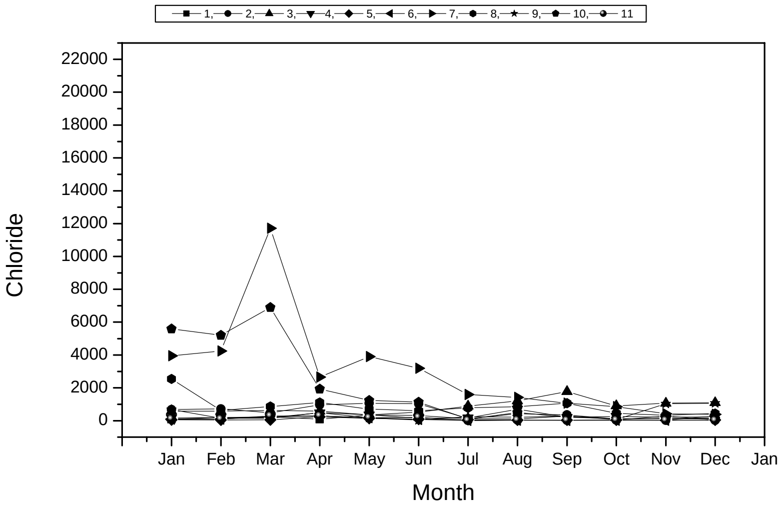

Figure 4.16: Temporal and spatial variation of Chloride at Various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well[CW]; stations 2(◆),3(▲),4 (▼), 7(▶), 8(⬢),9(★) & 10(⬟) are tsunami affected dug wells [TADW]badly inundated and stations 5(♦) 6 (◀) & 11(◐) are deep bore wells [BW]; Post tsunamic studies. Concentration of Chloride (mg/l).

Government of Kerala guidelines for the drinking water (KSPCB, 1997) assures to have a 250 mg/l of chloride as limit for Cl in drinking water with a relaxation allowed (1000 mg/l) if alternative sources are not available. BIS (1999) hold a requirement of 250 mg/l for certification for packaged drinking water. Nevertheless to the Cl control regime by Government directions protect public health examination of Cl content of drinking water sources after tsunami devastation in a vulnerable coastal area could guide us to many of the striking facts of halite contamination and dilution pattern in a post tsunamic situation. Augmentation of replenishment over time and space by hydrodynamics of the region is presented based on the gathered data from three distinct strata of sources.

4.3.15 Control Monitoring Station

This dug well source (station1; Figure 2.2) has a Cl content of 87mg/l just after 26 December 2004 tsunami event (7D, January 2005). The well is located near to the sea on the beach had a Cl of only 42 mg/l and the whole islet region has a Cl of 4.8±4 mg/l in 2001 (Table 3.1). But after 30D (February 2005) the chloride content of this control source shoot up to 193 mg/l and further to 241 mg/l by 60D (March 2005). Again goes to a maximum of 355mg/l exactly by120 days (May 2005) after the disaster. It declines to 320 mg/l by another 30 days (by June 2005) afterwards a decline is observed except for 240 days data(September 2005). A sudden dilution occurs with 177 mg/l by 180 days (July 2005) with the influx of prominent monsoonal dilution. However, it is observed that annual average of Cl of the control well is measured to be of 182±95 mg/l with CI of (87-277 mg/l) for n=12 for 95% significance level. This high jump to the higher edges of the chloride content has been due to the transfer of Cl^- ions from the finer and coarser forms of soil by rainwater showered as outcome of dispersive transport (Achari et al., 2007).

4.3.16 Tsunami Affected Dug Well (TADW)

This prominent strata of stations representative of both severely tsunami affected dug wells and those of dewatered and cleaned (n = 7) showed distinct features. The first sampling (January, 2005) has a mean Cl^- content of $\overline{x}(Cl^-) = 2027 \pm 2078$ mg/L shows the variability among the data as observe that those not subject to any refine process has a very high chloride content; CI is wide 0-4105 mg/l. As we saw it in the case of control station the data after 60 days in this stratum too have a sudden leap with chloride content of 2990±4540 mg/l with a wider CI of 0-7530 mg/l. This definitely support the fact that the regions expansive contamination by sea water. The salt is being kept saturated as halite ions on soil structure in the lean months of January and February exactly over a period of 60 days slowly transported to the groundwater by convective as well as advective way of discharge with a long residence time. April 2005 (1171±828 mg/l) and May 2005 (1114±1289 mg/l) have declined and steady chloride content. Respective steady CI profile at 95% level of significance are 343-

1999 and 0-2403 mg/l indicating dilution by heavy monsoonal dilution leading to a further decline in the following months. Spreads of the data in the remaining period of time indicate continuous replenishment of the groundwater against the heavy dose of chloride transported by heavy tsunami waves.

The augmentation of chloride replenishment becomes more prominent by a period of 330 days (December, 2005) to reach a level of 495±419 mg/l with a range value of 96-914 mg/l. Annual mean $\overline{x}(Cl^-)$ =1110±488 mg/L observed for 12 monthly sampling event for the tsunami affected dug wells has a CI of 612-1598 mg/l (n = 7). This clearly indicate that a chloride removal mechanism is active in the local tsunami hit region in regards to the chloride content measured first; that is sampling done 7 days after tsunami (2027±2078 mg/l). The chloride content in many of the surface water source dug wells on Tamilnadu coast after tsunami has been very high and above 7000 mg/l (Palanivelu, 2006). The chloride content on the strata of dug wells reported on Kerala coast could have been otherwise much higher if the wells were not dewatered and cleaned by the affected people within days of the impact. The coastal stretch felt severe drinking water shortage quickly after the tsunami hazard. Hardly there left any functioning road connectivity to bring water from distance by quick response system, power failures disrupted deep groundwater distribution maintained by the government agencies. The added agony of this magnitude prompted them to depend the existing source for drawing water after adopting quick cleaning procedures to remove the salinity.

The continuous monitoring of the dug well sources over period of time after completing a full circle in year 2005 the sampling repeated after 1430 days in December 2008. The results have been providing a set of new insight into the hydrochemistry of the region. The chloride content further declined to $\overline{x}(Cl^-)$ =148±288 mg/L with CI of 0-436 mg/l. The control well that has chloride content of 87 mg/l just after the tsunami event in January 2005 (7D) has 145 mg/l in December 2005 (330 D) and in December 2008 (1430D) has 48 mg/l. This further proves that the chloride removal mechanism active in a tsunami devastated region has many remarkable complexities to be answered by proper scientific judgments over years of rigorous monitoring effort.

4.3.17 Deep Ground Water (BW)

Like control well and unlike the tsunami affected dug wells (TADW), the deep ground water sources has a constant and steady Cl^- level (83±30 mg/l) at a time tsunami hit the region measured after 7 days (7D) in January, 2005 and it remained 81±31 mg/l even after 30 days. The respective levels for the control wells have been 87 and 193 mg/l for the above time interval against the TADW strata of samples measured as 2027±2078 mg/l and 1674±2114 mg/l measured in the same time. This indicates that the deep ground water is stable and is not directly been influenced by the tsunami impact for a distorted ionic imbalance.

Table 4.7: Summation of Chloride content of ground water sources of severely tsunami devastated Alappad coast of Kerala, India

Strata	n		3 Jan 2005 (7 Days)	3 July 2005 (180 Days)	3 Dec 2005 (330 Days)	Annual Mean (2005)	Dec 2008 (1430Days)
Control Well (CW)	1	$\bar{x} \pm \sigma$	87±0	117±0	145±0	182±95	48±0
		μ				182±61	
		CI				87-277	
Tsunami Affected Dug Well (TADW)	7	$\bar{x} \pm \sigma$	2027±2078	558±560	495±419	110±488	148±288
		μ	2027±1482	558±399	495±299	1110±348	148±205
		CI	545-3509	159-957	196±794	762-1458	57-436
Deep Bore well Ground Water (BW)	3	$\bar{x} \pm \sigma$	83±30	32±29	115±144	106±22	11±4
		μ	83±55	32±53	115±265	106±40	11±7
		CI	28-138	21-85	150-380	66-146	4-18
Mean	11	$\bar{x} \pm \sigma$	1320±1322	375±356	360±270	752±311	102±183
		μ	1320±888	375±239	360±181	752±209	102±123
		CI	432-2208	136-614	179-541	543-961	21-225

In the following period of time chloride content rises to 193±128 mg/l (60D March 2005) and moves up to a maximum of 273±28 mg/l within 90 days (April 2005) afterwards declines to 165±20 mg/l in May 2005. This rise of chloride content in respect of time could be decided by two factors. The chloride ions bound by soil saturated by seawater may have been finding its way to deep aquifer zones by a cone of depression mechanism during unrestricted pumping as excessive over exploitation by short time faced with fresh water shortage in the aftermath of the tragedy. The rapid corrosion of the casing material by excess salt content brought by tsunami material in the post tsunamic period might have perforated the already degraded metal surface to allow the seepage of excess ions washed by summer rain. Summation of Chloride content of ground water sources of Alappad coast is given in Table 4.7.

A third observation is that many locations with slope and depressions (such as swamps, pools and discarded and unused water sources) are pooled up with stagnant tsunami bound flood water remained over months has a good role in degrading the local soil environment and initiating a different corrosion kinetic in the case of drinking water sources, storage and distribution systems. Collected stagnant water rich in salt water may be slowly in filtered into the groundwater reserve through crevices of the casings.

The intense dilution occurred in the first two strata of sampling stations during active monsoon months of June, July, August and September registered a lowest Cl^- level (124±75, 32±29, 33±4 and 25±9 mg/l respectively) indicates that rain water grazes to deep ground water source by an indirect mechanism mentioned above. After this time (by 20days) the Cl level slowly rises to 15±144 mg/l in December 2005 (by 330 days) in common to features exhibited by former stations stratified as CW and TADW. This indicates that critical observations are unavoidably prominent in deciding the overall quality of the regions ground water.

4.4 Water Quality Index (WQI)

The worst hit tsunami area of Kerala – the Alappad and Arattupuzha narrow coastal strip, is precariously perched between a mesohaline estuary and the sea. It is endowed with a good reserve of fresh water, primarily because of the flat topography and the highly porous nature of the sandy soil- both factors contribute to easy recharging that ultimately makes up for the ground water pumped out in millions of litres for various utilities.

Table 4.8: Water quality parameters for WQI calculation in the month of January 2005 Alappad. Source specifications: See Table 4. 1

Stn	Temp. ^{0}C	pH	DO (mg/L)	Cl (mg/L)	PO$_4$ (μg/ L)	E.Coli (Mpn/100 ml)	BOD (mg/L)	Turbidity NTU	NO$_3$ (μg/ L)
1	29.2	7.9	3.9	87	231	120	7.3	5.1	1708
2	27.0	7.2	3.0	675	251	75	9.0	91.8	2563
3	27.0	8.4	2.0	578	BDL	93	3.4	2.2	5267
4	30.0	7.4	3.4	168	BDL	150	11.4	BDL	1826
5	31.7	7.9	3.7	48	BDL	12	8.7	0.4	12223
6	27.3	8.4	2.2	96	BDL	290	9.5	36.0	2427
7	27.4	8.5	3.2	3953	125	150	2.8	2.9	7201
8	28.9	7.5	3.9	2546	292	210	7.0	17.6	5433
9	28.0	8.1	7.0	675	413	75	2.2	11.6	2429
10	29.0	8.0	8.5	5594	136	160	10.0	2.4	1967
11	28.9	7.8	BDL	104	125	21	1.8	2.9	2293

It was in fact, this subterranean fresh water reservoir that to some extent diluted away the accumulated salts left behind by the tsunami waves thereby moderating the environmental trauma which would otherwise have been much more severe and long standing. The Water Quality Index uses a scale from 0 to 100 to rate the quality of the water, with 100 being the highest possible score. The indices reflect the comprehensive environmental quality of the water bodies in the light of the significant quality parameters.

Except for control and ground water sample, there was substantial temporal variation in WQI for all affected dug well sources (Table: 4.8). It is revealing that, both control and ground water samples had more or less stable quality status all through the sampling period indicating that seasonal environmental quality variation is not pronounced in these cases. As it is for sampling station 6, though a ground water source had been undergoing overall quality degradation across time indicating that the reservoir is steadily being deteriorated in quality. This exacerbation can be entirely on account of tsunami and the subsequent subterranean contacts with organic waste leached in the flooded seawater.

Station 5, which is close by, on the other hand exhibited a tendency for gradual amelioration in quality, but it is deep ground water (600 feet) whereas as station 6 water was mined from a depth of 300 feet anaerobic and iron rich. Sampling station 9, one of the oldest wells in the region dug in 1913, also registered a declining tendency across time as it is well cared by the house owner. The facts reflect that the tsunami induced concomitant accumulation and deterioration of the quality of the fresh water system. Sampling station 8 also followed the same pattern, as it had concomitant environmental conditions. It is clear that for sampling sites that was dewatered and cleaned time and time again, the water quality indices remained more or less stable.

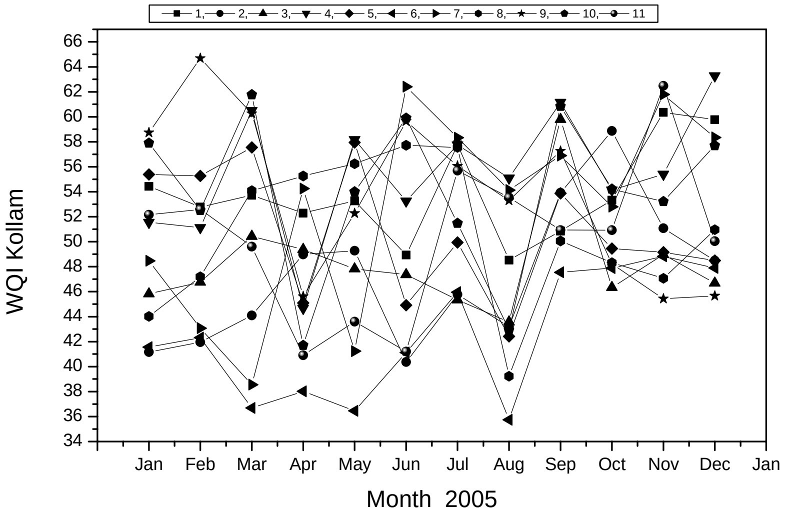

Figure 4.17: Temporal and spatial variation of Water Quality Index (WQI) at various sampling stations along Alappad coast (Kollam, Kerala) during 2005. Station 1(■) is the control well [CW]; stations 2(◆), 3(▲),4 (▼),7(▶), 8(⬢),9(★) & 10(⬟) are tsunami affected shallow dug wells [TADW]badly inundated and stations 5(♦) 6 (◀) & 11(⬟) are deep bore wells [BW]; Post tsunamic studies.

4.4.1 Water Quality Index (WQI) of Control Well

Variation of WQI shown in the Figure 4.17 reflects the water quality situation in the regions ground water after the tsunami impact. Graphically the trend is more fluctuating with many features reported in magnitude. WQI is inseparably connected to the chemical, physical and biological activity of the hydro geological system. Just after the tsunami event the WQI level is more quantified as $\overline{x}$(WQI) = 50±5 for the tsunami affected wells (TADW) being the control well have WQI 54. The deep ground water too seem to be contributing WQI level by $\overline{x}$(WQI) = 50±13. This indicates the logic of choosing WQI as a prominent factor to obtain a gross composition of water.

4.4.2 Tsunami Affected Dug Wells (TADW)

Tsunami high waves brought a well - defined WQI regime in the regional water quality by its never ending presence of extra ionic concentrations for many years since the disastrous event. The content dwindle to the minimum level after 90 days (April 2005) with $\bar{x}$(WQI) = 49±5 where both control well and deep groundwater sources registered a lower WQI value of 52 and 41±4 respectively. Further it gains to maximum by 150 days (June, 2005) with $\bar{x}$(WQI) = 54±6 for TADW, still with a level of 49 for control well and 42±4 for BW sources.

Table 4.9: Summation of Water Quality Index (WQI) of ground water sources of severely tsunami devastated Alappad coast of Kerala, India. Scale: 91- 100 (Excellent water quality), 71-90 (Good water quality), 51-70 (Medium or average water quality), 26- 50 (Fair water quality), 25 (poor water quality).

Strata	**n**	**t-test**	**3 Jan 2005 (7 Days)**	**3 June 2005 (180 Days)**	**3 Dec 2005 (330 Days)**	**Annual Mean (2005) N=12**	**Dec 2008 (1430 Days)**
Control Well (CW)	1	$\bar{x} \pm \sigma$	54±0	49±0	60±0	54±4	54±0
		µ				54±3	
		CI				51-57	
Tsunami Affected Dug Well (TADW)	5	$\bar{x} \pm \sigma$	50±7	54±8	53±7	52±2	57±6
		µ	50±5	54±6	53±5	52±1	57±4
		CI	45-55	48-60	48-58	51-53	53-61
Deep Bore well Ground Water (BW)	4	$\bar{x} \pm \sigma$	50±7	42±2	49±1	44±2	50±3
		µ	50±13	42±4	49±2	44±4	50±6
		CI	37-63	38-46	47-51	40-48	44-56
Mean	**10**	$\bar{x} \pm \sigma$	**50±5**	**50±5**	**53±5**	**50±1**	**55±4**
		µ	**50±3**	**50±3**	**53±3**	**50±2**	**55±3**
		CI	**47-53**	**47-53**	**50-56**	**48-52**	**52-58**

It is further observed that quality index remained $\bar{x}$(WQI) = 53±5 by 330 days (Dec, 2005) even after a time initiated improvement for all tsunami affected dug wells (TADW) has been expected. Rise to maximum WQI was observed once the full circle is about to complete in the twelfth sampling of 330 days with $\bar{x}$(WQI) = 60 for control well. On comparing the first and last sampling events the WQI level improved only to a less extent; from 50±5 to 53±5 for TADW over one year period, passing through a set of natural conditions. The deep ground water kept a stable character the entire period with WQI 50±7 and 49±1 respectively for the first and last sampling. However, the last sampling after fourth year of the tsunami devastation by December 2008 (by 1430 days) has $\overline{x}$(WQI) = 57±4 for TADW with a $\overline{x}$(WQI) = 54 for control well and 50±6.

The stable behavior of the deep ground water sources with respect to WQI (Table 4.9) and quality improvement of the severely damaged dug well sources (TADW) reveals is a slow process takes months to years for a better WQI change from 50±5 to 57±4.

Slow and the steady improvement of the WQI of tsunami affected dug wells over a period of time and the influence of the rainwater dilution indicates that there is marked difference in the overall quality of the water after tsunami impact. Mostly, the post tsunami WQI data had been in the range of 26-50 (Fair water quality), throughout the year irrespective of strata studied. Over the time the quality of even the control well and bore well too declining because of the nutrient and ionic enrichment from the contaminated tsunami lagoons as well as of leaching from chemically saturated soils particularly heavy mineral-rich deposit of the region. The passage of time have not brought any refinement on the quality of water in deep bore well strata as evidenced by the table.

However a slow refinement occurs as it is evidence by the 1430 day data ; that the almost all strata had a more quality profile decide as 51-70 (Medium or average water quality) range. The study of water quality glimpses out the extent of quality degradation brought about by the tsunami impact on ground water hence the limitation of the natural hydro geochemical system to improve over the sudden ionic equilibrium constraints. The pre-tsunami data is not available with respect to WQI but it does not restrict the rational to make impartial judgment that tsunami brought a direct impact on WQI level of the regions ground water. Ever since, it is most conclusive based on the data gathered that WQI has an irregular pulse in defining water quality of the region because the regions hydro geochemistry had dramatically changed a lot after the impact.

4.5 Sodium - Chloride Ratio

4.5.1 Control Well

The evaluation of the ground water has been made with respect to the ratio of Na and Cl in the three distinct strata of ground water analyzed to check what phenomena governs the ratio. The analysis of the data of control source well in all sampling occasion reveals that the $\frac{Na^+}{Na^+ + Cl^-}$ <0.5 indicate the contamination by seawater. The annual mean 0.28±0.09 of the results (Table 4.10) further confirms that the entire cycle of cleaning, recharging and monsoonal dilution does not change the original behavior of this representative water source. The ionic ratio Na^+/Cl^- over the entire period of post tsunamic situation retains a mean of 0.42±0.18 is an indication of reverse softening by seawater (Hounslow, 1995).

Table 4.10: Na^+ / Cl^- ionic ratio and probable inferences regarding ground water quality of a tsunami devastated Alappad region (situation existed after 26 December, 2004 tsunami event); Control Well.

Period	Day	EC	TDS	$\frac{Na}{Na+Cl}$	$\frac{Na}{Cl}$	Inference
Jan 05	07D	570	836	0.33	0.48	Reverse Softening
Feb05	30D	800	1259	0.23	0.30	Reverse Softening
Mar05	60D	800	970	0.18	0.22	Reverse Softening
Apr05	90D	630	661	0.40	0.67	Reverse Softening
May05	120D	690	861	0.14	0.16	Reverse Softening
Jun05	150D	900	960	0.22	0.28	Reverse Softening
Jul05	180D	540	644	0.28	0.39	Reverse Softening
Aug05	210D	700	589	0.33	0.49	Reverse Softening
Sep05	240D	1100	768	0.16	0.19	Reverse Softening
Oct05	270D	310	668	0.39	0.63	Reverse Softening
Nov05	300D	1080	794	0.35	0.54	Reverse Softening
Dec05	330D	1900	845	0.38	0.62	Reverse Softening
$\bar{X}_{\pm\sigma}$		**840±400**	**821±184**	**0.28±0.09**	**0.42±0.18**	**Reverse Softening**
C.I		**440-1240**	**637-1005**	**0.01-0.37**	**0.24-0.60**	**Reverse Softening**
Dec08	1430D	**300**	**456**	**0.46**	**0.84**	**Reverse Softening**

The computed ionic concentration of the ground water in the pre-tsunami situation ie; the mean ($Na^+ / Na^+ + Cl^-$) for the known five stations consisting of so-called control dug well (station 1) of this dug well source as well as the lone member of the strata control well has 0.52 and Na^+ / Cl^- has 1.12 indicate the situation of ion exchange. That is the more and more Na is released to the water from clay by exchanging Ca ions from the ground water. But the gross nature of the region in a time (2001) before tsunami occurred on 26 December 2004 has been characterized by existence of reverse softening (reverse ion exchange) in presence of seawater characterized by ($Na^+/Na^+ + Cl^-$) = 0.47 (< 0.5) indicates the prominence. The sodium to chloride ratio Na^+ / Cl^- = 0.89 (<1.0 indicate reverse softening in presence of seawater) [$Na^+/Na^+ + Cl^-$ >0.50 (ion exchange) and Na^+ / Cl^- >1.0 (ion exchange or softening)] as reported by Hounslow (1995).

After 1430 days after the tsunami the tendency becomes less prominent as revealed by $Na^+/Na^+ + Cl^-$) = 0.46 and Na^+ / Cl^- = 0.84 but the reverse softening is still existing as it is not crossed the limit of 0.5 and 1.0 respectively for the above ratio.

4.5.2 Tsunami Affected Dug Well (TADW)

The ionic ratio of the ground water from TADW strata has been made to check what phenomena govern the ratio. The analysis of the data of tsunami affected dug well in all sampling occasion reveals that the $\frac{\mathrm{Na}^+}{\mathrm{Na}^+ + \mathrm{Cl}^-}$ <0.5 indicate the contamination by seawater. The annual mean 0.34±0.05 of the results (Table 4.11) further confirms that the attempt of cleaning, recharging and monsoonal dilution does not change the original behavior of the all the tsunami inundated dug well water sources of the islet of Alappad coast. The expansive inundation by seawater altered the character significantly as evidenced by a sudden change from 0.47 ratio in 2001 to 0.34 in 2005. The ionic ratio Na^+/Cl^- over the entire period of post tsunamic situation retains a mean of 0.52±0.11 is an indication of reverse softening by seawater (Hounslow, 1995).

1430 days after the tsunami the tendency of the ground water for reverse softening becomes less prominent as revealed by $Na^+/Na^+ + Cl^-$) = 0.44 and Na^+ / Cl^- = 0.77 but the reverse softening is still existing as it has not crossed the limit of 0.5 and 1.0 respectively for the above ionic ratio.

Table 4.11: Na^{+} / Cl^{-} ionic ratio and probable inferences regarding ground water quality of a tsunami devastated Alappad region (situation existed after 26 December, 2004 tsunami event); TADW.

Period	**Day**	**EC**	**TDS**	$\frac{\mathrm{Na}}{\mathrm{Na}+\mathrm{Cl}}$	$\frac{\mathrm{Na}}{\mathrm{Cl}}$	**Inference**
Jan 05	07D	7960	6045	0.36	0.57	Reverse Softening
Feb05	30D	4740	4905	0.35	0.53	Reverse Softening
Mar05	60D	10470	7859	0.34	0.52	Reverse Softening
Apr05	90d	3870	3278	0.32	0.48	Reverse Softening
May05	120D	4500	3469	0.42	0.73	Reverse Softening
Jun05	150D	3320	2451	0.33	0.49	Reverse Softening
Jul05	180D	2080	1939	0.37	0.58	Reverse Softening
Aug05	210D	2130	2007	0.25	0.33	Reverse Softening
Sep05	240D	1060	1883	0.25	0.34	Reverse Softening
Oct05	270D	860	1475	0.38	0.61	Reverse Softening
Nov05	300D	2740	1766	0.35	0.55	Reverse Softening
Dec05	330D	2380	1953	0.37	0.59	Reverse Softening
$\overline{\mathrm{X}} \pm \sigma$		**3840±2830**	**3252±2015**	**0.34±0.05**	**0.52±0.11**	**Reverse Softening**
C.I		**1010-6678**	**1237-5267**	**0.29-0.39**	**0.41- 0.63**	**Reverse Softening**
Dec 08	**1430 D**	**900**	**732**	**0.44**	**0.77**	**Reverse Softening**

4.5.3 Bore Wells

This Na and Cl ionic ratio of the deep ground water has been analyzed to check what phenomena govern the ratio over a period of time after the tsunami inundation. The analysis of the data of control source well in all sampling occasions reveals that the $\frac{\mathrm{Na}^{+}}{\mathrm{Na}^{+}+\mathrm{Cl}^{-}}$ <0.5 indicate the contamination by seawater devastated the deep ground water sources.

Table 4.12: Na^+ / Cl^- ionic ratio and probable inferences regarding ground water quality of a tsunami devastated Alappad region (situation existed after 26 December, 2004 tsunami event); Bore Well.

Period	Day	EC	TDS	$\frac{Na}{Na + Cl}$	$\frac{Na}{Cl}$	Inference
Jan 05	07D	467	2109	0.25	0.33	Reverse Softening
Feb05	30D	420	2258	0.24	0.32	Reverse Softening
Mar05	60D	730	1282	0.10	0.11	Reverse Softening
Apr05	90D	513	1138	0.08	0.09	Reverse Softening
May05	120D	550	2087	0.13	0.14	Reverse Softening
Jun05	150D	613	1808	0.17	0.21	Reverse Softening
Jul05	180D	637	740	0.49	0.96	Reverse Softening
Aug05	210D	493	696	0.33	0.49	Reverse Softening
Sep05	240D	1053	762	0.54	1.15	Ion Exchange/ Natural Softening
Oct05	270D	693	659	0.37	0.60	Reverse Softening
Nov05	300D	673	708	0.16	0.20	Reverse Softening
Dec05	330D	640	708	0.6	0.19	Reverse Softening
$\bar{X} \pm \sigma$		**624±166**	**1246±641**	**0.25±0.15**	**0.4±0.34**	**Reverse Softening**
C.I.		**458 – 790**	**605-1887**	**0.019-0.37**	**0.06-0.74**	**Reverse Softening**
Dec08	**1430D**	**0.233**	**439**	**0.79**	**3.75**	**Ion Exchange/ Natural Softening**

How it happened is not clear as it goes to the prevailing assumption that the excessive salt might have degenerated already disintegrated metal casings of the bore wells that leads to percolation of the foreign ions brought by tsunami waves. The annual mean 0.25±0.15 of the results (Table 4.12) further confirms that the entire cycle of cleaning, recharging and monsoonal dilution does not change to retain the original behavior of this strata of water source as it has the ionic ratio Na^+/Cl^- over the entire period of post tsunamic situation retains a mean of 0.40±0.34 is an indication of reverse softening by seawater (Hounslow, 1995).

During December 2008, 1430 days after the tsunami the tendency of the ground water for reverse softening becomes less prominent as revealed by $Na^+ / Na^+ + Cl^-$) = 0.74 and Na^+ / Cl^- = 3.75. Once we consider these values undoubtedly we can say that the deep ground water has a strong tendency towards ion exchange after tsunami event over a period of time.

4.6 Piper Plots and Water Quality Evaluation

Piper diagrams of the Alappad region have been constructed with respect to three distinct strata of ground water sources, control well, tsunami affected dug well and deep bore well for over more than one year to ascertain the variation of the quality with respect to time. Piper diagrams (Piper, 1944) are a mathematical construct of two triangles that are supposed to share a common base line and each side are separated by an angular distance of 60^o apart.

The two triangles are interlocked by a diamond cut design shaped graph to contain reported values of the data (ionic concentrations) as circles. As it is well known that the area of this graph is proportional to TDS. The data position on Piper diagrams are really finger print information to reach tentative conclusions; origin of the water and its character in particular. Basically, Piper diagrams provide very valuable knowledge on the water type, precipitation or solution behavior, mixing character and ion exchange phenomena.

In this analyses of the data individual analysis are marked and trends are interpreted as an expression of the solution behavior and the graph is a singular representation of ionic character and fate of water under a set of specific conditions. In obtaining the chemical trends all analytical observations are presented as points in one diagram.

4.6.1 Control Well

The data given in the Table 3.1 is the gross composition of the ground water quality parameter of the Alappad- Arattupuzha region in the year 2001 and the sources are mainly dug wells (mean depth 2.0m) except the station No.4 which is a deep bore well with (depth 75.0m) to have a better picture of the existing ground water quality of the coastal region before the striking of the tsunami waves occurred on 26 December, 2004. Piper diagrams (Figure 3.1) have been constructed for the control well using the data available for the pre-tsunamic situation in 2001 and are favorably discussed.

Table 4.13: Classification of water according to Hill – Piper – Trilinear Plot.

Strata	1^{st} Triangle	2^{nd} Triangle	Interpretation	Remarks
Control 2001	No Specific Apex	Chloride Apex	Brine contamination	Reverse softening
Control Jan 05	No Specific Apex	No Specific Apex	No component at the corner of the triangle, that means no component is being added or removed	
Control 2005 combined and 2008	No Specific Apex	No Specific Apex	No component at the corner of the triangle, that means no component is being added or removed	Slightly saline
TADW Jan 05	Na apex	Cl apex	Halite solution	
TADW June 2005	Na apex	Cl apex	Halite solution	Saline
TADW July 2005	Slightly Na apex	Slightly Cl apex		Saline
TADW Dec 2005	Slightly Na apex	Slightly Cl apex		Saline
TADW Dec 2008	Slightly Na apex	Slightly Cl apex		Saline
BW Jan 2005	Slightly Na apex	Slightly Cl apex		
BW June 2005	Ca apex	HCO_3 apex	Calcite solution	
BW July 2005	Ca apex	HCO_3 apex	Calcite solution	
BW Dec 2005	Ca apex	HCO_3 apex	Calcite solution	
BW Dec 2008	Ca apex	HCO_3 apex	Calcite solution	

In most ground water analyses the accuracy of the determinations are focused to find any unusual ionic concentrations of the water. The ground water optimal in quality to be used as drinking water in many regions are originated from aquifers made of sand stone associated with some extent of carbonate cement, limestone or dolomite, glacial or till granitic rock. The Alappad coast the dug well sources are very shallow and the aquifer is consisting of ilmenite rich black sand and dolomitic components. Every time the glimpses on the concentration of evaluated ions will give an overview of the hydrochemistry of the groundwater and this in turn alert to avoid the probable inaccuracies of the investigations. The analysis of the diagram for control well in 2001 shows that the first triangle has a Na apex and second triangle has a prominent Cl apex. The diamond structure has data near the right hand side diagram typical for water with a specific nature for saline ($Na^+ + K^+$ and $Cl^- + SO_4^{2-}$). This shows that the water existed there with saline behavior in pre-tsunamic situation.

The control well just after tsunami in January 2005 has an ionic behavior shown by the above graph with no specific apex for the cation and anion triangle. The diamond has no data in the prominent location enough to categorize the water quality (Table 4.13).

The source is very distinct in behavior though it is placed in tsunami devastated location in no way it was directly inundated. Hill – Piper diagram reveals the unique character of no component at the corner of the triangle, which means no component is being added or removed. The station is not exhibiting any special character after the tsunamic event.

The critical evaluation of the results in the pre-tsunamic and post tsunamic situation reveals the common geographical pattern of the ionic behavior that Na >> K that potassium is rapidly assimilated in the ground water and the additional input of the Na is none other than the outcome of tsunami inundation of the shallow aquifers.Ca> = Mg behavior is elaborately evaluated for the entire section of the dug well sources being the major source of excessive calcium in the ground water has been the addition load by tsunamic waves.

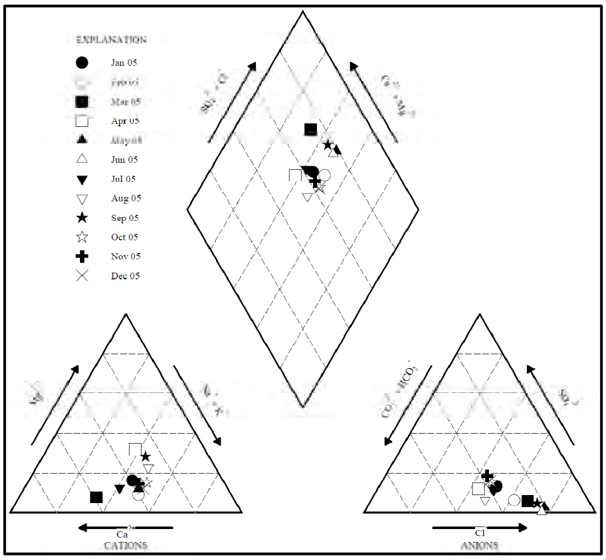

Figure 4.18: Hill Piper Trilinear diagrams of the tsunami affected control dug well Alappad coast in the post tsunamic year 2005. The control station were not directly inundated by tsunami waves on 26December, 2004, but it is located in the same region with a good history of serving as a perennial source of drinking water located as a temple well near to the shoreline.

The behaviors of this water source have been evaluated for the entire post tsunamic situation and spread of the data have been shown in the Figure 4.18. It is found that the figure has no specific apex for the cationic triangle that almost a stable cationic character is retained.

The anionic triangle too has the same character with slight tendency to move to chloride apex in certain months. However the diamond has distinct saline behavior. This shows that the control well maintains a stable saline character over the entire sampling period.

The Hill- Piper diagrams for the selected months including December 2008 have been shown in the Figure 4.19. The water has a tendency to retain saline character which may be due to the closeness to the sea. The calculation of Na/Cl ratio already shown that reverse softening in presence of seawater has been the active phenomenon occurs to control the ionic balance.

The region is specific with an appreciable extent of Ca even in the pre-tsunamic situation which may be the characteristic composition of the aquifer having heavy minerals and sedimentary carbonates.

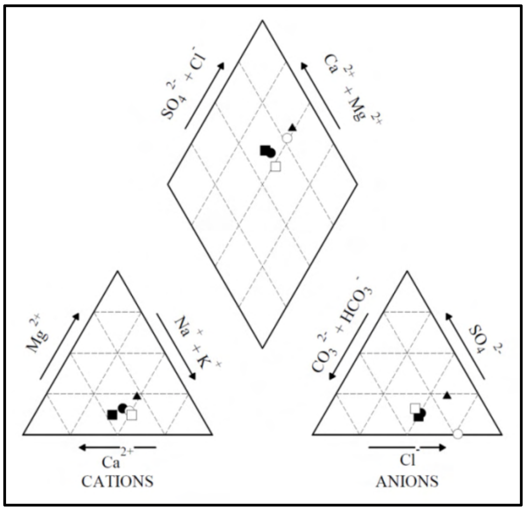

Figure 4.19: Hill Piper Trilinear diagrams of the tsunami affected control dug well Alappad coast in the post tsunamic year 2005 & December 2008. The control station were not directly inundated by tsunami waves on 26December, 2004, but it is located in the same region with a good history of serving as a perennial source of drinking water located as a temple well near to the shoreline. Symbols: 1 (●) Jan2005, (○) June 2005, 3 (■) July 2005, 4(□) December 2005 & 5 (▲) December 2008

The monthly profile of the ionic composition of calcium and sulphate revealed that Ca $\geq$ SO_4 in most situations for the three strata of dug well sources: control well, tsunami affected dug well sources as well as the deep bore well sources. The main concern in these analyses is the behavior of sodium and chloride as the research is mainly focused to come up with systematic observation of Na and Cl behavior of the ground water sources after the devastating tsunamic devastation.

4.6.2 Tsunami Affected Dug Well (TADW)

The analysis of the diagram for the strata TADW shows that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph constructed for the post tsunami period of January, 2005 after seven days (Figure 4.20). The diamond structure has data near the right hand side diagram typical for water with a specific nature for saline (Na^+ + K^+ and Cl^- + SO_4^{2-}). This shows that the water existed there with saline behavior in pre-tsunamic situation. The water has distinct saline character with Na 75%, Ca 15% and Mg 10% and Chloride has 85% , $SO_4^{2-}$is 1% and CO_3^{2-} and HCO_3^{2-} is 14%, the extra ions were brought about indeed by tsunami waves.

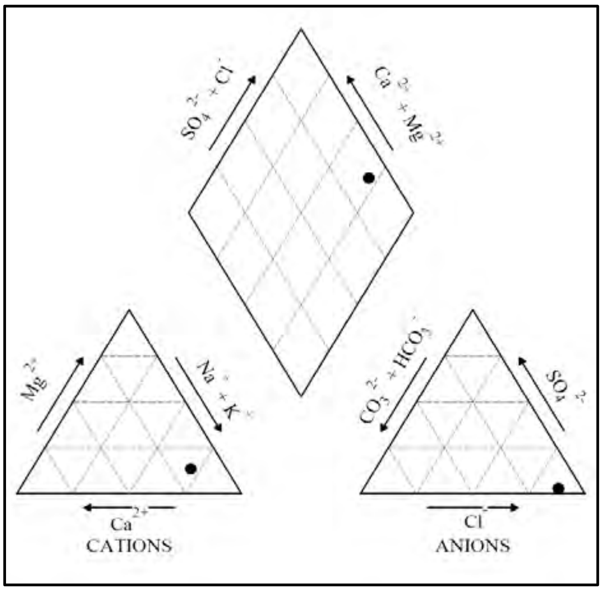

Figure 4.20: Hill Piper Trilinear diagrams of the 26 December, 2004 tsunami affected dug wells strata (mean of 7 TADW stations) Alappad coast seven days after tsunami in January 2005.

The analysis of the diagram (Figure 4.21) for the water shows that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph plotted for post tsunami period of 150 days (June 2005). The diamond structure has data near the right hand side diagram typical for water with a specific nature for saline ($Na^+ + K^+$ and $Cl^- + SO_4^{2-}$).

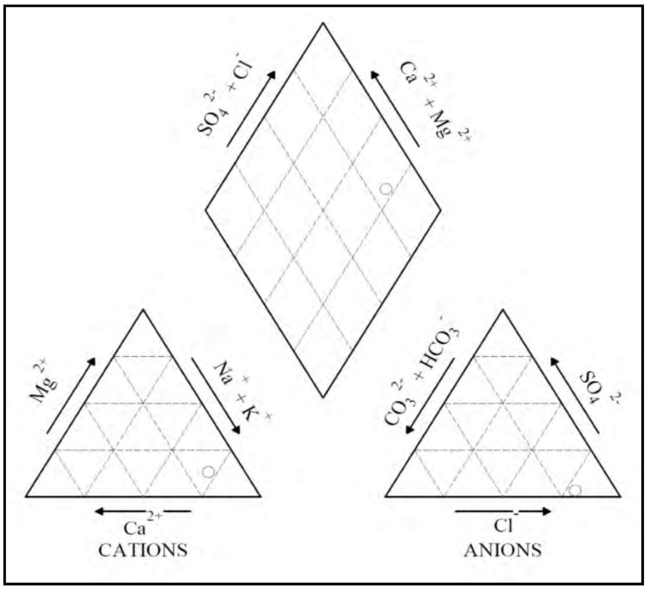

Figure 4.21: Hill Piper Trilinear diagrams of the tsunami affected dug wells strata (mean of 7 stations) Alappad coast in June 2005. All stations were inundated by tsunami waves on 26December, 2004.

The Piper plots of the tsunami affected dug wells of the region in the post monsoon period, the region experienced intense dilution by ground water augmented by the intense monsoon has the features shown in the figure. Saline behavior is retained as regards to the position in the diamond shape.

First triangle has a specific Na apex and second triangle has a chloride apex. But the water is saline with Na has 73%, Ca 15% and Mg 12% and Chloride has 80% , $SO_4^{2-}$is 1% and CO_3^{2-} and HCO_3^{2-} is 19% . The dilution brought about by the monsoon declined the chloride content by 5%.

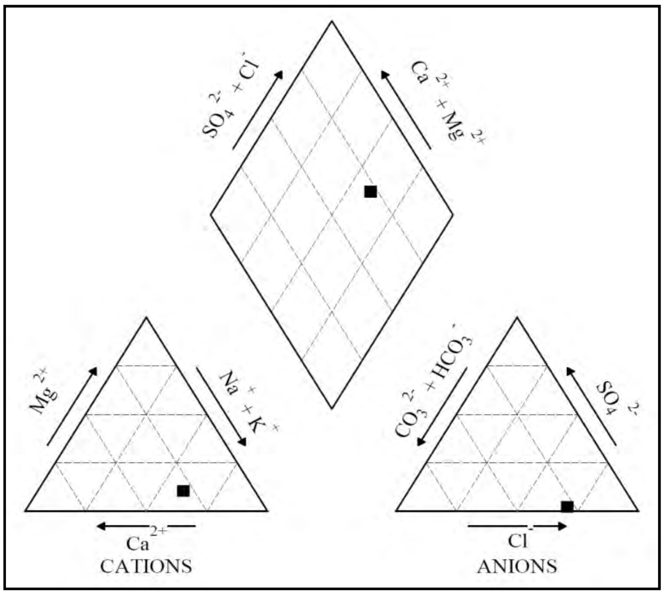

Figure 4.22: Hill Piper Trilinear diagrams of the tsunami affected dug wells strata (mean of 7 stations) Alappad coast in July 2005. All stations were inundated by tsunami waves on 26December, 2004.

Analysis of the Piper diagram for the strata TADW in the subsequent month of July 2005 (after 180 days since the tsunami event and when the monsoon becomes more prominent). Figure 4.22 shows that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph with less respective ionic contributions. The diamond structure has data near the right hand side of the diagram typical for water with a specific nature for less saline (Na^+ + K^+ and Cl^- + SO_4^{2-}) character. But not prominent enough to that existed in the preceding months. Slow, but definite replenishment is being initiated by the ground water dilution brought about by the rainwater.

First triangle has a specific Na apex and second triangle has a chloride apex. But the water is saline with Na has 58%, Ca 30% and Mg 12% and Chloride has 72% , $SO_4^{2-}$is 1% and CO_3^{2-} and HCO_3^{2-} is 27% . The dilution brought about by the monsoon declined the chloride content by another 8%.

The analysis of the Piper diagram for the strata TADW (Figure 4.23) shows that the first triangle has a distinct Na apex and second triangle has a pronounce Cl apex for the graph plotted for the December, 2005. The diamond structure has data near the right hand side of the diagram typical for water with a specific nature for saline ($Na^+ + K^+$ and $Cl^- + SO_4^{2-}$). But the water is saline with Na has 60%, Ca 25% and Mg 15% and Chloride has 60% , $SO_4^{2-}$is 8% and CO_3^{2-} and HCO_3^{2-} is 32% .

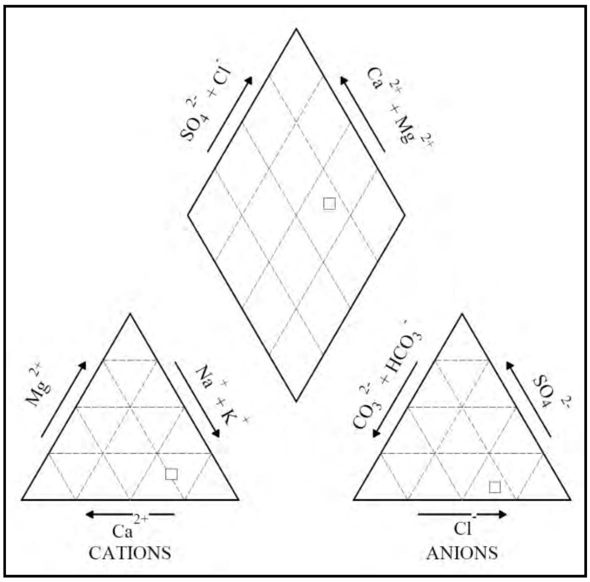

Figure 4.23: Hill Piper Trilinear diagrams of the tsunami affected dug wells strata (mean of 7 stations) Alappad coast in December 2005. All stations were inundated by tsunami waves on 26 December, 2004.

The analysis of the Piper diagram for the strata TADW for the entire post tsunamic period for the dug well strata of stations for the year 2005 (Figure 4.24) has been made and is shown that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph. The diamond structure has data near the right hand side of the diagram typical for water with a specific nature for saline ($Na^+ + K^+$ and $Cl^- + SO_4^{2-}$).

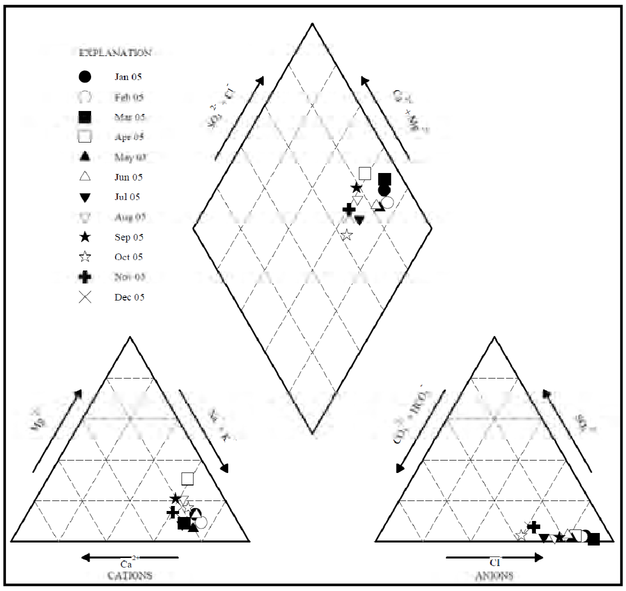

Figure 4.24: Hill Piper diagram for the strata TADW for the entire post tsunamic period of stations for the year 2005. All stations were inundated by tsunami waves on 26 December, 2004.

The analyses of the Piper Plots (Figure 4.24) shows that the cluster of data lies in a straight line pointing towards Na^+ apex in the cation triangle and towards Cl^- apex in the anion triangle. The basic indication is that of a NaCl contamination by some source. Two possibilities that exists are progressive solution of halite solution (or mixing with saline ground water formed by halite solution) or mixing with an oil-field brine. Sample at March 2005 contain 68% Na and 90% Cl result in a Na/(Na+Cl) ratio of <0.5. This suggests that a water having a halite origin as most brines have a ratio lower than 0.5 (Hounslow, 2005).

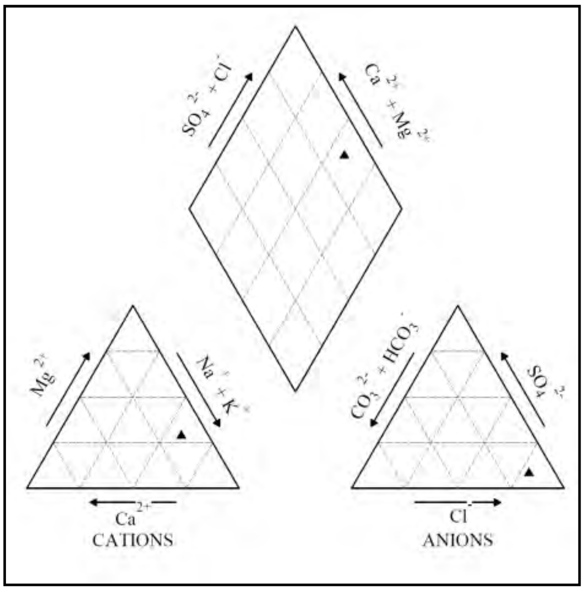

Figure 4.25: Hill Piper Trilinear diagrams of the tsunami affected dug wells strata (mean of 7 stations) Alappad coast in December 2008. All stations were inundated by tsunami waves on 26December, 2004.

The analysis of the diagram for the strata TADW for the month December 2008 (Figure 4.25) shows that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph December 2008. The diamond structure has data near the right hand side diagram typical for water with a specific nature for saline (Na^+ + K^+ and Cl^- + SO_4^{2-}). But the water is saline with Na has 55%, Ca 15% and Mg 30% and Chloride has 77% , $SO_4^{2-}$is 8% and CO_3^{2-} and HCO_3^{2-} is 15% . The analyses of the Piper Plots plot in a straight line pointing towards Na^+ in the cation triangle and towards Cl^- apex in the anion triangle. The basic indication is that of NaCl contamination by some source. Two possibilities that exists are progressive solution of halite solution (or mixing with saline ground water formed by halite solution) or mixing with an oil-field brine. Sample December 2008 contain 55% Na and 77% Cl result in a Na/(Na+Cl) ratio of <0.5. This suggests a halite origin as most brines have a ratio lower than 0.5.

Common dug well (1, 2, 3&5 of Table 3.2) sources which have been well documented with pre-tsunamic data of 2001 were later devastated and extensively degraded by tsunami inundation. This strata and a representative deep ground water source marked as station 4 (bore well depth 90.0m) has an ionic ratio of 0.47 (Chapter 3). This indicates the water is of infiltered rainwater origin. The deep ground water has the lowest ratio of 0.36 is having entirely a different character than the dug well source water. Since the ratio ranges between 0.36-0.52 band, and it does cross the limit of 0.5 only a single occasion either we could confirm that the ground water has an inherent existence originated from rain water over a period time probably millions of years. To confirm whether sources are contaminated by the seawater because of the closeness of the sea and if it is replenished by any geochemical mechanisms (reverse ion exchange in presence of seawater), more data treatment is distinctly necessitated and Piper plots are graphically simulated.

4.6.3 Deep Ground Water Profile (BW)

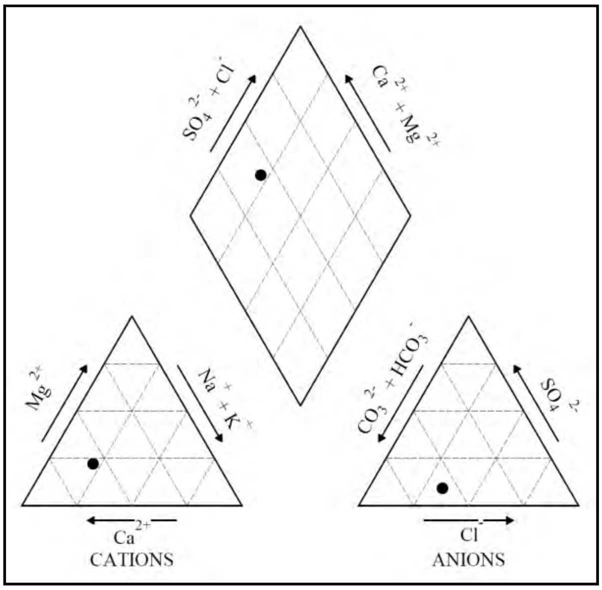

Figure 4.26: Hill Piper Trilinear diagrams of the bore well (BW) on Alappad coast seven days after 26 December, 2004 tsunami in January 2005.

The analysis of the diagram (Figure 4.26) for the ground water shows that the first triangle has a Ca apex and second triangle has a prominent CO_3^{2-} apex for the graph plotted for post tsunami period of 7 days (January, 2005). But the water is having Na has 23%, Ca 55% and Mg 22% and Chloride has 30% , $SO_4^{2-}$is 10% and CO_3^{2-} and HCO_3^{2-} is 60% .

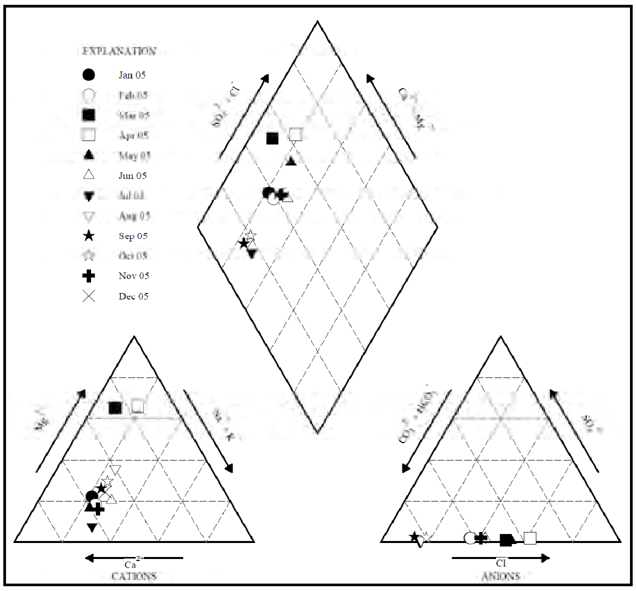

Figure 4.27: Hill Piper diagram for the strata bore well (BW) on Alappad coast for the entire post tsunamic period in the year 2005.

The analyses of the Piper Plots (Figure 4.27) shows that the cluster of data lies in a straight line pointing towards Ca^{2+} apex in the cation triangle and towards CO_3^- apex in the anion triangle. The diamond structure of the plot shows that the water is having a character of temporary hardness.

The Piper diagram (Figure 4.28) for the strata BW for the month December 2008 indicates that the first triangle has no specific apex and second triangle has a slight CO_3^- apex for the graph in December 2008. The diamond structure has data near the right hand side diagram typical for water without a specific nature. Na has 50%, Ca 25% and Mg 25% and Chloride has 30%, SO_4^{2-} is 8% and CO_3^{2-} and HCO_3^{2-} is 62%.

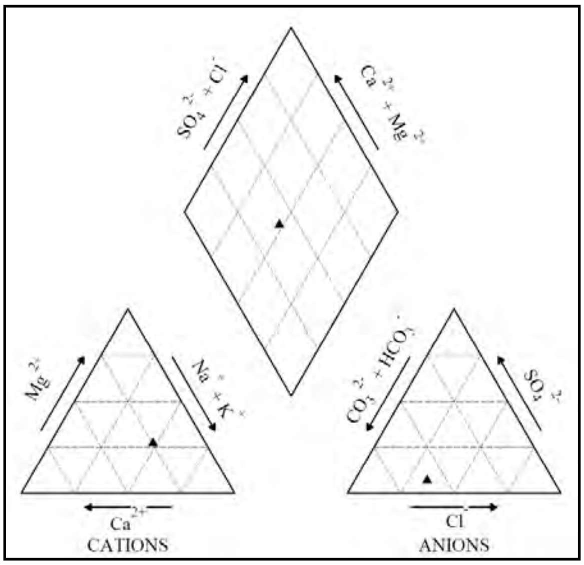

Figure 4.28: Hill Piper Trilinear diagrams of the strata bore well (BW) On Alappad coast in December 2008.

4.7 Groundwater Analysis

Table 4.14: Comparison of salinity (chloride content) means of water samples of the Tsunami-affected region with Student's *t*: sample size 7 months dtata (January, 2005 – July, 2005). Location: Alappad coast, Kollam, Kerala.

Stations Nos	Specification	Chloride Average x_i	Standard deviation s	Spooled	t-value*	t-table
1	Control Well (6ft)	204	106	$s_{1\&6}$ =106	$t_{1\&6}$ = 1.28	2.447
2	Tsunami Affected dug well & cleaned (6ft)	688	356	$s_{1\&2}$ =263	$t_{1\&2}$ = 3.45	2.447
6	Bore well (300 ft)	131	106	$s_{2\&6}$ = 263	$t_{2\&6}$ = 3.96	2.447

*Pooled students t test (Harris, 2006)

The study area Alappad (Kollam) and Arattupuzha (Alappuzha) coast has a good reservoir of the freshwater in its deep aquifers. To identify the quality of water collected from shallow ground water sources, mainly the control well and affected dug wells of average depth 6 feet and deep bore well stations > 300 ft, Pooled students *t* test (Harris, 2006) is identified as a useful tool to compare one set of measurements with another to decide whether they are "the same" or "different" in quality from each other at 95 % confidence level as a conservative standard. Or how far the original fresh water in its quality was distorted with respect to the chloride content brought about by the giant waves, even after severe monsoon dilution of the season in the month of July 2005 with recorded monthly rainfall of 242 mm. The region received a total of 1174.7 mm till July 2005 after tsunami event of December 26, 2004.

Analysis of the data (Table: 4.14) reveals that the chloride in the affected well water (station 2 in the Table 2.1) even after dewatering and cleaning 5- 6 times within first week after tsunami event has chloride content 337% higher than the control well (well not affected in the same region with similar features) and 523% higher than the chloride content of the deep ground water mined out from a depth of 300 ft. Further, cross examination of the quality of water sampled from above stations is possible with computational support to reach the following conclusions,

1. Whether the ground water at station (1) control well (depth 6ft) is same in quality with that from station 6 (bore well, depth 300 feet) of same origin with well expanded aquifers.
2. How far the dug well-affected and cleaned, station 2 (depth 6ft) shows variation in quality with respect to the control well water and deep bore well during the peak time of monsoon dilution in the month of July 2005.

Data pairs used in this computing is consisting of *station* (*1*) & (*6*) for the verification of the first hypothesis. Data pairs as *stations* (*1*) & (*6*) and (*2*) & (*6*) are used for the verification of second hypothesis. In this statistical analysis only chloride content alone is taken as the key parameter.

For the two sets of data consisting of n_1 and n_2 measurements (with averages x_1 and x_2) *t* value is calculated using the respective formula (2.20, 2.21, 2.22 and 2.23).

S_{pooled} is a pooled standard deviation making use of both sets of data. The value of *t* calculated and given in the above table is compared with standard value of student's *t* for n_1+n_2-2 degrees of freedom. If the calculated *t* is greater than the tabulated *t* at the 95% confidence level, the two results are considered to be different.

Analysis of the data of the water samples of the control station (1) and deep ground water bore well station (6), $t_{1\&6} = 1.28 < 2.447$ confirms that the difference is not significant. Samples collected from these stations are of same origin (with respect to chloride/ saline content). Affected and cleaned dug well station (2), has $t_{1\&2} = 3.45 > 2.447$ have significant difference in quality with the control dug well station (1). Also, this station has $t_{2\&6} = 3.96 > 2.447$ with respect to the deep ground water of the region station (6). This shows that even monsoon dilution does not have much impact to retain the original character of the ground water even after a recorded rainfall of 1174.7 mm by July 2005 the last peak time of the monsoon precipitation of the year in Kerala.

More analysis of the data collected for the entire year and prominent parameter wise could reveal more information that will form the major part of the extension of this work. Also, insight into the salt uptake and release behavior of the sediments as well as the physico – chemical characteristics of region's soil horizon will support more these cited findings in the future.

4.8 Overall Water Quality of Alappad Coast

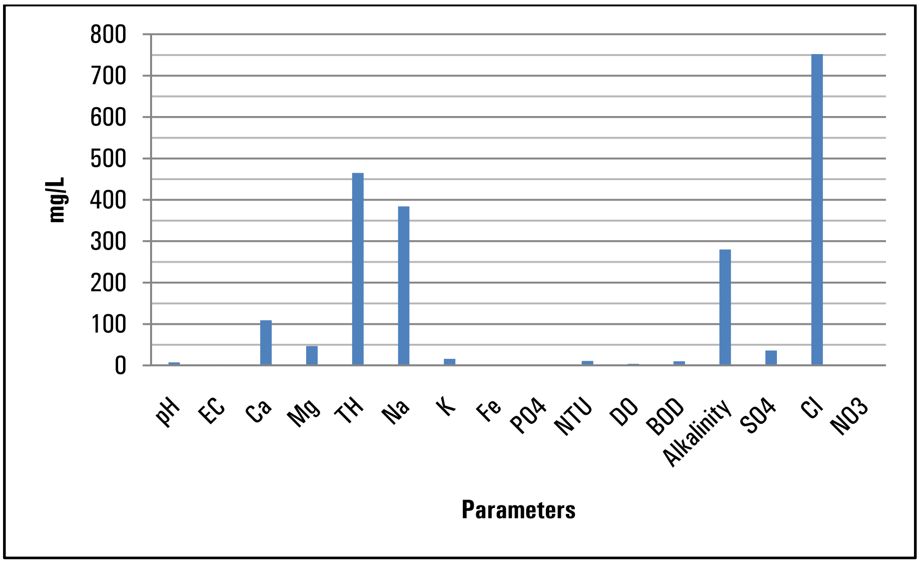

Figure 4.29: Variation of water quality parameters along the Alappad, Kollam coastal area in the post tsunami period of year, 2005, after 26 December 2004 Indian Ocean tsunami.

Pertinent water quality parameters of the region after the tsunami inundation are given in respective tables. However, the overall water quality of the region annual mean of the post tsunamic situation comprising eleven stations of the respective three strata are evaluated applying the t test; pH (7.6±0.2), EC (2.7±1.8) mS*/cm*, Ca (109±57) mg/l, Mg(47±20) mg/l, TH (465±210) mg $CaCO_3$/l, Na (384±356) mg/l, K (16±13) mg/l, Fe (0.28±0.21) mg/l, PO_4^{3-} (0.07±0.04) mg/l, Turbidity (11±7) NTU, DO (4±1) mg/l, BOD (10±3) mg/l, alkalinity (280±94) mg/l, SO_4^{2-} (36±18) mg/l, Cl^- (752±908) mg/l, NO_3^- (0.96± 0.22) mg/l (Figure 4.29). This basic data structure indicates the post tsunamic ground water quality of the Alappad coast is used to evaluate the hydrochemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 4.15.

The prominent parameters of the Alappad region after 26 December 2004 tsunami ranges from pH (7.4-7.8), EC (0.9-4.5) mS*/cm*, Ca (52-166) mg/l, Mg(27-67) mg/l, TH (255-675) mg $CaCO_3$/l, Na (28-740) mg/l, K (3-29) mg/l, Fe (0.07-0.48) mg/l, PO_4^{3-} (0.03-0.11) mg/l, Turbidity (4-18) NTU, DO (3-5) mg/l, BOD (7-13) mg/l, alkalinity (186-374) mg/l, SO_4 (18-54) mg/l, Cl (142-1362) mg/l, NO_3 (0.74-1.18) mg/l, AI(11.8-12.6).

Conclusions

Critical analysis of the post tsunami water quality profile of the Alappad region has been done to assess the temporal and spatial variability of the prominent parameters. It is found that there is significant change in their values before (2001) and after (2005) tsunami among the strata of control well (CW), tsunami affected dug wells (TADW) and deep bore well (BW). Variability is distinct in year 2008 (after 4 years) among the same strata though the region experienced many monsoonal dilutions. Shallow dug wells and bore wells have different characteristic behavior evidenced by significant change in their respective ionic ratio and Piper plots. Sodium, chloride, calcium hardness, total hardness and alkalinity have significant changes between stations and between months in tsunami affected dug well (TADW). Post tsunami evaluation of the ground water quality parameters on the nearby tsunami devastated coastal sections will expose more insight into the complex hydro geochemistry of the region. The succeeding chapter discusses the impact of tsunami on adjacent Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai cost of Kerala, marked by more or less devastation and inundation by 26 December 2004 Indian Ocean Tsunami waves.

Table 4.15: Overall water quality parameters of the ground water sources of Alappad coast, Kerala, India after 26 December 2004 Indian Ocean Tsunami

Coastal Section	Data	pH	EC mS/cm	Ca mg/L	Mg mg/L	TH mg/L	Na mg/L	K mg/L	Fe mg/L	PO_4 mg/L	NTU	DO mg/L	BOD mg/L	Alkalinity mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Control	$\overline{x} \pm \sigma$	7.5±0.5	0.84±0.4	49±16	13±6	174±40	62±12	9±1	0.10±0.18	0.07±0.15	3±2	4±0.6	7±3	133±19	34±21	182±95	1.06±0.53
	μ	7.5±0.3	0.84±0.26	49±10	13±4	174±25	62±10	9±1	0.10±0.11	0.07±0.1	3±1.5	4±0.4	7±1.8	133±12	34±13	182±61	1.06±0.34
	CI	7.2-7.5	0.58-1.1	39-59	9-17	149-199	52-62	8-10	0-0.11	0-0.17	1.5-4.5	3.6-4.4	5.2-8.8	121-145	21-47	121-243	0.72-1.4
TADW after 7 days (January 2005)	$\overline{x} \pm \sigma$	7.8±0.5	7.9±8.1	226±240	117±84	1045±794	1147±1174	34±32	0.79±0.37	0.17±0.15	18±33	4.4±2.4	6.5±3.8	344±258	89±65	2027±2078	0.3±0.1
	μ	7.8±0.4	7.9±6.8	226±202	117±70	1045±669	1147±989	34±27	0.79±0.31	0.17±0.13	18±27	4.4±2.0	6.5±3.2	344±217	89±54	2027±1750	0.3±0.1
	CI	7.4-8.2	1.1-14.7	24-428	47-187	376-1714	1058-2136	7-61	0.48-1.1	0.4-0.3	0.0-45	2.4-6.4	3.3-9.7	127-561	35-143	277-3777	0.2-0.4
TADW after 30 days (February 2005)	$\overline{x} \pm \sigma$	8.2±0.7	4.74±4.66	161±189	59±53	644±642	882±1191	23±35	0.88±0.5	0.14±0.38	10±23	4.6±3.2	6.4±3.6	336±263	65±60	1674±2114	0.38±0.21
	μ	8.2±0.3	4.74±3.92	161±159	59±45	644±540	882±1003	23±29	0.88±0.42	0.14±0.32	10±19	4.6±2.7	6.4±3.0	336±222	65±50	1674±1780	0.38±0.18
	CI	7.9-8.5	0.82-8.66	2-320	14-104	104-1184	0.0-1885	0-52	0.46-1.30	0.0-0.46	0-29	1.9-7.3	3.4-9.4	114-558	15-115	0.0-3454	0.2-0.56
TADW after 150 days (June 2005)	$\overline{x} \pm \sigma$	7.4±0.4	3.32±3.35	91±54	47±40	422±284	463±482	20±27	0.01±0.008	0.03±0.08	14±18	5.2±1.9	10.8±10.9	300±118	55±53	951±1068	0.06±0.01
	μ	7.4±0.3	3.32±2.57	91±45	47±33	422±239	463±406	20±22	0.01±0.007	0.03±0.07	14±15	5.2±1.6	10.8±9.2	300±99	55±45	951±900	0.06±0.01
	CI	7.1-7.7	0.75-5.89	46-136	14-80	183-661	57-869	0-42	0.09-0.10	0.0-0.10	0.0-29	3.6-6.8	1.6-20.0	201-399	10-100	51-1851	0.05-0.07
TADW after 330 days (December 2005)	$\overline{x} \pm \sigma$	7.7±0.3	2.38±1.64	101±52	36±23	397±206	294±204	16±8	0.07±0.05	0.14±0.14	8±4	4.4±2.6	5.2±1.3	357±193	75±59	495±419	0.06±0.04
	μ	7.7±0.2	2.38±1.38	101±44	36±19	397±174	294±172	16±6	0.07±0.04	0.14±0.12	8±3	4.4±2.2	5.2±1.0	357±162	75±50	495±353	0.06±0.03
	CI	7.7-7.9	1.0-3.76	57-145	17-55	223-571	122-466	10-22	0.03-0.11	0.02-0.26	5-11	2.2-6.6	4.2-6.2	195-519	25-125	142-848	0.03-0.09
TADW after 1430 days (December 2008)	$\overline{x} \pm \sigma$	7.4±0.4	0.90±1.16	23±8	31±27	185±106	115±127	7±6	0.16±0.08	0.08±0.05	7±3	6.8±3.4	9.9±5.4	33±11	21±26	148±288	0.16±0.09
	μ	7.4±0.3	0.90±0.97	23±7	31±22	185±90	115±107	7±5	0.17±0.07	0.08±0.04	7±3	6.8±2.8	9.9±4.6	33±9	21±21	148±243	0.16±0.07
	CI	7.1-7.7	0.0-1.87	16-30	9-53	95-275	8-222	2-12	0.1-0.24	0.004-0.12	4-11	4.0-9.6	5.3-14.5	24-42	0.0-42	0.0-391	0.09-0.23
BW after 7 days (January 2005)	$\overline{x} \pm \sigma$	8.0±0.4	0.47±0.15	72±29	17±14	252±123	27±14	7±3	1.3±0.9	0.17±0.15	13±20	2.0±1.9	6.7±4.2	200±43	6±6	83±30	0.18±0.05
	μ	8.0±0.5	0.47±0.18	72±37	17±18	252±158	27±18	7±4	1.3±1.1	0.17±0.09	13±25	2.0±2.4	6.7±5.4	200±55	6±8	83±39	0.18±0.06
	CI	7.5-8.5	0.29-0.65	35-109	0-35	94-410	9-45	3-11	0.02-2.4	0.08-0.26	0.0-38	0.0-4.4	1.3-12.1	145-255	0.0-14	44-122	0.12-0.24
BW after 30 days (February 2005)	$\overline{x} \pm \sigma$	8.0±0.3	0.42±0.03	61±20	12±5	200±55	26±13	8±4	0.15±0.7	0.0±0.0	12±20	2.1±1.9	6.7v4.4	192±39	6±5	81±31	0.2±0.06
	μ	8.0±0.3	0.42±0.04	61±25	12±6	200±71	26±16	8±5	0.15±0.9	0.0±0.0	12±26	2.1±2.5	6.7±5.7	192±50	6±6	81±39	0.2±0.08
	CI	7.7-8.3	0.38-0.46	36-86	6-18	129-271	10-42	3-13	0.6-0.24	0.0-0.0	0.0-38	0.0-4.6	1.0-12.4	142-242	0.0-12	42-120	0.12-0.28
BW after 150 days (June 2005)	$\overline{x} \pm \sigma$	6.7±0.3	0.61±0.05	40±12	10±2	143±27	26±13	4±0	1.2±1.9	0.0±0.0	30±17	1.3±1.2	11.5±4.2	229±36	8±3	124±75	0.06±0.01
	μ	6.7±0.4	0.61±0.06	40±16	10±2	143±35	26±16	4±0	1.2±2.5	0.0±0.0	30±21	1.3±1.5	11.5±5.5	229±45	8±3	124±96	0.06±0.01
	CI	6.3-7.1	0.55-0.67	24-56	8-12	108-178	10-42	4-4	0.0-3.7	0.0-0.0	9-51	0.0-2.8	6.0-17.0	184-274	5-13	28-220	0.05-0.07
BW after 330 days (December 2005)	$\overline{x} \pm \sigma$	7.4±0.3	0.64±0.15	44±14	13±9	165±15	22±17	7±5	0.05±0.04	0.0±0.0	24±33	1.4±1.1	8.6±7.1	233±44	8±3	115±144	0.03±0.01
	μ	7.4±0.4	0.64±0.19	44±18	13±11	165±20	22±22	7±6	0.05±0.05	0.0±0.0	24±43	1.4±1.4	8.6±9.1	233±56	8±4	115±185	0.03±0.02
	CI	7.0-7.8	0.45-0.83	26-62	2-24	145-185	0.0-0.0	1-13	0.0-0.10	0.0-0.0	0.0-67	0.0-2.8	0.0-17.7	177-289	4-12	0.0-300	0.01-0.05
BW after 1430 days (December 2008)	$\overline{x} \pm \sigma$	7.1±0.1	0.23±0.06	21±9	14±3	108±18	41±23	10±10	0.19±0.09	0.08±0.1	5±5	2.3±1.4	9.6±5.8	27±6	3±1	11±4	0.22±0.06
	μ	7.1±0.1	0.23±0.07	21±12	14±4	108±22	41±30	10±13	0.19±0.1	0.08±0.14	5±5	2.3±1.8	9.6±7.4	27±7	3±1	11±5	0.22±0.08
	CI	7.0-7.2	0.16-0.30	9-33	10-18	86-130	11-71	0-23	0.18-0.20	0.0-0.22	0.0-10	0.5-4.2	2.2-17.0	20-34	2-4	6-16	0.14-0.30
Overall region	$\overline{x} \pm \sigma$	7.4±0.3	0.7±1.0	22±7.5	25±23	156±92	88±106	8±6	0.17±0.07	0.1±0.08	6±4	5.4±3.4	9.3±5.2	30±10	17±22	102±232	1.65±0.96
	μ	7.4±0.2	0.7±0.6	22±5	25±15	156±62	88±71	8±4	0.17±0.05	0.1±0.06	6±2	5.4±2.3	9.3±3.5	30±7	17±15	102±156	1.65±0.64
	CI	7.2-7.6	0.1-1.3	17-27	10-40	94-218	17-159	4-12	0.12-0.22	0.04-0.16	4-8	3.1-7.7	5.8-12.8	23-37	2-32	0-258	1..01-2.29
BIS		6.5-8.5		75	30	300			0.3		5			200	200	250	50
USEPA		6.5-8.5					20		0.3		0.5-5				250	250	10
WHO		6.5-8.5					200		0.3		5				250	250	50
EEC		6.2-8.5			50	50	175	12	0.2	5	4				250		50
KSPCB		6.5-8.5		75		300			0.3		5			200	200	250	50

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Chapter 5

Post Tsunami Water Quality Profile of the Other Coastal Regions of Kerala

Contents

5.1 Introduction

True ferocity of 26 December 2004 Indian Ocean tsunami on Kerala was unleashed on the Alappad coast of Kollam and its impact on ground water has been evaluated and presented in the preceding sections. But the adjoining northern coastal strip of Kayamkulam kayal (Lake), defined by the very same bio-geological patterns and socioeconomic situation was not far behind. Though the death toll was comparatively less, the environmental havoc wreaked upon this equally thin sand bar virtually crippled the local economy and the life of the poor fishermen. The invading tsunami waves left most of the area heavily inundated.

This chapter of the thesis comprises the results and discussion on the water quality parameters of the ground water sources of the Arattupuzha [Valiyazheekal] region of the study area and the ground water chemistry. The data generated from the extensive field trips, chemical analyses and laboratory studies of the water samples from selected water sources of the region; dug wells (5 nos) and bore wells (4 nos) and tsunami pools (2). Control well for the comparison has been the one identified in the Alappad coast as it failed to identify a drinking water source in this study region to be treated as a control well in the same region not touched by tsunami waves.

Water quality in respect of the sources is interpreted following standard methods and tools. Pre-tsunami Water Quality of the Region has been presented in Chapter 3 in Table 3.1, which reveals that the waters of the affected coastal region are not by far hard even in the dry summer, except for sample 3 as per the data of CGWB.

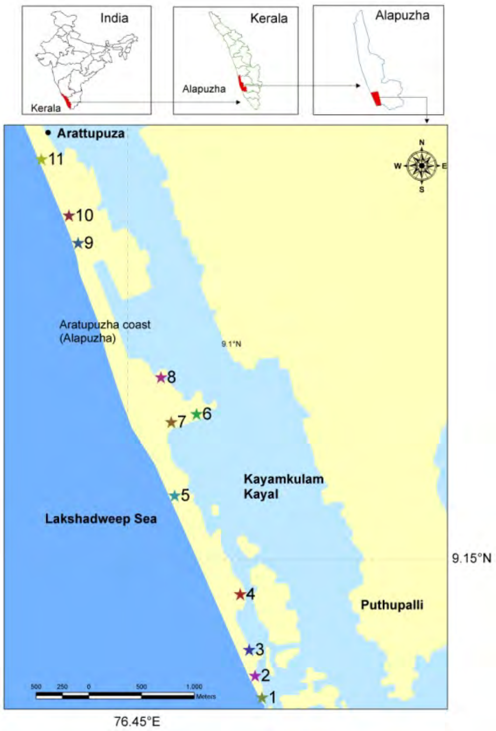

Figure 5.1: Location map of the tsunami affected Arattupuzha coast, Kerala, India

5.2 Tsunami Impact on Arattupuzha Coast, Alappuzha, Kerala, India

Arattupuzha coast referred to in this chapter of the thesis is one of the severely tsunami affected coastal section on the coastal Kerala situated north of the Kayamkulam inlet whose southern part is the Alappad coast discussed in Chapter 4. Compared to Alappad coast this section of the shore experiences intense sea erosion but is nurtured by rich black sand deposit. However the extent of devastation bought by tsunami waves was less compared to that occurred on Alappad. Most of the sampling locations are identified on the Valiyazheekal stretch near to the barrage. A new port is coming up there in the inlet thereby to boost fishing and trading. The region is prominent in economic utilization of natural resources of the state because this region has the highest quality heavy mineral deposits (Achari, 2005). In the following discussions the name Arattupuzha coast will be used to highlight the study details and findings.

As already mentioned before in the respective chapters run up levels are treated as an indicator of the extent to which the sea water forcefully intruded and left with indelible marks on geomorphic formations and manmade structures. The magnitude of the devastation, the energy and kinetics of wave propagations as well as the force implied for erosion and attrition can be obtained from the inundation data gathered in meters.

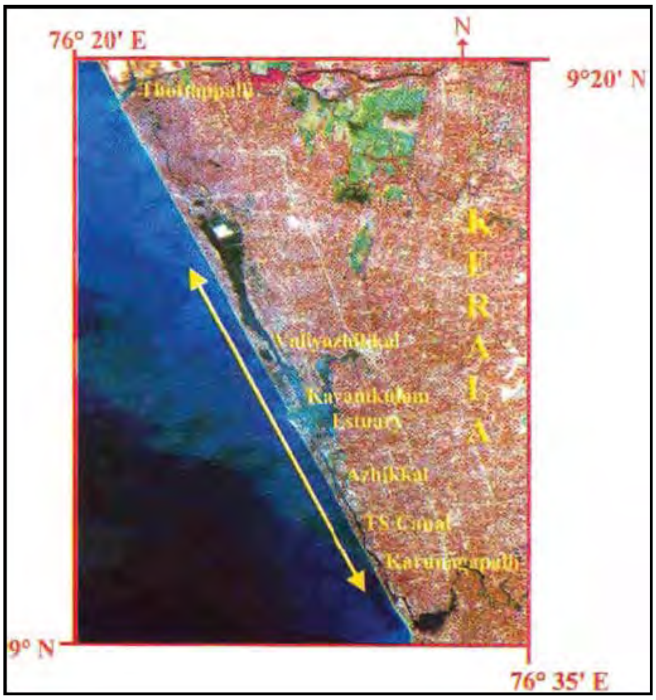

Figure 5.2: Indian Remote Sensing Satellite (IRS) imageries of the Kerala coast, captured after 26 December 2004 tsunami. (Image as on 27.12.2004)

Kurian et al (2006) and Prakash et al (2006) report that Azheekal (Kollam) and Valiyazheekal (Alappuzha) on the either side of Kayamkulam inlet had the highest run up of 4.5 to 5.0m. The tsunami wave being propagated through estuaries, backwaters and lagoons make it gather additional momentum so that the run up level becomes double. Secondary wave – ripples sum up the height of the rolled water columns as it was observed in Kanyakumari coast bringing maximum disaster in terms of human life and property loss. The Figure 5.1 is the location map of the incident and study area.

This part of the coast on the northern side of the Kayamkulam lagoon is severely eroded over the years taking away the coastline by the sea. The magnitude of the devastation could be seen from the picture (Figure 5.2) taken after the tsunami impact. The construction of the new barrage to build the proposed port affected the wave dynamics and extent of erosion and attrition decided by the seasonal variations. In monsoon the erosion is heavy followed by the attrition of black sand by the wave. There are reports (Prakash et al., 2006; Kurian et al., 2005) that bathymetric profile of the region after tsunami showed a widening of the inner shelf. After tsunami the existing bathymetry on comparison with one already available with the region noted that the bathymetry changed in the offshore. This change occurred beyond 10m in the offshore.

The distributions of sand in the inner shelf during 1987 and in 2005 are given in Chapter 1&2. It is confirmed that one of the geological impacts of tsunami has been the subsequent erosion of soil in the inner shelf of the coastal area (Moorthy et al., 2007). Analysis of quartz grain features of the sediments reveals that the deposit belongs to Holocene period (Prithviraj and Prakash, 1991). Extensive research by many research teams supports this conclusions based on the data of the analysis of more than 110 samples from the coastal Neendakara-Thottapally region. The distribution as well as the direct field observation reveals pinching out to the shore causing marked changes in the bathymetry profile. This acts as a direct evidence of erosion by the shifting of sand from the shelf region. Finer sediments rich in heavy minerals that constitute the major fraction have been taken away by tsunami waves. As we see in the former sections Alappad-Arattupuzha coast has a natural migration of sandy sediments in the region around Kayamkulam inlet. Surge of mighty waves with average run up of 5m triggered huge extent of sediment transport. These waves took away the finer fraction levitating the lighter quartz fractions to upper reaches of the barrier inlets. Arattupuzha had a history of severe inundation during the monsoon it become so severe decided by heavy erosion and attrition. Many a time in the year the areas becomes isolated either by seawater flooding or due to black sand deposition by the churning waves.

Figure 5.3: A pool formed by the tsunami waters called tsunami pool (TP) (sampling station1, Table 5.1)

In a background of the tsunami incidence, the gravity of the situation became worse and serious. It occurred in two ways as it happened in the Alappad coast. The region is interconnected through a network of lagoons and canals and finally extends to the Thottapally barrage in the north. One of the ways the inundation experienced has been the direct entry and encroachment of water as flooding tsunami waves and sweeping the land area. Bathymetric Changes along the TS-Canal in the Kollam – Thottapally stretch before (6/04) and after (5/05) tsunami have been extensively discussed in the preceding chapters.

5.3 Post tsunami Ground water Quality of Arattupuzha Coast

Water quality of the Arattupuzha region deteriorated after the excruciating tsunami event (Achari, 2005) by tsunami waves creating geomorphologic changes in the form of destruction of the dug well sources. Also, transferring mineral content into the soil formations, piling of refuse materials in swamps and depressions that ultimately degrades and supplement to the ground water. The shoreline features as well as in the coastal land are critically altered as seen below creating scourges of attrition refered as *tsunami pool in this study* (Figure 5.3).

The tsunami pools are selected as one of the sampling point in Arattupuzha coast it being a new water body confined with seawater by waves and is exposed as such over a period of time. Organic debris and other nutrients were washed out by the invading seawater enriches it in many ways that ultimately trigger a situation of algal growth and passes through different phases of degradation. In the course of time, dilution by rainwater and natural flow decided by the gradient make this station a heterogeneously complex system whose behavior study is of special interest for the study by looking into the nature of variation in physical and chemical parameters. Table 5.1 describes the location wise profile of the sampling stations.

Table 5.1: Water quality sampling stations representing various classes on tsunami Affected Arattupuzha coast (Alappuzha) in 2005.

Station	Remarks*	Location
1. Tsunami Pool-Valiyazheekal	Tsunami pool- depth 2 feet [TP]	09° 08’ 25N, 76° 27’ 43E
2. Thara- house owner	Groundwater supplied [BW]	09° 08’26N, 76° 27’ 40E
3. Bore well 250 feet (pump house)	Bore well (KWA) for local supply[BW]	09° 08’ 32N, 76° 28’ 02E
4. Subrahmanya Swami temple	Dug well affected and cleaned [AWDC]	09° 08’ 35N, 76°27’ 47E
5. Tsunami Pool-Tharayilkadavu	Tsunami pool- depth 2 feet [TP]	09° 09’ 35N, 76°27’ 12E
6. Kuriappassery Temple	Dug well affected not cleaned[AWNDNC]	09° 09’ 41N, 76° 27’17E
7. Bore well 250feet(KWA)-Panakkal	Ground water at source[BW]	09° 09’ 41N, 76° 27’ 17E
8. Panakal Devi Temple	Dug well affected and cleaned[AWDC]	09° 09’ 56N, 76°27’ 11E
9. Bore well 250 feet Ramanchery	Ground water at source[BW]	09° 10’ 37N, 76° 26’ 42E
10.Manoj-house water	Dug well affected not cleaned[AWNDNC]	09° 10’ 43N, 76° 26’ 40E
11.Bhaskaran-house owner	Dug well affected and cleaned[AWDC]	09° 11’ 02N, 76° 26’32E

*Tsunami Affected Shallow Dug Wells[TADW] = [AWDC] + [AWNDNC]

5.4 Ground Water Quality of the Region

5.4.1 pH

The data profile shows that all the water sources irrespective of their strata dug wells, tsunami pool, and deep bore wells has pH value that lie in a narrow range around 7.0

except the station (9) a 250 ft depth bore well marked as Ramanchery pumping station in the following months after tsunami till February, 2005. After that stations; tsunami pool (1), temple dug well (8), dug well (11) has a very high rise in pH to very alkaline range quite unusual for the other stations. The decline in monsoon dilution was also not steady as it observed for other sources. The physical status of the wells are identified as that they are open wells of the area but not cleaned or dewatered at all as if that done for other sources. All the cleaned and dewatered wells shows rapid replenishment with a uniform hydrochemical behavior as revealed in the graph by August, 2005, exactly after 210 days since the tsunami incident. While those not dewatered take more time to reach to a uniform behavior by a time of 330 days.

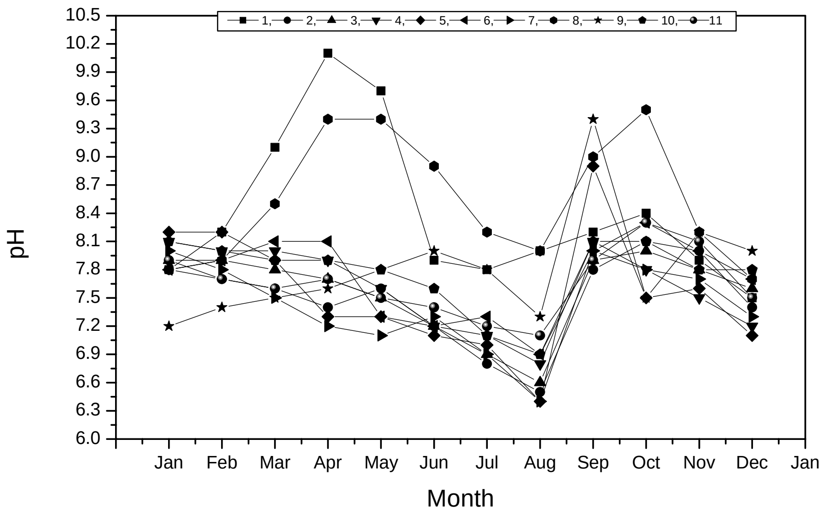

Figure 5.4: Temporal variation of pH at various sampling stations Along Arattupuzha coast during 2005. Stations 1(■) and 5(♦) are Tsunami Pools [TP] ; stations 2(◆),3(▲),7(►) & 9(★) are deep bore wells [BW]. are tsunami affected dug wells badly inundated [TADW]and stations 4 (▼), 6 (◄), 8(✱), 10(⬟) & 11(◖); Post tsunamic Studies.

The heavy rainfall of 624.mm received in July 2005 of the year could do much to the quality of the ground water by adding more rain water that distinctly found in the pH profile. By June – September, 2005 the region received a total of 1523 mm of rain against the normal fall of 1836mm expected. The shortfall has been -17% which is much higher than the shortfall for the Alappad region in Kollam District.

5.4.1.1 Tsunami Affected Dug wells [TADW]

The pH of ground water measured for the eleven samples are presented in Figure 5.4 Data points are the individual measurement for the each designated stations. It is found that all tsunami affected dug well sources have a value ranges from 7.1±0.4 to 8.4±0.6 for the 12 months data. The result well agrees with that reported for Alappad region. It never crossed the limit of permissible range pH 6.5- 8.5 BIS (BIS, 1999) even in a single event.

The water is found to be good enough after the dewatering and cleaning by the house owners. As it is seen that all the dug wells in the month of January 2005 just after the 7 days the inundation happened had an average pH of 7.9±0.1. But slowly enhances to 8.2±0.6 till April, 2005 (90 days). This slow enhancement is due to the diffusion of contaminated water from adjacent regions to the dug well water. This trend declines after in May (pH 7.9±0.8) reaches to the minimum of 7.1±0.4 in August by the heavy monsoonal dilution. Whereas it again rises to 8.4±0.6 in October, 2005 due to summer and decline to a value of 7.6±0.2 in December after completing a full cycle of 12 months after tsunami event. This may be quite confusing to the expectation and leads to the question why that an extensive seawater intrusion could not make any damaging changes in the chemical activity of the surface waters. Every time, the pH of the control well remained to be in a pH less to the average of the dug wells affected except in the month of February after 30 days may be due to contamination from nearby ground water flow regimes.

pH had steadily and nominally been falling until August 2005 (for Alappad coast, it has been up to July 2005). This may be due to the less dilution of trapped seawater brought about by natural salinity gradient and rainfall events as the Arattupuzha region is prone to less dilution by natural gradient. Most of the sampling stations are on the Valiazheekal coast which is totally under the toll of erosion particularly during monsoon. Wave activity inherently acts opposite to the natural gradient flow of ground water. Also the fine grains of the black sand deposit feebly permit the percolation of water by porosity restrictions. The annual mean of the whole of the surface ground water sampled from dug wells has been 7.9±0.4 in 2005. It remarkably changed to a value of 7.3±0.1 in December 2008 after four years.

5.4.1.2 Tsunami Pool

Tsunami pool is a new term introduced in this study to represent a sampling location inherently formed by tsunami wave activity that finally hold on tsunami water. We have identified two such pools in this section and made a sampling point to study the hydro- chemical behavior of the water confined. We could observe that the pH of the tsunami pool varies from 7.2±1.1 to 8.7±1.9. It always exhibited a high pH above 8.0 except a few months June to August and December, 2005. Consider tsunami pool as a representative sampling station like a dug well not dewatered and cleaned could be a water source in its original shape designed by the tsunami waves. The features exhibited by this station will be significant information to the hydrochemistry of the region unaltered by any human activity. That means the dewatering is a quick and easy procedure to be followed to preserve the original quality of drinking water sources. Quite interestingly both affected wells and tsunami pool exhibited a pH of 8.0 (affected dug wells pH 7.9±0.4 and tsunami pool pH 8.0±0.5) after 12 months will be due to the natural self purification by monsoon dilution and other geographical phenomena. However, after 4 years the pH dug wells become more to natural situation with pH 7.3±0.1. By the time the tsunami pool had been disappeared from the scene by erosion and other natural activities.

5.4.1.3 Deep Bore wells (BW)

In the study stations (2), (3), (7) and (9) has been deep ground water (bore wells) with average depth of 250 ft. Stations (1) & (2) have almost same pH (7.9) in the month of

January, 2005 except (9) has very ideal pH 7.2. Nevertheless, the mean pH for the four deep ground water remains to be 7.7 ± 0.3_5 just after the tsunami event. This indicates the inherent character of the deep ground water of the region in that month because the chances of contamination to deep aquifers by seawater cannot be quite possible within a short time. pH of the first three bore well samples slowly decreases to till august, 2005 the time point where all the ground water sources of the region has the lowest pH due to extensive rainfall orchestrated dilution (Table 5.2). But station (9) Ramanchery bore well has a very different behavior that pH slowly picks up from 7.2 to a rise to 8.0 in June them climbs down to pH of 7.3. In August, the time where the ground water of the region becomes more unique in behavior the deep ground water has a mean pH of $6.7\pm0.4_0$. By September, 2005 the pH rises to alkaline range ($8.3\pm0.7_5$) but it is within the permissible limit of 6.5 -8.5 range as per BIS. Again after September, 2005 the pH profile takes dip towards December the minimum point of the annual cycle with a mean of $7.6\pm0.3_0$. Conclusively, we observe that the mean pH of the deep ground water of the region as a full annual cycle has been 7.6±0.4.

Table 5.2: Temporal Precipitation pattern (in mm) on Kollam and Alappuzha coasts in 2005

Coast	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Kollam	34.0	32.5	4.2	374.0	166.3	321.0	242.7	63.0	222.2
Alappuzha	5.0	1.2	37.2	287.5	127.8	511.2	624.1	75.4	411.0

5.4. 2 Total Hardness

TADW strata of ground water sources on Arattupuzha has a high hardness of 1002±430 mg/l (7D) just after the tsunami event. Deep bore wells (BW) have at the same duration has a lower total hardness equal to 318±132mg/l $CaCO_3$. TH of 4640 mg/l has been observed after 7 days the tsunami created it. Total hardness has a dip in the both cases after 30 days with 824±251mg/l for TADW and 278±98 mg/l for BW (Figure 5.5). Afterwards, the TH moves up to as far as 652±139mg/l (60D) for TADW and 240±70 mg/l (60D) for BW.

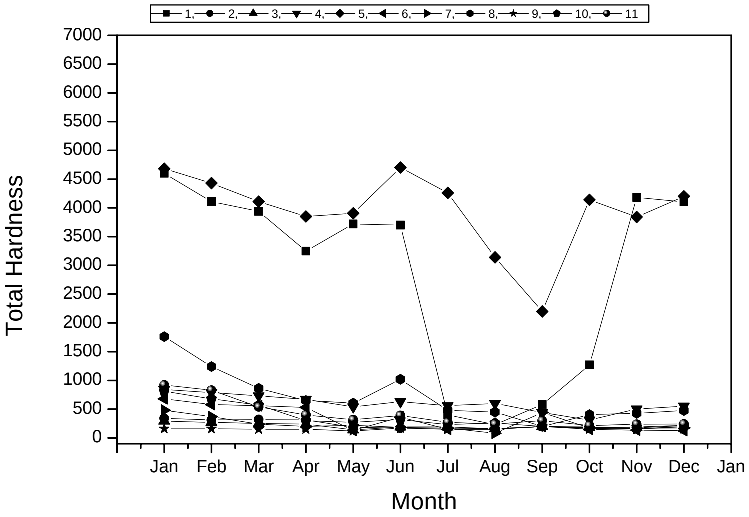

Figure 5.5: Temporal and spatial variation of Total Hardness at various sampling stations along Arattupuzha coast (Alappuzha, Kerala) during 2005. Stations 1(■) and 5(⧫) are Tsunami Pools [TP] ; stations 2(◆),3(▲),7(▶) & 9(★) are deep bore wells [BW] stations 4 (▼), 6 (◀), 8(⬢), 10(⬟) & 11(◆) are tsunami affected dug wells badly inundated [TADW] Concentration of TH (mg/l $CaCO_3$); Post tsunamic Studies.

As regards to TH the three sampling strata either control well (CW), tsunami affected dug well stations TADW or the deep bore well stations (BW) and tsunami pool all have upside down swing during the initial period and thereafter the stable feature is maintained. The control for the comparison of the data the same of the Alappad is retained. The Control Well has a hardness status of moderately hard to hard [MHH] with 125mg/l $CaCO_3$ mg/l representative to the region moves to very hard to excessively hard [VHEH] nature by 90Days with TH ranging 171-250 mg/l. This indicates that the region has a $\bar{x}$(TH) = 174 ± 40 mg/l as the annual mean establishes that the inherent behavior of the region is compatible with nature of [VHEH]. By the year 2008 after 1430 days the character became moderately hard to hard [MHH; range 91 - 130mg/l $CaCO_3$] with 101mg/l $CaCO_3$, the source regained the original character over the period of time four years.

Arattupuzha coastal region with respect to the TH showed many significant features. The strata of tsunami affected dug wells [TADW] have a TH position unaltered from the robust class - too hard for ordinary domestic use [THODU; with > 250mg/ l] with observed mean $\bar{x}$ (TH for TADW) = 477 ± 63 mg/l $CaCO_3$. The initial TH 1002 ± 432 mg/l $CaCO_3$ just after the tsunami event (7D) becomes 323 ± 183 mg/l $CaCO_3$ after almost completing one year (330D) indicates marked change in the hydrochemistry and ionic balance such that hardness is subjected to many a number of metamorphoses. But alkalinity measured are lower in every sampling event and a close examination for the comparison can be made; the initial AL of the TADW has been 229 ±58 mg/l $CaCO_3$ just after the tsunami event (7D) becomes AL 241 ± 99 mg/l $CaCO_3$ after almost completing one year (330D) with $\bar{x}$ (AL for TADW) = 261 ± 48 mg/l $CaCO_3$, a stable structure is retained. The data of TH and AL after 1430 D by December 2008 has the following values; TH 26±11 mg/l $CaCO_3$ for TH 120 ± 31mg/l $CaCO_3$ all occasions alkalinity is less to the TH for the strata of tsunami affected dug wells (TADW). The difference TH-AL is the measure of permanent hardness (Hounslow, 1995).

The new findings go parallel to the pre-tsunamic situation that existed in the region in year 2001; with TH 68±50 mg/l CaCO3 with AL 34.7 mg/l $CaCO_3$. It is seen that 33.4 mg/l $CaCO_3$ comes from the contribution of permanent hardness. This means that TH and AL in the above strata have lower measure of AL with a steady profile throughout, a sign of prominent temporary hardness due to HCO_3^- and CO_3^{2-} ions.

5.4.3 Sodium

The fate and distribution of sodium ions in the ground water after the tsunami incidence have been plotted in the Figure 5.6. The trend is more matching with that of conductivity of the individual water samples plotted (graph not shown) in features not in magnitude as exhibited by Alappad coast.

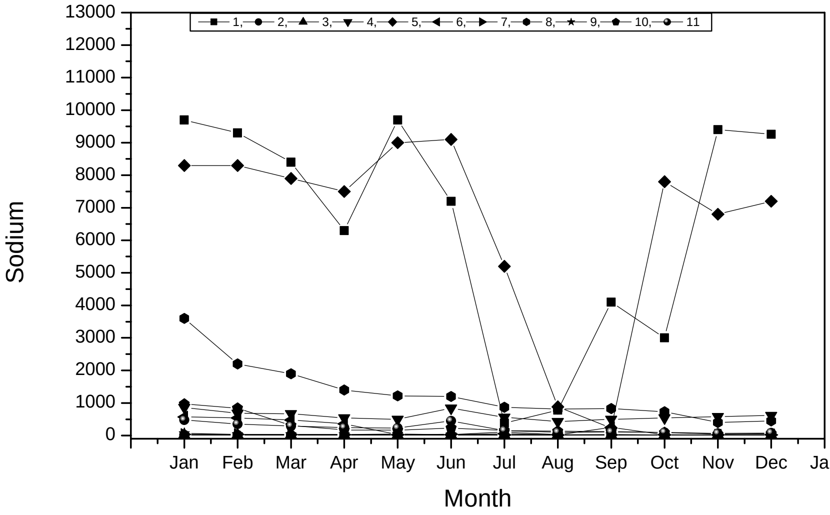

Figure 5.6: Temporal and spatial variation of Sodium at various sampling stations along Arattupuzha coast (Alappuzha, Kerala) during 2005. Stations 1(■) and 5(♦) are Tsunami Pools [TP]; stations 2(◆), 3(▲), 7(►) & 9(★) are deep bore wells [BW]. Stations 4 (▼), 6 (◄), 8(⬢), 10(⬟) & 11(◐) are tsunami affected dug wells badly inundated [TADW]. Concentration of sodium (mg/l); Post tsunamic Studies.

After the tsunami event the level of Na$^+$ is more quantified as $\bar{X}$(Na$^+$) 1296±1304 mg/L for the tsunami affected wells (TADW) being the control well have 42mg/L. The deep ground water, Bore well strata (BW) too seem to be contributing Na$^+$ level by $\bar{X}$(Na$^+$)= 35±24 mg/L. Tsunami pool has $\bar{X}$(Na$^+$)= 9000 ±990 mg/L. This indicates the logic of choosing Na$^+$ a prominent factor as it here act as a major constituent (> 5mg/L) for water analyses. By February 2005 (after 30D) $\bar{X}$(Na$^+$) = 922 ±737 mg/L for TADW, Bore wells, BW have $\bar{X}$(Na$^+$) = 26 ±11 mg/L and for Tsunami Pool (TP) have $\bar{X}$(Na$^+$) = 8800±707 mg/L. March 2005 (60Days) the tsunami affected dug wells (TADW) showed declining Na content of 730±672 mg/l.

On Arattupuzha too tsunami waves brought a well - defined sodium regime in the regional water quality. The Na content of TADW dwindle to the minimum level after 90 days (April 2005) with $\bar{X}$(Na$^+$) = 542±500 mg/L where as control well has 58 mg/l and deep groundwater BW has 22±9 mg/l that sources registered a steady Na$^+$ regime.

Further it exhibits a declining feature over the time after the highest Na value of 150D (550±472 mg/l; June 2005) to minimum by 240 day (September, 2005) with $\bar{X}(Na^+)$ = 362±305mg/l for TADW (Table 5.3). Deep ground water sources have a stable Na^+ level. The Na content of TADW unequivocally falls to $\bar{X}(Na^+)$ = 246±269 mg/L once the full circle is about to complete in the twelfth sampling by 330 days (December, 2005) though after 7D it has been 1296±1304mg/l for all tsunami affected dug wells (TADW).We have already seen that the control well exhibited a distinct feature that Na^+ though registered 42 mg/l just after the tsunami event further slowly but steadily rises over the time. This is due to the nature of the surrounding soil that are saturated with ions to release Na to the ground water flow regime of control well region though the location is no way exposed to direct hit- impact of tsunami waves. On comparing the first and last sampling events for control well the Na^+ level increased from 42 mg/L steadily to 90mg/L over the year, passing through a range of natural conditions.

Annual mean of the Na^+ content of strata has been found to be $\bar{X}(Na^+)$ =521±166 mg/L for TADW with a $\bar{X}(Na^+)$ = 62±16 mg/L for control well and 24±5 mg/L for deep bore wells. But Tsunami Pool has a mean Na of 6489±530 mg/l. However, the last sampling after fourth year of the tsunami devastation by December 2008 (by 1430 days) has $\bar{X}(Na^+)$ =106±59 mg/L for TADW with a $\bar{X}(Na^+)$ = 40 mg/L for control well and 60±7 mg/L for deep bore well. By this time the tsunami pool have been disappeared due to erosion by sea and invading wave activity. Since the pre-tsunami data is available with respect to Na^+ it is rational to make impartial judgment whether tsunami brought a direct impact on Na^+ level of the regions ground water (Table 3.2)

Table 5.3: Sodium ion content of Ground waters of Arattupuzha Coast (Alappuzha); Post tsunamic studies

Strata	**n**		**3 Jan 2005 (7 Days)**	**3 July 2005 (180 Days)**	**03 August 2005**	**3 Dec 2005 (330 Days)**	**Annual Mean (2005) N=12**	**Dec 2008 (1430 Days)**
Tsunami Pool	1	$\bar{x} \pm \sigma$	9000	2790	830	8230	6489	Nil
TADW	5	$\bar{x} \pm \sigma$	1296±1304	358±346	299±325	246±269	521±166	106±59
		μ	1296±1499	358±398	299±373	246±309	521±191	106±68
		CI	203-2795	40-756	74-672	63-555	330-712	38-174
BW	4	$\bar{x} \pm \sigma$	35±24	38±44	17±7	20±5	24±5	60±7
		μ	35±33	38±61	17±10	20±7	24±7	60±10
		CI	2-68	23-99	10-27	13-27	17-31	50-70
Mean	10	$\bar{x} \pm \sigma$	1562±660	473±383	239±163	954±198	919±985	38±33
		μ	1562±465	473±270	239±115	954±140	919±694	38±25
		CI	1097-2027	203-743	124-354	814-1094	225-1613	13-63
CW	1	$\bar{x} \pm \sigma$	42	46	56	90	62±16	40
Mean $\bar{X}$ (tsunami pool excluded	9	$\bar{x} \pm \sigma$	736±725	216±193	174±181	146±149	300±92	86±33
		μ	736±547	216±146	174±137	146±112	300±69	86±25
		CI	189-1283	70-362	37-311	34-258	231-369	61-111

TADW: Tsunami Affected Dug Well; BW: Deep Bore well Ground Water; CW: Control Well

Pre-tsunamic Na content of the region has been found to be $\bar{X}$ (Na^+) =33±4 mg/L (CI; 29-37 mg/l) for n=5 with four shallow dug wells and a single deep bore well (BW). However, the Na data of the monitored shallow dug wells has been in the range of 11-42mg/l below the permissible limit. Deep Bore Wells too have a Na content of 46 mg/l, it has been sure to say that more Na contamination has occurred due to tsunamic situation. Based on this, it is most conclusive to note that Na^+ brought by tsunami waves has a regular pulse in defining water quality of the region in the post tsunamic situation. To prove the impact more rigorous treatment of the data is implemented and the test results are presented in the following chapter.

5.4.4 Chloride

Examination of Cl content of drinking water sources after tsunami devastation on Arattupuzha coastal area guide us to many striking facts of halite contamination and dilution (Figure 5.7). Replenishment of ground water over time and space governed by the hydrodynamics of the region is being presented in the following sections based on the three distinct strata of sources represented as control well (CW), tsunami affected dug wells (TADW) and Tsunami Pool (TP).

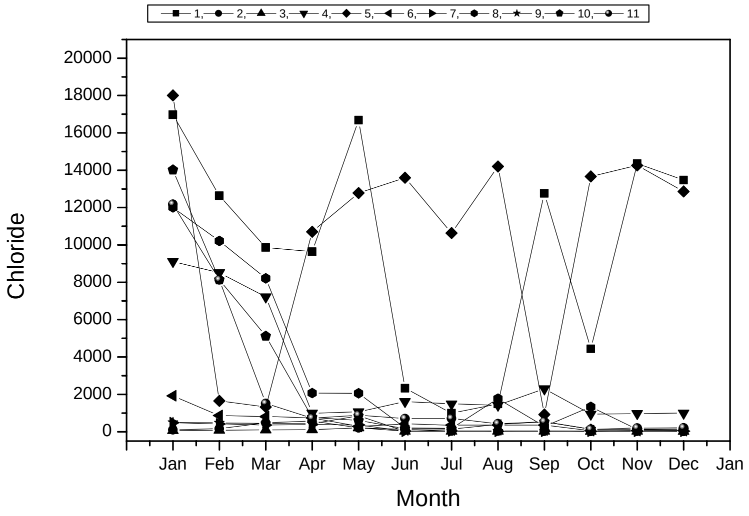

Figure 5.7: Temporal and spatial variation of Chloride at various sampling stations along Arattupuzha coast (Alappuzha, Kerala) during 2005. Stations 1(■) and 5(♦) are Tsunami Pools [TP] ; stations 2(◆),3(▲),7(▶) & 9(★) are deep bore wells [BW]. Stations 4 (▼), 6 (◀), 8(✸), 10(⬟) & 11(◖) are tsunami affected dug wells badly inundated [TADW]. Concentration of Chloride (mg/l); Post tsunamic Studies.

5.4.4.1 Chloride TADW

Tsunami Affected Dug wells (TADW) strata of stations of Arattupuzha coasts represents both severely tsunami affected dug wells and those of dewatered and cleaned (n=5). The first sampling (Jan 2005) has a mean Cl$^-$ content of $\bar{X}$ (Cl$^-$) = 9849±4766 mg/L shows the highest variability with respect to nearest Alappad coast. This definitely support the fact that the regions expansive contamination by sea water. The data is the highest observed chloride content observed for the strata with CI is wide 5083- 14615 mg/l. As we saw it in the case of control station the chloride has been 87 mg/l. After 30 days (February, 2005) Cl$^-$ content of the TADW strata have a sudden decline with chloride content of 7173±3629 mg/l. After 60 days (March 2005) the chloride declines to a value of 4576 ± 3318 mg/l. And subsequently it declined up to 150 days (July, 2005). By August 2005 (after 180 days) the chloride content of the strata rises to 873±673 mg/l. (Table 5.4).

The variation of Cl^- ion content in ground water is due to the release of halite ions from the saturated soil structure in the lean months of January and February exactly over a period of 60 days slowly transported to the groundwater by convective as well as advective way of discharge with a long residence time. The augmentation of chloride replenishment becomes more prominent by a period of 330 days (December, 2005) to reach a level of 306±388 mg/l with a range value of 0-694 mg/l.

Table 5.4: Chloride ion content of Ground waters of Arattupuzha Coast (Alappuzha); Post tsunami stations

Strata	n		03 Jan 2005 (7 Days)	03 July 2005 (180Day)	03 August 2005	03 Dec 2005 (330 Days)	Annual Mean (2005) N=12	Dec 2008 (1430 Days)
Tsunami Pool	1	$\bar{x} \pm \sigma$	17489±0	5814±0	7846±0	13165±0	10010±1686	0
TADW	5	$\bar{x} \pm \sigma$	9849±4766	574±558	873±673	306±388	2302±590	97±80
		μ	9849±5476	574±641	873±773	306±446	2302±678	97±92
		CI	4373-15325	67-1215	100-1646	140-752	1624-2980	5-189
BW	4	$\bar{x} \pm \sigma$	286±237	37±4	34±9	31±17	162±42	14±4
		μ	286±329	37±6	34±13	31±24	162±58	14±6
		CI	43-615	31-43	21-47	7-55	104±220	8-20
Mean	10	$\bar{x} \pm \sigma$	6788±2385	883±279	1235±336	1482±194	2217±340	60±45
		μ	6788±1681	883±197	1235±237	1482±137	2217±240	60±34
		CI	5107-8469	686-1080	998-1472	1345-1619	1977-2457	26-94
CW	1	$\bar{x} \pm \sigma$	87±0	117±0	114±0	145±0	182±95	48±0
Mean $\bar{X}$ (tsunami pool excluded	9	$\bar{x} \pm \sigma$	5599±2650	353±310	500±374	184±216	1351±328	60±45
		μ	5599±1998	353±234	500±282	184±163	1351±247	60±34
		CI	3601-7597	119-587	218-782	21-347	1104-1598	26-94

TADW: Tsunami Affected Dug Well; BW: Deep Bore well Ground Water; CW: Control Well

Ground waters of Arattupuzha region has an annual mean $\bar{X}(Cl^-)$ =2302±590 mg/L (μ 2302±678 with CI of 1624-2980) observed for 12 monthly sampling event for the tsunami affected dug wells (n=7). The sudden decline in chloride content in the subsequent months after tsunami indicate that a chloride removal mechanism is active in the Arattupuzha region in regards to the chloride content measured just after the sampling done 7 days after tsunami $\bar{x}$ (Cl$^-$) = 9849±4766 mg/L. Dilution by rain water could have been a major reason for the decline in the chloride content.

The continuous monitoring of the dug well sources (TADW) over period of time after completing a full circle in year 2005 the sampling repeated after 1430 days in December 2008. The results have been providing a set of new insight into the hydrochemistry of the region. The chloride content further declined to $\bar{x}$ (Cl$^-$) =97±80 mg/L (µ 97±92 with CI of 5-189 mg/l). The table describes the Cl$^-$ content of control well that has chloride content of 87 mg/l just after the tsunami event in January 2005 (7D) has 145 mg/l in December 2005 (330 D) and in December 2008 (1430D) has 48 mg/l. This further proves that the chloride removal mechanism active in a tsunami devastated region governed by many remarkable complexities decided by the hydrochemistry of the region. Impact of tsunami with respect to the excess enrichment of marine ions in ground water and soil has been an area of active research. In this respect these findings are most useful for further research endeavor (Srinivaslu et al., 2008; Kitagawa et al., 2006; Sil and Freymueller, 2006; Babu et al., 2007; Szczucinski et al., 2007; Ramasamy et al., 2006; Ramanmurthy et al., 2005; Oyedele and Momoh, 2009).

5.4.4.2 Deep Ground Water (BW)

The deep ground water sources of Arattupuzha has a constant and steady Cl$^-$ level (286±237mg/l) at a time tsunami hit the region measured after 7 days(7D) in January,2005 and it remained same 284±194 mg/l even after 30 days (February,2005). The respective levels for the control wells have been 87 and 193 mg/l for the above time interval against the TADW strata of samples measured as 9849±4766 mg/l and 7173±3629mg/l measured in the respective time interval. This indicates that the deep ground water is stable and is not directly been influenced by the tsunami impact for a distorted ionic imbalance. However, the Chloride content of both TADW and BW strata of Arattupuzha has a higher level compared to that of adjoining Alappad coast.

As in the case of Alappad coast Arattupuzha too had many locations with slope and depressions (such as swamps, pools and discarded and unused water sources) are pooled up with stagnant tsunami bound flood water remained over months has a good role in releasing Cl^- ions to the ground water. This accumulated stagnant water rich in salt water may be slowly infiltered into the groundwater reserve through crevices of the casings. Arattupuzha experiences intensive sea erosion and invading wave activity is highly intensive. This in turn degrades the local soil environment and initiating complex hydrolytic interactions. Altered ionic equilibrium of the water sources affects drinking water quality, storage and distribution systems of the region. Cl^- content of the BW in the following time intervals have a distinct pattern; 345±174 mg/l (60D; March, 2005), 376±198mg/l (90D; April, 2005), 412±303 mg/l (120 D May, 2005) mg/l. The chloride steadily rises in the post tsunamic and pre-monsoon situation.

The intense dilution occurred to the strata of sampling stations control well (CW) and TADW during active monsoon months of June (150D), July (180D), August (210D), September (240D), October (270D), November (300D) and December 2005 (330D) registered a lowest Cl^- level (55±49, 37±4, 34±9 , 28±0, 24±8, 34±13, 31±17 mg/l respectively) indicates that rain water grazes to deep ground water source by an indirect mechanism. After one full circle of 330days the Cl^- level slowly rises to 31±17 mg/l in December 2005 (by 330 days) in common to features exhibited by former stations stratified as CW(145mg/l) and TADW (306±388) mg/l. This indicates that critical observations are unavoidably prominent in deciding the overall quality of the regions ground water.

The exceptionally high chloride content in TADW on Arattupuzha coast and subsequently in its BW strata makes us believe that the accumulated Cl^- percolates to the deep aquifers over the time by convective transport mechanism. This rise of chloride content in respect of time in the initial months after tsunami event could be decided by two factors. The chloride ions bound by soil saturated by seawater may have been finding its way to deep aquifer zones by a cone of depression mechanism during unrestricted pumping as excessive over exploitation. In post tsunamic time faced fresh water shortage in the aftermath of the tragedy. The rapid corrosion of the casing material by excess salt content brought by tsunami material in the post tsunamic period might have perforated the already degraded metal surface to allow the seepage of excess ions washed by summer rain. Lower chloride content in the post monsoon periods is mainly because of the excessive dilution by rainwater.

5.4.5 Water Quality Index (WQI)

On Arattupuzha coast there was substantial temporal variation in WQI for all affected dug well sources as well as deep bore wells. It is revealing that, both control and ground water samples had more or less stable quality status all through the sampling period indicating that seasonal environmental quality variation is very prominent.

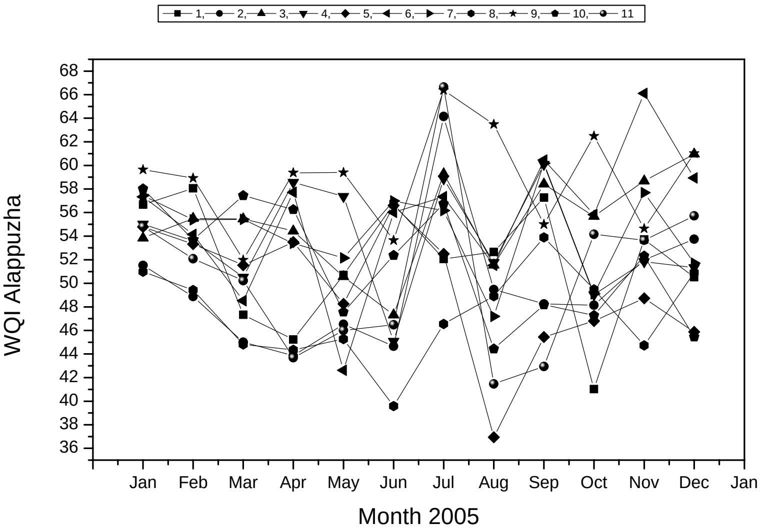

Figure 5.8: Temporal and spatial variation of WQI at various sampling stations along Arattupuzha coast (Alappuzha, Kerala) during 2005. Stations 1(■) and 5(♦) are Tsunami Pools [TP] ; stations 2(◆),3(▲),7(▶) & 9(★) are deep bore wells [BW]. Stations 4 (▼), 6 (◀), 8(⬣), 10(⬟) & 11. are tsunami affected dug wells badly inundated [TADW].

As it is seen in the case of Alappad coast in the preceding chapters water sources of Arattupuzha too undergo overall quality degradation across time intervals indicating that the ground water reservoir is steadily being deteriorated in quality. The overall change of ion concentration due to tsunami and the subsequent subterranean contact of the ground water with organic waste leached in the flooded seawater have a marked influence on the water quality of the groundwater.

On Arattupuzha coast high tsunami waves brought a well - defined WQI regime in the regional water quality. The extra ionic loading by the influx of seawater deteriorated the quality of the water for many years since the disastrous event. Figure 5.8 shows the temporal and spatial variation of water quality index at various sampling stations on the Alappad coast. For the strata of TADW in January 2005 (after 7 D) has $\bar{x}(WQI)$ = 55±3, in February 2005 (after 30 D) has $\bar{x}(WQI)$ = 53±2, in March 2005 (after 60 D) has $\bar{x}(WQI)$ = 50±5, the content improve to a level after 90 days (April 2005) with $\bar{x}(WQI)$ = 52±7. Both control well and deep groundwater sources registered a WQI value of 52 and 53±7 respectively from their initial WQI 54 and 56± 4 of January 2005(7D). During this period as per the classification water is of average quality (WQI: 51-70) existed with prominence for the distinct three strata of ground water sources. As against to the expectation it is seen that WQI gains to minimum by 120 days (May, 2005) with $\bar{x}(WQI)$ = 48±6 for TADW, still with a level of 53 for control well and 52±5 for BW sources. Both control well and bore well strata has a stable WQI feature in the pre-tsunamic situation. The rapid improvement in the quality index is exhibited by all ground water sources by 180 days (July, 2005) with $\bar{x}(WQI)$ = 57±7 for TADW, 58 for control well and $\bar{x}(WQI)$ = 62±5 for the strata of deep bore well (BW).

On Arattupuzha it is further observed that quality index remained (WQI) = 53±5 by 330 days (Dec, 2005) after completing almost one year a time where all tsunami affected dug wells (TADW) has been expected to achieve a complete refining. Rise to maximum WQI was observed once the full circle is about to complete in the twelfth sampling of 330 days with (WQI) = 60 for control well.

Table 5.5: Mean and summation of Water Quality Index (WQI) of severely TSUNAMI Affected Indian Coast: Arattupuzha, Kerala, India.

Strata	n		3 Jan 2005 (7 Days)	3 July 2005 (180 Days)	3 Dec 2005 (330 Days)	03 Dec 2008 (1430 Days)	Annual Mean (2005) (n=10)	03 August 2005
Tsunami Pool	1	$\overline{x} \pm \sigma$	56±0	52±0	48±0	0	51±1	45
TADW	5	$\overline{x} \pm \sigma$	55±3	57±7	53±5	50±5	52±2	48±5
		µ	55±4	57±8	53±6	50±6	52±2	48±6
		CI	51-59	49-65	47-59	44-56	50-54	42-54
BW	4	$\overline{x} \pm \sigma$	56±4	62±5	57±5	58±3	55±2	53±7
		µ	56±6	62±7	57±7	58±4	55±3	53±10
		CI	50-62	55-69	50-64	54-62	52-58	43-63
Mean	10	$\overline{x} \pm \sigma$	56±2	59±4	54±3	54±3	53±1	50±4
		µ	56±1	59±3	54±2	54±2	54±0	50±3
		CI	55-57	56-62	52-56	52-56	54	47-53
CW	1	$\overline{x} \pm \sigma$	54±0	49±0	60±0	54±0	54±4	49
Mean $\overline{X}$ (tsunami pool excluded)	9	$\overline{x} \pm \sigma$	55±2	59±5	55±4	54±3	53±1	50±4
		µ	55±2	59±4	55±3	54±2	53±0	50±3
		CI	53-57	55-63	52-58	52-56	53	47-53

TADW: Tsunami Affected Dug Well; BW: Deep Bore well Ground Water; CW: Control Well

The first and last sampling events the level improved only to a less extent; from 55±3 to 53±5 for TADW over one year period, passing through a set of natural conditions as in the case of Alappad coast. The deep ground water on Arattupuzha coast kept a stable character the entire period with WQI 56±4 and 57±5 respectively for the first and last sampling. However, the last sampling after fourth year of the tsunami devastation by December 2008 (by 1430 days) has (WQI) = 50±5 for TADW with a (WQI) = 54 for control well and (WQI) =58±3 for the deep bore wells.

The stable behavior of the deep ground water sources with respect to WQI (Table 5.5) and slow quality improvement of the severely damaged dug well sources (TADW) reveals that tsunami impact severely deteriorated quality of water and process of improvement takes months to years. Over a period of your years WQI deteriorated from 55±3 to 50±5. However a decline in quality occurs as it is evidence by the 1430 day data. Like Alappad almost all strata had a more quality profile decide as 51-70 (Medium or average water quality) range on Arattupuzha coast too. This study of water quality indices glimpses out the extent of quality degradation brought about by the tsunami impact on deep ground water too.

The pre-tsunami data is not available with respect to WQI of the Arattupuzha coast. It is rational to make impartial judgment that tsunami brought a direct impact on WQI level of the regions ground water. It is most conclusive based on the data gathered that WQI has a regular pulse in defining water quality of the Arattupuzha region because the regions hydro geochemistry had dramatically changed a lot after the impact.

5.5 Tsunami Pool

5.5.1 pH

We could observe that the pH of the tsunami pool varies from 7.2±1.13 to 8.7±1.97. It always exhibited a high pH above 8.0 except a few months June to August and December, 2005. Consider tsunami pool as a representative sampling station like a dug well not dewatered and cleaned could be a water source in its original shape designed by the tsunami waves. The features exhibited by this station will be significant information to the hydrochemistry of the region unaltered by any human activity. That means the dewatering is a quick and easy procedure to be followed to preserve the original quality of drinking water sources. Quite interestingly both affected wells and tsunami pool exhibited a pH of 8.0 (affected dug wells pH 7.9±0.4 and tsunami pool pH 8.0±0.58) after 12 months will be due the natural self purification by monsoon dilution and other geographical phenomena. However, after 4 years the pH dug wells become more to natural situation with pH 7.3±0.15. By the time the tsunami pool had been disappeared from the scene by erosion and other natural activities.

5.5.2 Sodium

Tsunami pool the tsunami brought natural shallow water body has exceptionally high level of sodium and chloride content being they are the seepage water collected in the erosion pits during inundation and subsequent draining of the tsunami water. Tsunami pool has highest sodium content just after the tsunami inundation $\bar{x}\,(Na^+) = 9000 \pm 990$ mg/L during the first sampling, after one week duration. Content declines over time, by February 2005 (after 30D) $\bar{x}\,(Na^+) = 8800 \pm 707$ mg/L, by March(after 60D) $\bar{x}\,(Na^+) = 8150 \pm 354$ mg/L, by April 2005(after 90D) $\bar{x}\,(Na^+) = 6900 \pm 849$ mg/L, by May(after 120D) $\bar{x}\,(Na^+) = 9350 \pm 495$ mg/L, by June 2005 (after 150D) $\bar{x}\,(Na^+) = 8150 \pm 1344$ mg/L, by July 2005 (after 180D) $\bar{x}\,(Na^+) = 2790 \pm 3408$ mg/L, by August 2005(after 210D) $\bar{x}\,(Na^+) = 830 \pm 71$ mg/L, by September 2005(after 240D) $\bar{x}\,(Na^+) = 2165 \pm 2737$ mg/L, by October 2005(after 270D) $\bar{x}\,(Na^+) = 5400 \pm 3394$ mg/L , by November, 2005(after 300D) $\bar{x}\,(Na^+) = 8100 \pm 1838$ mg/L, by December 2005(after 330D) $\bar{x}\,(Na^+) = 8230 \pm 1457$ mg/L. After one year the pools have been vanished by wave activity and erosion. However annual mean of the data shows that $\bar{x}\,(Na^+) = 6489 \pm 530$ mg/L.

5.5.3 Chloride

Tsunami pool has highest sodium content just after the tsunami inundation $\bar{x}\,(Cl) = 17489$ mg/L during the first sampling, after one week duration. Content declines over time, by February 2005 (after 30D) $\bar{x}\,(Cl) = 7145$ mg/L, by March(after 60D) $\bar{x}\,(Cl) = 5595$ mg/L, by April 2005(after 90D) $\bar{x}\,(Cl) = 10173$ mg/L, by May (after 120D) $\bar{x}\,(Cl) = 14733$ mg/L, by June 2005 (after 150D) $\bar{x}\,(Cl) = 7966$ mg/L, by July 2005 (after 180D) $\bar{x}\,(Cl) = 5814$ mg/L, by August 2005(after 210D) $\bar{x}\,(Cl) = 7846$mg/L, by September 2005(after 240D) $\bar{x}\,(Cl) = 6842$ mg/L, by October 2005(after 270D) $\bar{x}\,(Cl) = 9053$mg/L, by November, 2005 (after 300D) $\bar{x}\,(Cl) = 14308$ mg/L, by December 2005(after 330D) $\bar{x}\,(Cl) = 13165$ mg/L. However, annual mean of the data shows that $\bar{x}\,(Cl) = 10010 \pm 1686$ mg/L.

5.5.4 Total Hardness

Table 5.6: Water Quality parameters of Tsunami Pool (Arattupuzha), Kerala, India

Parameters	**Value (7 days ; Jan 2005)**	**(Annual Mean, 2005)**	
		Value	**Range**
pH	8	8±0.3	7.7-8.3
EC	42 mS/*cm*	21±3 mS/*cm*	18-24
Ca	1040 mg/L	653±55 mg/L	598-708
Mg	498 mg/L	431±64 mg/L	367-495
TH	4640 mg/L	3398±353 mg/L	3045-3751
Na	9000 mg/L	6489±530 mg/L	5959-7019
K	440 mg/L	240±19 mg/L	221-259
Fe	26 µg/L	37±10 µg/L	27-47
PO_4	0.03 µg/L	88±62 µg/L	26-150
Turbidity	4 NTU	6.4±2.4 NTU	4.0-8.8
DO	6 mg/L	6.2±1.1 mg/L	5.1-7.3
BOD	6 mg/L	9.5±1.3 mg/L	8.2-10.5
Alkalinity	183 mg/L	231±36 mg/L	195-267
SO_4	212 mg/L	243±33 mg/L	210-276
Cl	17489 mg/L	10010±1686 mg/L	8324-11696
NO_3	1.30 mg/L	0.95±0.1 mg/L	0.85-1.05
WQI	56	51±1	50-52

Tsunami pool has highest total hardness content just after the tsunami inundation $\bar{x}$ (TH) = 4640 mg/L during the first sampling, after one week duration (Figure 5.9). Content declines over time, by February 2005 (after 30D) $\bar{x}$ (TH) = 4270 mg/L, by March(after 60D) $\bar{x}$ (TH) = 4025 mg/L, by April 2005(after 90D) $\bar{x}$ (TH) = 3550 mg/L, by May (after 120D) $\bar{x}$ (TH) = 3813 mg/L, by June 2005 (after 150D) $\bar{x}$(TH) = 4200 mg/L, by July 2005 (after 180D) $\bar{x}$ (TH) = 2330 mg/L, by August 2005(after 210D) $\bar{x}$ (TH) = 1685mg/L, by September 2005(after 240D) $\bar{x}$ (TH) = 1390 mg/L, by October 2005(after 270D) $\bar{x}$ (TH) = 2705 mg/L, by November, 2005 (after 300D) $\bar{x}$ (TH) = 4010 mg/L, by December 2005(after 330D) $\bar{x}$ (TH) = 4152 mg/L. However, annual mean of the data shows that $\bar{x}$ (TH) =3398 ±353 mg/L (Table 5.6).

Tsunami pool has the lowest Water Quality Index *WQI* of 44 by 270 days (October, 2005). After the tsunami inundation $\bar{x}$ (*WQI*) = 56 during the first sampling, after one week duration. This means the water is having medium or average quality. Content declines over time, by February 2005 (after 30D) $\bar{x}$ (*WQI*) = 56, by March(after 60D) $\bar{x}$

(*WQI*) = 49, by April 2005 (after 90D) $\bar{X}$(*WQI*) = 49, by May (after 120D) $\bar{X}$(*WQI*) = 50, by June 2005 (after 150D) $\bar{X}$(*WQI*) = 57, by July 2005 (after 180D) $\bar{X}$(*WQI*) = 52, by August 2005 (after 210D) $\bar{X}$(*WQI*) = 45, by September 2005(after 240D) $\bar{X}$(*WQI*) = 51, by October 2005 (after 270D) $\bar{X}$(*WQI*) = 44, by November, 2005 (after 300D) $\bar{X}$ (*WQI*) = 51, by December 2005(after 330D) $\bar{X}$(*WQI*) = 48.

However, annual mean of the data shows that $\bar{X}$ (*WQI*) =51 maintain the average quality profile. Examination of the profile reveals that highest WQI of 57 is observed by 150 days (June, 2005). Monsoonal dilution might have improved the quality. Pertinent water quality parameters of the so-called tsunami pool after the tsunami inundation are given in respective tables given above.

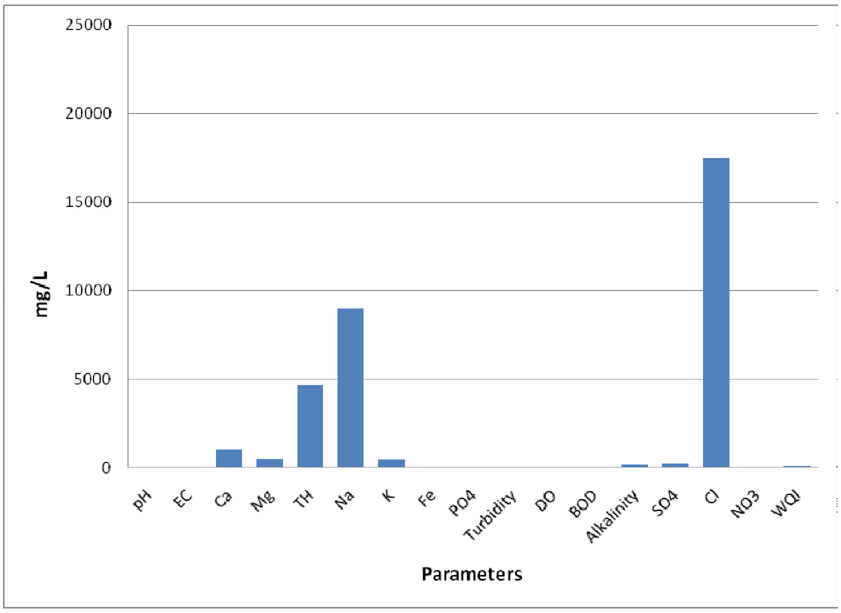

Figure 5.9: Water Quality parameters of Tsunami pool (7 Days after 26 December 2004 Indian Ocean Tsunami on Arattupuzha coast, Kerala, India)

However, the overall water quality of this station Seven day after post tsunamic situation pH (8), EC (42) mS/*cm*, Ca (1040) mg/l, Mg(498) mg/l, TH (4640) mg $CaCO_3$/l, Na (9000) mg/l, K (440) mg/l, Fe (0.03) mg/l, PO_4 (0.03) mg/l, Turbidity (4) NTU, DO (6) mg/l, BOD (6) mg/l, alkalinity (183) mg/l, SO_4 (212) mg/l, Cl (17489) mg/l, NO_3 (1.3) mg/l, WQI(56).

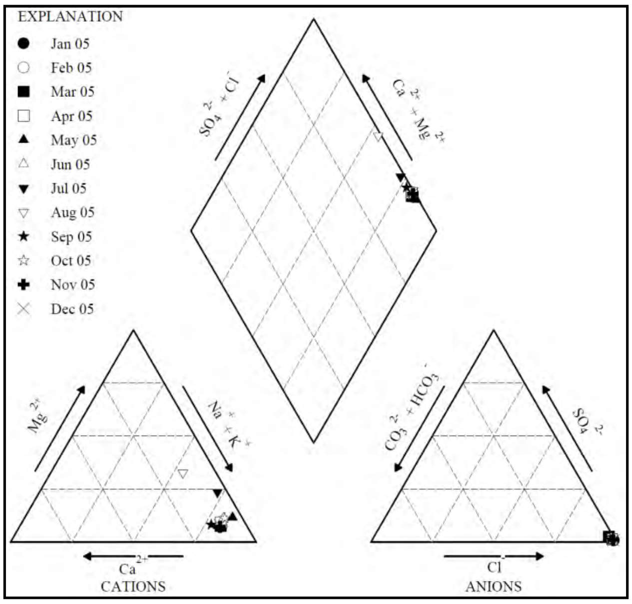

Figure 5.10: Hill – Piper- Trilinear plot of Tsunami pool on Arattupuzha Coast after 26 December 2004 Indian Ocean Tsunami: Behavior of tsunami water on coastal land. Persisting saline (Na$^+$ + K$^+$ and Cl$^-$ + SO$_4^{2-}$) character throughout the post tsunamic year.

This basic data structure indicates that post tsunamic water quality of the tsunami pool can be treated as a representative of the ground water source to evaluate the hydrochemical behavior of the regions ground water quality. Figure 5.11 shows that Ca, TH, Na and Cl of the tsunami pool is too high, but always less than that of TADW strata. Because, they are originated from the direct impact of tsunami waves on coastal plain by excessive erosion and subsequent accumulation of tsunami water.

Annual mean of the pertinent water quality parameters of the tsunami pool after the tsunami inundation are given in respective table. However, the overall water quality of the tsunami pool are evaluated; pH (8±0.3), EC (21±3) mS*/cm*, Ca (653±55) mg/l, Mg(431±64) mg/l, TH (3398±353) mg CaCO$_3$/l, Na (6489±530) mg/l, K (240±19) mg/l, Fe (0.04±0.01) mg/l, PO$_4$ (0.09±0.06) mg/l, Turbidity (6.4±2.4) NTU, DO (6.2±1.1) mg/l, BOD (9.5±1.3) mg/l, alkalinity (231±36) mg/l, SO$_4$ (243±33) mg/l, Cl (10010±1686) mg/l, NO$_3$ (0.95± 0.1) mg/l, WQI(51±1). Figure 5.1 represents the behavior of tsunami pool.

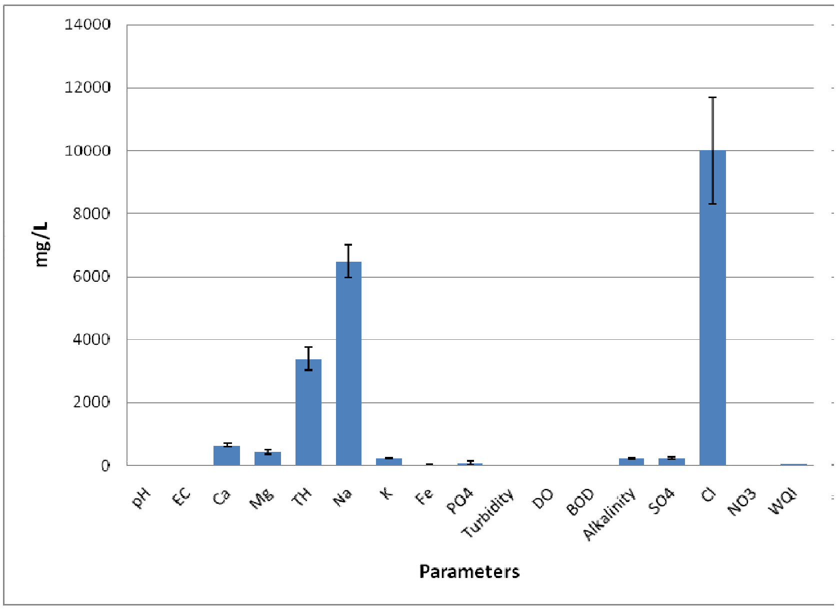

Figure 5.11: Water Quality parameters of Tsunami pool, annual mean after 26 December 2004 Indian Ocean Tsunami on Arattupuzha Coast, Kerala, India).

This basic data structure indicates the post tsunamic ground water quality of the tsunami pool which is exactly the seepage of tsunami water accumulated in the newly formed depressions caused by the massive erosion of the tsunami waves. This data has a special significance as it shows the profile of the water quality parameters once tsunami water undergoes quality variation on coastal stretches.

The prominent parameters of the tsunami seawater accumulated in the so-called Tsunami Pool on a representative coastal section, Arattupuzha coast of Kerala after 26 December 2004 tsunami ranges from pH (7.7- 8.3), EC (0.18-24) mS*/cm*, Ca (598-708) mg/l, Mg(367-495) mg/l, TH (3045- 3751) mg $CaCO_3$/l, Na (59-7019) mg/l, K (221-259) mg/l, Fe (0.03-0.05) mg/l, PO_4 (0.03-0.15) mg/l, Turbidity (4-8.8) NTU, DO (5.1-7.3) mg/l, BOD (8.2-10.5) mg/l, alkalinity (195-267) mg/l, SO_4 (210-276) mg/l, Cl (8324-11696) mg/l, NO_3 (0.85-1.05) mg/l, WQI(50-52).

5.6 Piper Plots and Water Quality Evaluation

The control well as well as the representative Piper diagram of the ground waters of the region prior to 26 December tsunami has an ionic behavior shown by the respective graphs (Chapter 3 &4) with no specific apex for the cation and anion triangle. The diamond has no data in the prominent location enough to categorize the water quality.

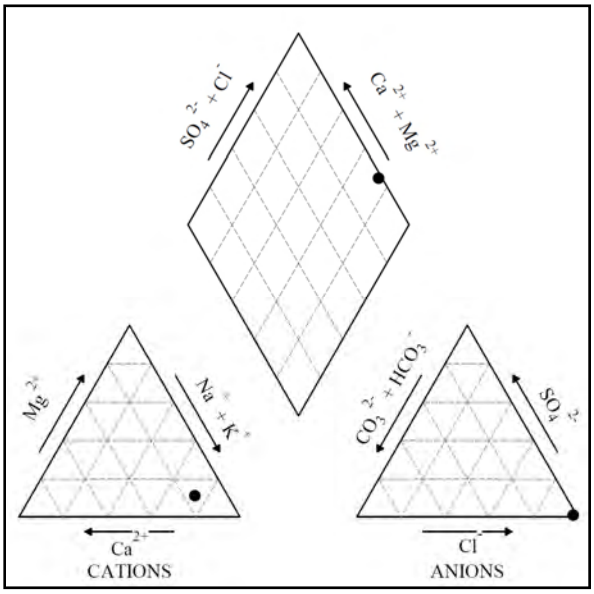

Figure 5.12: Hill Piper Trilinear diagrams of the tsunami affected dug well TADW (mean of 5 stations) Arattupuzha coast in January 2005. All stations were inundated by tsunami waves on 26 December, 2004.

But the diamond structure of the Hill- Piper- Trilinear plots of the TADW strata of dug well (Figure 5.13) of Arattupuzha coast has data near the right hand side diagram typical for water with a specific nature for saline ($Na^+ + K^+$ and $Cl^- + SO_4^{2-}$). The figure 5.12 shows that the water existed just after tsunami with strong saline behavior just after the tsunami event.

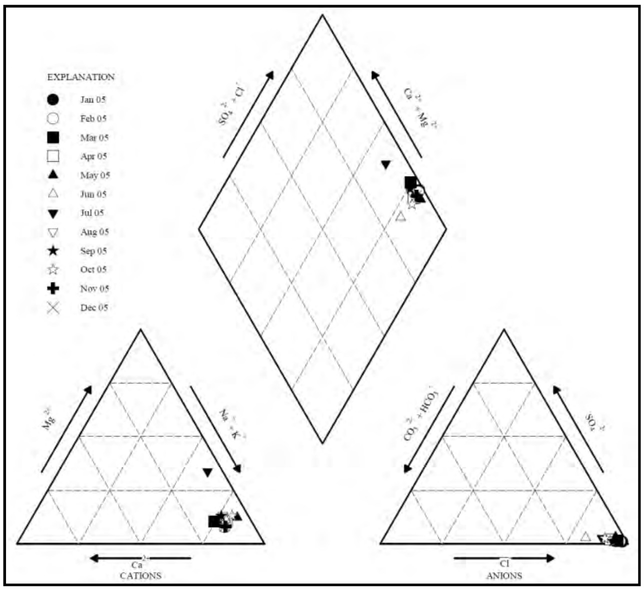

Figure 5.13: Hill Piper diagram for the strata TADW for the entire post tsunamic period for the year 2005. All stations were inundated by tsunami waves on 26 December, 2004 tsunami.

The diamond structure has data near the right hand side diagram typical for water with a specific nature for tsunami water contamination. This shows that the water existed with saline. The water has distinct ion character with Na 78%, Ca 12% and Mg 10%. But Chloride has 100% in ionic contribution in the anionic triangle. The ions were brought about indeed by tsunami waves.

Analysis of the Piper diagram for the strata TADW on the Arattupuzha in the subsequent months of the sampling shows that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph with persistent ionic contributions. The diamond structure has data near the right hand side of the diagram typical for water with a specific nature for strong saline character (Na^+ + K^+ and Cl^- + SO_4^{2-}) except month of June and July 2005 (by 180 days). Significant behavior of ions in ground water by this period may be due to the excessive dilution by rainwater. Slow but definite replenishment is being initiated by the ground water dilution brought about by the monsoonal activity of the region.

First triangle has a specific Na apex and second triangle has a chloride apex. But the water is saline with Na has 80-90%, Ca 5-10% and Mg 5-10% and Chloride has 92-100% (Figure 5.13). The contribution of SO_4^{2-} , CO_3^{2-} and HCO_3^{2-} are very negligible. Throughout the year the saline behavior is persistent with a very high ionic contribution.

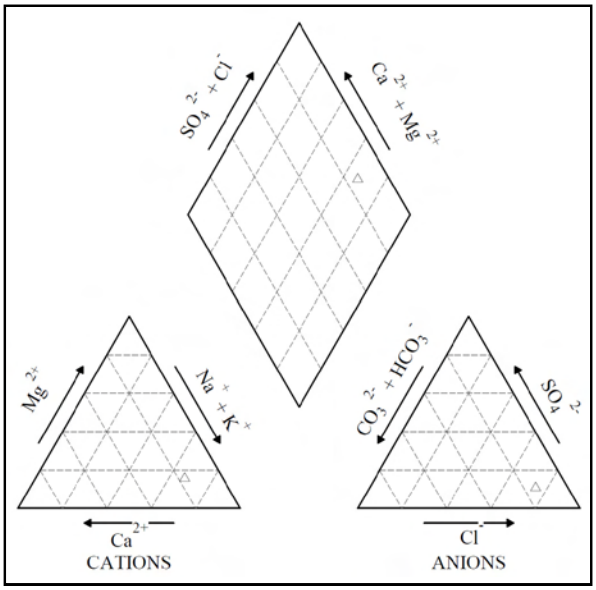

Figure 5.14: Hill Piper Trilinear diagrams of the tsunami affected dug well TADW (mean of 5 stations) Arattupuzha coast in December 2008. All stations were inundated by tsunami waves on 26 December, 2004.

Chloride contribution of 100% just after the tsunami comes down between 80-90% for the annual mean due to various factors regulated by the geographical features of the region by a period of one year duration. Further refinement of the water quality over the time is evaluated constructing Piper diagrams. Figure 5.14 shows that ground water of TADW as constructed Piper diagrams of the period after 4years (December, 2008; 1430 days).

The water is persistent with saline character with less ionic contribution of representative ions. The diamond structure of the Piper diagram has data near the right hand side typical for water with a specific nature for tsunami water contamination. This shows that the water still existed with saline nature with Na 64%, Ca 18% and Mg

18%. But Chloride has 77% in ionic contribution in the anionic triangle. The ions were brought about by tsunami waves have long term persistence in the region.

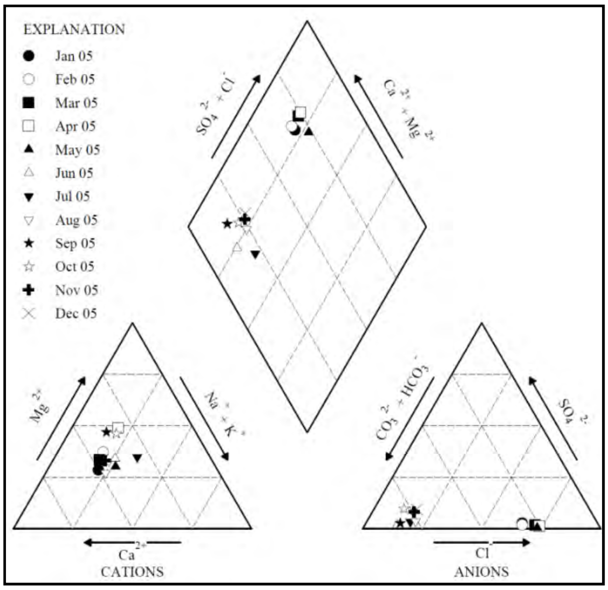

Figure 5.15: Hill Piper diagram for the strata of bore well BW; for the entire post tsunamic period of the year 2005. All stations were inundated by tsunami waves on 26 December, 2004 tsunami.

The quality profiles of the deep ground water of the region have also been evaluated over the same period of time and have been represented in the Hill – Piper - Trilinear plot shown in Figure 5.15. The triangles and diamonds have clusters of the data characteristic of temporary hardness (Ca^{2+}+ Mg^{2+} and Cl^- and SO_4^{2-}) with appreciable level of Chloride contribution in the post tsunamic period in the pre monsoonal session up to 120 days (by May 2005). In the post tsunamic post monsoonal session up to 330 days (by December 2005) deep ground water has features characteristic of temporary hardness (Ca^{2+}+ Mg^{2+} and HCO^{3-}) with representative ionic contributions.

5.7 Overall Water Quality of Arattupuzha coast, Kerala, India

Pertinent water quality parameters of the region after the tsunami inundation are given in respective tables. However, the overall water quality of the region consisting annual mean of the post tsunamic situation comprising eleven stations of the respective three strata are evaluated applying the t test; pH (8.0±0.4), EC (5.5±5.0) mS/cm, Ca (184±109) mg/l, Mg(110±56) mg/l, TH (895±392) mg CaCO3/l, Na (1412±957) mg/l, K (56±37) mg/l, Fe (0.05±0.04) mg/l, PO4 (0.14±0.23) mg/l, Turbidity (5.2±3.4) NTU, DO (4.7±1.5) mg/l, BOD (9.7±4.1) mg/l, alkalinity (221±47) mg/l, SO4 (78±78) mg/l, Cl (2844±2297) mg/l, NO_3 (0.0.81± 0.31) mg/l. This basic data structure indicates the post tsunamic ground water quality of the Alappad coast is used to evaluate the hydro chemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 5.7.

Prominent water quality parameters of Arattupuzha coast of Kerala in the post tsunamic situation ranges from pH (7.6-8.4), EC (0.5-10.5) mS/cm, Ca (75-293) mg/l, Mg(54-166) mg/l, TH (503-1287) mg CaCO3/l, Na (455-2369) mg/l, K (19-93) mg/l, Fe (0.01-0.09) mg/l, PO4 (0.0-0.37) mg/l, Turbidity (1.8-8.6) NTU, DO (3.2-6.2) mg/l, BOD (5.6-13.8) mg/l, alkalinity (174-268) mg/l, SO_4^{2-} (0-156) mg/l, Cl^- (547-5141) mg/l, NO_3^- (0.5-1.12) mg/l.

Table 5.7: Overall water quality parameters of the ground water sources of Arattupuzha, Alappuzha coast, Kerala, India in 2005 after 26 December 2004 Indian Ocean tsunami

Coastal Section	Data	pH	EC mS/cm	Ca mg/L	Mg mg/L	TH mg/L	Na mg/L	K mg/L	Fe mg/L	PO_4 mg/L	NTU	DO mg/L	BOD mg/L	Alkalinity mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Control	$\overline{x} \pm \sigma$	7.5±0.5	0.84±0.4	49±16	13±6	174±40	62±12	9±1	0.10±0.18	0.07±0.15	3±2	4±0.6	7±3	133±19	34±21	182±95	1.06±0.53
	μ	7.5±0.3	0.84±0.26	49±10	13±4	174±25	62±10	9±1	0.10±0.11	0.07±0.1	3±2	4±0.4	7±1.8	133±12	34±13	182±61	1.06±0.34
	CI	7.2-7.5	0.58-1.1	39-59	9-17	149-199	52-62	8-10	0-0.11	0-0.17	1-5	3.6-4.4	5.2-8.8	121-145	21-47	121-243	0.72-1.4
TADW after 7 days (January 2005)	$\overline{x} \pm \sigma$	7.9±0.2	9±3	230±88	104±52	1002±432	1296±1304	42±23	0.04±0.01	0.63±1.4	4±3	6.0±1.0	8.0±1.0	229±58	132±37	9849±4766	1.3±0.34
	μ	7.9±0.2	9±3	230±87	104±52	1002±430	1296±1299	42±23	0.04±0.01	0.63±1.4	4±3	6.0±0.7	8.0±0.8	229±57	132±37	9849±4749	1.3±0.34
	CI	7.7-8.1	6-12	143-317	52-156	572-1432	0.0-2595	19-65	0.03-0.05	0.0-2.03	1-7	5.3-6.7	7.2-8.8	172-286	95-169	5100-14598	0.96-1.64
TADW after 30 days (February 2005)	$\overline{x} \pm \sigma$	7.9±0.1	7.5±1.9	198±58	80±26	824±252	922±737	36±22	0.03±0.0	0.5±1.0	5±3	5.6±0.8	9.5±0.8	235±56	99±22	7173±3629	1.24±0.32
	μ	7.9±0.1	7.5±1.9	198±58	80±26	824±251	922±734	36±22	0.03±0.03	0.5±1.1	5±3	5.6±0.8	9.5±0.7	235±56	99±22	7173±3616	1.24±0.32
	CI	7.8-8.0	6-9.4	140-256	54-106	573-1075	188-1656	14-58	0.03-0.03	0.0-1.6	2-8	4.8-6.4	8.8-10.2	179-291	77-121	3557-10789	0.92-1.56
TADW after 150 days (June 2005)	$\overline{x} \pm \sigma$	7.7±0.7	4±2	102±49	70±61	544±292	550±472	23±16	0.03±0.02	0.16±0.35	3±1	3.8±1.3	14.1±1.7	532±524	81±22	623±597	0.54±0.29
	μ	7.7±0.7	4±2	102±49	70±60	544±291	550±470	23±16	0.03±0.02	0.16±0.35	3±1	3.8±1.3	14.1±1.7	532±521	81±22	623±594	0.54±0.29
	CI	7.0-8.4	2-6	53-151	10-130	253-835	80-1020	7-39	0.01-0.05	0.0-0.51	2-4	2.5-5.1	12.4-15.8	11-1053	59-103	29-1217	0.25-0.83
TADW after 330 days (December 2005)	$\overline{x} \pm \sigma$	7.6±0.2	2.3±2.1	92±61	23±9	323±183	246±269	22±19	0.06±0.02	0.32±0.22	3±3	3.3±1.5	5.2±2.3	241±99	42±19	306±388	0.67±0.2
	μ	7.6±0.2	2.3±2.1	92±61	23±9	323±182	246±268	22±18	0.06±0.02	0.32±0.11	3±3	3.3±1.5	5.2±2.2	241±99	42±19	306±387	0.67±0.2
	CI	7.4-7.8	0.2-4.4	31-153	14-32	141-505	0.0-514	4-40	0.04-0.08	0.21-0.43	0-6	1.8-4.8	3.0-7.4	142-340	23-61	0-693	0.47-0.87
TADW after 1430 days (December 2008)	$\overline{x} \pm \sigma$	7.3±0.2	0.6±0.3	25±8	14±8	120±31	106±59	11±8	0.14±0.04	0.39±0.71	3±1	2.4±1.6	9.2±5.3	26±11	19±18	97±80	0.88±0.71
	μ	7.3±0.2	0.6±0.3	25±8	14±8	120±31	106±59	11±8	0.14±0.04	0.39±0.71	3±1	2.4±1.5	9.2±5.0	26±11	19±18	97±80	0.88±0.71
	CI	7.1-7.5	0.3-0.9	17-33	6-22	89-151	47-165	3-19	0.1-0.18	0.0-1.10	2-4	0.9-3.9	4.2-14.2	15-37	1-37	17-177	0.17-1.59
BW after 7 days (January 2005)	$\overline{x} \pm \sigma$	7.7±0.4	1.0±0.0	81±45	28±9	318±132	35±24	8±3	0.11±0.17	0.0±0.0	5±5	5.0±3.0	7.0±3.0	220±15	16±9	286±237	1.0±0.39
	μ	7.7±0.4	1.0±0.3	81±50	28±10	318±147	35±27	8±3	0.11±0.19	0.0±0.0	5±5	5.0±3.0	7.0±3.0	220±17	16±10	286±264	1.0±0.43
	CI	7.3-8.1	0.7-1.3	31-131	18-38	171-465	8-62	5-11	0.0-0.30	0.0-0.0	0-10	2.0-8.0	4.0-11.0	203-237	6-26	22-550	0.57-1.43
BW after 30 days (February 2005)	$\overline{x} \pm \sigma$	7.7±0.2	0.5±0.2	60±24	31±8	278±88	26±11	7±2	0.08±0.13	0.0±0.0	5±4	4.5±3.0	8.2±2.0	239±30	11±5	284±194	0.91±0.39
	μ	7.7±0.2	0.5±0.2	60±26	31±9	278±98	26±12	7±2	0.08±0.15	0.0±0.0	5±5	4.5±3.3	8.2±2.2	239±33	11±5	284±215	0.91±0.43
	CI	7.5-7.9	0.3-0.7	34-86	22-40	180-376	14-38	5-9	0.0-0.23	0.0-0.0	0-10	1.2-7.8	6-10.4	206-272	6-16	69-499	0.48-1.34
BW after 150 days (June 2005)	$\overline{x} \pm \sigma$	7.5±0.6	0.7±0.2	39±15	20±8	179±10	25±12	6±1	0.02±0.01	0.0±0.0	11±7	3.1±1.8	21.4±12.7	229±15	10±10	55±49	0.61±0.14
	μ	7.5±0.4	0.7±0.2	39±17	20±9	179±11	25±13	6±1	0.02±0.01	0.0±0.0	11±7	3.1±1.9	21.4±14.1	229±16	10±11	55±55	0.61±0.15
	CI	7.1-7.9	0.5-0.9	22-56	11-29	168-190	12-38	5-7	0.01-0.03	0.0-0.0	4-18	1.2-5.0	7.3-35.5	213-245	0-21	0-110	0.46-0.76
BW after 330 days (December 2005)	$\overline{x} \pm \sigma$	7.3±0.3	0.8±0.1	45±5	20±4	194±15	20±5	6±1	0.02±0.02	0.32±0.23	2±2	3.8±2.4	4.2±2.0	211±18	22±19	31±17	0.91±0.26
	μ	7.3±0.3	0.8±0.1	45±6	20±4	194±17	20±5	6±1	0.02±0.02	0.32±0.25	2±2	3.8±2.6	4.2±2.2	211±20	22±21	31±19	0.91±0.29
	CI	7.0-7.6	0.7-0.9	39-51	16-24	177-211	15-25	5-7	0.0-0.04	0.07-0.57	0-4	1.2-6.4	2.0-6.4	191-231	1-43	12-50	0.62-1.2
BW after 1430 days (December 2008)	$\overline{x} \pm \sigma$	7.2±0.0	0.3±0.0	22±3	13±4	107±15	60±7	7±1	0.11±0.08	0.08±0.09	3±1	5.7±2.9	9.2±5.3	23±13	3±1	14±4	0.48±0.62
	μ	7.2±0.0	0.3±0.0	22±3	13±5	107±17	60±8	7±1	0.11±0.08	0.08±0.1	3±1	5.7±3.2	9.2±5.8	23±14	3±1	141±4	0.48±0.68
	CI	7.2-7.2	0.3-0.3	19-25	8-18	90-124	52-68	5-8	0.03-0.19	0.0-0.18	2-4	2.5-8.9	3.4-15.0	9-37	2-4	10-18	0.00-1.16
Overall region	$\overline{x} \pm \sigma$	8.0±0.5	5.5±6.9	184±162	110±83	895±584	1412±1424	56±56	0.05±0.05	0.14±0.35	5.2±5.1	4.7±2.2	9.7±6.1	221±70	78±117	2844±3419	0.81±0.47
	μ	8.0±0.4	5.5±5.0	184±109	110±56	895±392	1412±957	56±37	0.05±0.04	0.14±0.23	5.2±3.4	4.7±1.5	9.7±4.1	221±47	78±78	2844±2297	0.81±0.31
	CI	7.6-8.4	0.5-10.5	75-293	54-166	503-1287	455-2369	19-93	0.01-0.09	0-0.37	1.8-8.6	3.2-6.2	5.6-13.8	174-268	0-156	547-5141	0.5-1.12
BIS Standard		6.5-8.5		75	30	300			0.3		5			200	200	250	50
USEPA		6.5-8.5					20		0.3		0.5-5				250	250	10
WHO		6.5-8.5					200		0.3		5				250	250	50
EEC		6.2-8.5			50	50	175	12	0.2	5	4				250		50
KSPCB		6.5-8.5		75		300			0.3		5			200	200	250	50

5.8 Post-Tsunami Water Quality of Andhakaranazhy Coast, Alappuzha, Kerala, India

Andhakaranazhy coast situated on the northern coastal segment of Alappuzha district is one of the severely inundated region after Arattupuzha with marked loss of five human lives, crashing residential buildings and affecting narrow barrier land putting to expansive inundation. Andhakaranazhy is a bay region near to and south of Cochin bar mouth is characterized by seasonally opening sand bar. Tsunami struck very hard on the southern tip of the barrier islet that has been thickly populated living mostly semi permanent and permanent houses. The region is highly under severe water stress as there is only few dependable fresh water dug well sources. Most of them were very shallow but gifted with fresh water though placed very near to the shoreline. Figure 5.16 is the location map of tsunami devastated Andhakaranazhy coast, badly inundated during tsunami event. A view of the Andhakaranazhy coastal strip is given in Figure 5.18.

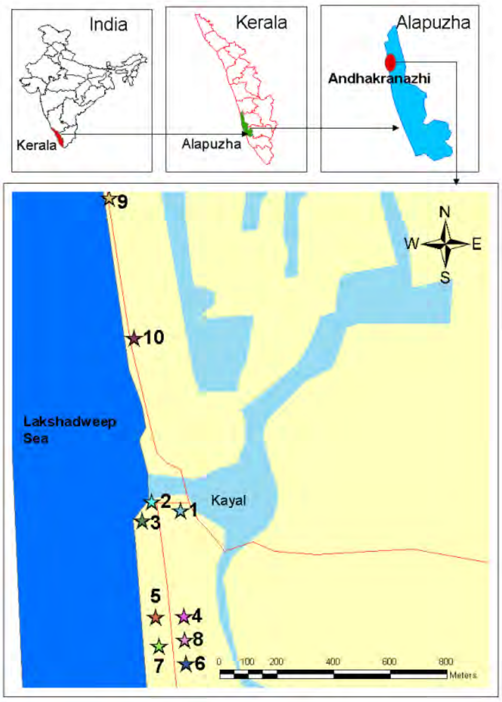

Figure 5.16: Location map of the tsunami affected Andhakaranazhy coast

The region is highly under severe water stress as there are only few dependable fresh water dug well sources. Most of them were very shallow but gifted with fresh water though placed very near to the shoreline. (Figure 5.17 is a representative fresh water dug well situated near the shore badly inundated during tsunami event. This well is later identified as a sampling station but is having a peculiar feature of quality fresh water throughout the year). There are ten sampling stations identified in this coastal section and the location and the nature of the sources are described in the Table 5.8. Of the total 10 sampling stations seven are of dug wells with average depth six feet, two are of shallow bore wells and one is an open shallow pond. Many households of the location meet their daily fresh water requirement from this poorly maintained open pond situated in the courtyard of four hundred years old house (Achari, 2005) presented in Figure 1.15.

Table 5.8: Water quality sampling stations representing various classes on Tsunami affected Andhakaranazhy coast (Alappuzha) in 2005.

Station	Remarks	Location
1. Dug well-canal side	Dug well Affected, not cleaned	09° 44’ 50N, 76° 17’ 07E
2. Mariamma-house owner	Dug well Affected and cleaned	09° 44’ 50N, 76° 17’ 05E
3. Maniyan- house owner -	Dug well Affected and cleaned	09° 44’ 48N, 76° 17’ 04E
4. James- house owner	Dug well Affected and cleaned	09° 44’ 37N, 76° 17’ 08E
5. Pius- house owner	Dug well Affected and cleaned	09° 44’ 37N, 76° 17’ 07E
6. Sebastian- house owner	Tube well – 6 feet depth	09° 44’ 35N, 76° 17’ 07E
7. Devdas- house owner	Tube well – 5 feet depth	09° 44’ 35N, 76° 17’ 07E
8. Babu- house owner	Open Community Pond affected-	09° 44’ 36N, 76° 17’ 08E
9. Purushothaman- house owner	Dug well Affected and cleaned	09° 45’ 25N, 76° 17’ 00E
10.George- house owner	Dug well Affected and cleaned	09° 45’ 09N, 76° 17’ 03E

The tsunami waves that propagated through the barmouth devastatingly rolled into the bay and engulfed the populated southern islet stretch moved eastwardly into the canal. Finally causing severe damage to houses and rolling packs of seawater into the coastal land of course the dug wells. The sampling and analyses of the groundwater samples from the respective stations have been done month wise as per the common protocol followed.

Figure 5.17: Water quality monitoring station 3 at Andhakaranazhy coast, Alappuzha. It is a dug well directly affected by tsunami waves, but exists as perennial fresh water source situated on the shoreline.

Unlike in the earlier sections the clustering of the data under separated strata is not attempted. Since the earlier studies specifically showed that few parameters such as pH, alkalinity, hardness, sodium and chloride has a significant persistence in the costal hydrosphere over a period of time. Hence the major discussion in this section is limited to the study of the overall contribution of these ions though the complete data is available after rigorous sampling and analyses. Overall water quality parameters and their intervariability are critically discussed.

Figure 5.18: A view of the thin coastal strip of Tsunami affected Andhakaranazhy coast, Alappuzha, Kerala, India.

The pH varies from 7.0 ±0.2 to 7.9 ±0.3. The region exhibited a high pH 8.3 is observed for the station1, a dug well near the canal side close to the barrage in the month of September 2005 (240 D).. Throughout the month the pH of this station has been high due to proximity to the bar mouth and chances of fluctuating wave activity. This station marked as station1 in the location map is a public well not maintained by any one. All sampling stations (Table 5.8) in this coastal section are well dewatered and cleaned after the strong inundation by tsunami waves except the station 1.

Figure 5.19 shows the pH profile of the region for the tsunami affected dug wells on this coastal section. Just after the tsunami the pH of the ground water sources has been high with pH 7.7±0.3. In the following months it is coming down to the lowest pH of 7±0.2 by July 2005 (180 days). Thereafter the pH rises to maximum of 7.9±0.3. Afterwards, pH declines to a stable and consistent level. Every time the pH of the ground water in the post tsunami situation remained within the permissible limit. The dedicated effort by the people ushered to dewatering helped to improve the original quality of drinking water sources. But pH becomes 7.2 ±0.2 by December 2008 (after 1430D).

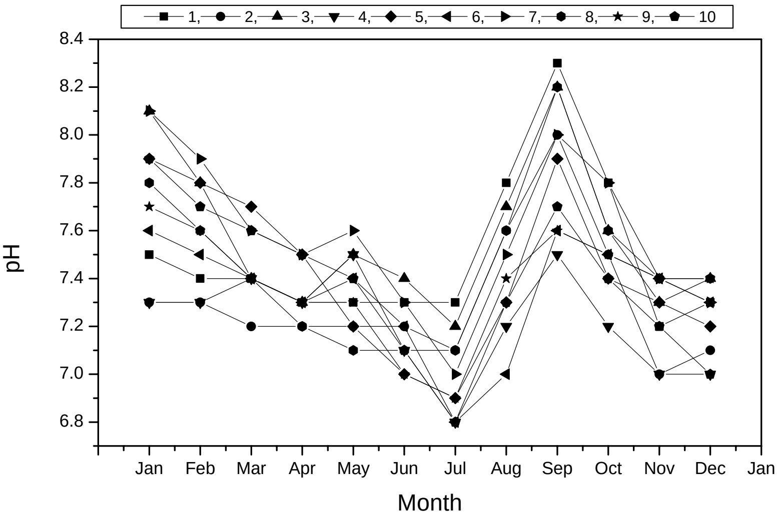

Figure 5.19: Temporal and spatial variation of pH at various sampling stations along Andhakaranazhy coast (Alappuzha, Kerala) during 2005; Post tsunamic Studies.

5.8.1 Sodium

Sodium content of ground water at Andhakaranazhy is given in the Figure 5.20. Highest sodium content has been observed just after the tsunami inundation $\bar{X}(Na^+)$ = 554 ±66 mg/L during the first sampling, after one week duration. This indicates direct inundation of the dug well sources by tsunami waves.

The sodium content has been very high in the initial months just after tsunami inundation declines to minimum by July 2005 (180days) thereafter a stable profile is maintained in the following months.

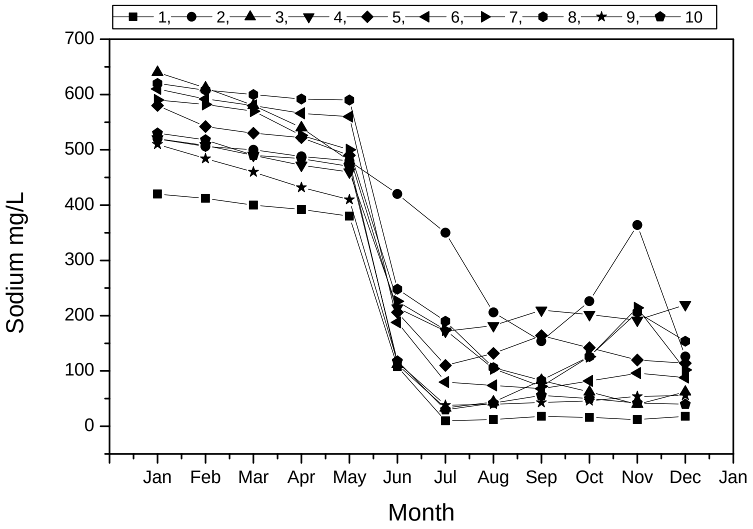

Figure 5.20: Temporal and spatial variation of Sodium at various sampling stations along Andhakaranazhy coast (Alappuzha, Kerala) during 2005; Post tsunamic Studies.

But the sodium content declines over time, by February 2005 (after 30D) $\bar{X}$ (Na^+) = 536 ±64 mg/L, by March (after 60D) $\bar{X}$ (Na^+) = 520 ±64 mg/L, by April 2005(after 90D) $\bar{X}$ (Na^+) = 501 ± 61 mg/L, by May(after 120D) $\bar{X}$ (Na^+) = 482 ±62 mg/L, by June 2005 (after 150D) $\bar{X}$ (Na^+) = 196 ±95 mg/L, by July 2005 (after 180D) $\bar{X}$ (Na^+) = 119±105 mg/L, by August 2005(after 210D) $\bar{X}$ (Na^+) = 94 ±64 mg/L, by September 2005(after 240D) $\bar{X}$ (Na^+) = 95 ±61 mg/L, by October 2005(after 270D) $\bar{X}$ (Na^+) = 108 ±69 mg/L , by November, 2005(after 300D) $\bar{X}$ (Na^+) = 134 ±110 mg/L, by December

2005(after 330D) $\bar{X}$ (Na^+) = 98 ±60mg/L. However annual mean of the data shows that $\bar{X}$ (Na^+) =286 ±73 mg/L. But sodium becomes 79 ±69 by December 2008 (after 1430D).

5.8.2 Chloride

Chloride content of the ground water sources of the Andhakaranazhy coast is given in Figure 5.21. It is seen that chloride slowly declines with respect to time and the lowest and stable level is attained after September 2005 (240 days).

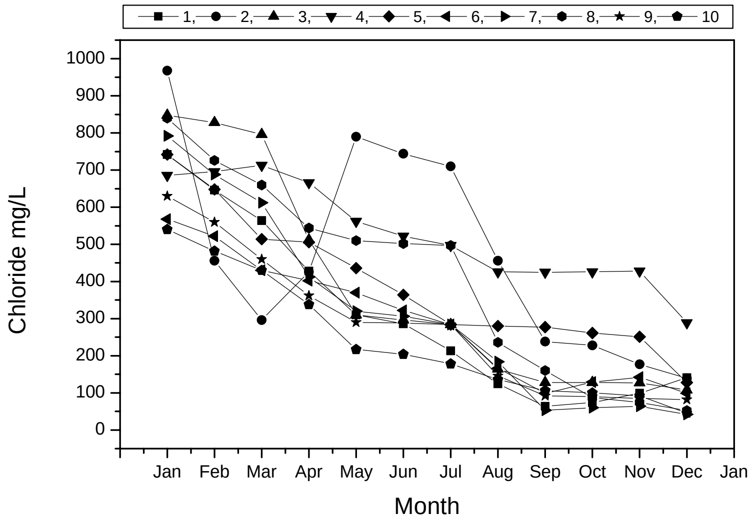

Figure 5.21: Temporal and spatial variation of Chloride at various sampling stations along Andhakaranazhy coast (Alappuzha, Kerala) during 2005; Post tsunamic Studies.

Ground water sources of Andhakaranazhy coast has highest chloride content just after the tsunami inundation $\bar{X}$ (Cl) = 736 ±134 mg/L during the first sampling, after one week duration.

Content declines over time, by February 2005 (after 30D) $\bar{X}$ (Cl) = 625±118 mg/L, by March(after 60D) $\bar{X}$ (Cl) = 548±151 mg/L, by April 2005(after 90D) $\bar{X}$ (Cl) = 460 ±98 mg/L, by May (after 120D) $\bar{X}$(Cl) = 412±170 mg/L, by June 2005 (after 150D) $\bar{X}$ (Cl) = 383±161 mg/L, by July 2005 (after 180D) $\bar{X}$ (Cl) = 352±164 mg/L, by August 2005(after 210D) $\bar{X}$ (Cl) = 232±120 mg/L, by September 2005(after 240D) $\bar{X}$ (Cl) = 164±117 mg/L, by October 2005(after 270D) $\bar{X}$ (Cl) = 158±115mg/L, by November, 2005 (after 300D) $\bar{X}$ (Cl) = 154±112 mg/L, by December 2005(after 330D) $\bar{X}$ (Cl) = 113±72 mg/L. However, annual mean of the data shows that $\bar{X}$ (Cl) =361 ±121 mg/L a level above the permissible level. But chloride becomes 76 ±43 by December 2008 (after 1430D).

5.8.3 Total Hardness

Total hardness of the ground water of the Andhakaranazhy region has been very high just after the tsunami inundation with $\bar{X}$(TH) = 702±177 mg/L during the first sampling, after one week duration.

Afterwards it declines to a minimum and lowest level after July 2005(180 D) thereafter a slight increase is found for all stations but maintains a steady and stable profile (Figure 5.22).

High total hardness in the initial stages will be due to the presence of excess hardness contributing ions by tsunami waves. The decline over the time may be due to the exchange of calcium and magnesium ions by soil. Evaluation of calcium and magnesium content of the ground water shows that the magnesium of the region is very fast removed with respect to time.

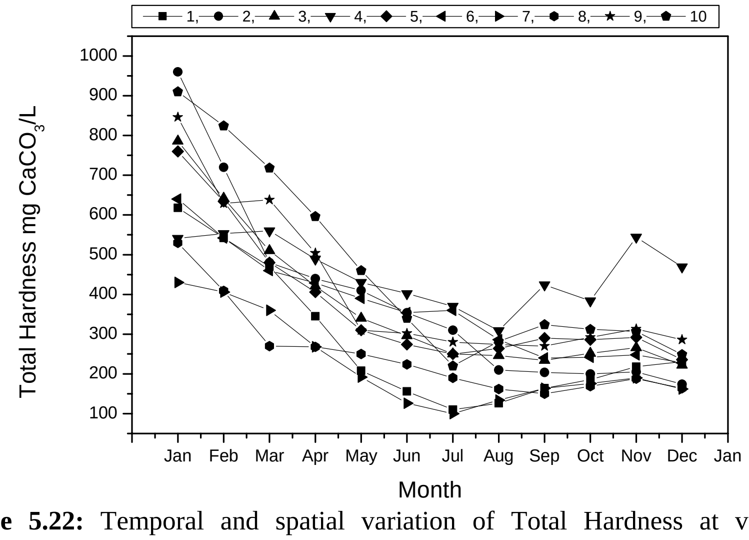

Figure 5.22: Temporal and spatial variation of Total Hardness at various sampling stations along Andhakaranazhy coast (Alappuzha, Kerala) during 2005; Post tsunamic Studies.

The total hardness content of the ground water with respect to the time interval is given by February 2005 (after 30D) $\bar{x}$ (TH) = 590±129 mg/L, by March(after 60D) $\bar{x}$ (TH) = 495±127 mg/L, by April 2005(after 90D) $\bar{x}$ (TH) = 417±103mg/L, by May (after 120D) $\bar{x}$ (TH) = 330±93 mg/L, by June 2005 (after 150D) $\bar{x}$ (TH) = 283±90 mg/L, by July 2005 (after 180D) $\bar{x}$ (TH) = 244±93 mg/L.

Table 5.9: Water Quality parameters of Andhakaranazhy coast in 2005 after 26 December 2004 Indian Ocean Tsunami.

Parameters	(7 days ; Jan 2005)		(Annual Mean, 2005)		(Annual Mean, 2008)	
	Value	Range	Value	Range	Value	Range
pH	7.7±0.2	7.5-7.9	7.4±0.2	7.2-7.6	7.2±0.2	7.0-7.4
EC	5.7±0.8 mS/*cm*	4.9-6.5	2.7±1.5	1.2-4.2	0.9±0.6 mS/*cm*	0.3-1.7
Ca	132±22 mg/L	110-154	101±37	64-138	41±9 mg/L	32-50
Mg	81±16 mg/L	65-97	34 ±44	0-78	24±10 mg/L	14-34
TH	702±125 mg/L	577-827	382±207	175-589	203±59 mg/L	144-262
Na	554±47 mg/L	507-601	286±150	136-436	79±49 mg/L	30-128
K	25±4 mg/L	21-29	13±6	7-19	9±7 mg/L	2-16
Fe	0.07±0.05 mg/L	0.02-0.12	0.11±0.07	0.03-0.18	0.16±0.18 mg/L	0.02-0.34
PO_4	0.34±0.25 mg/L	0.09-0.59	0.28±0.08	0.20-0.36	0.38±0.3 mg/L	0.08-0.68
Turbidity	16±4 NTU	12-20	7±4	3-11	5±2 NTU	3-7
DO	2.9±0.9 mg/L	2.0-3.8	2.0±0.5	1.5-2.5	1.3±0.7 mg/L	0.6-2.0
BOD	2.8±0.5 mg/L	2.3-3.3	5.6±1.8	3.8-7.4	8.3±3.5 mg/L	4.8-11.8
Alkalinity	439±39 mg/L	400-478	324±63	261-387	34±8 mg/L	26-42
SO_4	23±13 mg/L	10-36	16±3	13-19	5±6 mg/L	0-11
Cl	736± 94mg/L	642-830	361±158	203-519	76±30 mg/L	46-106
NO_3	0.54±0.13 mg/L	0.41-0.67	0.40±0.09	0.31-0.49	1.42±0.12 mg/L	1.30-1.54
WQI	48±5	43-53	47±3	44-50	47±1	46-48

By August 2005 (after 210D) $\bar{x}$ (TH) = 229±67mg/L, by September 2005(after 240D) $\bar{x}$ (TH) = 246±85 mg/L, by October 2005 (after 270D) $\bar{x}$ (TH) = 250±70 mg/L, by November, 2005 (after 300D) $\bar{x}$ (TH) = 277±105 mg/L, by December 2005 (after 330D) $\bar{x}$ (TH) = 242±89mg/L. However, annual mean of the data shows that $\bar{x}$ (TH) =359 ±101 mg/L. But total hardness becomes 203 ±84 by December 2008 (after 1430D). (Table 5.9 & Figure 5.23).

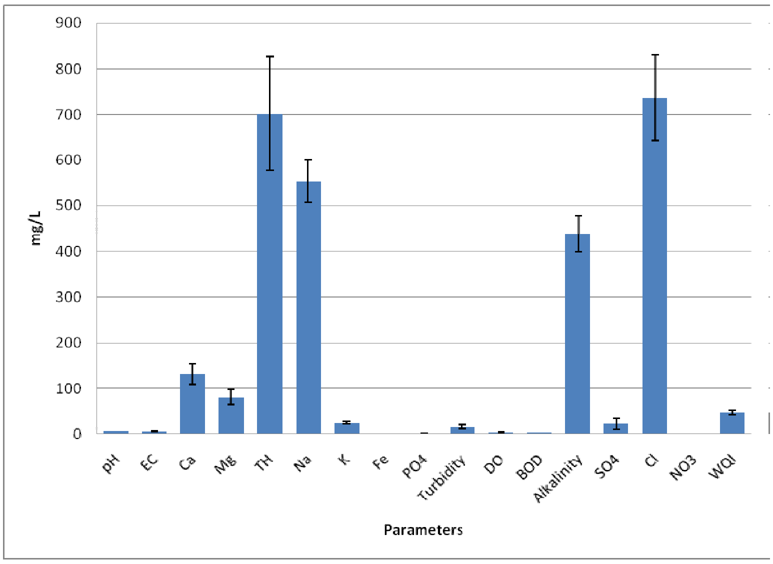

Figure 5.23: Water Quality parameters of Andhakaranazhy coas, Kerala India (7 Days after 26 December 2004 Indian Ocean Tsunami)

5.8.4 Water Quality Index (WQI)

Groundwater sources of the Andhakaranazhy have the lowest Water Quality Index *WQI* of 45 by 90 days (April, 2005). After the tsunami inundation $\bar{x}$(*WQI*) = 48±5 during the first sampling, after one week duration. This means the water is having fair quality just below medium/ average quality. Though the dug wells are well dewatered and cleaned after the inundation, the quality is not seem to be improved.

Water quality index of the region varies over the time by February 2005 (after 30D) $\bar{x}$(*WQI*) = 47±5, by March(after 60D) $\bar{x}$(*WQI*) = 46±4, by April 2005 (after 90D) $\bar{x}$(*WQI*) = 45±3, by May (after 120D) $\bar{x}$(*WQI*) = 46±4, by June 2005 (after 150D) $\bar{x}$(*WQI*) = 47±4, by July 2005 (after 180D) $\bar{x}$(*WQI*) = 47±5, by August 2005(after 210D) $\bar{x}$(*WQI*) = 48±4, by September 2005(after 240D) $\bar{x}$(*WQI*) = 49±4, by October 2005(after 270D) $\bar{x}$(*WQI*) = 48±4, by November, 2005 (after 300D) $\bar{x}$(*WQI*) = 47±4, by December 2005(after 330D) $\bar{x}$(*WQI*) = 47±3 (Figure 5.24 & Figure 5.25).

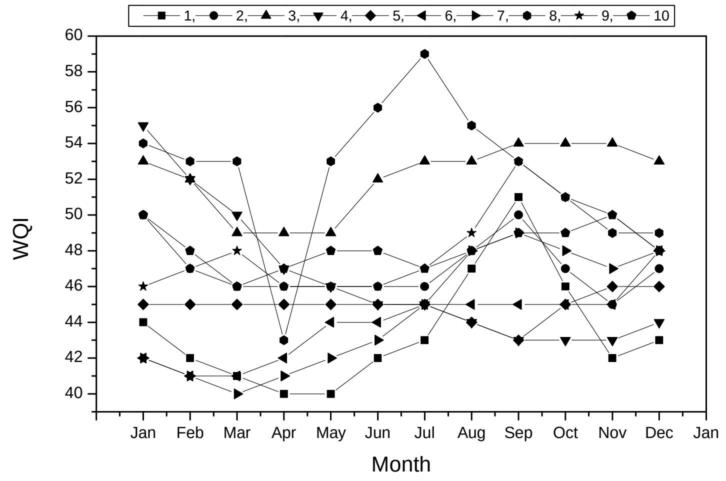

Figure 5.24: Temporal and spatial variation of WQI at various sampling stations along Andhakaranazhy coast, Kerala, India (Alappuzha, Kerala) during 2005, after 26 December 2004 Indian Ocean tsunami.

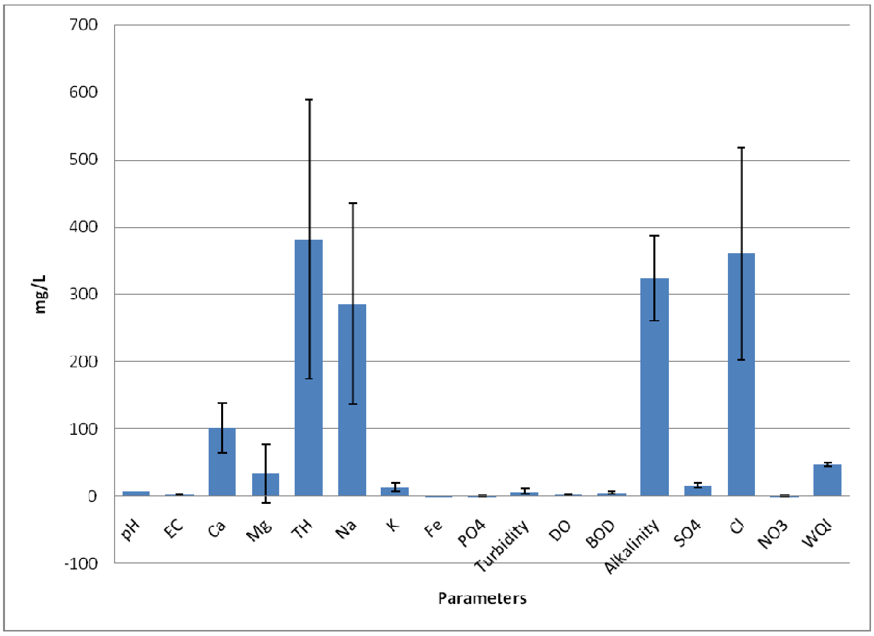

Figure 5.25: Water Quality parameters (Annual mean 2005) of Andhakaranazhy coast, Kerala, India, after 26 December 2004 Indian Ocean tsunami.

Annual mean of the WQI of the Andhakaranazhy region has been $\bar{X}(WQI) = 47 \pm 4$. But WQI becomes 48 ±3 by December 2008 (after 1430D). This shows that the water is not improving to a level above fair quality range. Even a single occasion of having average water quality is not observed in the coastal section.

5.8.5 Piper Plots and Water Quality Evaluation

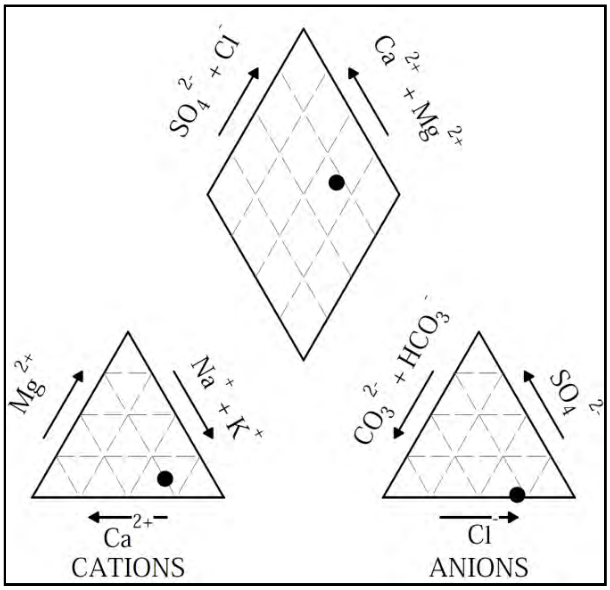

Figure 5.26: Hill Piper Trilinear diagrams of the tsunami affected dug well (mean of 10 stations) Andhakaranazhy coast in January 2005. All stations were inundated by tsunami waves on 26 December, 2004.

The diamond structure of the Hill- Piper- Trilinear plots of the ground water sources of Andhakaranazhy coast has data near the right hand side diagram typical for water with a specific nature for saline (Na^+ + K^+ and Cl^- + SO_4^{2-}). The Figure 5.26 shows that the water existed just after tsunami with strong saline behavior. Data near the right hand side of the diamond diagram is typical for water with a specific nature for tsunami water contamination. This shows that the water existed with saline. The ground water has distinct ion character with Na 68%, Ca 25% and Mg 7%. But Chloride has 70% in ionic contribution in the anionic triangle. The ions were indeed brought about indeed by tsunami waves.

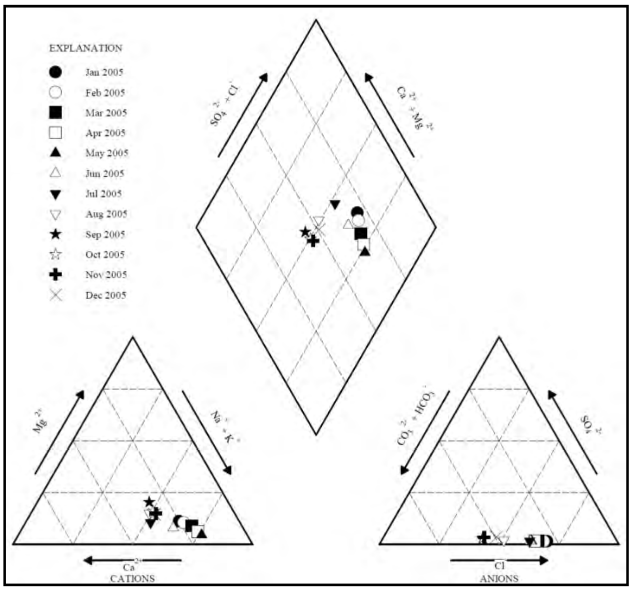

Figure 5.27: Hill Piper Trilinear diagrams of the tsunami affected dug wells, Andhakaranazhy coast in 2005, after 26 December 2004 Indian Ocean tsunami.

Analysis of the Piper diagram for the ground water of the Andhakaranazhy region in the subsequent months of post tsunamic period for the entire year of 2005 (Figure 5.27) shows that the first triangle has a Na apex and second triangle has a prominent Cl apex for the graph with persistent ionic contributions. The diamond structure has data near the right hand side of the diagram typical for water with a specific nature for strong saline character (Na^+ + K^+ and Cl^- + SO_4^{2-}) for a quite period of time till June 2005 (150 Days). By July 2005 (by 180 days) a transition in the quality occurs moving the ionic content specified by the position in the diamond. By August 2005 (210 D) the character of the water is shifting from the usual saline to the region of temporary hardness (Ca^{2+} + Mg^{2+} and HCO_3^-).

By August 2005 (210 D) the character of the water is shifting from the usual saline to the region of temporary hardness (Ca^{2+} + Mg^{2+} and HCO_3^-). This rapid shift in the quality is well revealed by a decline of Na content from 119 to 94mg/l (Table 5.11), Ca remains stable with 98 and 92 mg/l in the respective months (Mg content is 60 to 56 mg/l in the respective months). Excessive dilution by rainwater and other ionic exchange occurring in the sediment may be the reason for the change. Ground water is undergoing rapid refinement in this coastal segment compared to the other regions studied.

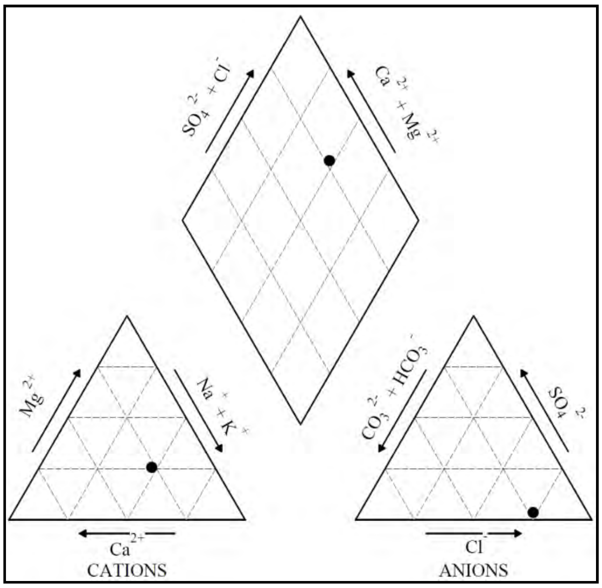

Figure 5.28: Hill Piper Trilinear diagrams of the tsunami affected dug well (mean of 10 stations) Andhakaranazhy coast in December 2008. All stations were inundated by tsunami waves on 26December, 2004.

Figure 5.28 shows the Piper diagram behavior of ground water of the Andhakaranazhy coast after 4years (December, 2005; 1430 days). The water is persistent with a slight saline character with less ionic contribution of representative ions. This shows that the water still existed with saline nature with a marginal Na apex and second triangle has a distinct chloride apex. But the water is saline with Na has 50%, Ca 25% and Mg 25% and Chloride has 75% , $SO_4^{2-}$is 1% and CO_3^{2-} and HCO_3^{2-} is 24%. The variation of WQI and Chloride are given in Tables 5.10 and 5.12 respectively.

Table 5.10: Water Quality Index data (WQI) of Andhakaranazhy coast, Kerala, India.

Strata	n		3 Jan 2005 (7 Days)	3 July 2005 (180 Days)	03 August 2005	3 Dec 2005 (330 Days)	Annual Mean 2005	2008 (1430Days)
TADW	10	$\bar{x} \pm \sigma$	48±5	47±5	48±4	47±3	47±4	48±3
		μ	48±4	47±4	48±3	47±2	48±3	48±2
		CI	44-52	43-51	45-51	45-49	45-51	46-50
Control Well	1	$\bar{x} \pm \sigma$	54	58	49	60	54±4	54

Table 5.11: Sodium data of Andhakaranazhy coast, Kerala, India.

Strata	n		3 Jan 2005 (7 Days)	3 July 2005 (180 Days)	03 August 2005	3 Dec 2005 (330 Days)	Annual Mean 2005	2008 (1430Days)
TADW	10	$\bar{x} \pm \sigma$	554±66	119±105	94±64	98±60	286±73	79±69
		μ	554±47	119±74	94±45	98±42	286±52	79±49
		CI	507-601	45-193	49-139	56-140	234-338	30-128
Control Well	1	$\bar{x} \pm \sigma$	42	46	56	90	62±16	40

Table 5.12: Chloride data of Andhakaranazhy coast, Kerala, India.

Strata	n		3 Jan 2005 (7 Days)	3 July 2005 (180 Days)	03 August 2005	3 Dec 2005 (330 Days)	Annual Mean 2005	2008 (1430Days)
TADW	10	$\bar{x} \pm \sigma$	736±134	352±164	232±120	113±72	361±121	76±43
		μ	736±95	352±116	232±85	113±51	361±85	76±30
		CI	641-831	236-468	147-317	62-164	26-446	46-106
Control Well	1	$\bar{x} \pm \sigma$	87	117	114	145	182±95	48

5.8.6 Overall Water Quality of Andhakaranazhy Coast

Overall water quality parameters of the Andhakaranazhy region after the tsunami inundation are given in respective tables. However, the overall water quality of the region annual mean of the post tsunamic situation comprising ten stations are evaluated as mean of the respective values after twelve months sampling and applying the students' t test.

Figure 5.29 shows the variation of chloride (TADW) with days at Andhakaranazhy coast as a function of time in the post tsunamic period after 26 December 2004 tsunami and Figure 5.30 that of Sodium(TADW) .

The evaluated parameters ranges from pH (7.4±0.2), EC (2.7±1.5) mS/cm, Ca (101±37) mg/l, Mg (34±44) mg/l, TH (382±207) mg CaCO3/l, Na (286±150) mg/l, K (13±6) mg/l, Fe (0.11±0.07) mg/l, PO_4 (0.28±0.08) mg/l, Turbidity (7±4) NTU, DO (2±0.5) mg/l, BOD (5.6±1.8) mg/l, alkalinity (324±63) mg/l, SO_4 (16±3) mg/l, Cl (361±158) mg/l, NO_3 (0.4± 0.09) mg/l. This basic data structure indicates the post tsunamic ground water quality of the Andhakaranazhy coast is used to evaluate the hydro chemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 5.13

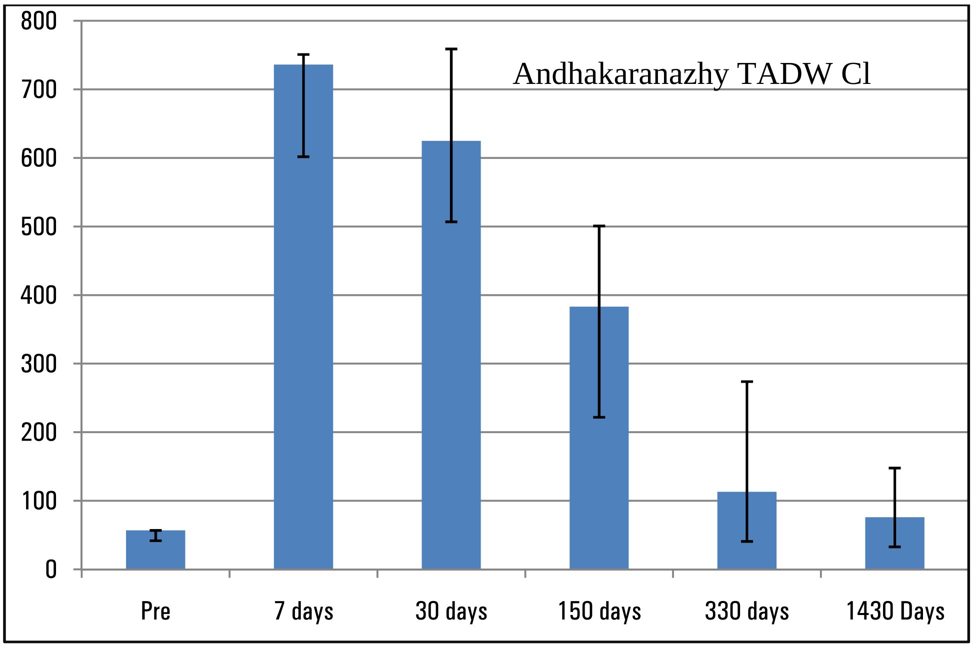

Figure 5.29: Variation of Chloride (TADW) with days at Andhakaranazhy coast, Kerala, India as a function of time in the post tsunamic period after 26 December 2004 Indian Ocean tsunami.

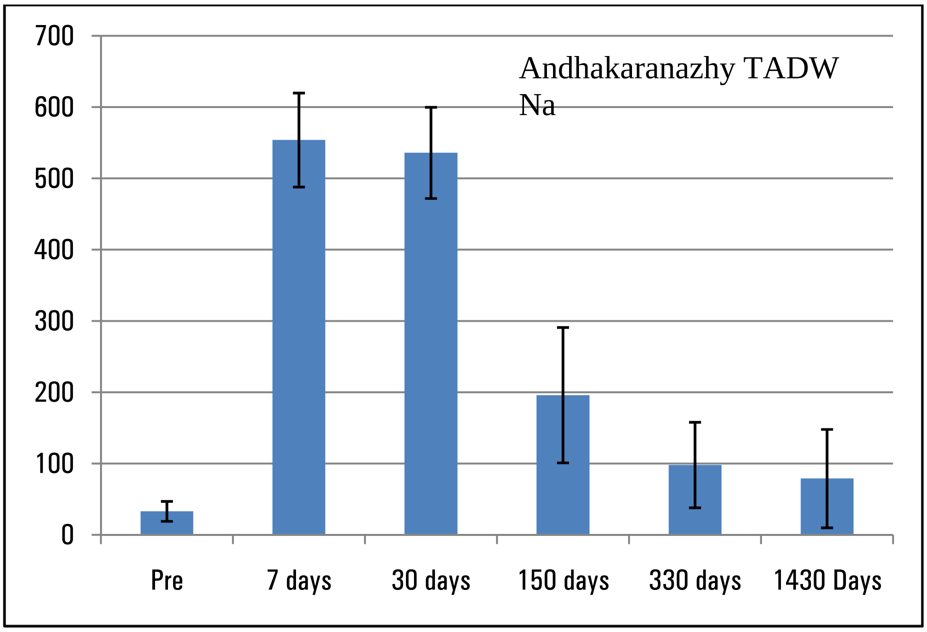

Figure 5.30: Variation of Sodium(TADW) with days at Andhakaranazhy coast, Kerala, India as a function of time in the post tsunamic period after 26 December 2004 Indian Ocean tsunami.

Prominent water quality parameters of Andhakaranazhy coast of Kerala in the post tsunamic situation ranges from pH (7.2-7.6), EC (1.2- 4.2) mS/cm, Ca (64 -138) mg/l, Mg (0-78) mg/l, TH (175-589) mg CaCO3/l, Na (136-436) mg/l, K (72-19) mg/l, Fe (0.03-0.18) mg/l, PO_4 (0.20-0.36) mg/l, Turbidity (3-11) NTU, DO (1.5-2.5) mg/l, BOD (3.8-7.4) mg/l, alkalinity (261-387) mg/l, SO_4^{2-} (13-19) mg/l, Cl^- (203-519) mg/l, NO_3^- (0.31-0.49) mg/l.

Table 5.13: Overall water quality parameters of the ground water sources of Andhakaranazhy coast, Kerala, India in 2005 after 26 December 2004 Indian Ocean tsunami

Coastal Section	Data	pH	EC mS/cm	Ca mg/L	Mg mg/L	TH mg/L	Na mg/L	K mg/L	Fe mg/L	PO_4 mg/L	NTU	DO mg/L	BOD mg/L	Alkalinity mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Control	$\overline{x} \pm \sigma$	7.5±0.5	0.84±0.4	49±16	13±6	174±40	62±12	9±1	0.10±0.18	0.07±0.15	3±2	4±0.6	7±3	133±19	34±21	182±95	1.06±0.53
	μ	7.5±0.3	0.84±0.26	49±10	13±4	174±25	62±10	9±1	0.10±0.11	0.07±0.1	3±2	4±0.4	7±1.8	133±12	34±13	182±61	1.06±0.34
	CI	7.2-7.5	0.58-1.1	39-59	9-17	149-199	52-62	8-10	0-0.11	0-0.17	1-5	3.6-4.4	5.2-8.8	121-145	21-47	121-243	0.72-1.4
TADW after 7 days (January 2005)	$\overline{x} \pm \sigma$	7.7±0.3	5.7±1.1	132±31	81±23	702±177	554±66	25±5	0.07±0.07	0.34±0.35	16±5	2.9±0.9	2.8±0.7	439±55	23±18	736±134	0.54±0.18
	μ	7.7±0.2	5.7±0.8	132±22	81±16	702±125	554±47	25±4	0.07±0.05	0.34±0.25	16±4	2.9±0.9	2.8±0.5	439±39	23±13	736±94	0.54±0.13
	CI	7.5-7.9	4.9-6.5	110-154	65-97	577-827	507-601	21-29	0.02-0.12	0.09-0.59	12-20	2.0-3.8	2.3-3.3	400-478	10-36	642-830	0.41-0.67
TADW after 30 days (February 2005)	$\overline{x} \pm \sigma$	7.6±0.2	5.3±1.1	123±36	69±22	590±129	536±64	23±5	0.07±0.07	0.34±0.34	14±4	2.7±0.8	3.2±0.7	414±40	21±18	625±118	0.49±0.19
	μ	7.6±0.2	5.3±0.8	123±25	69±15	590±91	536±45	23±3	0.07±0.05	0.34±0.24	14±3	2.7±0.6	3.2±0.5	414±28	21±13	625±83	0.49±0.13
	CI	7.4-7.8	4.5-6.1	98-148	54-84	499-681	491-581	20-26	0.02-0.12	0.1-0.58	11-17	2.1-3.3	2.7-3.7	386-442	8-34	542-708	0.36-0.62
TADW after 150 days (June 2005)	$\overline{x} \pm \sigma$	7.2±0.1	2.5±0.7	117±34	61±17	283±90	196±95	7±3	0.11±0.16	0.24±0.31	6±2	1.7±1.2	5.0±1.0	309±89	14±16	383±161	0.36±0.3
	μ	7.2±0.1	2.5±0.5	117±24	61±12	283±63	196±67	7±2	0.11±0.11	0.24±0.22	6±2	1.7±0.9	5.0±0.7	309±63	14±11	383±113	0.36±0.21
	CI	7.1-7.3	2.0-3.0	93-141	49-73	220-346	129-263	5-9	0.0-0.22	0.02-0.46	4-8	0.8-2.6	4.3-5.7	246-372	3-25	270-496	0.15-0.57
TADW after 330 days (December 2005)	$\overline{x} \pm \sigma$	7.2±0.2	1.1±0.4	0.0±0.0	0.0±0.0	242±89	98±60	9±6	0.08±0.04	0.26±0.36	3±3	1.1±0.8	8.7±3.2	168±32	14±20	113±72	0.35±0.19
	μ	7.2±0.1	1.1±0.3	0.0±0.0	0.0±0.0	242±63	98±42	9±4	0.08±0.03	0.26±0.25	3±2	1.1±0.6	8.7±2.2	168±23	14±14	113±51	0.35±0.14
	CI	7.1-7.3	0.8-1.4	0.0-0.0	0.0-0.0	179-305	56-140	5-13	0.05-0.11	0.01-0.51	1-5	0.5-1.7	6.5-10.9	145-191	0.0-28	62-164	0.21-0.49
TADW after 1430 days (December 2008)	$\overline{x} \pm \sigma$	7.2±0.2	0.9±0.8	0.0±0.0	0.0±0.0	203±84	79±69	9±9	0.16±0.25	0.38±0.42	5±3	1.3±1.0	8.3±5.0	34±12	5±8	7643	1.42±0.17
	μ	7.2±0.1	0.9±0.6	0.0±0.0	0.0±0.0	203±59	79±49	9±7	0.16±0.18	0.38±0.3	5±2	1.3±0.7	8.3±3.5	34±8	5±6	76±30	1.42±0.12
	CI	7.1-7.3	0.3-1.5	0.0-0.0	0.0-0.0	144-262	30-128	2-16	0.0-0.34	0.08-0.68	3-7	0.6-2.0	4.8-11.8	26-42	0.0-11	46-106	1.30-1.54
Overall region	$\overline{x} \pm \sigma$	7.2±0.3	0.9±0.8	41±14	24±14	203±84	79±70	9±9	0.16±0.25	0.38±0.42	5±3	1.3±1.0	8.3±5.0	34±12	5±8	76±43	1.42±0.17
	μ	7.2 ±0.2	0.9±0.6	41±9	24±10	203±59	79± 49	9±7	0.16±0.18	0.38±0.30	5±2	1.3±0.7	8.3±3.5	34±8	5±6	76±30	1.42±.12
	CI	7.0-7.4	0.3-1.7	32-50	14-34	144-262	30-128	2-16	0.02-0.34	0.08-0.68	3-7	0.6-2.0	4.8-11.8	26-42	0-11	46-106	1.30-1.54
BIS Standard		6.5-8.5		75	30	300			0.3		5			200	200	250	50
USEPA		6.5-8.5					20		0.3		0.5-5				250	250	10
WHO		6.5-8.5					200		0.3		5				250	250	50
EEC		6.2-8.5			50	50	175	12	0.2	5	4				250		50
KSPCB		6.5-8.5		75		300			0.3		5			200	200	250	50

5.9 Edavanakkad - Cherai Coast, Ernakulam

Edavanakkad-Cherai coast is the northern part of Vypin island of Ernakulam district, Kerala India. 26 December 2004 Indian Ocean tsunami had most devastated striking on this coast at 14.30 hours local time with a highest run-up of 4.0-4.5 m. The giant sea wall built on the coast has been crashed and heavy stones were moved away to hundreds of meters, leading mighty tsunami waves to advance to the coastal land area. Cherai beach is an upcoming international tourist destination with enough potential and numerous resources are the major attraction. Sampling stations selected on this coast are perennial dug well fresh water sources, those was directly flooded by the advancing tsunami waves.

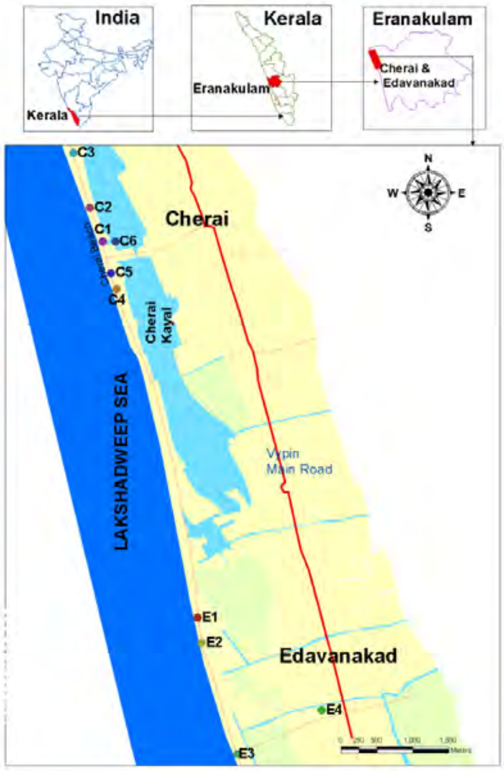

Figure 5.31: Location map of the tsunami affected Cherai coast, Kerala India. The region was severely inundated by the 26 December 2004 Indian Ocean tsunami.

Location map of the tsunami affected Cherai coast is given in Figure 5.31. The sampling stations are given in Tables 5.14 and 5.15.

Table: 5.14 Water quality-sampling stations on tsunami affected Edavanakkad-Cherai coast (Cochin) in 2005.

Station	Remarks	Location
1.Puthenkadappuram1	Open pond-between sea and backwater	10^o 05’ 13N, 76^o 11’ 33E
2.Puthenkadappuram2	Open pond- between sea and backwater	10^o 05’ 25N, 76^o 11’ 31E
3.EdvSouth	Open pond- between sea and backwater	10^o 04’ 20N, 76^o 11’ 50E
4.Ambrose-house owner	Not affected open cut well -control	10^o 04’ 41N, 76^o 12’ 30E

Table: 5.15 Water quality sampling stations representing various classes on Tsunami Affected Edavanakkad-Cherai coast (Cochin) in 2005.

Station	Remarks	Location
1. Francis- house owner	Dug well Affected and cleaned	10^o 08’ 24N, 76^o 10’ 46E
2. Varghese- house owner	Dug well Affected and cleaned	10^o 08’ 40N, 76^o 10’ 40E
3. Rosamma- house owner	Dug well Affected and cleaned	10^o 09’ 06N, 76^o 10’ 32E
4. RosammaTube well- house owner	Tube well-5 feet depth	10^o 08’ 06N, 76^o 10’ 32E
5. Varghese Madavana- house owner	Dug well Affected not cleaned	10^o 08’ 09N, 76^o 10’ 50E
6. Anandhan- house owner	Dug well Affected and cleaned well	10^o 08’ 24N, 76^o 10’ 52E

5.9.1 pH

pH variation of the ground waters of Edavanakkad - Cherai Coast, Ernakulam has been shown in the Figure 5.32. It is seen that pH slowly decline over the time that minimum is attained in the month of July 2005, thereafter it moves up with sharp jump up to September 2005. Then decline to minimum by December 2005.We could observe that the pH of the ground water is of Edavanakkad - Cherai Coast, Ernakulam varies from 6.9 ±0.2 to 8.0±0.4. It exhibited a high pH of 8.0±0.4 only one occasion September 2005.

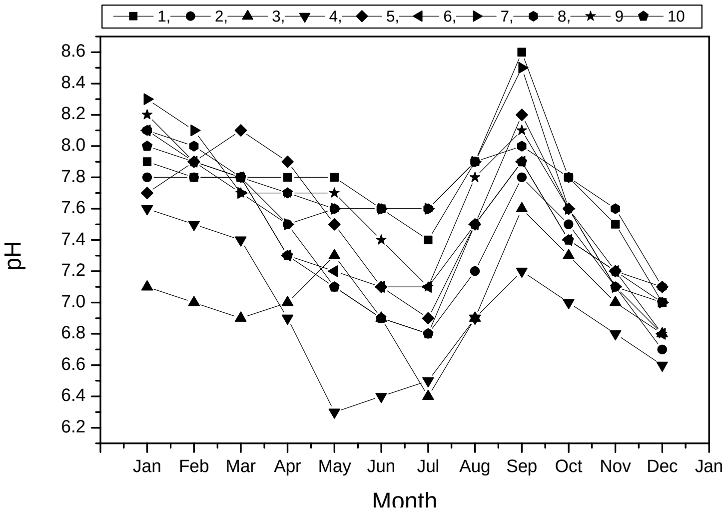

Figure 5.32: Temporal and spatial variation of pH at various sampling stations along Edavanakkad-Cherai coast (Ernakulam, Kerala) during 2005 after 26 December 2004 Indian Ocean tsunami; Post tsunamic Studies.

The shallow dug wells of the region are cleaned and dewatered. Just after tsunami incident the pH of the groundwater has been 7.9±0.4. By December 2005 (after 330Days) pH declines to 6.9±0.2. The decline in pH 7±0.4 observed in July 2005 (180 Days) will be due the natural self purification by monsoon dilution and other geographical phenomena. However, after 4 years the pH of the regions ground water becomes more to natural situation with pH 7.3±0.15. The overall water quality is retained in the level of 6.5 – 8.5.

5.9.2 Sodium

Sodium content of the region has been very high in the Edavanakkad - Cherai Coast, Ernakulam. The feature of sodium and its variability is shown in the Figure 5.33 that sodium has been very high just after the tsunami event and sharply declines to minimum after 150 days. Most sampling stations are shallow open ponds close to sea and the marsh with thin population of mangroves on the Edavanakkad coast. The continuous wave activity brought seawater could be reaching into the marsh. Groundwater has highest sodium content just after the tsunami inundation $\bar{X}(Na^+) = 3126 \pm 908$ mg/L during the first sampling, after one week duration. Content declines over time, by February 2005 (after 30D) $\bar{X}(Na^+) = 2941 \pm 929$ mg/L, by March (after 60D) $\bar{X}(Na^+) = 2769 \pm 949$ mg/L, by April 2005(after 90D) $\bar{X}(Na^+) = 2456 \pm 919$ mg/L.

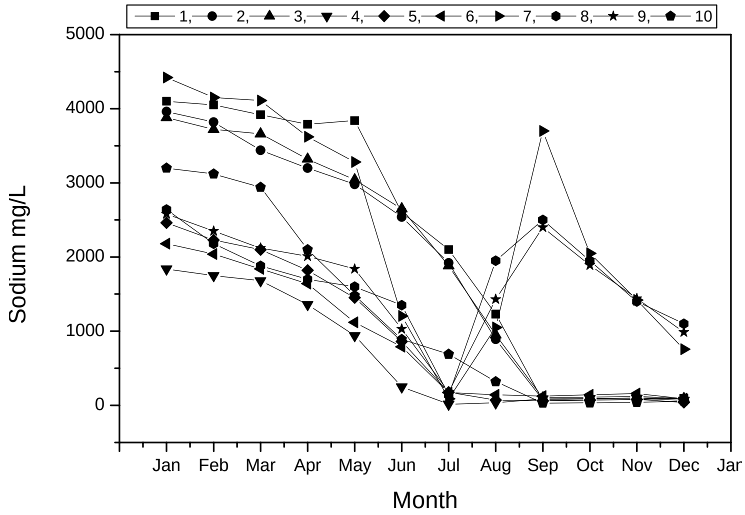

Figure 5.33: Temporal and spatial variation of Sodium at various sampling stations along Edavanakkad-Cherai coast (Ernakulam, Kerala) during 2005 after 26 December 2004 Indian Ocean tsunami; Post tsunamic Studies.

By May(after 120D) $(Na^+) = 2157 \pm 1026$ mg/L, by June 2005 (after 150D) $\bar{X}\ (Na^+) = 1416 \pm 864$ mg/L, by July 2005 (after 180D) $\bar{X}\ (Na^+) = 737 \pm 869$ mg/L, by August 2005 (after 210D) $\bar{X}\ (Na^+) = 807 \pm 648$ mg/L, by September 2005(after 240D) $\bar{X}\ (Na^+) = 914 \pm 1390$ mg/L, by October 2005 (after 270D) $\bar{X}(Na^+) = 650 \pm 908$ mg/L , by November, 2005 (after 300D) $\bar{X}\ (Na^+) = 494 \pm 640$ mg/L, by December 2005 (after 330D) $\bar{X}\ (Na^+) = 337 \pm 430$ mg/L. However annual mean of the data shows that $\bar{X}\ (Na^+) = 1567 \pm 876$ mg/L. By December 2008, sodium content declines to $\bar{X}\ (Na^+) = 95 \pm 325$ mg/L.

5.9.3 Chloride

Chloride content of ground waters of Edavanakkad - Cherai coast has been shown in the Figure 5.34.Highest chloride content of the ground water just after the tsunami inundation has been $\bar{x}$ (Cl) = 4273±2941 mg/L during the first sampling in January 2005. Afterwards the chloride content declines over time, by February 2005 (after 30D) $\bar{x}$ (Cl) = 3794±2686 mg/L, by March (after 60D) $\bar{x}$ (Cl) = 3367±2391 mg/L, by April 2005(after 90D) $\bar{x}$ (Cl) = 2702±2089 mg/L, by May (after 120D) $\bar{x}$ (Cl) = 2233±1949 mg/L, by June 2005 (after 150D) $\bar{x}$ (Cl) = 1898±1826 mg/L, by July 2005 (after 180D) $\bar{x}$ (Cl) = 1630±1885 mg/L.

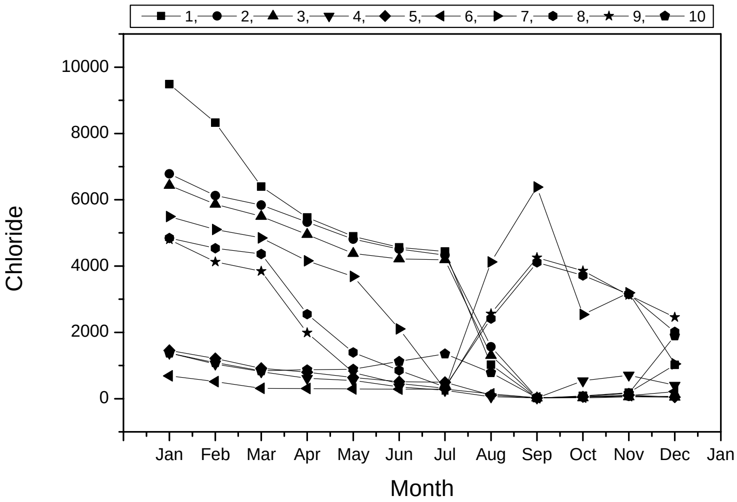

Figure 5.34: Temporal and spatial variation of Chloride at various sampling stations along Edavanakkad-Cherai coast (Ernakulam, Kerala) during 2005 after 26 December 2004 Indian Ocean tsunami; Post tsunamic Studies.

By August 2005(after 210D) $\bar{x}$ (Cl) = 1409±1309 mg/L, by September 2005(after 240D) $\bar{x}$ (Cl) = 1491±2438 mg/L, by October 2005 (after 270D) $\bar{x}$ (Cl) = 1097±1612 mg/L, by November, 2005 (after 300D) $\bar{x}$ (Cl) = 1084±1442 mg/L, by December 2005(after 330D) $\bar{x}$ (Cl) = 922±916 mg/L. However, annual mean of the chloride has been that $\bar{x}$ (Cl) = 2158 ± 1294 mg/L.

5.9.4 Total Hardness

Figure 5.35 shows the total hardness content of the ground waters of Edavanakkad-Cherai coast just after the tsunami inundation $\bar{X}$ (TH) = 1167±1067 mg/L during the first sampling, after one week duration. Afterwards, TH content declines over time, by February 2005 (after 30D) $\bar{X}$ (TH) = 967±827 mg/L, by March (after 60D) $\bar{X}$ (TH) = 786±640 mg/L, by April 2005(after 90D) $\bar{X}$ (TH) = 571±380 mg/L, by May (after 120D) $\bar{X}$ (TH) = 440±251 mg/L, by June 2005 (after 150D) $\bar{X}$ (TH) = 269±109 mg/L, by July 2005 (after 180D) $\bar{X}$ (TH) = 135±88 mg/L.

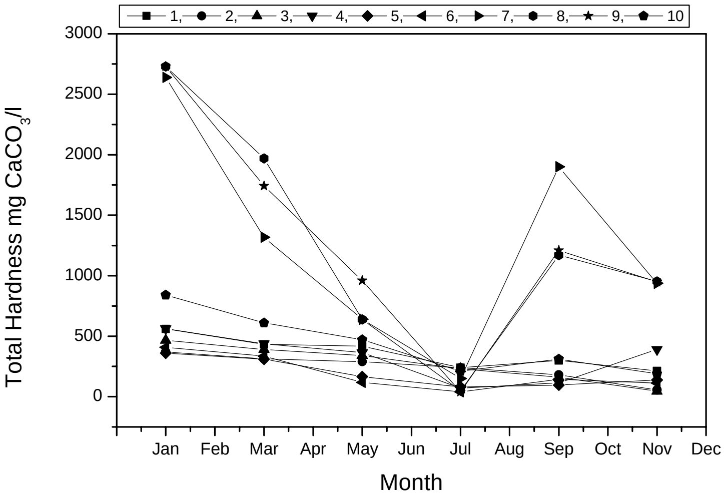

Figure 5.35: Temporal and spatial variation of TH at various sampling stations along Edavanakkad-Cherai coast (Ernakulam, Kerala) during 2005 after 26 December 2004 Indian Ocean tsunami; Post tsunamic Studies.

By August 2005 (after 210D) $\bar{X}$ (TH) = 289±200mg/L, by September 2005(after 240D) $\bar{X}$ (TH) = 558±634 mg/L, by October 2005 (after 270D) $\bar{X}$ (TH) = 463±479 mg/L, by November, 2005 (after 300D) $\bar{X}$ (TH) = 398±390 mg/L, by December 2005(after 330D) $\bar{X}$ (TH) = 294±259 mg/L.

Table: 5.16 Water Quality parameters of Edavanakkad – Cherai Coast in 2005 after 26 December Indian Ocean tsunami; post tsunami studies.

Parameters	(7 days ; Jan 2005)		(Annual Mean, 2005)		(Annual Mean, 2008)	
	Value	Range			Value	Range
pH	7.9±0.2	7.7-8.1	7.4±0.3	7.1-7.7	6.6±0.1	6.5-6.7
EC	6.0±4.0 mS/*cm*	2-10	4.1±1.6 mS/*cm*	2.5-5.7	0.9±0.7 mS/*cm*	0.2-1.6
Ca	334±220 mg/L	114-554	141±94 mg/L	47-235	113±151 mg/L	0-264
Mg	80±50 mg/L	30-130	43±30 mg/L	13-73	61±77 mg/L	0-138
TH	1166±750 mg/L	414±1918	528±312 mg/L	216-840	533±686 mg/L	0-1219
Na	3126±640 mg/L	2486-4034	1567±876 mg/L	691-2443	95±57 mg/L	38-152
K	168±42 mg/L	126-210	86±47 mg/L	39-133	10±7 mg/L	3-17
Fe	0.09±0.02 mg/L	0-7-0.11	0.10±0.08 mg/L	0.02-0.18	0.12±0.07 mg/L	0.05-0.19
PO_4	0.65±0.31 mg/L	0-34-0.96	0.55±0.22 mg/L	0.33-0.77	0.40±0.21 mg/L	0.19-0.61
Turbidity	20±9 NTU	11-29	12±4 NTU	8-16	1.3±1.0 NTU	0.6-2.0
DO	3.2±0.9 mg/L	2.3-4.1	3.6±1.2 mg/L	2.4-4.8	2.3±1.1	1.2-3.4
BOD	12.9±2.0 mg/L	10.9-14.9	9.4±1.9 mg/L	7.5-11.3	5.8±1.3 mg/L	4.5-7.1
Alkalinity	266±52 mg/L	214-318	190±40 mg/L	150-230	19±5.2 mg/L	13.8-24
SO_4	146±24 mg/L	122-90	84±32 mg/L	52-116	54±52 mg/L	2-106
Cl	4273±2073 mg/L	2200-6346	2158±1294 mg/L	864-3452	650±647 mg/L	3-1297
NO_3	1.6±0.8 mg/L	0.8-2.4	0.97±0.27 mg/L	0.70-1.24	0.93±0.26 mg/L	0.67-1.19
WQI	41±4	37-45	46±3	43-49	46±2	44-48

However, annual mean of the data shows that $\bar{x}$(TH) =528 ±312 mg/L (Table 5.16 & Figure 5.36).

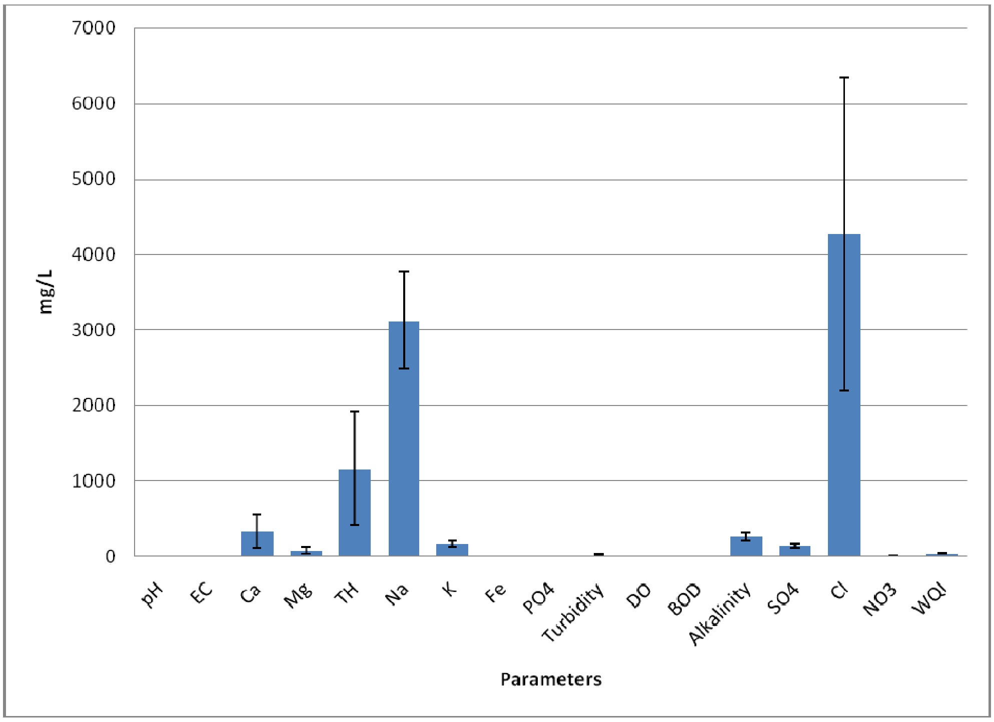

Figure 5.36: Water Quality parameters of Edavanakkad-Cherai coast (7 Days after 26 December 2004 Indian Ocean tsunami)

5.9.5 Water Quality Index (WQI)

Figure 5.37 shows the variation of Water Quality Index *WQI* of Edavanakkad- Cherai coast of Ernakulam District. After the tsunami inundation $\bar{X}(WQI) = 41 \pm 4$ during the first sampling, after one week duration. This means the water is having fair water quality. Afterwards, the water quality index declines over time, by February 2005 (after 30D) $\bar{X}(WQI) = 43 \pm 5$, by March (after 60D) $\bar{X}(WQI) = 46 \pm 6$, by April 2005 (after 90D) $\bar{X}(WQI) = 46 \pm 6$, by May (after 120D) $\bar{X}(WQI) = 47 \pm 6$, by June 2005 (after 150D) $\bar{X}(WQI) = 47 \pm 6$, by July 2005 (after 180D) $\bar{X}(WQI) = 47 \pm 6$.

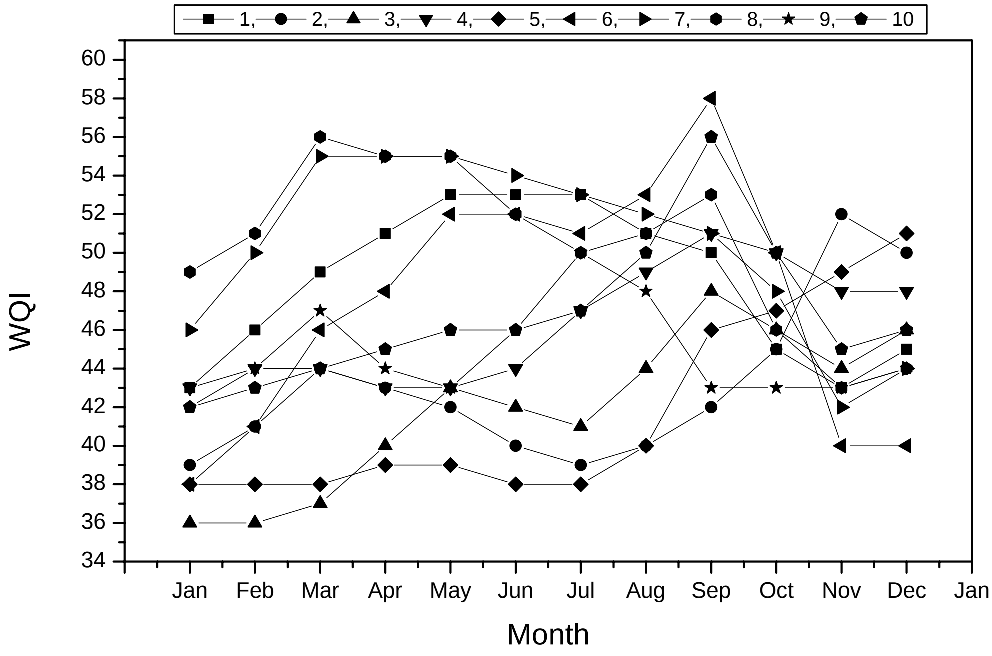

Figure 5.37: Temporal and spatial variation of WQI at various sampling stations along Edavanakkad-Cherai coast (Alappuzha, Kerala) during 2005 afetr 26 December 2004 Indian Ocean tsunami; Post tsunamic Studies.

By August 2005(after 210D) $\bar{x}$ (*WQI*) = 48±5, by September 2005(after 240D) $\bar{x}$ (*WQI*) = 50±5, by October 2005(after 270D) $\bar{x}$ (*WQI*) = 48±2, by November, 2005 (after 300D) $\bar{x}$ (*WQI*) = 45±4, by December 2005(after 330D) $\bar{x}$ (*WQI*) = 46±3.

However, annual mean of the water quality index has been $\bar{x}$ (*WQI*) = 46±3 maintain the fair water quality profile. Examination of the profile reveals that highest WQI of 50 is observed by 240 days (September, 2005). Monsoonal dilution might have improved the quality. Pertinent water quality parameters of the so-called *tsunami pool* after the tsunami inundation are given in respective table given above. Figure 5.38 shows the variation of water quality parameters of Cherai coast.

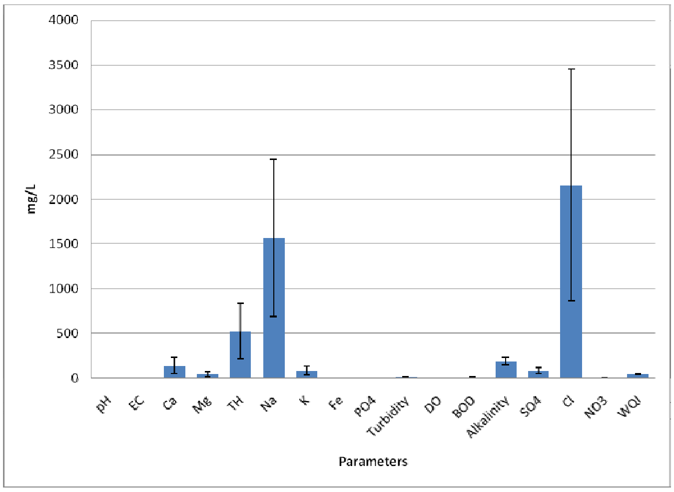

Figure 5.38: Water Quality parameters of Edavanakkad-Cherai coast, Kerala, India after 26 December 2004 Indian Ocean tsunami (Annual mean 2005)

5.9.6 Piper Plots and Water Quality Evaluation

The diamond structure of the Hill- Piper- Trilinear plots of this ground water sources has data near the right hand side diagram typical for water with a specific nature for saline (Na^+ + K^+ and Cl^- + SO_4^{2-}) type. It reveals that the water existed just after tsunami with strong saline behavior due to inundation by seawater.

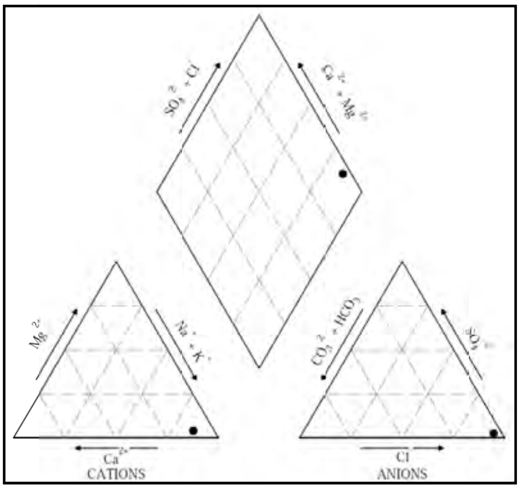

Figure 5.39: Hill Piper Trilinear diagrams of the tsunami affected dug well (mean of 10 stations) Edavanakkad-Cherai coast in January 2005. All stations were inundated by tsunami waves on 26December, 2004.

The Figure5.39 shows the Hill – Piper – Trilinear plots of the ground water just after tsunami is shown in the Figure. Diamond structure has data near the right hand side of the diagram typical for water with a specific nature for strong saline character (Na^+ + K^+ and Cl^- + SO_4^{2-}) with Na 85%, Ca 10% and Mg 5%. But Chloride has 95% in ionic contribution in the anionic triangle with CO_3^- 4% and SO_4^{2-} 1%.

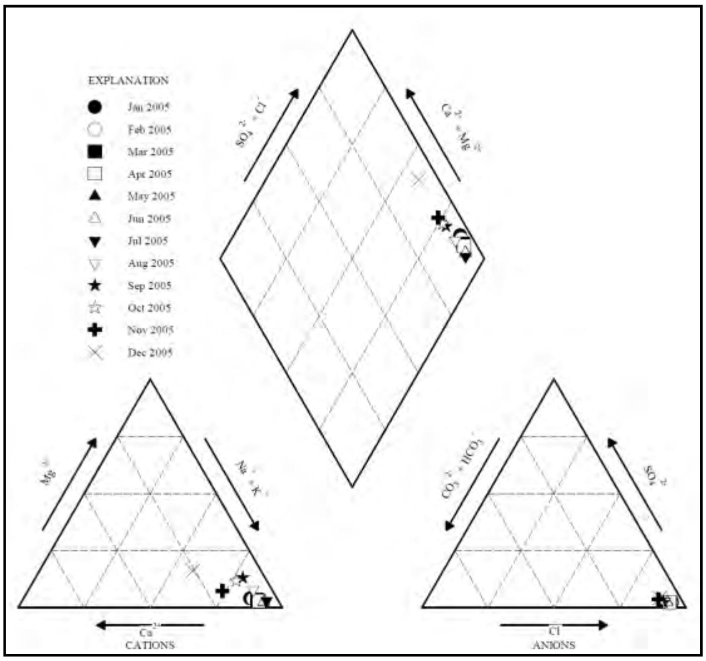

Figure 5.40: Hill Piper Trilinear diagrams of the tsunami affected dug wells Edavanakkad-Cherai coast in the year 2005. All stations were inundated by tsunami waves on 26 December, 2004

The Figure 5.40 shows the water type behavior of the Edavanakkad –Cherai coast, month wise in the post tsunamic year, 2005. Data near the right hand side of the diamond diagram is typical for water with a specific nature for tsunami water contamination. In the post tsunamic year of 2005 the ground water has distinct ion character with Na 55- 100%, Ca 0- 25% and Mg 0-20%. But Chloride has 90-100% in ionic contribution in the anionic triangle. The ions were indeed brought about indeed by tsunami waves.

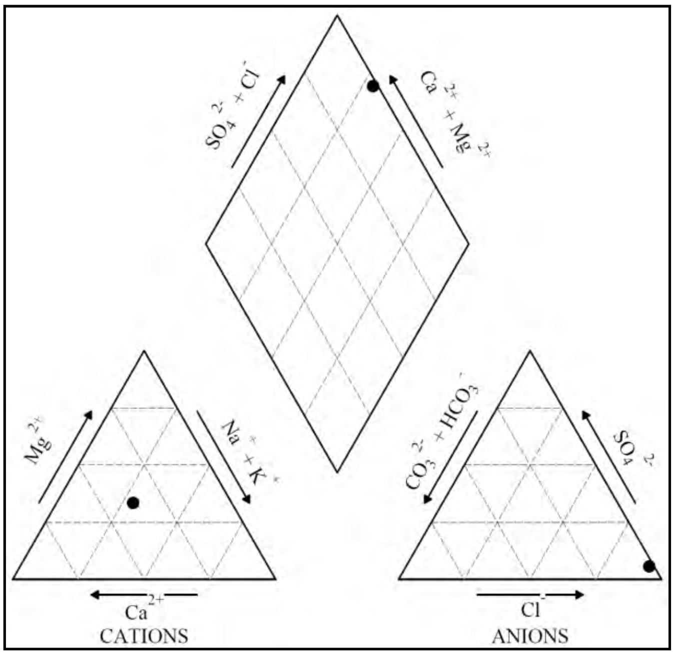

Figure 5.41: Hill Piper Trilinear diagrams of the tsunami affected dug well (mean of 10 stations) Edavanakkad-Cherai coast in December 2008. All stations were inundated by tsunami waves on 26December, 2004.

The Figure 5.41shows the water type behavior of the Edavanakkad –Cherai coast, in December 2008. Data upper side of the diamond diagram is typical for water with permanent hardness. The water after 4 years has a distinct ion character with Na 28%, Ca 37% and Mg 35%. But Chloride has 95% in ionic contribution in the anionic triangle with CO_3^- 1% and SO_4^{2-} 4%.

Table 5.17: Overall water quality parameters of the ground water sources of Edavanakkad-Cherai coast, Kerala, India in 2005 after 26 December 2004 Indian Ocean tsunami

Coastal Section	Data	pH	EC mS/cm	Ca mg/L	Mg mg/L	TH mg/L	Na mg/L	K mg/L	Fe mg/L	PO$_4$ mg/L	NTU	DO mg/L	BOD mg/L	Alkalinity mg/L	SO$_4$ mg/L	Cl mg/L	NO$_3$ mg/L
Control	$\overline{x} \pm \sigma$	7.5±0.5	0.84±0.4	49±16	13±6	174±40	62±12	9±1	0.10±0.18	0.07±0.15	3±2	4±0.6	7±3	133±19	34±21	182±95	1.06±0.53
	μ	7.5±0.3	0.84±0.26	49±10	13±4	174±25	62±10	9±1	0.10±0.11	0.07±0.1	3±2	4±0.4	7±1.8	133±12	34±13	182±61	1.06±0.34
	CI	7.2-7.5	0.58-1.1	39-59	9-17	149-199	52-62	8-10	0-0.11	0-0.17	1-5	3.6-4.4	5.2-8.8	121-145	21-47	121-243	0.72-1.4
TADW after 7 days (January 2005)	$\overline{x} \pm \sigma$	7.9±0.4	6.0±5.7	334±312	80±70	1166±1067	3126±908	168±60	0.09±0.03	0.65±0.43	20±12	3.2±1.3	12.9±2.9	266±74	146±34	4273±2941	1.6±1.2
	μ	7.9±0.2	6.0±4.0	334±220	80±50	1166±752	3126±640	168±42	0.09±0.02	0.65±0.31	20±9	3.2±0.9	12.9±2.0	266±52	146±24	4273±2073	1.6±0.8
	CI	7.7-8.1	2.0-10.0	114-554	30-130	414-1918	2486-4034	126-210	0.07-0.11	0.34-0.96	11-29	2.3-4.1	10.9-14.9	214-318	122-190	2200-6346	0.8-2.4
TADW after 30 days (February 2005	$\overline{x} \pm \sigma$	7.8±0.3	5.7±5.6	283±253	64±56	967±826	2941±929	160±54	0.08±0.03	0.55±0.33	15±10	3.4±1.7	11.6±2.1	253±76	130±37	3794±2686	1.0±0.56
	μ	7.8±0.2	5.7±3.9	283±178	64±40	967±582	2941±655	160±38	0.08±0.02	0.55±0.23	15±7	3.4±1.2	11.6±1.5	253±53	130±26	3794±1894	1.0±0.39
	CI	7.6-8.0	1.8-11.3	105-461	24-104	385-1549	2286-3596	122-198	0.06-0.10	0.32-0.78	8-22	2.2-4.6	10.1-13.1	200-306	104-156	1900-5688	0.61-1.39
TADW after 150 days (June 2005)	$\overline{x} \pm \sigma$	7.2±0.4	4.7±5.3	79±47	18±11	269±109	1416±864	80±64	0.05±0.03	0.62±0.50	11±7	4.1±2.8	8.5±2.8	183±73	79±47	1898±1826	0.84±0.43
	μ	7.2±0.3	4.7±3.7	79±33	18±8	269±77	1416±609	80±45	0.05±0.02	0.62±0.35	11±5	4.1±2.0	8.5±2.0	183±51	79±33	1898±1287	0.84±0.30
	CI	6.9-7.5	1.0-8.4	46-112	10-26	192-346	807-2025	35-125	0.03-0.07	0.27-0.97	6-16	2.1-6.1	6.5-10.5	132-234	46-112	611-3185	0.54-1.14
TADW after 330 days (December 2005)	$\overline{x} \pm \sigma$	6.9±0.2	2.4±2.6	87±86	19±15	294±259	337±430	20±15	0.13±0.05	0.43±0.17	6±6	2.0±0.7	6.3±1.5	111±37	47±58	922±916	1.01±0.37
	μ	6.9±0.1	2.4±1.8	87±60	19±11	294±182	337±302	20±11	0.13±0.11	0.43±0.12	6±4	2.0±0.5	6.3±1.0	111±26	47±41	922±645	1.01±0.26
	CI	6.8-7.0	0.6-4.2	27-147	8-30	112-476	35-639	9-31	0.02-0.24	0.31-0.55	2-0	1.5-2.5	5.3-7.3	85-137	6-88	277-1567	0.75-1.27
TADW after 1430 days (December 2008)	$\overline{x} \pm \sigma$	6.6±0.2	0.9±2.9	112±159	61±79	533±704	95±325	10±13	0.12±0.13	0.40±0.24	1±5	2.3±1.2	5.8±1.7	12±5	54±64	250±118	0.93±0.36
	μ	6.60.2	0.9±1.5	112±112	61±56	533±496	95±229	10±9	0.12±0.09	0.40±0.17	1±3	2.3±0.9	5.8±1.2	12±4	54±45	250±98	0.93±0.25
	CI	6.4-6.8	0.0-2.4	0.0-224	5-117	37-1029	0-324	1-19	0.03-0.21	0.23-0.57	0.0-4	1.4-3.2	4.6-7.0	8-16	9-99	152-348	1.18-0.68
Overall region	$\overline{x} \pm \sigma$	6.6± 0.2	0.9±1.0	113±214	61±110	533±974	95±81	10±9.5	0.12±0.10	0.40±0.30	1.3±1.0	2.3±1.6	5.8±1.9	19±7.4	54±73	650±918	0.93±0.37
	μ	6.6± 0.1	0.9±0.7	113±151	61±77	533±686	95±57	10±7	0.12±0.07	0.40±0.21	1.3±1.0	2.3±1.1	5.8±1.3	19±5.2	54±52	650±647	0.93±0.26
	CI	6.5-6.7	0.2-1.6	0-264	0-138	0-1219	38-152	3-17	0.05-0.19	0.19-0.61	0.6-2.0	1.2-3.4	4.5-7.1	13.8-24	2-106	3-1297	0.67-1.19
BIS Standard		6.5-8.5		75	30	300			0.3		5			200	200	250	50
USEPA		6.5-8.5					20		0.3		0.5-5				250	250	10
WHO		6.5-8.5					200		0.3		5				250	250	50
EEC		6.2-8.5			50	50	175	12	0.2	5	4				250		50
KSPCB		6.5-8.5		75		300			0.3		5			200	200	250	50

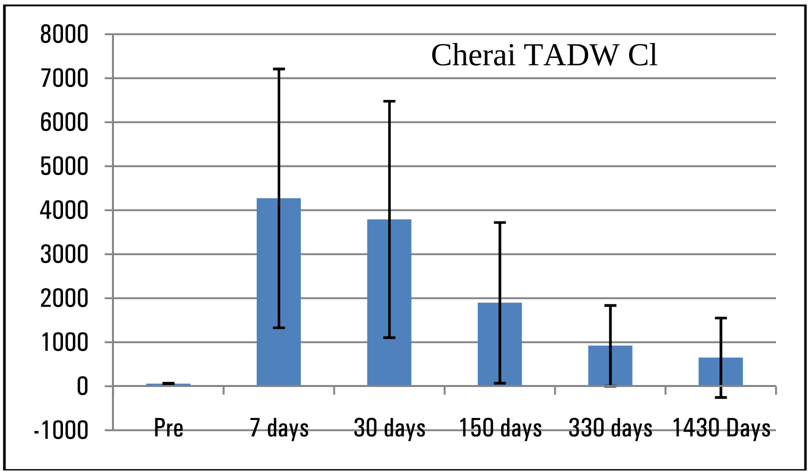

Figure 5.42: Variation of Chloride (TADW) with days at Edavanakkad-Cherai coast as a function of time in the post tsunamic period after 26 December 2004 Indian Ocean tsunami. *Pre* means pre-tsunami year 2001 (Refer Chapter 3).

5.9.7 Overall Water Quality of Edavanakkad-Cherai Coast, Kerala, India

Figure 5.42 shows the variation of chloride (TADW) with days at Cherai-Edavanakkadcoast as a function of time in the post tsunamic period after 26 December 2004 tsunami and Figure 5.43 that of sodium.Table: 5.18 shows the chloride data of Cherai coast in 7, 180, 210, 330 and 1430 days interval and Table: 5.19 that of Sodium and Table: 5.20 that of Water Quality Index (WQI).

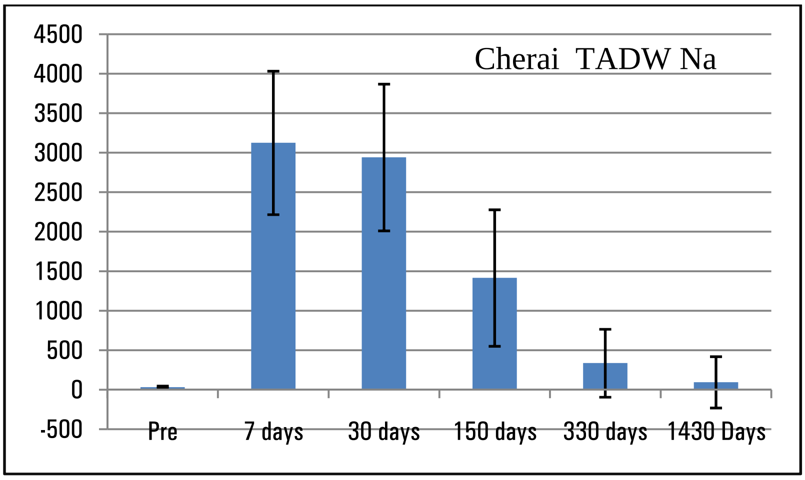

Figure 5.43: Variation of Sodium(TADW) with days at Edavanakkad-Cherai coast as a function of time in the post tsunamic period after 26 December 2004 *Pre* means pre-tsunami year 2001 (Refer Chapter 3).

Pertinent water quality parameters of the region after the tsunami inundation are given in respective tables. However, the overall water quality of the region annual mean of the post tsunamic situation comprising eleven stations of the respective three strata are evaluated applying the t test; pH (7.4±0.3), EC (4.1±1.6) mS*/cm*, Ca (141±94) mg/l, Mg(43±30) mg/l, TH (528±312) mg $CaCO_3$/l, Na (1567±876) mg/l, K (86±47) mg/l, Fe (0.10±0.08) mg/l, PO_4^{3-} (0.55±0.22) mg/l, Turbidity (12±4) NTU, DO (3.6±1.2) mg/l, BOD (9.4±1.9) mg/l, alkalinity (190±40) mg/l, SO_4 (84±32) mg/l, Cl (2158±1294) mg/l, NO_3 (0.97±0.27) mg/l. This basic data structure indicates the post tsunamic ground water quality of the Alappad coast is used to evaluate the hydrochemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 5.17. However it is essential to proceed with long term monitoring and evaluation to decide the extent of quality damage and process of self purification of ground water by natural hydrological cycle (Achari, 2005; Achari, 2008; Ramasamy et al., 2006; Ramanmurthy et al., 2005; Oyedele and Momoh, 2009). The study discussed in the above sections shows ground water quality for the post tsunamic period with respect of Tsunami Affected Dug Well (TADW) sources.

Table 5.18: Chloride data of Edavanakkad-Cherai coast after 24 December 2004 Indian Ocean tsunami in the year 2005.

Strata	**n**		**3 Jan 2005 (7 Days)**	**3 July 2005 (180 Days)**	**03 August 2005 (210 Days)**	**3 Dec 2005(330 Days)**	**Annual Mean 2005**	**2008 (1430Days)**
TADW	10	$\bar{x} \pm \sigma$	4273±2941	1630±1885	1409±1309	922±916	2158±1876	650±903
		μ	4273-2073	1630±1329	1409±923	922±646	2158±1323	650±637
		CI	2200-6346	301-2959	486-2332	276-1568	835-3481	13-1287
Control Well	1	$\bar{x} \pm \sigma$	87	117	114	145	182±95	48

Table 5.19: Sodium data of Edavanakkad-Cherai coast after 24 December 2004 Indian Ocean tsunami in the year 2005.

Strata	**n**		**3 Jan 2005 (7 Days)**	**3 July 2005 (180 Days)**	**03 August 2005 (210 Days)**	**3 Dec 2005 (330 Days)**	**Annual Mean 2005**	**2008 (1430 Days)**
TADW	10	$\bar{x}\pm\sigma$	3126±908	737±869	807±648	337±430	1567±831	95±325
		μ	3126±640	737±613	807±457	337±303	1567±585	95±229
		CI	2486-3766	124-1350	350-1264	34-640	982-2152	134-324
Control Well	1	$\bar{x}\pm\sigma$	42	46	56	90	62±16	40

Water quality parameters of Cherai – Edavanakkad ranges from pH (7.1-7.7), EC (2.5-5.7) mS/*cm*, Ca (47-235) mg/l, Mg (13-73) mg/l, TH (216-840) mg $CaCO_3$/l, Na (691-2443) mg/l, K (39-133) mg/l, Fe (0.02-0.18) mg/l, PO_4 (0.33-0.77) mg/l, Turbidity (8-16) NTU, DO (2.4-4.8) mg/l, BOD (7.5-11.3) mg/l, alkalinity (150-230) mg/l, SO_4 (52-116) mg/l, Cl^- (864-3452) mg/l, NO_3 (0.70±1.24) mg/l.

Table 5.20: Water Quality Index (WQI) data of Edavanakkad-Cherai coast after 24 December 2004 Indian Ocean tsunami in the year 2005.

Strata	**n**		**3 Jan 2005 (7 Days)**	**3 July 2005 (180 Days)**	**03 August 2005(210 Days)**	**3 Dec 2005 (330 Days)**	**Annual Mean 2005**	**2008 (1430Days)**
TADW	10	$\bar{x}\pm\sigma$	41±4	47±6	48±5	46±3	46±5	48±4
		μ	41±3	47±4	48±4	46±2	46±4	48±3
		CI	38-44	43-51	44-52	44-48	42-50	45-51
Control Well	1	$\bar{x}\pm\sigma$	54	58	49	60	54±4	54

Conclusions

Almost complete and comprehensive analysis of the ground water quality of the Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai coastal sections are done in post tsunami period after the severe inundation and devastation brought about by 26 December 2004 Indian Ocean tsunami. Variation of the prominent parameters and their inter-variability are evaluated such that gross water quality of the respective region are well established in this research work. However it is decided to examine and compare the water quality parameters in TADW during 2005 using ANOVA to prove whether there is any significant difference in the water quality parameter under study between stations and between months in TADW. One of the observation has been that Edavanakkad-Cherai registered significantly higher sodium compared to other stations ($p<0.001$). Sodium content was significantly higher during January to March ($p<0.001$). More conclusive inferences are critically presented in the succeeding chapter.

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Chapter 6

Summary: Overall Water Quality of the Tsunami Affected Region of Kerala

Contents

6.1 Introduction

The study presented in the preceding chapters descriptively discussed the post tsunamic situation of the ground water quality profile of the severely tsunami inundated coastal areas of Kerala. Accordingly respective sections exhaustively and critically evaluated the impact of tsunami waves on the three distinct strata of ground water sources classified as control well, tsunami affected dug wells and deep bore wells of the most devastated Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad – Cherai coastal sections continuously month-wise over a period of one year after 26 December 2004. The study had been repeated after four years gap in December 2008 to ascertain the variability of the ground water quality with respect to time and space.

Aim and scope of the study has been (1) To establish the temporal ground water quality variation profile after 26 December 2004 Indian Ocean tsunami event on coastal regions of Kerala within the local geo-physical constraints for a period starting just 7 days after tsunami to 1430 days (2) To study the variation of the ground water quality profile of the study area with respect to depth profile of ground water sources classified into three distinct strata; control well [CW], tsunami affected dug wells [TADW, average depth 6feet] and deep groundwater source- bore wells [BW, average depth 300feet]. Evaluation and critical analysis of prominent water quality parameters and their variability with respect to time and location. (3) Statistical interpretation of the post tsunami water quality data of the region with respect to BIS and WHO standards. Also to pre-tsunamic situation with a baseline data of year 2001. (4) To compute the monthly water quality index (WQI) of the region giving adequate weightage to significant quality parameters of the ground water with respect to specific depth profile and tsunami affected coastal region. (5) To consolidate a database, as elemental supporting material for further studies as a model for the study of coastal hazard and its consequences with respect to ground water quality. (6) Study of the ground water chemistry of the region in relation to the pre and post tsunami situation (after 26 December 2004 Tsunami). (7) Classification of water types with respect to Hill-Piper Trilinear plots, hardness and salinity hazard values. (8) To evaluate the overall water quality parameters of the severely Tsunami devastated coastal regions of the state. (9) To come out with viable managerial options pertaining to rehabilitation and restoration of the fresh water sources of the tsunami affected coastal regions of the state.

The hypotheses to be tested are (1) whether there is any significant difference in the water quality parameter under study between stations and between months in Tsunami Affected Dug Well (TADW). (2) Whether the selected water quality parameters vary significantly from BIS and WHO standards. (3) Whether the water Quality parameters differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW). (4) Whether the water quality index differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW). (5) Whether there is any significant difference in the water quality parameters during December 2005 and December 2008. (6) Is there any significant change in the water quality parameters before (2001) and after tsunami (2005) in TADW.

To test the hypothesis in (i), (iii) and (iv) listed above, the collected data for the study were subjected to statistical analysis using Two-Factor ANOVA. Where ever treatment effects were found to be significant, least significant difference (LSD) at 5% level were calculated to identify the significant treatment component. For testing the hypothesis listed in (ii) and (v), students‘t’ test was employed.

For testing hypothesis (vi), the mean of Water Quality Parameters in 2001 and 2005 in TADW are compared using independent student’s ‘t’ test.

The significance of the study focused on to evaluate influence of the physico-chemical and biological parameters of the over forty two (42) ground water resources of the region for a period of 12 months starting from the month of January, 2005 to December, 2005. Major parameter analyzed includes pH, Conductivity, Redox potential, Turbidity, Alkalinity, Hardness, Total hardness, DO, BOD, Chloride, PO_4, Iron, Na, K and Total coliform. Specific protocols were followed for the sampling, preservation, chemical analyses and investigations. Specific statistical tools were used for the correlation of water quality parameters and evaluation of water quality index (WQI) of the shallow surface and deep ground waters of the tsunami affected study regions.

This study of the ground water quality variation of the severely affected water sources of the coastal regions of Kerala had been started immediately after the tsunami event on December 26, 2004. First sampling was done on 2 January 2005 (7 Day after tsunami event). A complete evaluation of the ground water quality of the above stations has been done in December, 2008 to monitor the severity of the impact on the ground water quality in post tsunamic years. This study is essential for understanding the hydrochemistry of the region as a basis for the evaluation/comparison of the impact of tsunami on total environmental quality. Changes on the water quality parameters are indicators for the understanding of the tsunami brought seawater inundation. Major results of the study are being presented in preceding chapters with critical interpretation of the results.

The preliminary reconnaissance survey has been carried out in the first week of January 2005, in order to chalk out a working and viable strategy for monitoring with first sampling. A few sites of regular spatial intervals were tentatively selected; samples were collected and analyzed to ascertain the drastic quality change. Thereafter, based on extensive field surveys the sampling stations for regular monthly water sampling were fixed. The fresh water dug well maintained outside the Cheriazheeckal Vadakkenada Bhagavathy Temple on Alappad coast. Hindu temples have a custom of maintaining sacred wells near to the sanctum- sanctorium to draw the holy water for pooja and ritualistic practices, maintained protected in full sanctity mostly within temple compound. In this study the above mentioned temple well is well protected though it is very close to the shore.

This well has a striking significance peculiar to the location where it is maintained. Though it is close to the tsunami affected region with same geo-morphological setting, it is not directly inundated by tsunami waves or its secondary impacts. The freshwater quality remained stable mostly in parallel with the pre-tsunamic conditions. This well was selected as the control station (marked as station 1 in Alappad coast). The entire stretch of the devastative tsunami affected coastal area in Kerala, India has been hyphenated into four coastal regions with a total of 42 identified groundwater sources for regular monthly sampling and monitoring. This comprises (1) Alappad Coast in Kollam District, Kerala, India [22 km - with selected 11 stations],(2) Arattupuzha Coast in Alappuzha District, Kerala, India [18 km –with selected 11 stations], (3) Andakaranazhy coast in Alappuzha District, Kerala, India [12 km – with selected 10 stations],(4) Edavanakkad-Cherai coast in Ernakulam District, Kerala, India [6 km of Edavanakkad- Cherai stretch–with 10 stations].

The ground water sources chosen for the present study have specific utility as a potential fresh water source. Each one has a definite water regime with a representative nature and some degree of specific economic utility. The data graphically presented in the following sections are experimental observations obtained after rigorous analyses of samples. These have meticulously been correlated to sift out the salient temporal and spatial tendencies characteristic of each water source. Standard methods were systematically followed in each stage of analyses during sampling and preservation.

With well planned four field trips per month, each station of the above strata singled out for the study is sampled in prominence. The locations chosen for the study, the sampling sites earmarked for each location and their respective serial numbers are well specified as a part of robust protocol followed. White plastic cans of three-liter capacity were used as sample containers. They were thoroughly washed with distilled water in advance and those cans were washed again with dilute HCl and then with distilled water to avoid the chances of contamination by persistent stains.

They were labeled with the name of the sampling site, the respective serial number and date. BOD bottles also subjected to the same preliminaries of sampling in line with the plastic containers. In the field diary, the day and date of sampling sites and their respective serial numbers were entered well before the sampling trip was embarked upon. At the site, the time of sampling and the temperature of the sample taken were individually recorded.

Ground water sample were collected from those marked station every month. Most of the water sources were dug well less than 2.0 M in depth and for uniformity samples are collected from the surface. In case of deep bore wells special standard method for deep ground water were strictly followed. It is assumed that vertical mixing in sampling sources is complete and the stratification is nonexistent in all stations.

Water Quality Index (WQI) has been evaluated according to a known standard procedure referred in literature (United States Department of Education and Technology Innovation, http://pathfinderscience.net/stream/cproto4.cfm). This Index has been devised as a simple methodology to subject a water source to water quality ranking with the intension of its utility. Following the same procedure the water quality index of the tsunami affected ground water sources of the study area has been critically evaluated.

This WQI uses a scale from 0 to 100 to rate the quality of the water, with 100 being the highest possible score that represents excellent quality water. Once the overall WQI score is known, it can be compared against the following scale to determine how healthy the water is on a given day.

6.2 Major Findings and Inferences

Major finding and inferences reaped out of this long and exhaustive study spanning four coastal sections are given in the respective chapters in highly descriptive approach. There is definite change in the water quality parameters of the ground water sources after the tsunami inundation along the entire coastal stretch studied. The geochemistry and pre and post monsoon have a strong impact on the quality of the ground water.

6.2.1 Pre-tsunamic Water Quality of the Region

Kollam coast is the most affected region of the Kerala, India by 26 December, 2004 tsunami event and the non availability of the pre-tsunami ground water quality of the place had been a great limitation to arrive a scientific judgment on its extent of quality damage (Achari, 2005). The study presented comprises the critical analysis of the ground water sources of the region with already available data. It is found that data analyzed for the gross composition of the ground water quality parameter of the Alappad – Arattupuzha region are mostly represented by groundwater sampled from dug wells (mean depth 2.0m) except the station No.4 which is a deep bore well with (depth 75.0m).

The data given in the Table 3.1 is the gross composition of the ground water quality parameter of the Alappad – Arattupuzha region in the year 2001 and the sources are mainly dug wells (mean depth 2.0m) except the station No.4 which is a deep bore well with (depth 75.0m). Pertinent parameters given are mean ($\bar{x} \pm \sigma$)of the five determinations such that these values pH (7.6±0.1), EC mS*/cm* (0.352±0.018), TH mg $CaCO_3$/l (68±13), Ca mg/l (19±4.8), Mg mg/l (4.8±0.6), Na mg/l (33±4), K mg/l (10.0±2.5), CO_3 mg/l (0.5±0.3), HCO_3 mg/l (34.2± 13.8), SO_4 mg/l (20.4±5.3), Cl mg/l (57±3.9), F mg/l (0.08±0.03). This basic data's are used to evaluate the hydro chemical behavior of the regions ground water quality.

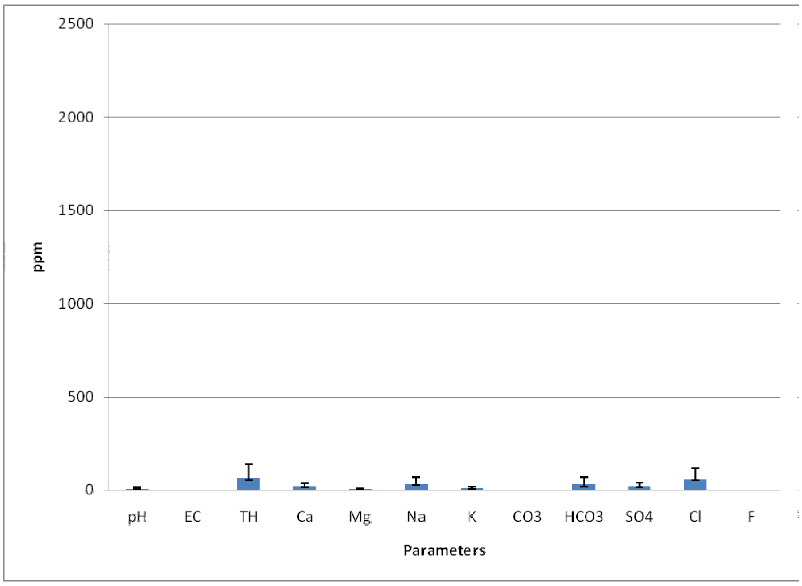

Figure 6.1: Ground water quality profile of the Alappad coast prior to 26 December 2004 Indian Ocean tsunami inundation (2001 Data)

There is more than 95% chance that the true value of the representative parameters lies in the confidence interval; pH (7.5-7.7), EC mS*/cm* (0.334-0.370), TH mg $CaCO_3$/l (55-81), Ca mg/l (14.2-23.8), Mg mg/l (4.2-5.4), Na mg/l (29-37), K mg/l (7.5-12.5), CO_3 mg/l (0.2-0.3), HCO_3 mg/l (20.4-48.0), SO_4 mg/l (15.1-25.7), Cl mg/l (53.1-60.9), F mg/l (0.077-0.083) (Figure 6.1). This can be of very useful in two ways; (1) To have a picture of the hydrochemical behavior of the regions ground water quality existed (2) as a reference point to quantify the impact of 26 December 2004 Indian Ocean tsunami on the groundwater chemistry of the region in the post tsunami studies.

These results will extensively help to circumnavigate through a series of similar studies accomplished in post tsunami era as an ever valuable document. It is proved that the water in the region is originated from rainwater source subjected to ‘mild contamination’ geologically subjected to reverse softening by the sediment layers characterized by a higher proportion of heavy mineral sands. Hill-Piper Trilinear plots indicate that slight contamination by sea water has been prevalent; may be the geographical features of the place- a narrow barrier islet infringed by Laccadive Sea and an arm of Ashtamudy lake regionally called T S canal.

6.2.2 Post Tsunamic Water Quality Studies

Major finding and inferences culled out of this long and exhaustive study spanning four coastal sections are given in the respective chapters in highly descriptive approach. There is definite change in the water quality parameters of the ground water sources after the tsunami inundation along the entire coastal stretch studied. The geochemistry and pre and post monsoon have a strong impact on the quality of the ground water.

Figures 6.2, 6.3 & 6.4 shows the variation of the prominent parameters of the groundwater as a function of time in the post tsunamic situation on the Alappad coast plotted as stratum wise. The region marked with a pH of 7.6±*0.1* with CI of 7.5-7.7 at 95% significant level before the tsunami drastically changed to value of 7.8 just after the seventh day of the disaster in January, 2005.

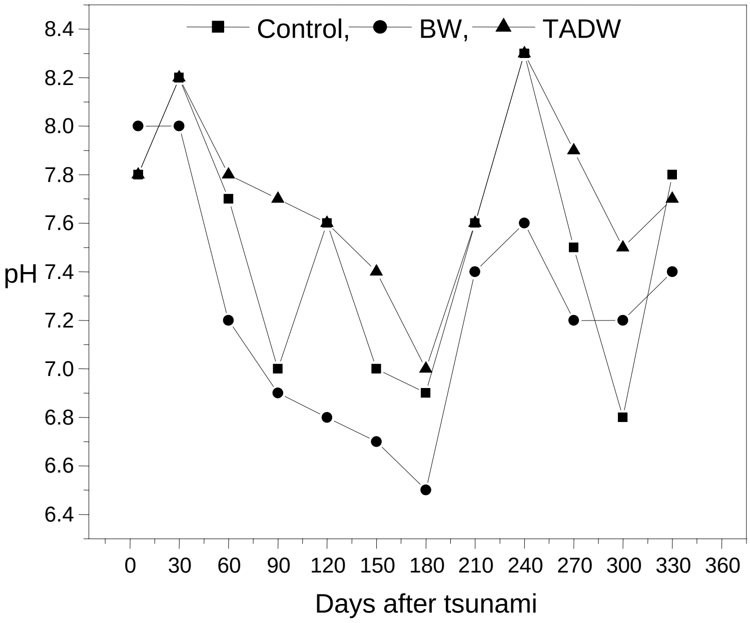

Figure 6.2: Variation of pH of ground water as a function of time after 26 December, 2004 tsunami.Stratum wise; control well (CW), bore well (BW) and tsunami affected dug wells (TADW) at Alappad region, Kollam, Kerala, India.

Most of the directly affected dug wells have a pH 7.8±*0.5* by this time showing not much damaging behavior initially, drastically changes to pH 8.2±*0.7* by a time of 30 days in February, 2005. In the time before the tsunami (pre-tsunamic situation) the region's water has a normal behavior with pH 7.6 ±*0.1* with CI of 7.5-7.7 (with µ 7.5 - 7.7). After 4 year (1430 days in December2008) the pH of the region is existing with CI of 7.4±*0.2* (with µ 7.2-7.6) for the same degrees of freedom.

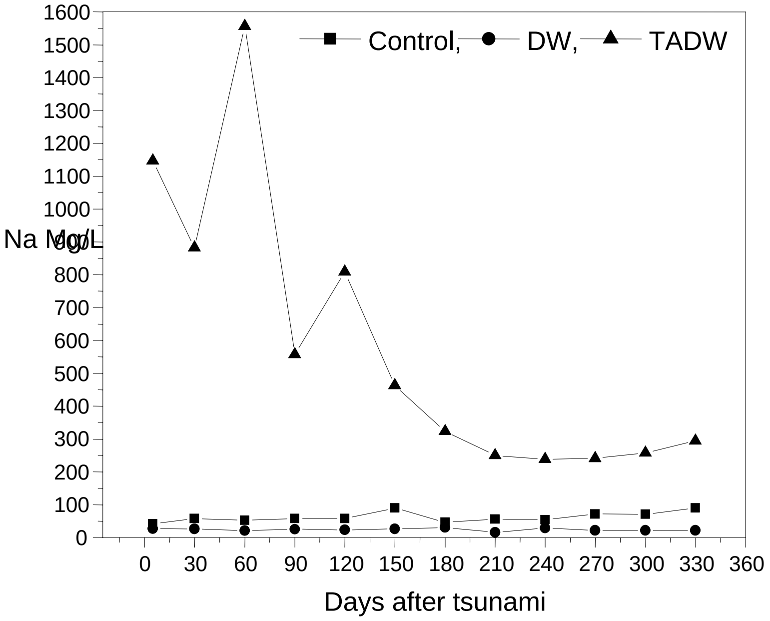

Figure 6.3: Variation of Na of ground water as a function of time after 26 December, 2004 Indian Ocean tsunami.Stratum wise; control well (CW), bore well (BW) and tsunami affected dug wells (TADW) at Alappad region, Kollam, Kerala, India

Pre-tsunamic Na content of the region has been found to be $\bar{x}(Na^+)$ =33±4 mg/L (CI; 29-37 mg/l) for n=5 with four shallow dug wells and a single deep bore well (BW). Just after the tsunami event the level of Na^+ is more quantified as $\bar{x}(Na^+)$ 1147±1174 mg/L for the tsunami affected wells (TADW) being the control well have 42mg/L

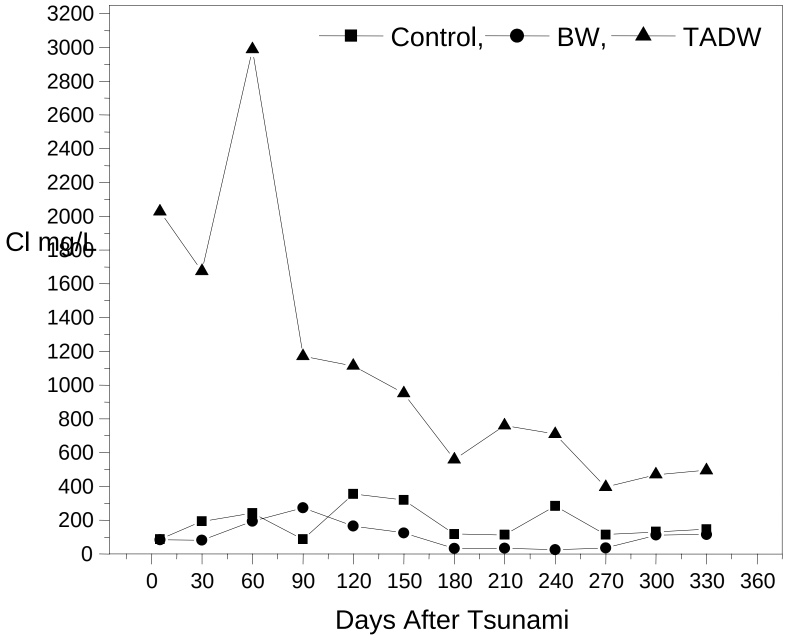

Figure 6.4: Variation of Cl of ground water as a function of time after 26 December, 2004 Indian Ocean tsunami.Stratum wise; control well (CW), bore well (BW) and tsunami affected dug wells (TADW) at Alappad region, Kollam, Kerala, India

The deep ground water too seem to be contributing Na^+ level by $\bar{x}(Na^+)$ = 27±14 mg/L. This indicates the logic of choosing Na^+ a prominent factor as it here act as a major constituent (> 5mg/L). By March 2005 (60Day) the tsunami affected dug wells showed highest Na content of 1556±2556 mg/l. Annual mean of the Na^+ content of strata has been found that $\bar{x}(Na^+)$ =585±280 mg/L for TADW with a $\bar{x}$ (Na^+) = 62±16 mg/L for control well and 24±4 mg/L for deep bore wells. However, the last sampling after fourth year of the tsunami devastation by December 2008 (by 1430 days) has $\bar{x}$ (Na^+) =115±127 mg/L for TADW with a $\bar{x}$ (Na^+) = 40 mg/L for control well and 41±23 mg/L.

Table 6.1: SAR and Salinity – sodium hazard of dug well sources of 26 December 2004 Indian Ocean tsunami affected Alappad coast, Kerala India; Control well – post tsunami period.

Strata	Period	Day	Conductivity µS/cm	Salinity Hazard	SAR	Sodium Hazard
Control Well	Jan 05	07D	570	C2	1.5	C2-S1
	Feb05	30D	800	C3	2.0	C3-S1
	Mar05	60D	800	C3	1.4	C3- S1
	Apr05	90D	630	C2	1.9	C2- S1
	May05	120D	690	C2	1.8	C2- S1
	Jun05	150D	900	C3	2.8	C3- S1
	Jul05	180D	540	C2	1.5	C2- S1
	Aug05	210D	700	C2	2.1	C2- S1
	Sep05	240D	1100	C3	1.9	C3- S1
	Oct05	270D	310	C2	2.3	C2- S1
	Nov05	300D	1080	C3	2.1	C3- S1
	Dec05	330D	1900	C3	2.8	C3- S1
	$\bar{x}\pm\sigma$		840±400		2±0.5	(C2-S1)-(C3-S1)
	CI		440 – 1240		1.5-2.5	(C2-S1)-(C3-S1)
	Dec08	1430D	300	C2	1.6	C2- S1

This prominent strata of stations representative of both severely tsunami affected dug wells and those of dewatered and cleaned (n=7) showed distinct features. The first sampling (Jan 2005) has a mean Cl^- content of $\bar{x}(Cl^-)$ =2027±2078 mg/L shows the variability among the the data as observe that those not subject to any refine process has a very high chloride content; CI is wide 0-4105 mg/l.

Table 6.2: SAR and Salinity – sodium hazard of Dug well sources of 26 December 2004 Indian Ocean tsunami affected Alappad coast; deep bore well (BW) – post tsunami period.

Strata	Period	Day	Conductivity µS/cm	Salinity Hazard	SAR	Sodium Hazard
BW	Jan 05	07D	467	C2	0.874	C2-S1
	Feb05	30D	420	C2	0.866	C2-S1
	Mar05	60D	730	C2	0.731	C2- S1
	Apr05	90D	513	C2	1.183	C2- S1
	May05	120D	550	C2	0.762	C2- S1
	Jun05	150D	613	C2	0.988	C2- S1
	Jul05	180D	637	C2	0.976	C2- S1
	Aug05	210D	493	C2	0.682	C2- S1
	Sep05	240D	1053	C3	0.925	C3- S1
	Oct05	270D	693	C2	0.848	C2- S1
	Nov05	300D	673	C2	0.798	C2- S1
	Dec05	330D	640	C2	0.791	C2- S1
	$\bar{x}\pm\sigma$		624±166		0.869±0.136	C2- S1
	CI		458 – 790		0.733-1.005	C2- S1
	Dec08	1430D	233	C1	2.067	C1- S1

As we saw it in the case of control station the data after 60 days in this stratum too have a sudden leap with chloride content of 2990±4540 mg/l with a wider CI of 0-7530 mg/l. This definitely support the fact that the regions expansive contamination by sea water. The salt is being kept saturated as halite ions on soil structure in the lean months of January and February exactly over a period of 60 days slowly transported to the groundwater by convective as well as advective way of discharge with a long residence time.

Table 6.3: SAR and Salinity – sodium hazard of dug well sources of 26 December 2004 Indian Ocean tsunami affected Alappad coast; Tsunami Affected Dug wells (TADW) – post tsunami period.

Strata	Period	Day	Conductivity µS/cm	Salinity Hazard	SAR	Sodium Hazard
TADW	Jan 05	07D	7960	C4	11.60	C4-S2
	Feb05	30D	4740	C4	7.37	C4-S1
	Mar05	60D	10470	C4	11.70	C4- S2
	Apr05	90D	3870	C4	7.54	C4- S1
	May05	120D	4500	C4	9.14	C4- S1
	Jun05	150D	3320	C4	7.92	C4- S1
	Jul05	180D	2080	C3	5.62	C3- S1
	Aug05	210D	2130	C3	5.14	C3- S1
	Sep05	240D	1060	C3	4.56	C3- S1
	Oct05	270D	860	C3	5.19	C3- S1
	Nov05	300D	2740	C4	4.61	C4- S1
	Dec05	330D	2380	C4	6.44	C4- S1
	$\bar{x}$ ±σ		3840±2830		7.23±2.51	(C3-S1)
	CI		1010 –6670		4.72-9.74	(C3-S1)-(C4- S1)
	Dec08	1430D	900	C3		C3- S1

The augmentation of chloride replenishment becomes more prominent by a period of 330 days (December, 2005) to reach a level of 495±419 mg/l with a range value of 96-914 mg/l. Annual mean $\bar{x}(Cl^-)$ = 1110±488 mg/L observed for 12 monthly sampling event for the tsunami affected dug wells has a CI of 612-1598 mg/l (n= 7). This clearly indicate that a chloride removal mechanism is active in the local tsunami hit region in regards to the chloride content measured first; that is sampling done 7 days after tsunami (2027±2078mg/l).

Tsunami high waves brought a well - defined WQI regime in the regional water quality by its never ending presence of extra ionic concentrations for many years since the disastrous event. The content dwindle to the minimum level after 90 days (April 2005) with $\overline{x}$(WQI) = 49±5 where both control well and deep groundwater sources registered a lower WQI value of 52 and 41±4 respectively. Further it gains to maximum by 150 days (June, 2005) with $\overline{x}$(WQI) = 54±6 for TADW, still with a level of 49 for control well and 42±4 for BW sources.

Summation of Water Quality Index (WQI) of ground water sources of severely tsunami affected Alappad coast of Kerala, India. Scale: 91- 100 (Excellent water quality), 71-90 (Good water quality), 51-70 (Medium or average water quality), 26- 50 (Fair water quality), 25 (poor water quality).

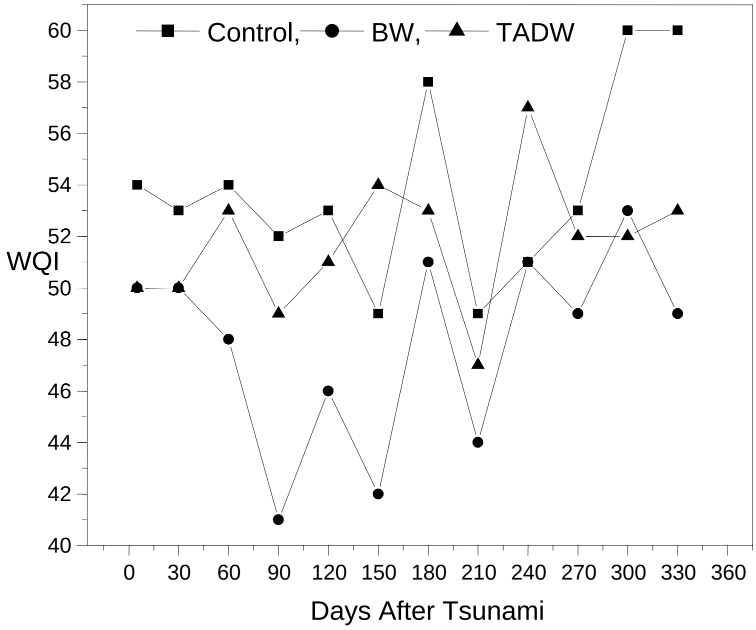

Figure 6.5: Variation of WQI of ground water as a function of time after 26 December, 2004 Indian Ocean tsunami. Stratum wise; control well(CW), bore well(BW) and tsunami affected dug wells (TADW) at Alappad region, Kollam, Kerala India.

It is further observed that quality index remained $\overline{x}$(WQI) = 53±5 by 330 days (Dec, 2005) even after a time initiated improvement for all tsunami affected dug wells (TADW) has been expected. Rise to maximum WQI was observed once the full circle is about to complete in the twelfth sampling of 330 days with $\overline{x}$(WQI) = 60 for control well. On comparing the first and last sampling events the WQI level improved only to a less extent; from 50±5 to 53±5 for TADW over one year period, passing through a set of natural conditions (Figure 6.5). Tables 6.1, 6.2 and 6.3 shown above clearly describe the variation of SAR (Sodium Adsorption Ratio) and salinity and sodium based classification of ground waters of tsunami affected coastal areas of Kerala with respect to the distinct strata of control well, tsunami affected shallow dug well and deep bore well.

The control well have character similar to that of C2-S1 (medium salinity – low sodium) water after tsunami inundation (7Days) maintains the quality as that of C3-S1(high salinity- low sodium) water as the mean quality throughout the year. The overall character of the water ranges from (C2-S1)-(C3-S1).That is water maintains the quality in the range (medium salinity-low sodium water) – (high salinity-low sodium water).

The Tsunami Affected Dug Wells (TADW) have character similar to that of C4-S2 (very high salinity – medium sodium) water after tsunami inundation (7Days) maintains the quality as that of C3-S1(high salinity- low sodium) water as the mean quality throughout the year. The overall character of the water ranges from (C3-S1)-(C4-S1).That is water maintains the quality in the range (high salinity-low sodium water) – (very high salinity-low sodium water).

The Deep Bore Wells (BW) have character similar to that of C2-S1 (medium salinity – low sodium) water after tsunami inundation (7Days) maintains the quality as that of C2-S1(medium salinity- low sodium) water as the mean quality throughout the year. The overall character of the water ranges from C2- S1. That is water maintains the quality in the range (medium salinity- low sodium).

6.2.3 Post Tsunamic Water Quality of Alappad Coast, Kerala, India

The overall water quality of the region annual mean of the post tsunamic situation comprising eleven stations of the respective three strata are evaluated applying the t test; pH (7.6±0.2), EC (2.7±1.8) mS*/cm*, Ca (109±57) mg/l, Mg(47±20) mg/l, TH (465±210) mg $CaCO_3$/l, Na (384±356) mg/l, K (16±13) mg/l, Fe (0.28±0.21) mg/l, PO_4

(0.07±0.04) mg/l, Turbidity (11±7) NTU, DO (4±1) mg/l, BOD (10±3) mg/l, alkalinity (280±94) mg/l, SO_4 (36±18) mg/l, Cl (752±908) mg/l, NO_3 (0.96± 0.22) mg/l, AI(12.2±0.4). This basic data structure indicates the post tsunamic ground water quality of the Alappad coast is used to evaluate the hydrochemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 4.15. Figure 6.6, 6.7, 6.8, 6.9 and 6.10 shows ground water quality profile of the Alappad coast in January 2005, 7 days, February 2005, 30 days, June 2005, 150 days, December 2005, 330 days and December 2008, 1430 days after tsunami inundation for strata tsunami affected dug well sources (TADW).

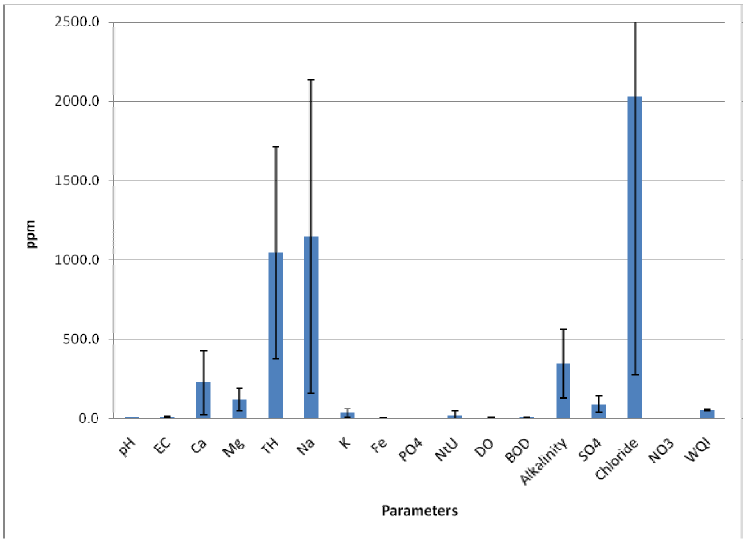

Figure 6.6: Ground water quality profile of the Alappad coast in January 2005, 7 days after 26 December 2004 Indian Ocean tsunami Inundation; strata: Tsunami Affected Dug Well sources (TADW).

The prominent parameters of the Alappad region after 26 December 2004 tsunami ranges from pH (7.4-7.8), EC (0.9-4.5) mS*/cm*, Ca (52-166) mg/l, Mg (27-67) mg/l, TH (255-675) mg $CaCO_3$/l, Na (28-740) mg/l, K (3-29) mg/l, Fe (0.07-0.48) mg/l, PO_4 (0.03-0.11) mg/l, Turbidity (4-18) NTU, DO (3-5) mg/l, BOD (7-13) mg/l, alkalinity (186-374) mg/l, SO_4 (18-54) mg/l, Cl (142-1362) mg/l, NO_3 (0.74-1.18) mg/l, AI(11.8-12.6).

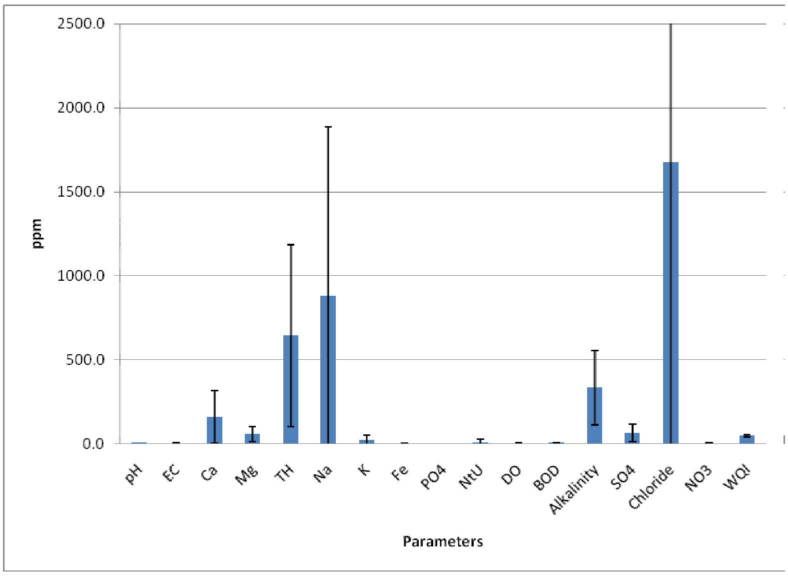

Figure 6.7: Ground water quality profile of the Alappad coast in February 2005, 30 days after 26 December 2004 Indian Ocean tsunami Inundation; strata: Tsunami Affected Dug Well sources (TADW).

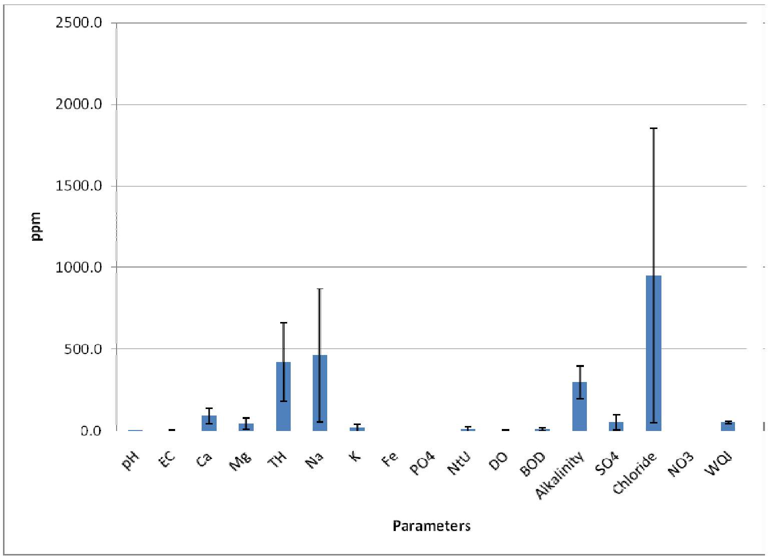

Figure 6.8: Ground water quality profile of the Alappad coast in June 2005, 150 days after 26 December 2004 Indian Ocean tsunami Inundation; strata: Tsunami Affected Dug Well sources (TADW).

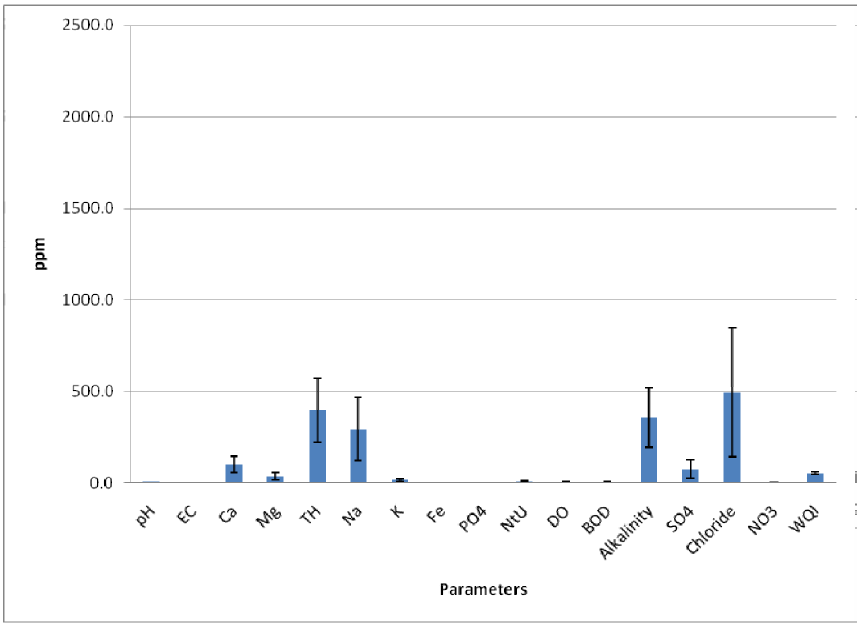

Figure 6.9: Ground water quality profile of the Alappad coast in December 2005, 330 days after 26 December 2004 Indian Ocean tsunami Inundation; strata: Tsunami Affected Dug Well sources (TADW).

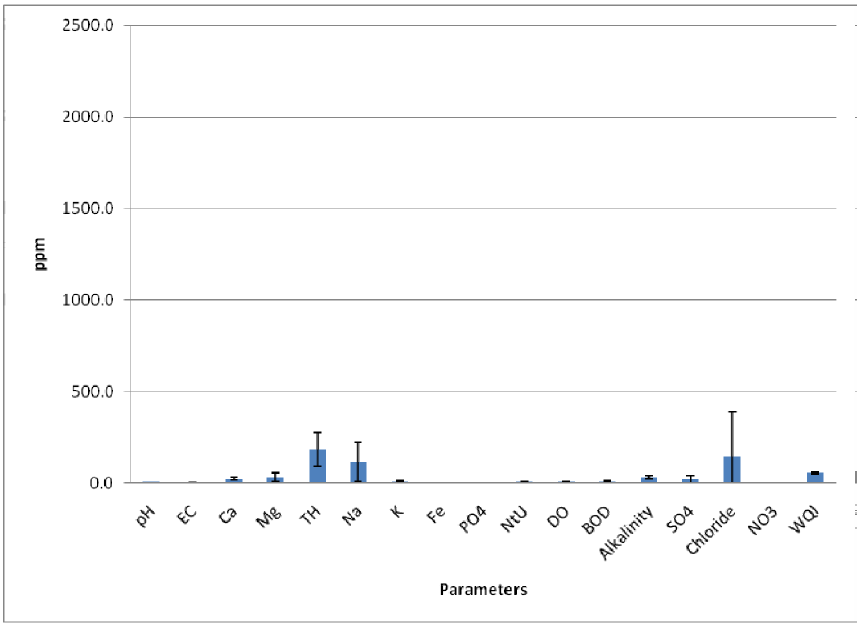

Figure 6.10: Ground water quality profile of the Alappad coast in December 2008, 1430 days after 26 December 2004 Indian Ocean tsunami Inundation; strata: Tsunami Affected Dug Well sources (TADW).

6.2.4 Post Tsunamic Water Quality of Arattupuzha Coast, Kerala, India

Pertinent water quality parameters of the region after the tsunami inundation are given in respective tables. However, the overall water quality of the region annual mean of the post tsunamic situation comprising eleven stations of the respective three strata are evaluated applying the t test; pH (8.0±0.4), EC (5.5±5.0) mS/cm, Ca (184±109) mg/l, Mg(110±56) mg/l, TH (895±392) mg CaCO3/l, Na (1412±957) mg/l, K (56±37) mg/l, Fe (0.05±0.04) mg/l, PO4 (0.14±0.23) mg/l, Turbidity (5.2±3.4) NTU, DO (4.7±1.5) mg/l, BOD (9.7±4.1) mg/l, alkalinity (221±47) mg/l, SO4 (78±78) mg/l, Cl (2844±2297) mg/l, NO_3 (0.0.81± 0.31) mg/l. This basic data structure indicates the post tsunamic ground water quality of the Alappad coast is used to evaluate the hydro chemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 5.7.

Prominent water quality parameters of Arattupuzha coast of Kerala in the post tsunamic situation ranges from pH (7.6-8.4), EC (0.5-10.5) mS/cm, Ca (75-293) mg/l, Mg(54-166) mg/l, TH (503-1287) mg CaCO3/l, Na (455-2369) mg/l, K (19-93) mg/l, Fe (0.01-0.09) mg/l, PO4 (0.0-0.37) mg/l, Turbidity (1.8-8.6) NTU, DO (3.2-6.2) mg/l, BOD (5.6-13.8) mg/l, alkalinity (174-268) mg/l, SO_4^{2-} (0-156) mg/l, Cl^- (547-5141) mg/l, NO_3^- (0.5-1.12) mg/l.

6.2.5 Post Tsunamic Water Quality of Andhakaranazhy Coast, Kerala, India

Overall water quality parameters of the Andhakaranazhy region after the tsunami inundation are given in respective tables. However, the overall water quality of the region annual mean of the post tsunamic situation comprising ten stations are evaluated as mean of the respective values after twelve months sampling and applying the t test; pH (7.4±0.2), EC (2.7±1.5) mS/cm, Ca (101±37) mg/l, Mg(34±44) mg/l, TH (382±207) mg CaCO3/l, Na (286±150) mg/l, K (13±6) mg/l, Fe (0.11±0.07) mg/l, PO_4 (0.28±0.08) mg/l, Turbidity (7±4) NTU, DO (2±0.5) mg/l, BOD (5.6±1.8) mg/l, alkalinity (324±63) mg/l, SO_4 (16±3) mg/l, Cl (361±158) mg/l, NO_3 (0.4± 0.09) mg/l. This basic data structure indicates the post tsunamic ground water quality of the

Andhakaranazhy coast is used to evaluate the hydro chemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 5.13

Prominent water quality parameters of Andhakaranazhy coast of Kerala in the post tsunamic situation ranges from pH (7.2-7.6), EC (1.2- 4.2) mS/cm, Ca (64 -138) mg/l, Mg(0-78) mg/l, TH (175-589) mg $CaCO_3$/l, Na (136-436) mg/l, K (72-19) mg/l, Fe (0.03-0.18) mg/l, PO_4 (0.20-0.36) mg/l, Turbidity (3-11) NTU, DO (1.5-2.5) mg/l, BOD (3.8-7.4) mg/l, alkalinity (261-387) mg/l, SO_4 (13-19) mg/l, Cl^- (203-519) mg/l, NO_3 (0.31-0.49) mg/l.

6.2.6 Overall Water Quality of Edavanakkad-Cherai Coast, Kerala, India

Pertinent water quality parameters of the region after the tsunami inundation are given in respective tables. However, the overall water quality of the region annual mean of the post tsunamic situation comprising eleven stations of the respective three strata are evaluated applying the t test; pH (7.4±0.3), EC (4.1±1.6) mS*/cm*, Ca (141±94) mg/l, Mg(43±30) mg/l, TH (528±312) mg $CaCO_3$/l, Na (1567±876) mg/l, K (86±47) mg/l, Fe (0.10±0.08) mg/l, PO_4 (0.55±0.22) mg/l, Turbidity (12±4) NTU, DO (3.6±1.2) mg/l, BOD (9.4±1.9) mg/l, alkalinity (190±40) mg/l, SO_4 (84±32)mg/l, Cl(2158±1294) mg/l,NO_3 (0.97±0.27) mg/l. This basic data structure indicates the post tsunamic ground water quality of the Alappad coast is used to evaluate the hydrochemical behavior of the regions ground water quality. The post tsunamic ground water quality of the region with respect to these parameters over a period of time is given in the Table 5.17

Water quality parameters ranged from pH (7.1-7.7), EC (2.5-5.7) mS*/cm*, Ca (47-235) mg/l, Mg(13-73) mg/l, TH (216-840) mg $CaCO_3$/l, Na (691-2443) mg/l, K (39-133) mg/l, Fe (0.02-0.18) mg/l, PO_4 (0.33-0.77) mg/l, Turbidity (8-16) NTU, DO (2.4-4.8) mg/l, BOD (7.5-11.3) mg/l, alkalinity (150-230) mg/l, SO_4 (52-116) mg/l, Cl (864-3452) mg/l, NO_3 (0.70±1.24) mg/l. Overall data of four regions in 2005 and 2008 are given in Tables 6.4 and 6.5 respectively.

Table 6.4: Overall ground water quality parameters of Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai coastal regions of kerala in the year 2005 after 26 December 2004 Indian Ocean tsunami; post tsunamic studies

Coastal Section	Data	pH	EC mS/cm	Ca mg/L	Mg mg/L	TH mg/L	Na mg/L	K mg/L	Fe mg/L	PO_4 mg/L	NTU	DO mg/L	BOD mg/L	Alkalinity mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Alappad (Run-up: 5m) (Inundation: 1.0Km)	$\overline{x} \pm \sigma$	7.6±0.5	2.7±4.2	109±176	47±46	465±515	384±689	16±20	0.28±0.54	0.07±0.13	11±16	4±2	10±15.6	280±70	36±34	752±1229	0.96±0.11
	μ	7.6±0.3	2.7±2.8	109±118	47±31	465±346	384±463	16±13	0.28±0.36	0.07±0.09	11±11	4±1	10±10	280±47	36±23	752±826	0.96±0.77
	CI	7.3-7.9	0.0-5.5	0-227	16-78	119-811	0-847	3-29	0.0-0.64	0.0-0.16	0-22	3-5	0-10	233-327	13-59	0-1578	0.19-1.73
Arattupuzha (Run-up: 3.5m) (Inundation: 1.0Km)	$\overline{x} \pm \sigma$	8.0±0.5	5.5±6.9	184±162	110±83	895±584	1412±1424	56±56	0.05±0.05	0.14±0.35	5.2±5.1	4.7±2.2	9.7±6.1	221±70	78±117	2844±3419	0.81±0.47
	μ	8.0±0.4	5.5±5.0	184±109	110±56	895±392	1412±957	56±37	0.05±0.04	0.14±0.23	5.2±3.4	4.7±1.5	9.7±4.1	221±47	78±78	2844±2297	0.81±0.31
	CI	7.6-8.4	0.5-0.5	75-293	54-166	503-287	455-2369	19-93	0.01-0.09	0-0.37	1.8-8.6	3.2-6.2	5.6-3.8	174-268	0-156	547-5141	0.5-1.12
Andhkaranazhy (Run-up: 3.5m) (Inundation: 1.0Km)	$\overline{x} \pm \sigma$	7.4±0.3	2.7±2.2	101±55	34±62	382±294	286±213	13±8	0.11±0.09	0.28±0.11	7±5	2.0±0.8	5.6±2.6	324±89	16±5	361±225	0.40±0.13
	μ	7.4±0.2	2.7±1.5	101±37	34±44	382±207	286±150	13±6	0.11±0.07	0.28±0.08	7±4	2.0±0.5	5.6±1.8	324±63	16±3	361±158	0.40±0.09
	CI	7.2-7.6	1.2-4.2	64-138	0-78	175-589	136-436	7-19	0.03-0.08	0.20-0.36	3-11	1.5-2.5	3.8-7.4	261-387	13-19	203-519	0.31-0.49
Cherai (Run-up: 3.0m) (Inundation: 0.5Km)	$\overline{x} \pm \sigma$	7.4±0.4	4.1±2.3	141±134	43±43	528±443	1567±1243	86±67	0.10±0.12	0.55±0.32	12±5	3.6±1.6	9.4±2.7	190±56	84±46	2158±1837	0.97±0.38
	μ	7.4±0.3	4.1±1.6	141±94	43±30	528±312	1567±876	86±47	0.10±0.08	0.55±0.22	12±4	3.6±1.2	9.4±1.9	190±40	84±32	2158±1294	0.97±0.27
	CI	7.1-7.7	2.5-5.7	47-235	13-73	216-840	691-2443	39-133	0.02-0.18	0.33-0.77	8-16	2.4-4.8	7.5-1.3	150-230	52-116	864-3452	0.70-1.24
BIS Standard		6.5-8.5		75	30	300			0.3		5			200	200	250	50
USEPA		6.5-8.5					20		0.3		0.5-5				250	250	10
WHO		6.5-8.5					200		0.3		5				250	250	50
EEC		6.2-8.5			50	50	175	12	0.2	5	4				250		50
KSPCB		6.5-8.5		75		300			0.3		5			200	200	250	50

Table 6.5: Overall ground water quality parameters of Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai coastal regions of kerala in the year 2008 after 26 December 2004 Indian Ocean tsunami; post tsunamic studies

Coastal Section	Data	pH	EC mS/cm	Ca mg/L	Mg mg/L	TH mg/L	Na mg/L	K mg/L	Fe mg/L	PO_4 mg/L	NTU	DO mg/L	BOD mg/L	Alkalinity mg/L	SO_4 mg/L	Cl mg/L	NO_3 mg/L
Alappad (Run-up: 5m) (Inundation: 1.0Km)	$\overline{x}\pm\sigma$	7.4±0.3	0.7±1.0	22±7.5	25±23	156±92	88±106	8±6	0.17±0.07	0.1±0.08	6±4	5.4±3.4	9.3±5.2	30±10	17±22	102±232	1.65±0.96
	μ	7.4±0.2	0.7±0.6	22±5	25±15	156±62	88±71	8±4	0.17±0.05	0.1±0.06	6±2	5.4±2.3	9.3±3.5	30±7	17±15	102±156	1.65±0.64
	CI	7.2-7.6	0.1-1.3	17-27	10-40	94-218	17-159	4-12	0.12-0.22	0.04-0.16	4-8	3.1-7.7	5.8-12.8	23-37	2-32	0-258	1.01-2.29
Arattupuzha (Run-up: 3.5m) (Inundation: 1.0Km)	$\overline{x}\pm\sigma$	7.3±0.1	0.5±0.3	20±11	11±8	114±25	86±49	9±6	0.12±0.05	0.25±0.53	3±1	4±2.7	9±4.8	24±11	12±15	60±72	0.70±0.66
	μ	7.3±0.1	0.5±0.2	20±8	11±5	114±17	86±33	9±4	0.12±0.04	0.25±0.36	3±1	4±1.8	9±3.2	24±8	12±10	60±48	0.70±0.45
	CI	7.2-7.4	0.3-0.7	12-28	6-16	97-131	53-119	5-13	0.08-0.16	0.00-0.61	2-4	2.2-5.8	5.8-12.2	16-32	2-22	12-108	0.25-1.15
Andhkaranazhy (Run-up: 3.5m) (Inundation: 1.0Km)	$\overline{x}\pm\sigma$	7.2±0.3	0.9±0.8	41±14	24±14	203±84	79±70	9±9	0.16±0.25	0.38±0.42	5±3	1.3±1.0	8.3±5.0	34±12	5±8	76±43	1.42±0.17
	μ	7.2±0.2	0.9±0.6	41±9	24±10	203±59	79±49	9±7	0.16±0.18	0.38±0.30	5±2	1.3±0.7	8.3±3.5	34±8	5±6	76±30	1.42±0.12
	CI	7.0-7.4	0.3-1.7	32-50	14-34	144-262	30-128	2-16	0.02-0.34	0.08-0.68	3-7	0.6-2.0	4.8-11.8	26-42	0-11	46-106	1.30-1.54
Cherai (Run-up: 3.0m) (Inundation: 0.5Km)	$\overline{x}\pm\sigma$	6.6±0.2	0.9±1.0	113±214	61±110	533±974	95±81	10±9.5	0.12±0.10	0.40±0.30	1.3±1.0	2.3±1.6	5.8±1.9	19±7.4	54±73	650±918	0.93±0.37
	μ	6.6±0.1	0.9±0.7	113±151	61±77	533±686	95±57	10±7	0.12±0.07	0.40±0.21	1.3±1.0	2.3±1.1	5.8±1.3	19±5.2	54±52	650±647	0.93±0.26
	CI	6.5-6.7	0.2-1.6	0-264	0-138	0-1219	38-152	3-17	0.05-0.19	0.19-0.61	0.6-2.0	1.2-3.4	4.5-7.1	13.8-24	2-106	3-1297	0.67-1.19
BIS Standard		6.5-8.5		75	30	300			0.3		5			200	200	250	50
USEPA		6.5-8.5					20		0.3		0.5-5				250	250	10
WHO		6.5-8.5					200		0.3		5				250	250	50
EEC		6.2-8.5			50	50	175	12	0.2	5	4				250		50
KSPCB		6.5-8.5		75		300			0.3		5			200	200	250	50

6.3 Variation of Prominent Water Quality Parameters

***Hypothesis 1**: The first hypothesis to be tested has been whether there is any significant difference in the water quality parameters under study between stations and between months in tsunami affected dug well sources (TADW) [ANOVA TEST;* Montgomery, 2009, Harris, 2006]

The study of tsunami impact on ground water sources of Kerala and variability among the sixteen parameters evaluated reveals that alkalinity (Figure 6.18), total hardness (Figure 6.16), calcium harness (Figure 6.17) sodium (Figure 6.11), chloride (Figure 6.13) and water quality index (Figure 6.19) have a permanent influence in determining the quality of the ground water (Table 6.6).

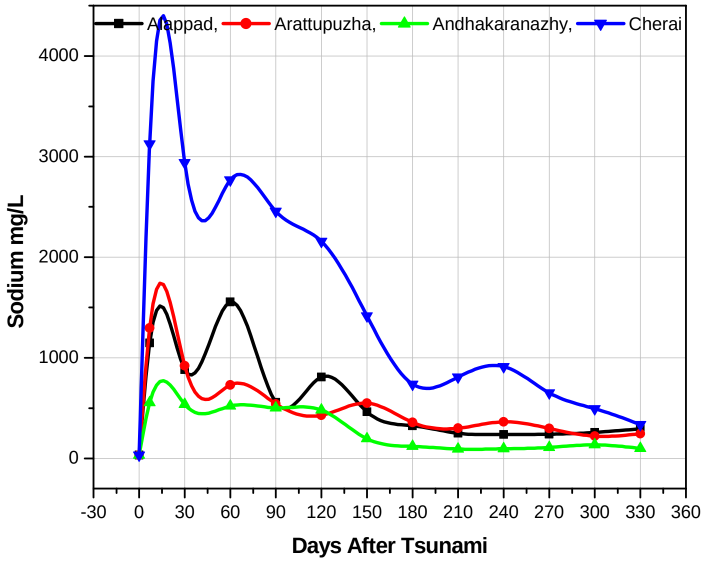

Figure 6.11: Variation of Sodium(TADW) as a function of time at Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai region after 26 December 2004 Indian Ocean tsunami

This is clearly shown by the bar diagrams shown (Figure 6.12, 6.14 and 6.15) for the post tsunamic period with respect of Tsunami Affected Dug Well (TADW) sources. Thereafter it is decided to examine and to compare the water quality parameters in TADW during 2005 using ANOVA to prove whether there is any significant difference in the water quality parameter under study between stations and between months in

TADW. Cherai- Edavanakkad registered significantly higher sodium compared to other stations ($p<0.001$). Sodium content was significantly higher during January to March ($p<0.001$).

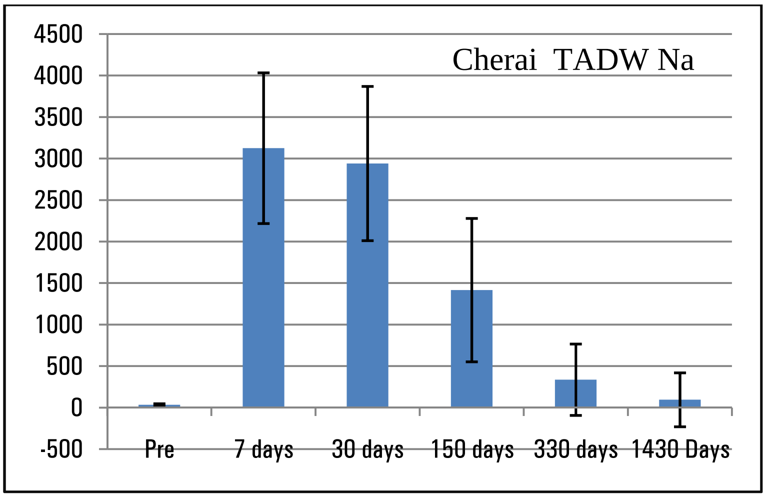

Figure 6.12: Variation of Sodium(TADW) with days at Cherai- Edavanakkad coast as a function of time in the post tsunamic period after 26 December 2004 Indian Ocean tsunami.

Chloride profile of the four tsunami affected coastal sections are given in figure and the data are compared and tested with ANOVA.

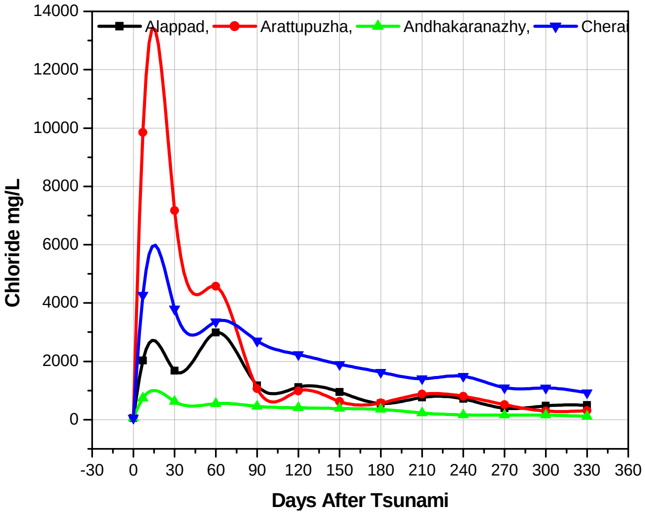

Figure 6.13: Variation of Chloride (TADW) as a function of time at Alappad, Arattupuzha, Andhakaranazhy and Cherai region after 26 December 2004 Indian Ocean tsunami.

In Arattupuzha and Cherai- Edavanakkad coastal sections, Chloride level was significantly higher than other two stations ($p<0.001$). From January to March, Chloride level was significantly higher ($p<0.001$).

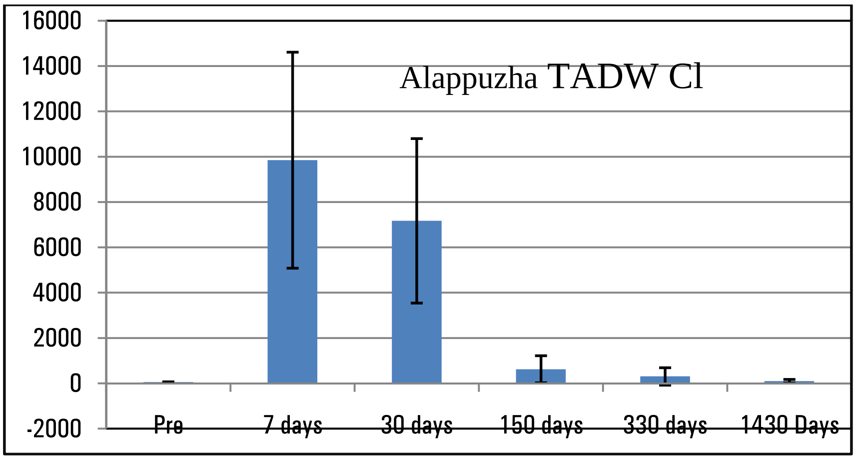

Figure 6.14: Variation of Chloride (TADW) with days at Arattupuzha coast as a function of time in the post tsunamic period after 26 December 2004 Indian Ocean tsunami

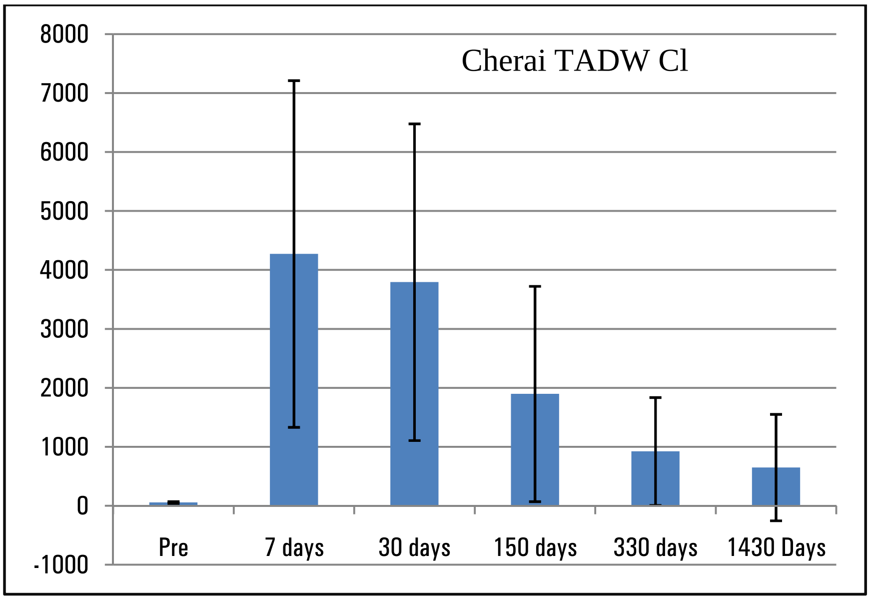

Figure 6.15: Variation of Chloride (TADW) with days at Cherai- Edavanakkad coast as a function of time in the post tsunamic period after 26 December 2004 Indian Ocean tsunami

Hardness Significantly higher levels of hardness is experienced in Alappad and Cherai (p<0.001).January-March experienced significantly lower hardness.

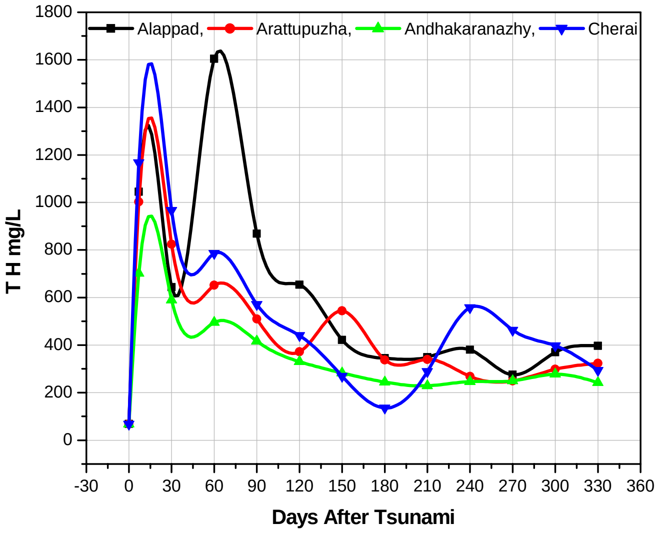

Figure 6.16: Variation of Total Hardness (TADW) with days at Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai region

Calcium Hardness Between stations, the difference is not significant (p>0.05). Significantly higher Calcium hardness is observed during January-March.

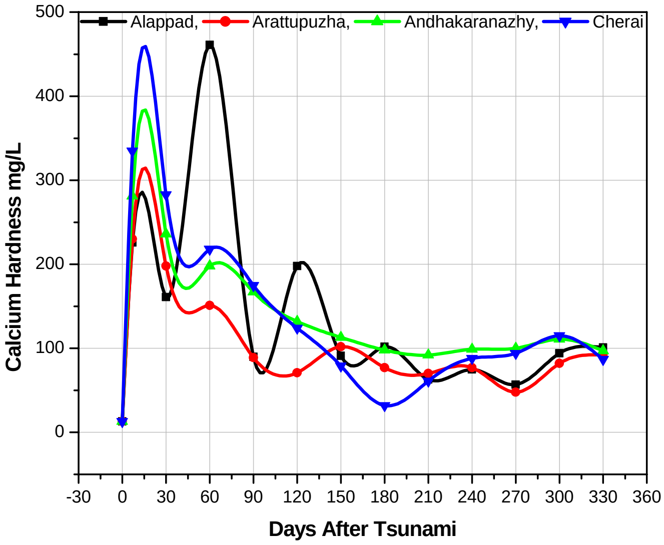

Figure 6.17: Variation of Ca Hardness (TADW) with days at Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai region

Alkalinity Significantly a higher level of Alkalinity was observed in Alappad and Andhakaranazhy compared to other stations. Between months the difference is not significant.

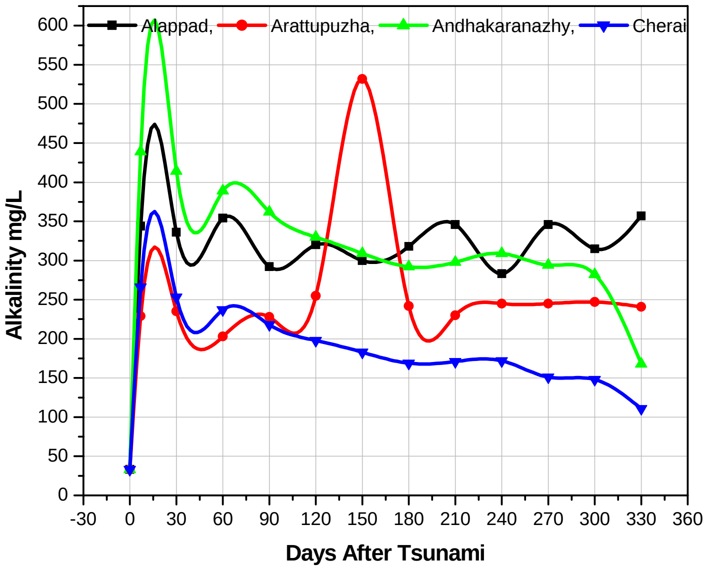

Figure 6.18: Variation of Alkalinity (TADW) with days at Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai region

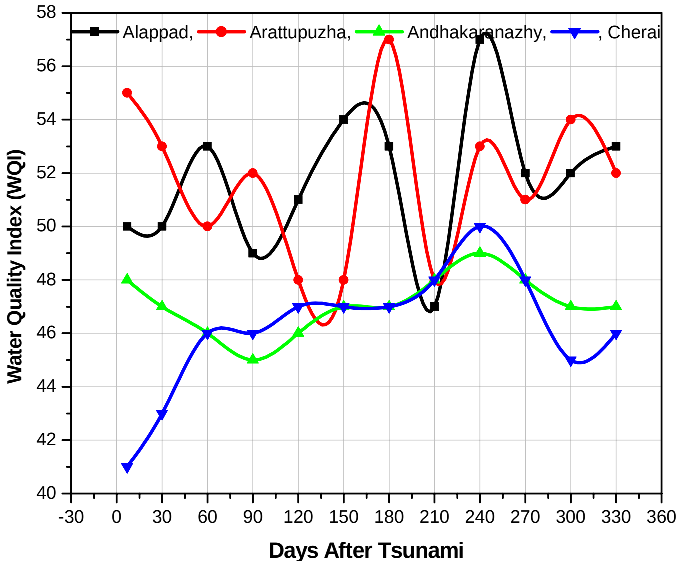

Figure 6.19: Variation of WQI (TADW) with days at Alappad, Arattupuzha, Andhakaranazhy and Edavanakkad-Cherai region

Table 6.6: Comparison of Water Quality parameters in TADW during 2005; ANOVA Table [Hypothesis 1, ANOVA TEST]

Parameter	Source	SS	df	m.s	F	P value	Inference
Sodium	Total	27292421	47				Cherai registered significantly higher sodium compared to other stations (p<0.001). Sodium content was significantly higher during January to March (p<0.001).
	Stations	11676505	3	3892168	23.56	P<0.001	
	Months	10163820	11	923984	5.59	P<0.001	
	Error	5452096	33	165215			
Chloride	Total	161887514	47				In Arattupuzha and Cherai, Chloride level was significantly higher than other two stations (p<0.001). From January to March, Chloride level was significantly higher (p<0.001).
	Stations	30292482	3	10097494	5.40	P<0.001	
	Months	69908874	11	6355352	3.48	P<0.001	
	Error	61686158	33	1869278			
Hardness	Total	4035223	47				Significantly higher levels of hardness is experienced in Alappad and Cherai (p<0.001). January-March experienced significantly lower hardness.
	Stations	406477	3	135492	4.89	P<0.01	
	Months	2715207	11	246837	8.92	P<0.001	
	Error	913539	33	27683			
Calcium Hardness	Total	326706	47				Between stations, the difference is not significant (p>0.05). Significantly higher Calcium hardness is observed during January-March.
	Stations	11306	3	3769	1.46	P>0.05	
	Months	230426	11	24948	9.68	P<0.001	
	Error	84974	33	2578			
Alkalinity	Total	317901	47				Significantly a higher level of Alkalinity was observed in Alappad and Andhakaranazhy compared to other stations. Between months the difference is not significant.
	Stations	149288	3	49763	13.58	P<0.001	
	Months	47709	11	4337	1.18	P>0.05	
	Error	120904	33	3664			

SS = sum of squares, f = variance ratio, df = degrees of freedom, ms = mean square, p = level of significance SS/df = ms

6.4 Comparison of levels of water quality parameters with BIS and WHO standards

Hypothesis 2: *Whether the selected water quality parameters vary significantly from BIS and WHO standards [STUDENTS't TEST; BIS, 1999; Harris, 2006]*

Ensuring of the quality of ground water is essential for the very human existence, specifically with respect to the maintenance of the groundwater sources especially after the impact of tsunami on coastal land. Bureau of Indian Standards specifies a requirement of permissible limit for drinking waters with pH 6.5 – 8.5, Mg 30mg/l, 300 mg/l $CaCO_3$ as maximum total hardness of drinking water, Fe 0.3 mg/l, Turbidity 5 NTU, alkalinity 150 mg/l, $SO_4{}^{2-}$, Cl^- 250mg/l (BIS, 1999) as essential for water supply structure and adverse effects on domestic use. Necessarily, a maximum of 0.3 mg/l of Fe is permitted as beyond this limit taste/ appearance are affected, has adverse effect on domestic uses and water supply structures, and promotes iron bacteria. WHO in its standards – guidelines (WHO, 2004) specifies no minimum limit to hardness for the drinking water. However it recommends a maximum of 0.2 mg/l of iron whereas EEC (EEC) and USEPA (USEPA) proposes a maximum admissible concentration of 0.2 and 0.3mg/l respectively (Table 6.7).

Major parameters investigated for ground water sources of the tsunami affected coastal areas are compared with the BIS and WHO standards

Table 6.8: Comparison of levels of water quality parameters with BIS standards; Students' t Test [Hypothesis 2, Students' t test]

Parameter	Stations	't' value	df	p-value
pH	Alappad	1.106	10	p>0.05
	Arattupuzha	3.317	10	p<0.01
	Andhakaranazhy	3.162	9	p<0.05
	Cherai	14.230	9	p<0.001
Mg	Alappad	8.292	10	p<0.001
	Arattupuzha	3.196	10	p<0.01
	Andhakaranazhy	4.743	9	p<0.01
	Cherai	14.004	9	p<0.001
T.H	Alappad	53.803	10	p<0.001
	Arattupuzha	587.040	10	p<0.001
	Andhakaranazhy	61.032	9	p<0.001
	Cherai	183.763	9	p<0.001
Fe	Alappad	6.159	10	p<0.001
	Arattupuzha	16.583	10	p<0.001
	Andhakaranazhy	1.771	9	p<0.05
	Cherai	5.692	9	p<0.001
NTU	Alappad	0.829	10	p>0.05
	Arattupuzha	0.130	10	p>0.05
	Andhakaranazhy	0.000	9	p>0.05
	Cherai	5.376	9	p<0.001
Alkalinity	Alappad	39.799	10	p<0.001
	Arattupuzha	3.364	10	p<0.05
	Andhakaranazhy	30.569	9	p<0.001
	Cherai	55.981	9	p<0.001
Sulfate	Alappad	303.471	10	p<0.001
	Arattupuzha	404.628	10	p<0.001
	Andhakaranazhy	75.895	9	p<0.001
	Cherai	65.954	9	p<0.001
Chloride	Alappad	3.893	10	p<0.001
	Arattupuzha	3061.245	10	p<0.001
	Andhakaranazhy	0.077	9	p>0.05
	Cherai	202.034	9	p>0.05

Error = Total- stations- months, F = Stations/Error = 'f' for stations and F = month/error = 'f' for months

Table 6.9: Comparison of Water Quality Parameters between TADW and BW; ANOVA Table [Hypothesis 3 & 4, ANOVA TEST]

Parameter	Source	5S	df	ms	F	p-value	Inference
Sodium	Total	39926491	95				Level of Sodium is significantly higher in TADW compared to BW ($p < 0.05$). In Cherai station, level of sodium is significantly higher than other stations ($p < 0.001$).
	Bet.TADW&BW	12796901	1	12796901	5.73	$P < 0.05$	
	Bet. Stations	6814296	3	2271432	10.17	$P < 0.001$	
	Error	20315294	91	223245			
Chloride	Total	210585205	95				Chloride level is significantly higher in TADW compared to BW ($p < 0.01$). Arattupuzha and Cherai registered significantly high chloride content compared to Andhakaranazhy and Alappad.
	Bet.TADW&BW	16383498	1	16383498	10.21	$P < 0.01$	
	Bet. Stations	48114256	3	16038085	9.99	$P < 0.001$	
	Error	146087451	91	1605357			
Hardness	Total	8323162	95				Hardness is significantly higher in TADW than BW. Hardness is significantly higher at Cherai and low at Andhakaranazhy
	Bet.TADW&BW	3449321	1	3449321	76.04	$P < 0.001$	
	Bet. Stations	745827	3	248609	5.48	$P < 0.001$	
	Error	4128014	91	45363			
Calcium Hardness	Total	644365	95				Calcium Hardness is significantly higher in TADW than BW ($p < 0.001$). Between stations the difference is not significant ($p > 0.05$)
	Bet.TADW&BW	290400	1	290400	77.01	$P < 0.001$	
	Bet. Stations	10833	3	3611	0.96	$P > 0.05$	
	Error	343132	91	3771			
Alkalinity	Total	1619789	95				Alkalinity in TADW is significantly higher compared to BW ($p < 0.001$). Alappad and Arattupuzha experienced significantly higher alkalinity compared to Cherai and Andhakaranazhy ($p < 0.001$). Significantly low Alkalinity reported in Cherai
	Bet.TADW&BW	681792	1	681792	152.63	$P < 0.001$	
	Bet. Stations	531537	3	177179	39.66	$P < 0.001$	
	Error	406460	91	4467			
Water Quality Index	Total	5495	95				TADW registered significantly higher water quality index compared to BW ($p < 0.001$). Alappad and Arattupuzha showed significantly higher WQI compared to Andhakaranazhy and Cherai ($p < 0.001$).
	Bet.TADW&BW	13348	1	13348	67.95	$P < 0.001$	
	Bet. Stations	19307	3	6496	26.27	$P < 0.001$	
	Error	22296	91	245			

6.4.1 Comparison with BIS Standards

pH **:** Observed were significantly higher than BIS with station Arattupuzha ($p<0.01$) and significantly lower than BIS in Cherai and Andhakaranazhy. ($p<0.001$).

Magnesium **:** Mg is significantly higher than BIS in Cherai and Arattupuzha ($p<0.01$) and significantly lower than BIS in Alappad and Andhakaranazhy ($p<0.001$)

Total Hardness **:** In all the 4 stations TH was significantly higher than BIS ($p<0.001$)

Total Iron **:** Compared to BIS, Fe is significantly low in Alappad, Arattupuzha and Cherai ($p<0.01$)

Turbidity **:** Turbidity is significantly low in Cherai, compared to BIS. In all other 3 stations they are agreed with BIS.

Alkalinity **:** In Cherai, Alappad and Andhakaranazhy, Alkalinity is significantly lower than BIS ($p<0.001$) and significantly higher in Arattupuzha ($p<0.001$).

Sulfate **:** In all the 4 stations, sulphate is significantly less than BIS ($p<0.001$).

Chloride **:** In all the 3 stations, Alappad, Arattupuzha and Cherai, Chloride levels found to be significantly higher than BIS ($p<0.01$) (Table 6.8).

Table 6.7: Comparison of selected Water Quality Parameters in 2005 with WHO standard **[Hypothesis 2]**

Parameter	‘t’ Value	df	p-Value	Inference
1. pH	4.157	10	$p<0.01$	Significantly higher than WHO
2. Na	0.925	10	$p>0.05$	Agreeing with WHO standard
3. Fe	0.128	10	$p>0.05$	Agreeing with WHO standard
4.Turbidity	1.299	10	$p>0.05$	Agreeing with WHO standard
5. SO_4	21.800	10	$p<0.001$	Significantly less than that of WHO
6. Cl	1.415	10	$p>0.05$	Agreeing with WHO standard
7. NO_3	1544.99	10	$p<0.001$	Significantly less than that of WHO

6.4.2 Comparison of Water Quality Parameters between TADW and BW

Hypothesis 3 **:** *Whether the water Quality parameters differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW) [ANOVA TEST]*

In the earlier sections discussed it is found that sodium, chloride, hardness, calcium hardness, alkalinity are having an indelible marking in determining the post tsunamic profile of the region. The comparisons of these five parameters are made using ANOVA test method (Table 6.9).

Sodium : Level of Sodium is significantly higher in TADW compared to BW ($p<0.05$).

In Cherai station, level of sodium is significantly higher than other stations ($p<0.001$).

Chloride : Chloride level is significantly higher in TADW compared to BW ($p<0.01$).

Arattupuzha and Cherai registered significantly high chloride content compared to Andhakaranazhy and Alappad.

Hardness : Hardness is significantly higher in TADW than BW. Hardness is significantly higher at Cherai and low at Andhakaranazhy.

Calcium Calcium Hardness is significantly higher in TADW than BW ($p<0.001$).

Hardness : Between stations the difference is not significant ($p>0.05$)

Alkalinity : Alkalinity in TADW is significantly higher compared to BW ($p<0.001$). Alappad and Arattupuzha experienced significantly higher alkalinity compared to Cherai and Andhakaranazhy ($p<0.001$). Significantly low Alkalinity reported in Cherai-Edavanakkad coastal section.

Hypothesis 4 **:** *Whether the water quality index differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW) [ANOVA TEST]*

The Water Quality Index (WQI) that comprises the combination of nine prominent parameters consisting of Temperature, pH, BOD, DO, FC (Faecal Coliform), Nitrate, TDS, Phosphate and Turbidity. Figure shows the variation of WQI in the specific coastal sections as a function of time.

WQ I : TADW registered significantly higher water quality index compared to BW ($p<0.001$). Alappad and Arattupuzha showed significantly higher WQI compared to Andhakaranazhy and Cherai ($p<0.001$).

6.4.3 Comparison of various Water Quality Parameters during December 2005 and December 2008 (Table 6.10).

Hypothesis 5 **:** *Whether there is any significant difference in the water quality parameters during December 2005 and December 2008 [STUDENTS't TEST]*

Table 6.10: Comparison of various Water Quality Parameters during December 2005 and December 2008

Parameter	't' Value	df	p-Value	Inference
1. Sodium	1.57	6	$p>0.05$	No Significant difference
2. Chloride	1.45	6	$p>0.05$	No Significant difference
3. Hardness	0.55	6	$p>0.05$	No Significant difference
4. Calcium Hardness	2.86	6	$p<0.05$	Calcium Hardness is significantly high in December 2005 compared to December 2008
5. Alkalinity	3.60	6	$p<0.05$	Alkalinity is significantly high in December 2005 compared to December 2008
6. WQI	0.35	6	$p>0.05$	No Significant difference

6.4.4 Comparison of Water Quality Parameters before (2001) and after (2005) tsunami

Hypothesis 6 **:** *Is there any significant change in the Water Quality Parameters before (2001) and after tsunami (2005) in TADW [Independent student's t test]* (Montgomery, 2009)

One of the main objectives of the study was to establish the temporal ground water quality variation profile after 26 December 2004 Indian Ocean tsunami event on coastal regions of Kerala within the local geo-physical constraints for a period starting just 7 days after tsunami to 1430 days. Study of the ground water chemistry of the region in relation to the pre and post tsunami situation (after 26 December 2004 Tsunami) was essential to attain conclusive inferences. In this regard independent student's t test have been implemented to compare the water quality parameters before (2001) and after (2005) tsunami (Table 6.11).

pH : No Significant difference

E.C : E.C in 2005 is significantly higher than 2001

Calcium : Calcium in 2005 is significantly higher than 2001

Magnesium : Magnesium in 2005 is significantly higher than 2001

T.H : T.H in 2005 is significantly higher than 2001

Sodium : Sodium in 2005 is significantly higher than 2001

Potassium : Potassium in 2005 is significantly higher than 2001

Iron : No Significant difference

Chloride : Chloride in 2005 is significantly greater than 2001

Sulphate : Sulphate in 2005 is significantly greater than 2001

HCO_3 : HCO_3 in 2005 is significantly greater than 2001

Table 6.11: Comparison of Water Quality Parameters before (2001) and after (2005) tsunami

Parameter	2001		2005		Pooled standard error	t	df	p-value	Inference
	n	mean	n	mean					
pH	5	7.60	42	7.61	0.24	0.042	45	$P>0.05$	No Significant difference
E.C	5	0.35	42	3.77	0.71	4.814	45	$P<0.001$	E.C in 2005 is significantly higher than 2001
Ca	5	19.00	42	134.36	23.96	4.815	45	$P<0.001$	Ca in 2005 is significantly higher than 2001
Mg	5	4.80	42	59.45	9.23	5.921	45	$P<0.001$	Mg in 2005 is significantly higher than 2001
T.H	5	68.00	42	572.45	82.59	6.112	45	$P<0.001$	T.H in 2005 is significantly higher than 2001
Na	5	33.00	42	911.57	180.59	4.665	45	$P<0.001$	Na in 2005 is significantly higher than 2001
K	5	10.00	42	42.43	9.42	3.443	45	$P<0.01$	K in 2005 is significantly higher than 2001
Fe	5	0.08	42	0.14	0.05	1.200	45	$P>0.05$	No Significant difference
Cl	5	57.00	42	1541.57	332.44	4.466	45	$P<0.001$	Cl in 2005 is significantly greater than 2001
SO_4	5	20.40	42	53.67	13.86	2.400	45	$P<0.05$	SO_4 in 2005 is significantly greater than 2001
HCO_3	5	34.20	42	325.00	24.19	12.201	45	$P<0.001$	HCO_3 in 2005 is significantly greater than 2001

6.5 Combination of mean and SD of the various parameters in 2005 for the entire coast

The overall water quality of the tsunami affected coastal areas of Kerala has been evaluated by combining the individual parameters determined by the respective four coastal sections such as Alappad, Arattupuzha, Andhakaranazhy, Edavanakkad – Cherai coasts of Kerala (Table 6.12).

Table 6.12: Combination of mean and SD of the various parameters in 2005 for the entire coastal section studied.

Parameter	Mean	SD	Mean ±SD	Range
1. pH	7.61	0.50	7.61±0.50	7.1-8.1
2. EC	3.77	4.57	3.77±4.57	0-8.34
3. Ca	134.36	145.16	134.36±145.16	0-279
4. Mg	59.45	73.26	59.45±73.26	0-132
5. TH	572.86	515.24	572.86±515.24	58-1088
6. Na	911.57	1169.63	911.57±1169.63	0-2082
7. K	42.43	53.85	42.43±53.85	0-96
8. Fe	0.14	0.30	0.14±0.30	0-0.44
9. PO4	0.25	0.31	0.25±0.31	0-0.56
10. Turbidity	8.77	9.68	8.77±9.68	0-19
(NTU)	3.61	3.44	3.61±3.44	0.17-7.05
11. DO	8.73	4.50	8.73±4.50	4.23-13.23
12. BOD	253.60	88.34	253.60±88.34	166-342
13. Alkalinity	53.67	67.40	53.67±67.40	0-121
14. SO_4	1541.57	2154.01	1541.57±2154.01	0-3696
15. Cl	0.79	0.39	0.79±0.39	0.4-1.18
16. NO_3				

The Table shows the water quality parameters the entire coastal section of the tsunami devastated coastal region of Kerala combining the individual parameters determined for the above four different coasts. The results are pH (7.61±0.50), EC (3.77±4.570), Ca (134.36±145.16), Mg (59.45±73.26), TH (572.86±515.24), Na (911.57±1169.63), K (42.43±53.85), Fe (0.14±0.30), PO_4 (0.25±0.31), Turbidity (8.77±9.68 NTU), DO (3.61±3.44), BOD (8.73±4.50), Alkalinity (253.60±88.34), SO_4 (53.67±67.40), Cl (1541.57±2154.01), NO_3 (0.79±0.39).

Conclusions

26 December 2004 Indian Ocean tsunami devastated the ground water quality of the coastal environment of Kerala by the severe inundation by brought about by the tsunami waves on the barrier islet formations. The study focused on four coastal sections Alappad, Arattupuzha, Andhakaranazhy, Edavanakkad – Cherai coasts of Kerala revealed there are drastic changes on the ground water quality. Statistical analysis shows that there are significant changes in the magnitude of the parameters determined on temporal and spatial basis. Most parameters determined in the post tsunamic year 2005 have values significantly higher than the pre-tsunamic data available in 2001. The overall water quality of the tsunami affected coastal region of Kerala in the post tsunamic year 2005 ranges from pH (7.1-8.1), EC (0-8.34), Ca (0-279), Mg (0-132), TH (58-1088), Na (0-2082), K (0-96), Fe (0-0.44), PO_4 (0-0.56), Turbidity (0-19 NTU), DO (0.17-7.05), BOD (4.23-13.23), Alkalinity (166-342), SO_4 (0-121), Cl (0-3696), NO_3 (0.4-1.18).

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CONCLUDING REMARKS

The major conclusions of this research study are

1. There are drastic changes in the overall quality of the coastal environment of the tsunami affected coastal areas of Kerala after 26 December 2004 Indian Ocean Tsunami.
2. 26 December 2004 Indian Ocean Tsunami and subsequent expansive inundation by giant tsunami waves brought temporal and spatial variation of the ground water quality of the severely devastated Alappad (Kollam District), Arattupuzha (Alappuzha District), Andhakaranazhy (Alappuzha District), Edavanakkad – Cherai (Ernakulum District) coastal sections of the Kerala coast.
3. There is more than 95% chance that the true value of the representative water quality parameters of the Alappad region in the pre-tsunamic period of the year 2001 lies in the confidence interval; pH (7.5-7.7), EC (0.334-0.370) mS*/cm* , TH (55-81) mg $CaCO_3$/l, Ca (14.2-23.8) mg/l, Mg (4.2-5.4) mg/l, Na (29-37) mg/l, K (7.5-12.5) mg/l, CO_3 (0.2-0.3) mg/l, HCO_3 (20.4-48.0) mg/l, SO_4 (15.1-25.7) mg/l, Cl (53.1-60.9) mg/l, F (0.077-0.083) mg/l.
4. The extent of damage on the overall quality of the ground water evaluated in the post tsunamic period of 2005 and 2008 showed that quality of the ground water has been damaged for the strata of shallow dug wells (common drinking water sources) of mean depth 6 feet designated as Tsunami Affected Dug wells (TADW) between stations and between months.
5. The prominent parameters of the Alappad coastal region of Kerala after 26 December 2004 tsunami ranges from pH (7.4-7.8), EC (0.9-4.5) mS*/cm*, Ca (52-166) mg/l, Mg(27-67) mg/l, TH (255-675) mg $CaCO_3$/l, Na (28-740) mg/l, K (3-29) mg/l, Fe (0.07-0.48) mg/l, PO_4^{3-} (0.03-0.11) mg/l, Turbidity (4-18) NTU, DO (3-5) mg/l, BOD (7-13) mg/l, alkalinity (186-374) mg/l, SO_4 (18-54) mg/l, Cl (142-1362) mg/l, NO_3 (0.74-1.18) mg/l, AI(11.8-12.6).

6. Prominent water quality parameters of Arattupuzha coast of Kerala in the post tsunamic situation ranges from pH (7.6-8.4), EC (0.5-10.5) mS/cm, Ca (75-293) mg/l, Mg(54-166) mg/l, TH (503-1287) mg CaCO3/l, Na (455-2369) mg/l, K (19-93) mg/l, Fe (0.01-0.09) mg/l, PO4 (0.0-0.37) mg/l, Turbidity (1.8-8.6) NTU, DO (3.2-6.2) mg/l, BOD (5.6-13.8) mg/l, alkalinity (174-268) mg/l, SO_4^{2-} (0-156) mg/l, Cl^- (547-5141) mg/l, NO_3^- (0.5-1.12) mg/l.
7. Prominent water quality parameters of Andhakaranazhy coast of Kerala in the post tsunamic situation ranges from pH (7.2-7.6), EC (1.2- 4.2) mS/cm, Ca (64 -138) mg/l, Mg(0-78) mg/l, TH (175-589) mg CaCO3/l, Na (136-436) mg/l, K (72-19) mg/l, Fe (0.03-0.18) mg/l, PO_4 (0.20-0.36) mg/l, Turbidity (3-11) NTU, DO (1.5-2.5) mg/l, BOD (3.8-7.4) mg/l, alkalinity (261-387) mg/l, SO_4^{2-} (13-19) mg/l, Cl^- (203-519) mg/l, NO_3^- (0.31-0.49) mg/l.
8. Water quality parameters of Cherai – Edavanakkad ranges from pH (7.1-7.7), EC (2.5-5.7) mS*/cm*, Ca (47-235) mg/l, Mg (13-73) mg/l, TH (216-840) mg $CaCO_3$/l, Na (691-2443) mg/l, K (39-133) mg/l, Fe (0.02-0.18) mg/l, PO_4 (0.33-0.77) mg/l, Turbidity (8-16) NTU, DO (2.4-4.8) mg/l, BOD (7.5-11.3) mg/l, alkalinity (150-230) mg/l, SO_4 (52-116) mg/l, Cl^- (864-3452) mg/l, NO_3 (0.70±1.24) mg/l.
9. Evaluation of the parameters for whether there is any significant difference in the water quality parameters under study between stations and between months in tsunami affected dug well sources (TADW) showed many specific observations.
10. Cherai- Edavanakkad registered significantly higher sodium compared to other stations ($p<0.001$). Sodium content was significantly higher during January to March ($p<0.001$).
11. In Arattupuzha and Cherai- Edavanakkad coastal sections, Chloride level was significantly higher than other two stations ($p<0.001$). From January to March, Chloride level was significantly higher ($p<0.001$).

12. Hardness significantly higher levels of hardness is experienced in Alappad and Cherai ($p<0.001$). January-March experienced significantly lower hardness.
13. Calcium Hardness between stations, the difference is not significant ($p>0.05$). Significantly higher Calcium hardness is observed during January-March.
14. Alkalinity significantly a higher level of Alkalinity was observed in Alappad and Andhakaranazhy compared to other stations. Between months the difference is not significant.
15. Evaluation of the parameters for whether the selected water quality parameters vary significantly from BIS and WHO standards.
16. *pH:* Observed were significantly higher than BIS with station Arattupuzha ($p<0.01$) and significantly lower than BIS in Cherai and Andhakaranazhy. ($p<0.001$).
17. *Magnesium:* Mg is significantly higher than BIS in Cherai and Arattupuzha ($p<0.01$) and significantly lower than BIS in Alappad and Andhakaranazhy ($p<0.001$).
18. *Total Hardness:* In all the 4 stations TH was significantly higher than BIS ($p<0.001$)
19. *Total Iron:* Compared to BIS, Fe is significantly low in Alappad, Arattupuzha and Cherai ($p<0.01$).
20. *Turbidity:* Turbidity is significantly low in Cherai, compared to BIS. In all other 3 stations they are agreed with BIS.
21. *Alkalinity:* In Cherai, Alappad and Andhakaranazhy, Alkalinity is significantly lower than BIS ($p<0.001$) and significantly higher in Arattupuzha ($p<0.001$).
22. *Sulfate:* In all the 4 stations, sulphate is significantly less than BIS ($p<0.001$).
23. *Chloride:* In all the 3 stations, Alappad, Arattupuzha and Cherai, Chloride levels found to be significantly higher than BIS ($p<0.01$) (Table 6.8).

24. Evaluation of the parameters whether they differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW).

25. Level of Sodium is significantly higher in TADW compared to BW ($p<0.05$).

    In Cherai station, level of sodium is significantly higher than other stations ($p<0.001$).

26. Chloride level is significantly higher in TADW compared to BW ($p<0.01$).

    Arattupuzha and Cherai registered significantly high chloride content compared to Andhakaranazhy and Alappad.

27. Hardness is significantly higher in TADW than BW. Hardness is significantly higher at Cherai and low at Andhakaranazhy.

28. Calcium Hardness is significantly higher in TADW than BW ($p<0.001$). Calcium

    Hardness: Between stations the difference is not significant ($p>0.05$).

29. Alkalinity in TADW is significantly higher compared to BW ($p<0.001$). Alappad and Arattupuzha experienced significantly higher alkalinity compared to Cherai and Andhakaranazhy ($p<0.001$). Significantly low Alkalinity reported in Cherai- Edavanakkad coastal section.

30. Evaluation of the parameter whether the water quality index (WQI) differ significantly between Tsunami Affected Dug Well (TADW) and Bore Well (BW).

31. TADW registered significantly higher water quality index compared to BW ($p<0.001$). Kollam and Alappuzha showed significantly higher WQI compared to Andhakaranazhy and Cherai ($p<0.001$).

32. Evaluation of the parameters whether there is any significant difference in the water quality parameters during December 2005 and December 2008.

33. Sodium: No Significant difference, Chloride: No Significant difference, Total hardness: No Significant difference, Calcium Hardness is significantly high in December 2005 compared to December 2008.Alkalinity is significantly

high in December 2005 compared to December 2008. WQI: No Significant difference.

34. Evaluation of the parameters whether there is any significant change in the Water Quality Parameters before (2001) and after tsunami (2005) in TADW [Independent student's t test].
35. *pH:* No Significant difference
36. E.C in 2005 is significantly higher than 2001
37. Calcium in 2005 is significantly higher than 2001
38. Magnesium in 2005 is significantly higher than 2001
39. T.H in 2005 is significantly higher than 2001
40. Sodium in 2005 is significantly higher than 2001
41. Potassium in 2005 is significantly higher than 2001
42. I*ron:* No Significant difference
43. Chloride in 2005 is significantly greater than 2001
44. Sulphate in 2005 is significantly greater than 2001
45. HCO_3 in 2005 is significantly greater than 2001
46. The overall water quality of the tsunami affected coastal region of Kerala in the post tsunamic year 2005 ranges from pH (7.1-8.1), EC (0-8.34), Ca (0-279), Mg (0-132), TH (58-1088), Na (0-2082), K (0-96), Fe (0-0.44), PO_4 (0-0.56), Turbidity (0-19 NTU), DO (0.17-7.05), BOD (4.23-13.23), Alkalinity (166-342), SO_4 (0-121), Cl (0-3696), NO_3 (0.4-1.18).

FUTURE SCOPE OF THE STUDY

Evaluation of the water quality of the region for another 25 years from the post tsunamic year 2005 till 2029 is planned to generate a baseline data structure to model and predict the water quality variation of the ground water sources of coastal Kerala. The study will give more insight into the long term impact of the 26 December 2004 Indian Ocean Tsunami on shallow and deep ground water with respect to incidence of salinity intrusion and salinity hazard, water quality, aggressiveness and corrosion indices, dissolved organic carbon content distribution and other prominent parameters. Data obtained as on year 2001, 2005 & 2008 are already analyzed and discussed in this thesis. Evaluation of water quality parameters for the complete cycle of the year 2012 is being carried out by another team of researchers of the same group.

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Appendix

APPENDIX 1

Water Quality Parameters – Sodium, Chloride and Total Hardness of Tsunami Affected Dug well Sources [TADW] in the year 2005 & 2008.

TADW Sodium													
Region	**Jan-05**	**Feb-05**	**Mar-05**	**Apr-05**	**May-05**	**Jun-05**	**Jul-05**	**Aug-05**	**Sep-05**	**Oct-05**	**Nov-05**	**Dec-05**	**Dec-08**
Kollam (CS1)	1147	882	1556	557	809	463	323	250	238	241	258	294	115
Alappuzha (CS2)	1296	922	730	542	428	550	358	299	362	297	221	246	106
Andhakaranazhy (CS3)	554	536	520	501	482	196	119	94	95	108	134	98	79
Cherai (CS4)	3126	2941	2769	2456	2157	1416	737	807	914	650	494	337	95

TADW Chloride													
Region	**Jan-05**	**Feb-05**	**Mar-05**	**Apr-05**	**May-05**	**Jun-05**	**Jul-05**	**Aug-05**	**Sep-05**	**Oct-05**	**Nov-05**	**Dec-05**	**Dec-08**
Kollam (CS1)	2027	1674	2990	1171	1114	951	558	761	709	396	471	495	148
Alappuzha (CS2)	9849	7173	4577	1060	980	623	574	873	802	518	291	306	97
Andhakaranazhy (CS3)	736	625	548	460	412	383	352	232	164	158	154	113	76
Cherai (CS4)	4273	3794	3367	2702	2233	1898	1630	1409	1491	1097	1084	922	650

TADW Total Hardness													
Region	**Jan-05**	**Feb-05**	**Mar-05**	**Apr-05**	**May-05**	**Jun-05**	**Jul-05**	**Aug-05**	**Sep-05**	**Oct-05**	**Nov-05**	**Dec-05**	**Dec-08**
Kollam (CS1)	1045	644	1604	869	654	422	345	349	380	275	370	397	185
Alappuzha (CS2)	1002	824	652	510	372	544	338	340	268	250	298	323	120
Andhakaranazhy (CS3)	702	590	495	417	330	283	244	229	246	250	277	242	203
Cherai (CS4)	1167	967	786	571	440	269	135	289	558	463	398	294	533

APPENDIX 2

Water Quality Parameters –Calcium Hardness, Alkalinity and Water Quality Index (WQI) of Tsunami Affected Dug well Sources [TADW] in the year 2005 & 2008

TADW Ca Hardness													
Region	**Jan-05**	**Feb-05**	**Mar-05**	**Apr-05**	**May-05**	**Jun-05**	**Jul-05**	**Aug-05**	**Sep-05**	**Oct-05**	**Nov-05**	**Dec-05**	**Dec-08**
Kollam (CS1)	226	161	461	90	198	91	102	63	75	57	94	101	23
Alappuzha (CS2)	230	198	151	89	71	102	77	70	77	48	82	92	25
Andhakaranazhy (CS3)	281	236	198	167	132	113	98	92	99	100	111	97	81
Cherai (CS4)	335	283	218	175	124	79	32	61	88	94	115	87	113

TADW Alkalinity													
Region	**Jan-05**	**Feb-05**	**Mar-05**	**Apr-05**	**May-05**	**Jun-05**	**Jul-05**	**Aug-05**	**Sep-05**	**Oct-05**	**Nov-05**	**Dec-05**	**Dec-08**
Kollam (CS1)	344	336	354	292	320	300	318	346	283	346	315	357	33
Alappuzha (CS2)	229	235	203	228	255	532	242	230	245	245	247	241	26
Andhakaranazhy (CS3)	439	414	389	362	330	309	292	298	309	294	282	168	34
Cherai (CS4)	266	253	237	218	198	183	169	171	172	151	148	111	19

TADW Water Quality Index (WQI)													
Region	**Jan-05**	**Feb-05**	**Mar-05**	**Apr-05**	**May-05**	**Jun-05**	**Jul-05**	**Aug-05**	**Sep-05**	**Oct-05**	**Nov-05**	**Dec-05**	**Dec-08**
Kollam (CS1)	50	50	53	49	51	54	53	47	57	52	52	53	57
Alappuzha (CS2)	55	53	50	52	48	48	57	48	53	51	54	53	50
Andhakaranazhy (CS3)	48	47	46	45	46	47	47	48	49	48	47	47	48
Cherai (CS4)	41	43	46	46	47	47	47	48	50	48	45	46	48

APPENDIX 3

Water Quality Parameters – Sodium, Chloride and Total Hardness of Calcium Hardness, Alkalinity and Water quality Index (WQI) of Bore Well sources [BW] in the year 2005 & 2008

BW Sodium

Region	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Dec-08
Kollam (CS1)	27	26	21	25	24	26	31	16	29	22	22	22	41
Alappuzha (CS2)	35	26	23	22	26	25	38	17	18	16	18	20	60

BW Chloride

Region	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Dec-08
Kollam (CS1)	83	81	193	273	165	124	32	33	25	36	111	115	11
Alappuzha (CS2)	286	284	345	376	412	55	37	34	28	24	34	31	14

BW Total Hardness

Region	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Dec-08
Kollam (CS1)	252	200	500	277	192	143	191	133	240	178	152	165	108
Alappuzha (CS2)	318	278	240	225	167	179	170	138	260	177	164	194	107

BW Ca Hardness

Region	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Dec-08
Kollam (CS1)	72	61	56	21	60	40	68	28	64	44	47	44	21
Alappuzha (CS2)	81	60	56	35	39	39	32	35	46	30	38	45	22

BW Alkalinity

Region	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Dec-08
Kollam (CS1)	200	192	249	230	195	229	230	237	233	226	220	233	27
Alappuzha (CS2)	220	239	241	238	218	229	248	222	238	225	230	211	23

BW Water Quality Index (WQI)

Region	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Dec-08
Kollam (CS1)	50	50	48	41	46	42	51	44	51	49	53	49	50
Alappuzha (CS2)	56	55	52	53	52	51	62	53	56	54	56	57	58

List of Publications

1. Sivanandan Achari, V.; **Jaison, C. A**.; Alex, P. M.; Seralathan, P.; Pradeepkumar, A. P.; Shaji, E. Tsunami on Kerala Coast: A Study of Ground Water Quality along Arattupuzha and Alappad Coast, *ICFAI Journal of Environmental Sciences*. 2007, 43-54.
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3. Sivanandan Achari, V.; **Jaison, C. A**.; Alex, P. M.; Seralathan, P.; Pradeepkumar, A. P.; Sreenath, G. *Tsunami Impact on the Ground Water Quality on Alappad Coast, Kollam, Kerala*, In Environmental Impact of Tsunami in the Kerala Coast, Kerala State Council for Science , Technology and Environment , Government of Kerala, ISBN 81 – 86366 – 58-X, pp. 2006, 83- 92.
4. Sivanandan Achari, V.; **Jaison, C. A**.; Alex, P. M.; Seralathan, P.; Pradeepkumar, A. P. *Monthly variation of water quality indices on the tsunami affected coast of Kerala, Extended abstrac*t, XVIII Kerala Science Congress, 29-31January 2006, CESS, Akulam, Thiruvananthapuram, India, 380-382. 2006.