Delineation of Submarine Groundwater Discharge (SGD) Zones along the Coast of Uttara Kannada District, Karnataka

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SUMMARY

The groundwater quality of coastal aquifers plays a significant role in locating groundwater discharge to oceans, which is broadly termed as Submarine Ground Discharge (SGD). SGD may be both volumetrically and chemically important to coastal water and chemical budgets. SGD influences the life of organisms in the nearshore coastal environments. Therefore, this study is taken up as part of the national network project as a pilot study on SGD sponsored by the MoES. NIH-HRRC, Belagavi (WG-3) has carried out this study in the coastal region of Uttara Kannada district, Karnataka. The methodology adopted involves collection of archival data on groundwater and aquifer characteristics from different sources, field and laboratory investigations. These includes analysis of groundwater, hydrogeology, topographic, in-situ isotope and water quality samples, meteorological, and land use data. The detailed water quality investigations were carried out to understand the water balance between the land and seawater interaction in parts of Uttara Kannada district. The groundwater and seashore water samples were collected during pre-monsoon, post-monsoon 2019 and post monsoon 2020 season. Sixty-two sites have been identified for water sampling and tested for physical and chemical parameters. Also, collected thirty-eight seashore water and eighteen groundwater samples. Detailed analysis for major anions and cations were carried out. The present investigation is an attempt to make quantitative and qualitative assessment of SGD based on hydrological, hydrogeological and hydro-chemical components. The water balance components were evaluated based on hydrological and hydrogeological investigations. Hydro-chemical parameters were also evaluated to understand the impact of seawater intrusion. Study revealed that there are signatures of considerable quantity of SGD in parts of Honnavara, Kumta, Ankola and Karwar talukas. The influence of seawater in coastal aquifers is quite rare all along the coast of Uttara Kannada district which attributed to high groundwater recharge (15-20%) occurring in the catchment areas.

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1. INTRODUCTION

1.1 Background

Management of water has been a matter of great concern to the global community; it is the only commodity that has the capacity to provide sustenance of life for all the living beings of the world. The matter has attained greater significance primarily due to rapid development and climatic uncertainties that seriously affects the spatio-temporal distribution of water. The erratic distribution pattern of precipitation has taken its toll on the biosphere. In such a scenario, water is an essential ingredient to stabilize the biosphere. The current approach to water management lays stresses mainly on "Blue water" (river water and groundwater). This considerably limits the option to deal with water scarcity and the vulnerability of water induced by climate change.

The interaction of the two hydrological systems that is groundwater and sea water take place at the coastal areas either by seawater intrusion to land or by submarine groundwater discharges (SGD). SGD includes any and all flow of water on continental margins from the seabed to the coastal oceans and seas, regardless of fluid composition or driving force (Burnett et al. 2003). In the water cycle river discharge is a major pathway for discharge of water from land to the ocean. Rivers are open channels that carry water from great distances inland, and their contributions to the oceans are very portentous. Surface water inputs (e.g., rivers and streams) are typically large point material sources to the coastal ocean (Mulligan and Charette 2009) and hence, the contribution of surface water discharge to the ocean, its hydrodynamics, impact on geochemical cycles of elements and its influence on the ocean ecosystem has been well recognized. On the contrary, Groundwater discharge typically has a smaller water flow rate compared to river flow rate and hence not well demarcated. Groundwater flow into the marine environment can have a significant impact on many processes taking place in the coastal areas and therefore there is a need for the process to be better understood. Measuring the groundwater discharge rate is one of the primary concerns to the coastal area management.

Coastal aquifers usually consist of complicated systems made up of confined, semi-confined and unconfined aquifers. Freshwater can flow through an aquifer forced by hydraulic head and enter seawater. There are several forces that drive groundwater flow to the coastal environment. The primary terrestrial driving force of fluid flow through coastal aquifers is the hydraulic gradient. Groundwater flows from the upland region of a watershed to aquifers on the coast where it intersects the sea water (Burnett et al. 2006). Usually, there are more than one driving force behind SGD and includes terrestrial and marine forces (Moore 2010). The main forces that influence SGD are water level differences across a permeable barrier; tidal pumping, wave setup (Taniguchi et al. 2002; Burnett et al. 2003), storms, current-induced pressure gradients in the coastal zone; upland recharge causing seasonal inflow and outflow of seawater into the aquifer (Michael et al. 2005) and geothermal heating (Kohout 1965).

Generally, SGD into oceans and sea occurs constantly all over the world along coast lines (Moore 2010). Groundwater discharge to the sea has been a topic of interest for many centuries (Burnett et al. 2006). Recently, Scientists have started determining SGD influence on the environment and chemical substances fluxes via SGD, however there are still issues that need to be solved as well as a number of unrecognized geographical areas impacted by groundwater discharge. One of the most challenging issues is identifying the effect of chemical substances fluxes via SGD on their concentrations and the reactions taking place in subterranean estuaries. Another outstanding issue would be the recognition of the local and global importance of SGD and its influence on chemical substances budgets (Moore 2010).

The SGD to the coastal ecosystems have been recognised as a source of dissolved chemical substances that cause chemical and ecological effects on sea waters. Groundwater, in many coastal areas, becomes contaminated or at least enriched with a variety of chemical substances (e.g. nutrients, metals, organic compounds) and can have higher concentrations of dissolved solids than river water. As a result, SGD makes a larger contribution to the flux of dissolved chemical compounds than river runoff.

Quantifying groundwater discharge to the seas is a challenging task, since groundwater flow is temporally and spatially variable. Groundwater discharge to the coastal ecosystem can be estimated by a number of methods. However, each technique has certain limitations because of generalized assumptions and natural variability. Typically, researchers address limitations of the implemented method at particular study area or use several techniques to detect and measure SGD. Burnette et al 2006 summarized different techniques which is being used worldwide to study SGD. These techniques includes direct measurement by seepage meter, natural tracers, infrared thermal imaging numerical modelling Piezometers etc. Although, these techniques are highly used, but it is difficult to visualise the extent of the groundwater below the seabed and as a result delineating the exact location of the ground water discharge becomes a herculean task.

Little information is available about SGD in India. Most of the studies conducted in the coastal region is focused on water quality aspects and radon concentration (Krishan et al., 2014a,b) including sea water intrusion in aquifers. A few studies conducted in Bengal basin using barium, radon and 86sr/87sr indicate SGD into the bay to Bengal through the Ganga

Brahmaputra River systems (e.g. Moore et al., 1997; Taniguchi 2002). Suresh Babu et al. (2009) studied SGD from SW Indian coastal zone. The SGD is suspected from a recent hydrogeological and groundwater modelling study conducted in a shallow aquifer of Vizhinjam Kerala.

1.2 Scope of the study

Coastal environmental management concerns should certainly consider SGD where undesirable contaminants in groundwater can be discharged into the nearshore marine environment. Although nutrient discharge from fertilizers and sewage is by far the most common, the other form of contamination is also possible. Ecological effects in estuaries and the coastal zone may depend on water quality that is influenced by SGD. Thus, the location and volume (or flux) of SGD has to be delineated.

Understanding SGD is also important for coastal zone management from the hydrological perspective. Saltwater intrusions, for example, occur in many areas near the coast due to excessive groundwater mining. At first glance, the processes of SGD and seawater intrusion may seem to be exactly opposite. However, it is clear that saltwater intrusion into coastal aquifers and SGD are entirely complementary processes. The extent of SGD or seawater intrusion at a given location is essentially an issue of balance between hydraulic and density gradients in groundwater and seawater. Thus, many reasons exist to evaluate SGD near the coast as a coastal management issue.

1.3 Objectives

The general objective of this study is to identify the possible SGD zones in the coastal regions of West Bengal.

Specific objectives of the study are:

i) To recognise and quantify potential zones of SGD
ii) To characterise hydrogeological layers conducting the fresh groundwater along the coastal belt:
iii) To identify the concepts to improve coastal zone management

2. STUDY AREA

2.1 Location

The Uttara Kannada district is located between north latitudes 13^0 55' 02" to 15˚31' 01" and east longitudes 74˚00′35″ to 75˚10′23″ falling in the survey of India degree sheet Nos – 48 I,48 J, 48 K, 48 M, and 48N. The district is having geographical area of 10222 km^2 (**Figure 1**).

The study area is mainly covered by lateritic soils. Geological formation include Pre-Cambrians (Dharwar Super group) dominated by granitic gneisses, schists, greywackes and phyllites. There are basically two types of aquifers encountered in the study area, namely confined and unconfined aquifers. Ground water occurs under unconfined condition in alluvium, laterite soil cover and weathered crystalline rocks like granites, basic rocks and Deccan traps. Confined layers located at deeper depth which includes shear zones, fractured and jointed crystalline rocks, iron ore and chert, kankar, sand and gravel.

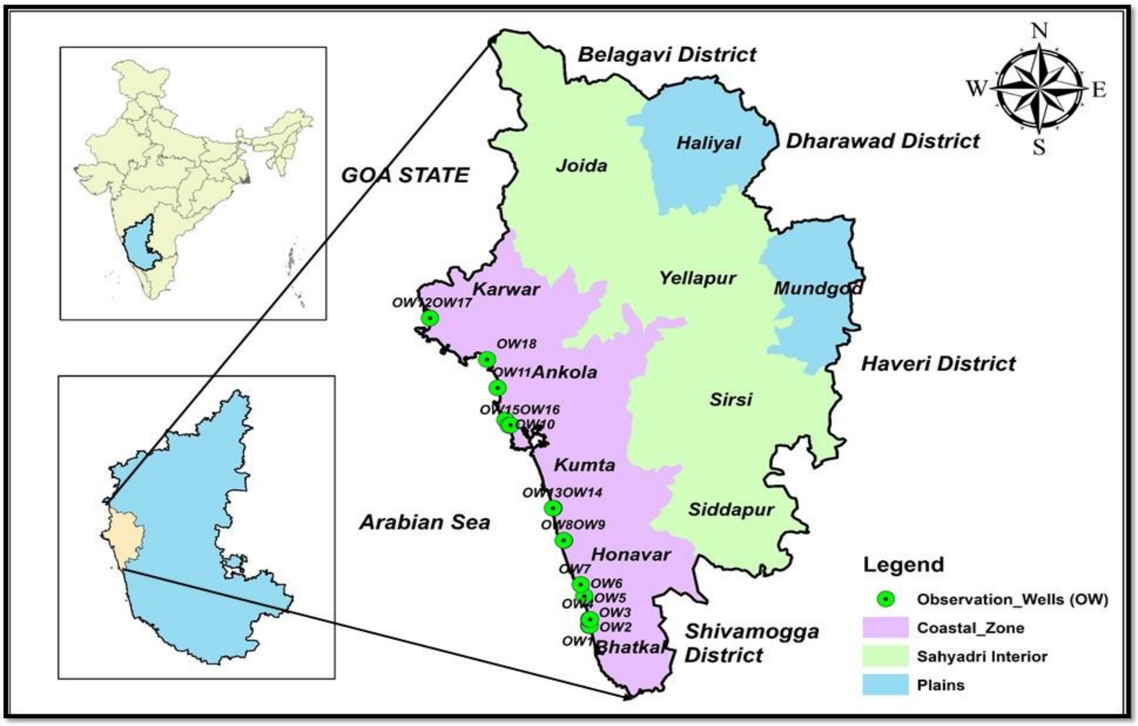


Figure 1: Location of the study area in Uttara Kannada district

With the increase in demography and rapid industrialization water regime has been greatly perturbed along the coastal tract of Uttara Kannda district. This life sustaining commodity is under quadruple stress-consumptive, agricultural, industrial and climatic. Due to rapid urbanisation and change in land use pattern recharge to groundwater is also reduced. All these factors have induced measurable changes in water dynamics equilibrium conditions and in coming years it may turn to be a major problem if corrective measures are not initiated at this stage. The quantum of water available on earth being finite there can be no additions to it. It is humanity's ingenuity to manipulate the resource in such a way that it caters to the sustenance of life.

2.2 Geomorphology

Based on the general topography, the Uttara Kannada district can be divided into two major units 1) Hilly areas or high lands; 2) low lands. The hilly area includes well known Western Ghats, having an average elevation of 915 m (3,000 ft), broken by valleys and very irregular hillocks. The laterites occur in the low lands and as plateau give barren appearance with wide distribution of black soils. Uttara Kannada district is endowed with large cover of forests and also involved in active afforestation activities. **Figure 2** Shows the land use/land cover variation found in Uttara Kannada district.

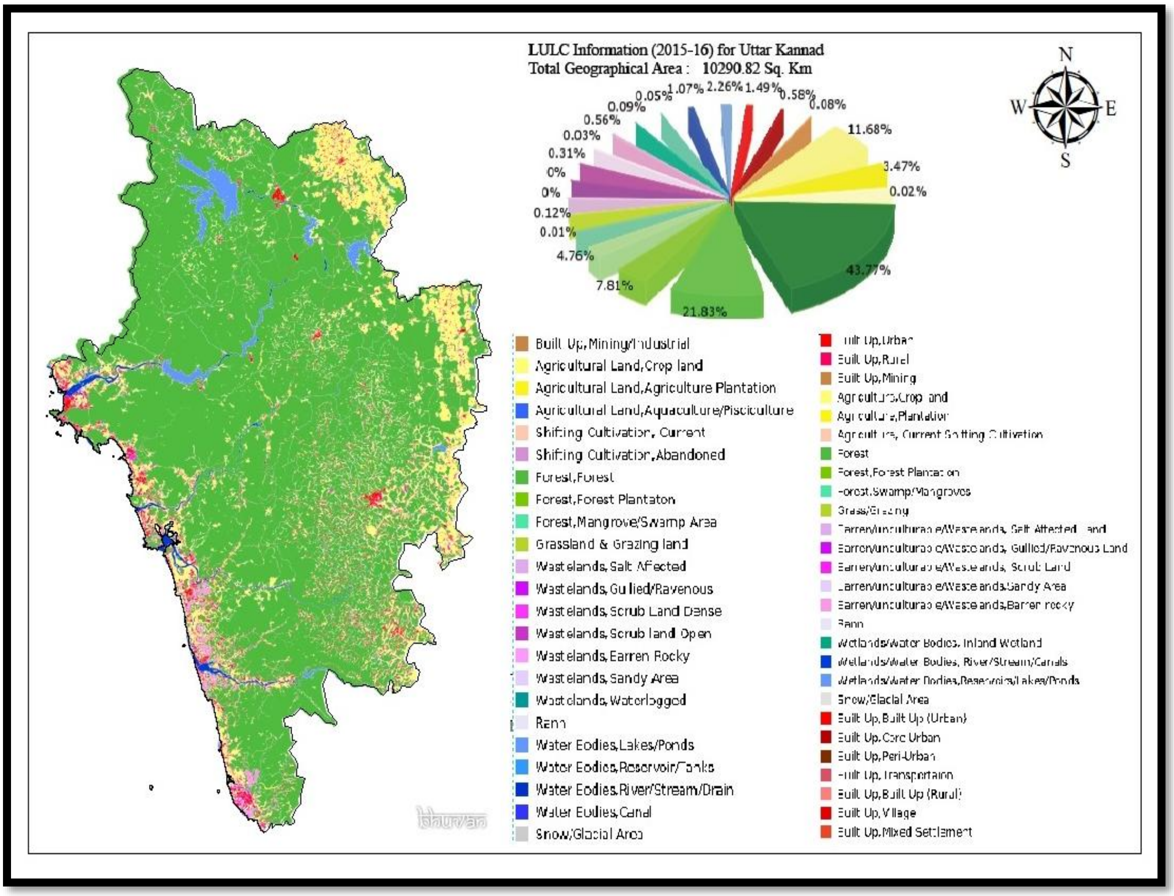


Figure 2: Land Use/Land Cover map of Uttara Kannada district

2.3 Drainage

The important rivers in the district are Sharavathi, Kali, Aghanashini, and Gangavali. all these rivers flowing in westerly direction to Join Arabian Sea. All the rivers in the district together with their tributaries exhibit dendritic drainage pattern. **Figure 3** shows the National Hydrographic stations maintained by Central Ground Water Board, Bengaluru.

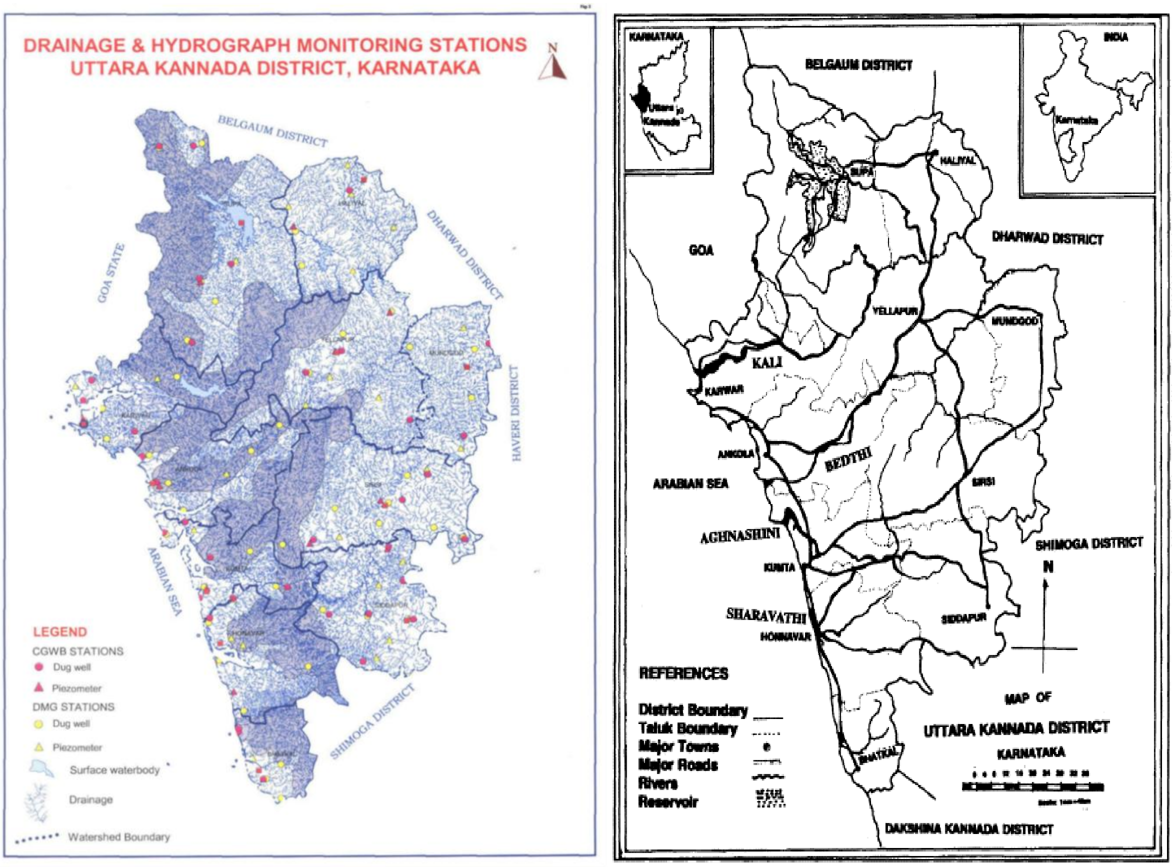


Figure 3: Drainage and hydrograph monitoring stations of CGWB

2.4 Geology

Uttara Kannada is made up of a sequence of Precambrian geo-synclinal deposits of the Dharwar Supergroup consisting of quartzites, manganiferous cherts, argillites, banded iron formations, greywackes and phyllites with granitic gneiss as the basement (**Figure 4**). The coastal belt is characterised by precambrian crystalline rocks (Granitic gneiss, schists and granites), basic dykes, titaniferous magnetite etc. At places these are capped by laterites. The laterites are reddish brown to yellowish in colour. The granitic gneisses/granites cover a major portion of the coastal plain. These gneisses and sands constitute the part of north western coastal continuation of Peninsular gneiss (Radhakrishna, 1968), or northern continuation of South Kanara gneisses/granites (Balasubrahmanyan, 1978). The Western Ghat ranges are composed of granitic gneiss forming prominent hills along the coast and at several places enter into Arabian Sea as sea cliffs. The gneisses are moderate to well banded with an alternate dark and white colored layers enriched in mafic and felsic minerals. The older metamorphic, which have been recognised as the oldest lithological units associated with a suite of ultrabasic rocks (Schists). Metabasic rocks (Amphibolites), are present in the northern most portions (North of Karwar) and east of Honnavar besides smaller patches within gneiss as enclaves.

The crystalline and other associated rocks of Precambrian age have no appreciable primary Intergranular porosity and therefore are not capable of holding and transmitting water in their primary state. However, the secondary processes such as weathering, jointing, fracturing play an important role in making an otherwise non porous rock capable of storing copious amount of ground water. There are basically two types of aquifers encountered in the study area, namely confined and unconfined aquifers. Ground water occurs under unconfined condition in alluvium, coastal alluvium, laterite soil cover and weathered crystalline rocks like granites, basic rocks and Deccan traps. Whereas shear zones, fractured and jointed crystalline rocks, iron ore and chert, kankar, sand and gravel occurring at deeper levels covered with confining layer at top and bottom constitute confined aquifers.

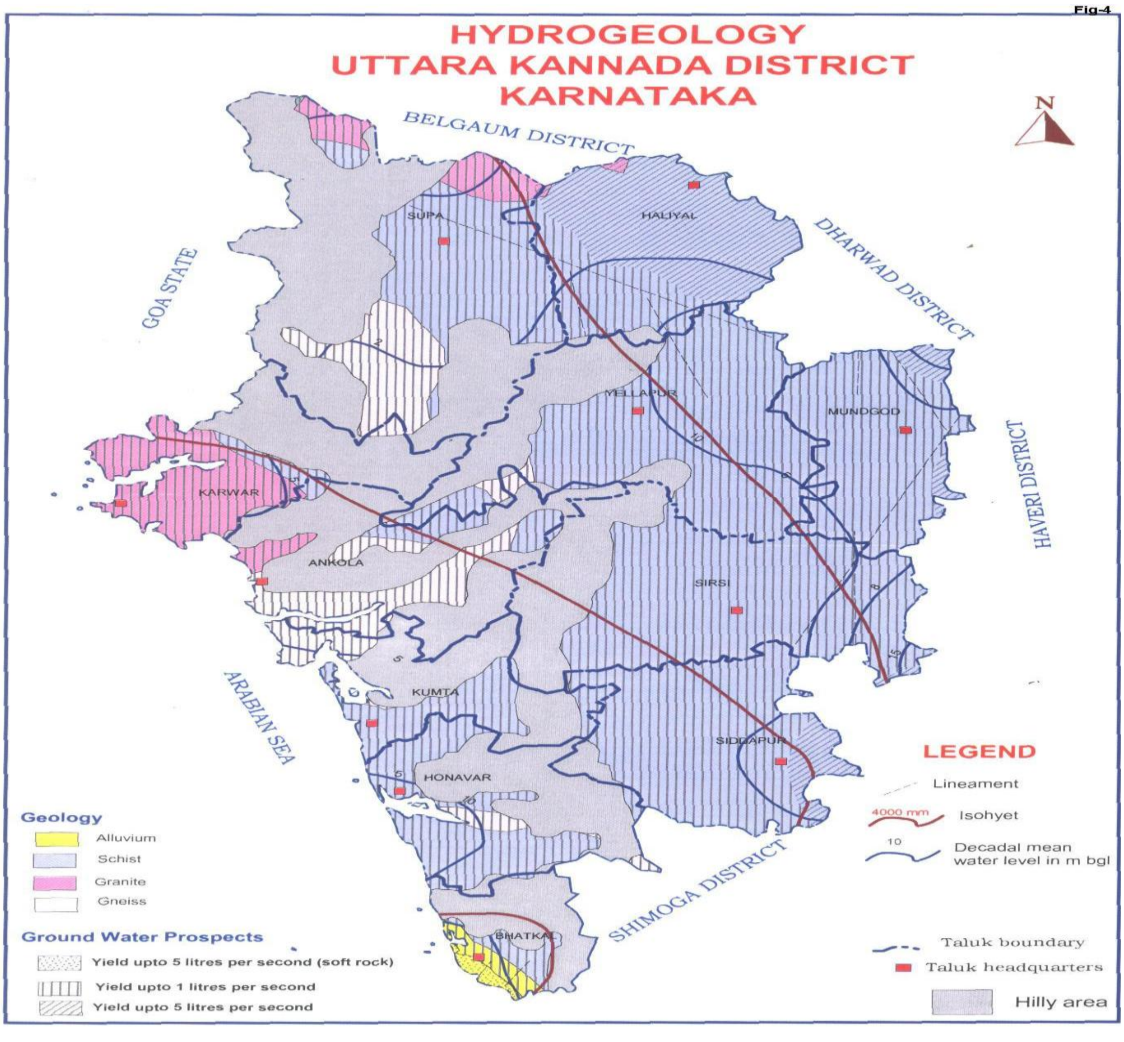


Figure 4: Drainage and hydrograph monitoring stations of CGWB

3. MATERIALS AND METHODS

There are different methods adopted by the scientists to quantify SGD such as thermal measurements, hydrologic models, seepage measurements, tracer measurements etc. In the present investigation, the following methodology were adopted (**Table 1**) and discussed subsequent sections.

Table 1: Methodology adopted in the present study

Parameter	**Specific variable**	**Method/Technique**
Soil: Physical	Texture Soil Profile	Auger sample Sieve and Pippette Analysis
Soil: Hydrological	Infiltration, Saturated & unsaturated hydraulic conductivity	Disc permeameter/ Guelph permeameter and double ring infiltrometer
	Soil moisture	Gravimetric
Hydro-geological	Lithology of the area	Resistivity techniques
Water Quality	Major anions, cations Samples were collected for Isotope analysis	Using APHA standard methods/ NIH Water Quality manual HACH instruments

3.1 Archival data collection

To delineate the SGD and SWI zones based on groundwater dynamics, the primary and secondary data are collected from regional office of CGWB, Bengaluru. The archival data includes groundwater level, its chemistry, aquifer properties (e.g., lithology, hydrogeology). Using ArcGIS software, the groundwater level as contour was plotted to understand the spatial distribution of groundwater level. Further, SGD and SWI zones are marked based on groundwater level from mean sea level.

3.2 Hydrogeological analysis

The primary and secondary data was used to carryout hydro-geological analysis obtained from regional office of CGWB, Bengaluru. The study of aquifer geometry and parameters were obtained from CGWB for the study area. In addition, The Infiltration, sorptivity and saturated hydraulic conductivity were determined with reference to soil types and LULC changes.

3.3 Geophysical Survey

In this study, a total of fifteen VES (Vertical Electrical Sounding) stations were carried out. Resistivity meter was used for the geophysical survey. The apparent resistivity values were obtained using the product of apparent resistance and geometric factor. For the manual data interpretation, apparent resistivity values were plotted against half current electrode separation (AB/2) on a log-log graph. Partial curve-matching was performed using the Schlumberger array master curve and auxiliary curves to determine the layer resistivity values and thicknesses. Based on the interpretation of the VES resistivity data, the inferred geo-electric sections indicate the thickness of the various formations in the study area.

3.4 Field investigations

The field investigations were carried out to collect different data related with groundwater, sea water and porewater in the coastal areas of Uttara Kannada district. The primary and secondary data from different sources were collected, which includes groundwater, hydrogeology, in-situ isotopes, water quality samples, meteorological and LULC data. The water samples of groundwater, sea water and porewater were collected along the coast in the study area. Groundwater samples were collected during pre-monsoon and post-monsoon seasons of year 2019. Sixty-two sites have been identified for water sampling and tested for physical and chemical parameters. Also, collected thirty-eight seashore water and eighteen groundwater samples. Detailed analysis for major anions and cations were carried out. In-situ measurement of water quality parameters (e.g., salinity, temperature, EC, DO, pH, DO etc.) of pore water, groundwater and seawater were performed by using multi-parameter water quality analyser. In the field, water samples have been collected for Oxygen and Hydrogen isotopes and samples have been analyzed at NIH Roorkee isotope laboratory.

3.5 Suitability of water for irrigation

The suitability of the groundwater for irrigation were evaluated based on the TDS, EC, percentage of sodium (%Na), Salinity, sodium adsorption ratio (SAR), Permeability index (PI), Magnesium hazard (HM), Kelly's ratio (KR) and Residual sodium carbonate (RSC).

3.6 Water balance estimation

The hydrological modelling has been carried out to estimate water balance components in the study area using Soil and Water Assessment Tool (SWAT). SWAT model has been set up for the study area by calibration and validation and estimated the groundwater recharge components primarily. SWAT is a physically based, semi distributed river basin or watershed scale model was applied to quantify hydrological components such as runoff, evapotranspiration and groundwater recharge (shallow as well as deep groundwater recharge). The details of the SWAT model can be referred in Arnold et al., 1998 and SWAT user's manual (SWAT, 2007).

Data pertaining to rainfall, groundwater levels and soil hydraulic properties was collected for a period of eleven years (2002 to 2012). The empirical methods were also used to calculate the groundwater recharge [Chaturvedi (1973), Eqn. 1; Rao (1970), Eqn. 2). The groundwater recharge is compared by the empirical methos and SWAT model.

$$Rg= 2(P-15)^{0.4} \tag{1}$$

Where, Rg is the Groundwater recharge and P is the annual precipitation

$$Rg = K (P-X) \tag{2}$$

Where,Rg = groundwater recharge, K is constant (based on climatic homogeneity), P is annual precipitation (in mm), X is normal annual average rainfall zones, accordingly, the following equation was adopted Rainfall recharge (Rr) = 0.35(P-600) for areas with rainfall more than 600 mm.

3.7 Quantification of SGD and SMI

Based on archival data, field investigations and laboratory analysis of various data related with groundwater, porewater and sea water were analyzed and identified possible signatures of SGD in the coastal regions of Uttara Kannada district in Karnataka.

Seawater mixing index (SMI) was also calculated based on the concentrations of Na, Mg, Cl, and SO4 ions. SMI is a statistical approach for chemical data that is used in coastal locations to determine how geochemical processes affect groundwater quality. This parameter is based on the concentration of four major ionic constituents in seawater such as Na, Cl, Mg, and SO4. It can be calculated using Eq.3.

$$SMI = a * \frac{C_{Na}}{T_{Na}} + b * \frac{C_{Mg}}{T_{Mg}} + c * \frac{C_{Cl}}{T_{Cl}} + d * \frac{C_{SO4}}{T_{SO4}} \tag{3}$$

Where, a=0.31, b=0.04, c=0.57, and d=0.08 denote the relative proportions of Na, Mg, Cl, and SO4 in seawater, respectively; T denotes the calculated regional threshold values of selected ions, which can be estimated from cumulative probability curves for each ion in a specific site; C denotes the measured ion concentration in mg/L.

4. RESULTS AND DISCUSSION

The following results were obtained based on archival data, field and laboratory investigations of groundwater, seawater and porewater to quantify the possible SGD zones using various techniques and methodology.

4.1 Soil characteristics

Soil profile investigations have been carried out in selected locations along the coast of Uttara Kannada. Major soil types identified in the study area are interspersed with leguminous laterites underline by hard sandy clay to medium dense sandy layer. In some of the areas slightly weathered granites are the basement rocks. The soil types across the profile play a significant role in holding moisture content as well as it influences the groundwater recharge. Textural analysis of the soil showed that the soils between Murudeshwar and Honnavara are relatively more permeable than the adjoining northern taluks of Uttara Kannada. Typical soil profiles of the study area based on excavation data collected from the selected locality. **Figure 5** shows the composition of the soil.

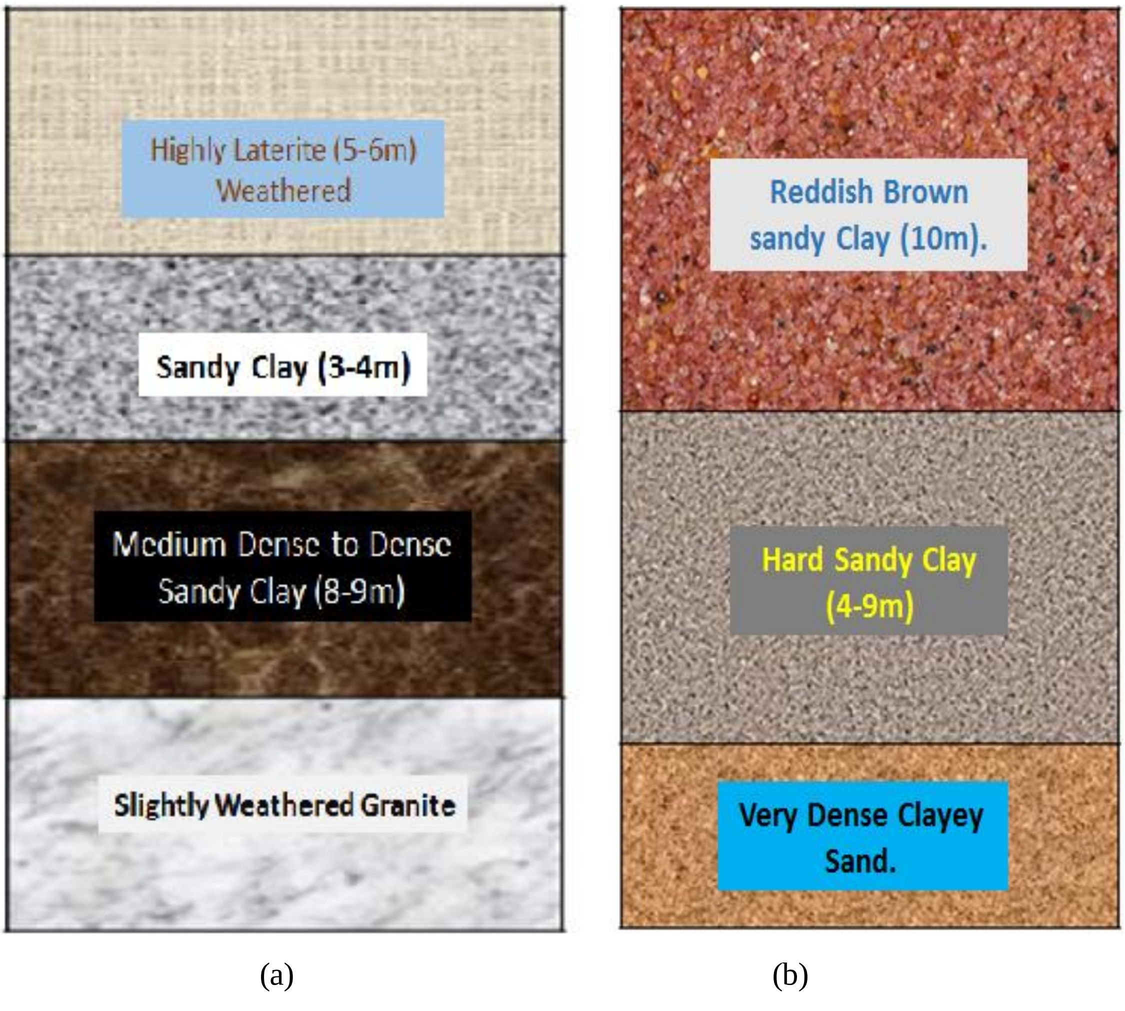


Figure 5: Soil Profile observed at Murudeshwar and Honnavara

The Infiltration, sorptivity and saturated hydraulic conductivity were determined with reference to soil type and land use/land cover change. Rate of infiltration is significantly high in lateritic area covered with forests and acacia plantation. Highly weathered laterites were found in parts of Kumta and Ankola taluks. Apart from and in Hattikeri, laterite cover exhibited very high infiltration rate and hydraulic conductivity (**Table 2**). This could be attributed to the land cover such as forest and acacia plantation which open up the top soil layers and influence the development of preferential flow paths leading to high groundwater recharge and pipe flow.

4.2 Hydrogeological analysis

The primary and secondary laterites of in-situ and detrital origin forms the main crust of the entire study area. The primary laterite, mainly the duri-crusted surface is hard and massive whereas the secondary laterite which is derived from the primary laterite by weathering and erosion and which often occupies the valley portion forms the most important water bearing formation. The contact zone between the laterites and underlying lithomarge forms the repository of groundwater. In addition, the lithomarge forms an effective aquitard between the laterites and the fracture system of the underlying crystalline rocks.

Table 2: Hydraulic properties of different soils along the coast of Uttara Kannada

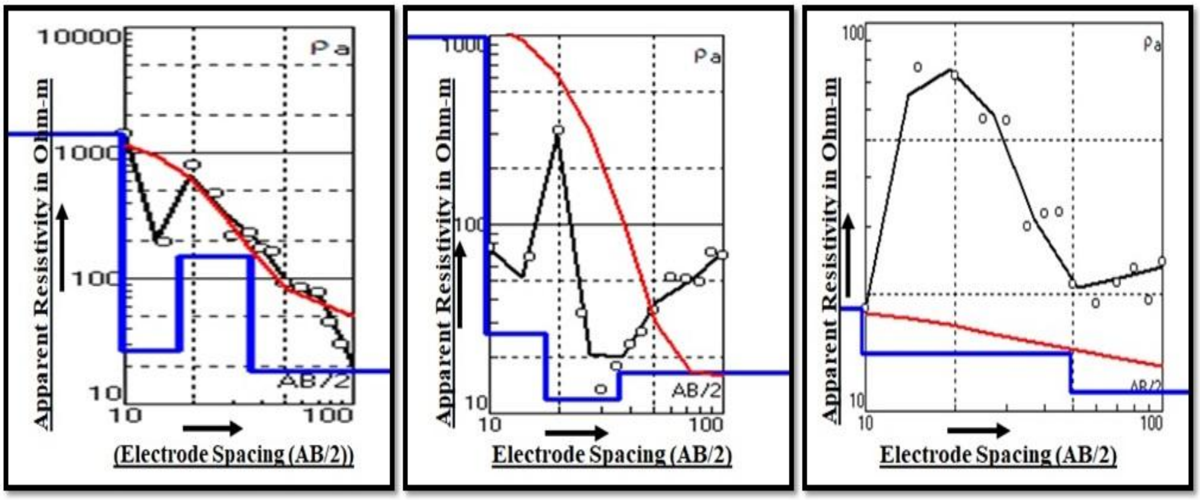
Sl No	Soil type along the coast	Infiltration rate, mm/hr	Sorptivity, $mm/hr^{-1/2}$	Saturated Hydraulic conductivity, mm/hr
1	Laterite in forest catchment (Honnavar)	60 -192	30-120	70-80
2	Laterite in acacia plantation	120-175	80-120	40-50
3	Barren land (laterite cover)	12-24	6-8	6-12
4	Laterite (Hattikeri)	25-245	10-130	85-120
5	Beach sand with plantation (transitional zone between beach and land area)	70-280	20-60	60-180
6	Shrubs	28-76	12-40	8-18
7	Leguminous laterites	22-88	0-4	6-14
8	Clay dominated laterites	2 -18	1-15	1-9

The study of aquifer geometry and parameters have been attempted by CGWB, South western Region, Bangalore, under its ground water exploration programme through drilling exploratory bore wells at selected places as depicted in **Figure 5**. The ground water exploration in the district was carried out in two phases. During 1988-89, by constructing 5 exploratory wells and four observation wells in coastal alluvium of Honnavar and Karwar taluks. The depth of the wells ranged between 16-47 m. The discharge recorded were in the range of 1.88 to 225 lpm for a drawdown of 1.6 to 10.39 m. Aquifer material encountered was fine to medium sand with alternative layers of silt and clay.

During the second phase of exploration which started during 2003-04 and continuing till date in hard rocks of the district in Ankola, Haliyal, Honnavar, Karwar, Kumta, Mundgod, Siddapur, Sirsi, Supa, and Yellapur taluks, total of 33 wells were drilled with depth range of 89 to 200 m and the aquifers tested reveal that an effective porosity of about 1-3%. The yield cum recuperation tests conducted on these wells show that the discharge of the wells ranges from negligible to 8.5 lps. The transmissivity of aquifer material in general ranges from 2.09 to 24.41 m^2/day.

4.3 Geophysical survey analysis

Quantitative interpretation allows getting the real numbers of layers, their resistivity and thicknesses. The selected resistivity data obtained through field investigations were plotted on log-log graph (**Figure 6**) for three different sections of the study area (i.e. Q, H and K type curves).



(a) (b) (c)

Figure 6: Typical resistivity curves of the study area

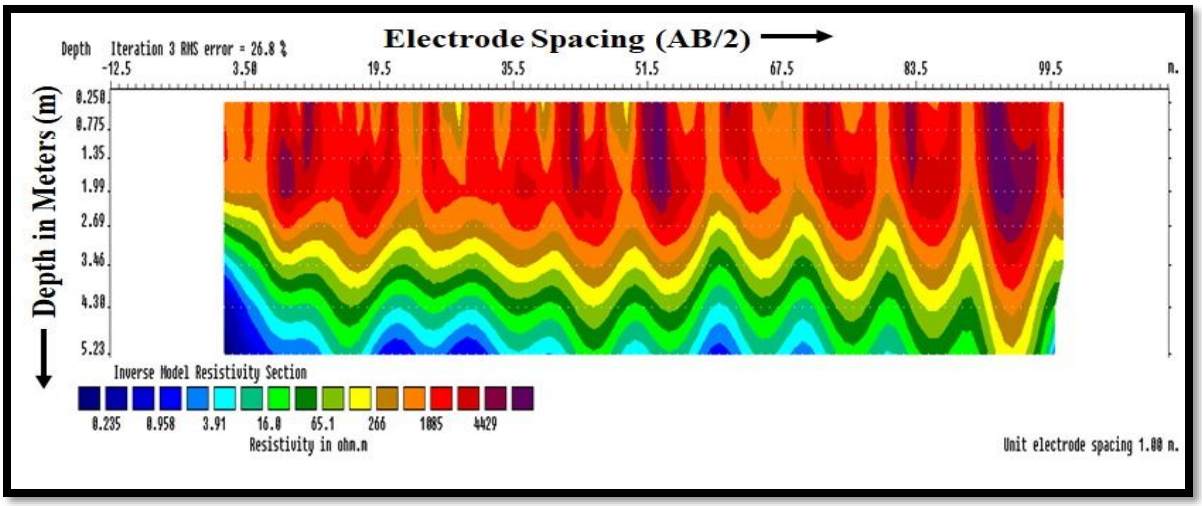
Q Type: (p1> p2> p3): A resistivity curve with a continuously decreasing resistivity is called 'Q' type curves. Figure 6a shows the cross-section of the coastal zone with varying apparent resistivity. This is the most common section found in hard lateritic terrain occupying the top layer.

H Type: (p1> p2 <p3): Seen generally in hard rock terrains consisting of top soil of high resistivity followed by either a water saturated or weathered layer of low resistivity and then a compact hard rock of very high resistivity at the bottom. **Figure 6b** indicate the H-type curve with initial fluctuation with relatively high resistivity at the top which is followed by a water

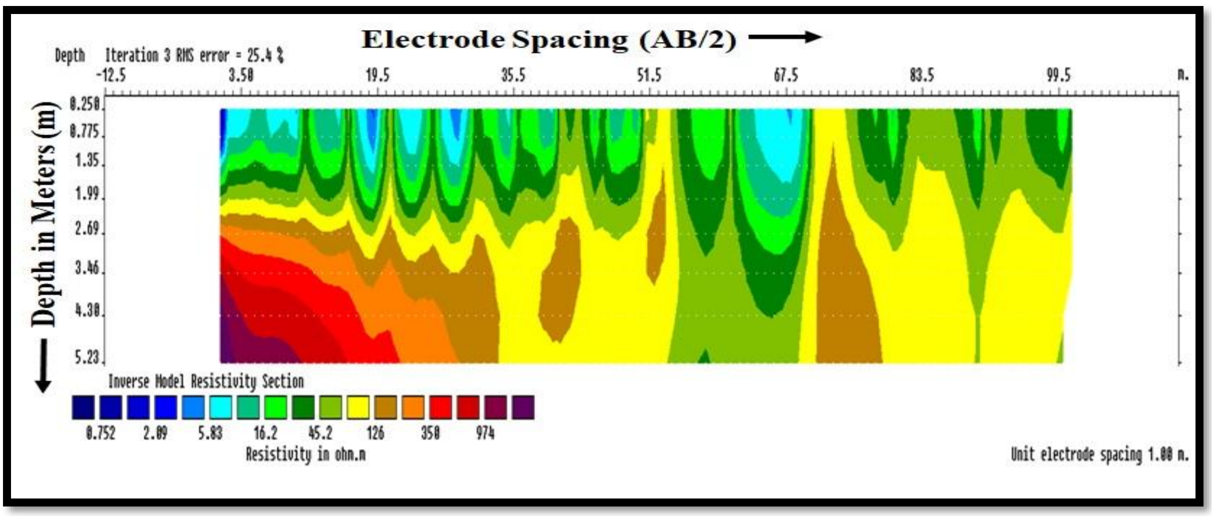
saturated and weathered layers of low resistivity and then a compact hard rock of high resistivity at the bottom.

K type (p1< p2> p3): Seen usually in basaltic areas such the 'K' type curves show a peak with values lowering towards the sides. Also present in coastal areas where freshwater aquifer occurs between clayey layer at the top and a saline zone in the bottom. Though this type of curves (**Figure 6c**) common in basaltic area, in the present case, it indicates the fresh water zone between clay layer and saline zone.

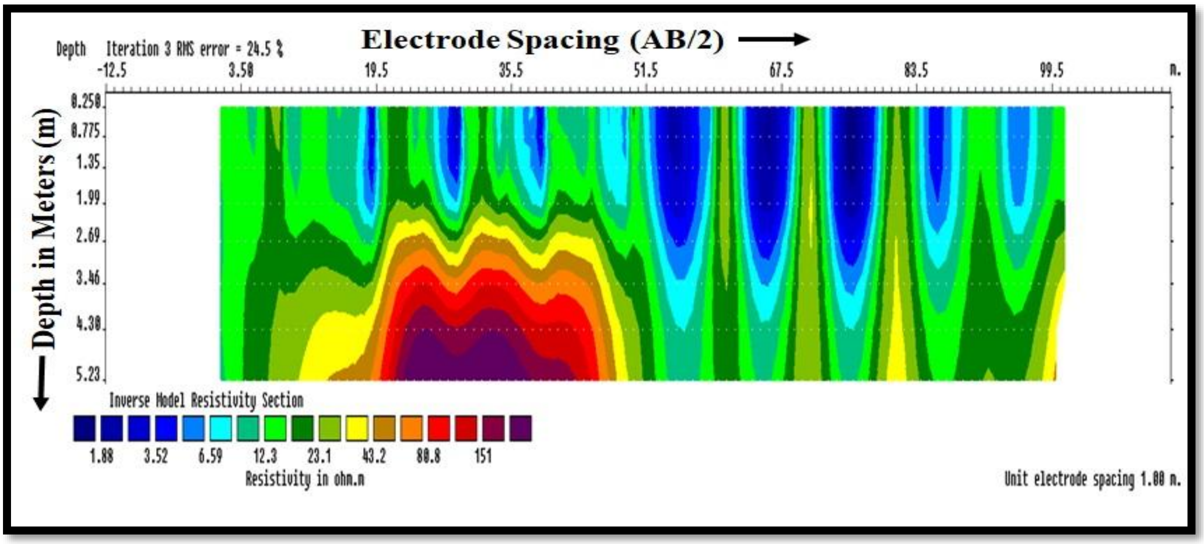
The resistivity data was converted to 2D images and presented in **Figure 7** (a to c). Comparison of the Electrical resistivity ERT image and field observations indicated reasonably good agreement. The profile up to 5m depth with a very low resistivity in range of 0.2 to more than 4000 Ωm has been observed which indicate the presence of the top soil and sand within the clay formation. The high resistivity values could be attributed to the extension of lateritic plateau in the deeper layer.



(a) ERT profile of Q –type curve



(b) ERT profile of H –type curve



(c) ERT profile of K type curves

Figure 7: Electrical Resistivity survey results

The maximum current electrode spread and potential electrode separation were 100 and 10m, respectively. Data acquired were interpreted using the manual partial curve matching method and a fast computer iteration technique to generate the geoelectric layer of various resistivity values and thicknesses. The geoelectric sections revealed the lithological sequence as: topsoil, weathered layer and fresh bedrock. The overburden coefficient of anisotropy also revealed that, the underlying basement rock is suspected to be granite gneiss/granite. At locations where current terminated at the fresh bedrock region, the thicknesses were undetermined. Groundwater potential is presumed to be very low except in few isolated patches within the study area as outcrops of gneissic rocks dominate the area. Locations where the regolith is of appreciable thickness, the resistivity of the layer suggests a material medium likely composed of clay/sandy clay or clayey sand which are not good aquiferous media from which groundwater could be extracted.

Most of the sounding curves are of H, QH and KH types, which are considered as the most suitable types of resistivity curves to estimate the hydraulic parameters where current flow is approximately horizontal. The occurrence of a significant typical H type curve indicates the presence of a highly resistive top lateritic soil followed by a saturated zone and then the basement topography (Anoop et al., 2021). In the present study also the prevalence of 'H' type and its combinations can be taken as indicator of the top lateritic layer followed by saturated zone and then the basement. Additionally, inspection of the field curves reveals that, the H curve type is dominant all over the entire area indicating that, most of the sounding curves have the same number of layers. However, the thicknesses of those layers may differ from one locality to another.

Weathering is not a uniform phenomenon in any environment and results in heterogeneity in hydrological characteristics of the rock formations. The conceptual structure of hard rocks is that of a fresh basement overlain by materials which have undergone different stages of weathering. Groundwater availability is therefore attributed to weathering in the overburden and basement surface. Basement weathering presents themselves as zones of disintegration. These zones appear as low electrical resistivity anomalies compared to the massive basement rocks that surround them. Consequently, basement troughs with deep weathering are points of disintegration which are hydro-geologically viable as far as groundwater aquifers are concerned (K'Orowe et al., 2008). A fence diagram based on hydrogeological characteristics is presented below (**Figure 8**).

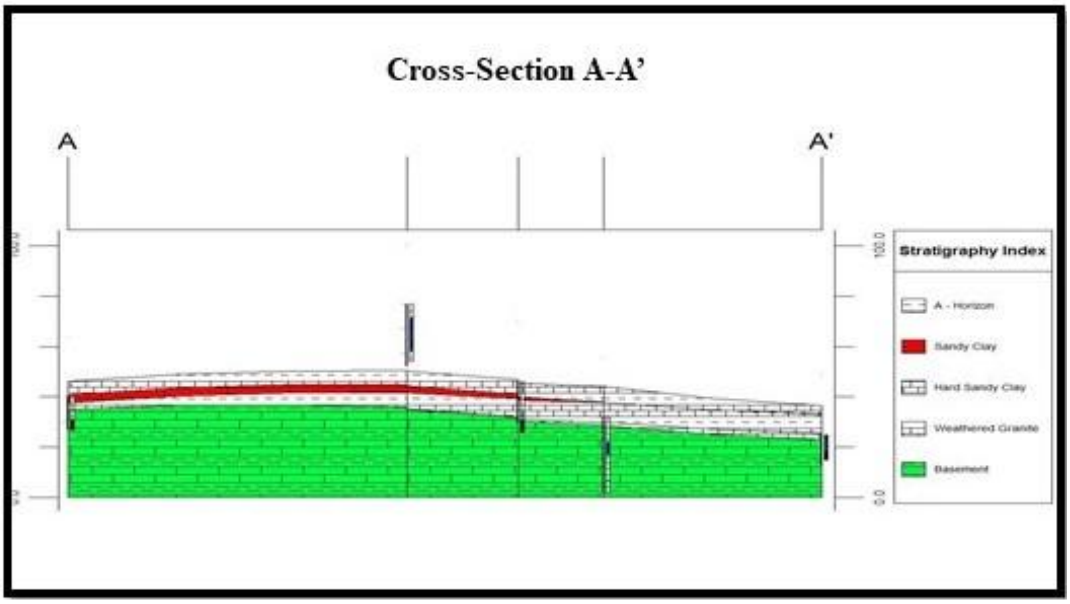
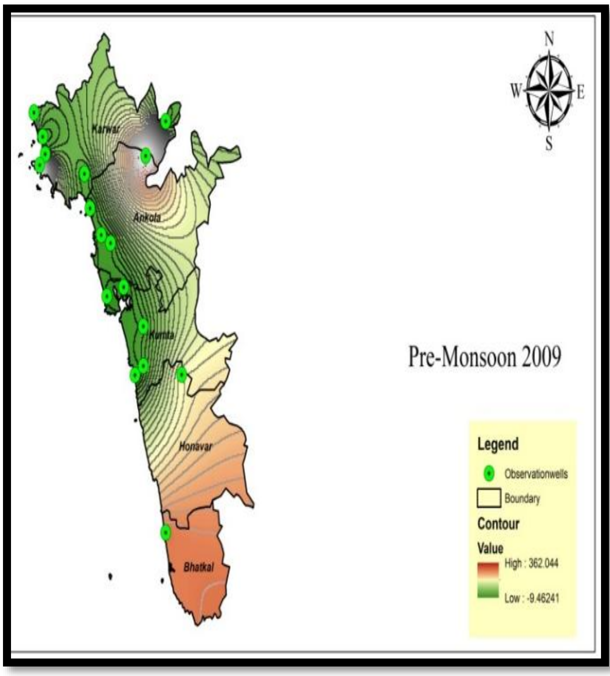


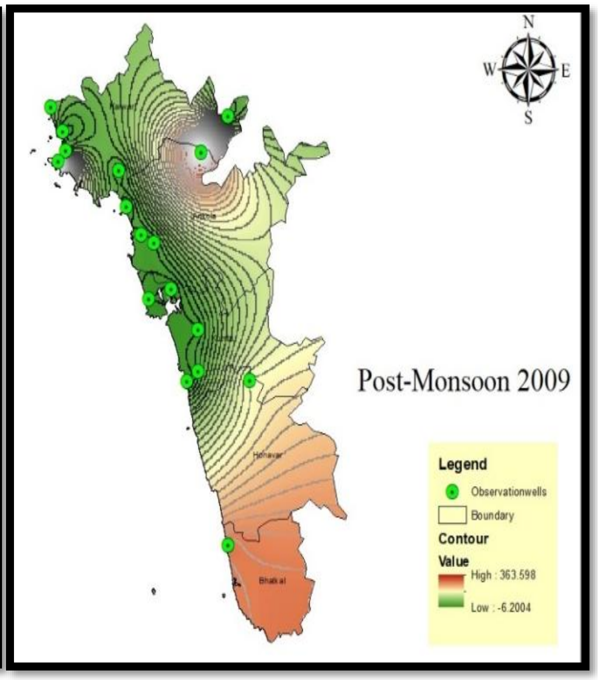
Figure 8: Stratigraphy of coastal tract of Uttara Kannada district

4.4 Groundwater level contours

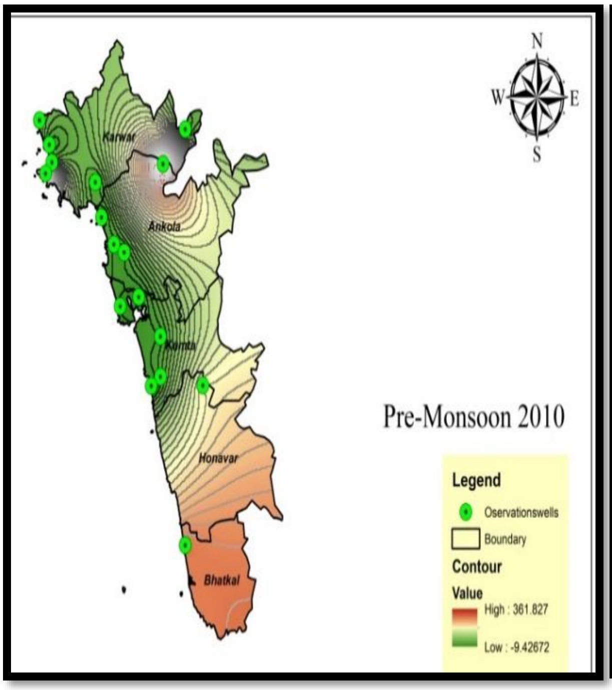
A pre-monsoon water level observation of CGWB taken during May 2006 for the 30 national hydrograph network monitoring stations (**Figure 9**). The major part of the Uttara Kannada district is having the pre monsoon water levels between 5 to 10 mbgl during 2006. The area having water levels less than 2 mbgl is observed around Karwar town. Water levels between 2-5 m bgl were observed around Karwar town, along the coast between Kumta and Ankola, also on southern parts of Ankola. The major part of the Uttara Kannada district is having the post monsoon water levels between 2 to 5 mbgl during 2006. The perusal of the table shows is in the range of -0.19 – 13.03 m. The maximum water level fluctuation recorded is 13.03 m in Honnavar station and negative fluctuation of –0.19 m is recorded at Murudeshwara station. The seasonal water level fluctuation, available for 10 piezometer hydrograph network stations in the range between –0.14 – 6.07m. The maximum water level fluctuation of 6.07 m recorded at Bandel piezometer national hydrograph station in Halyal taluk and minimum water level fluctuation of –0.14 m was recorded at Karwar piezometer national hydrograph station. Groundwater level contours for a period from 2008 to 2018 are shown in **Figures 9** (a to t) (Data Source: CGWB, Bengaluru).



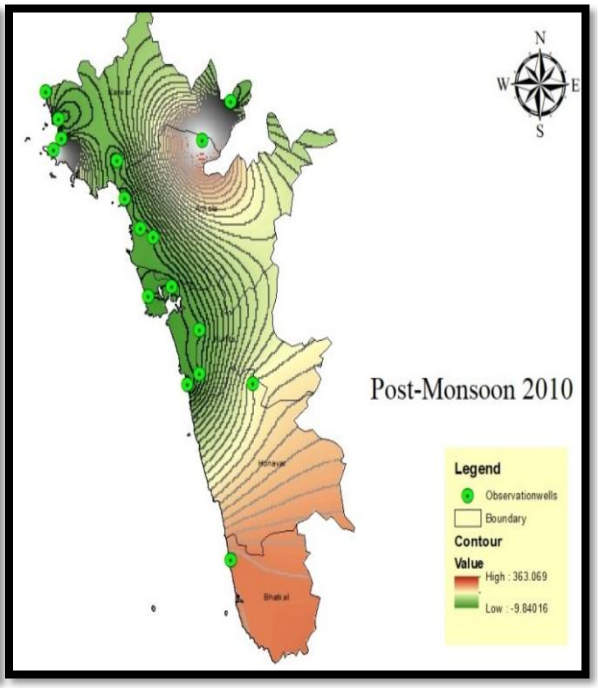
(a)



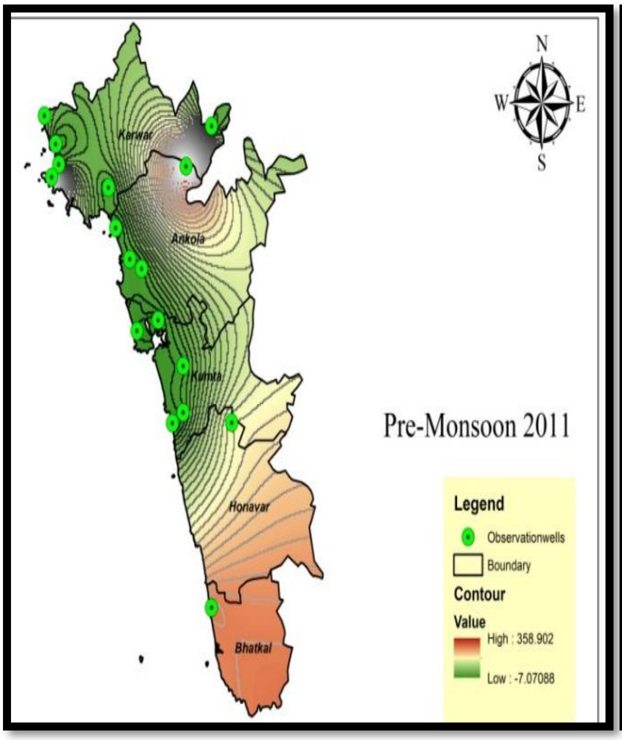
(b)



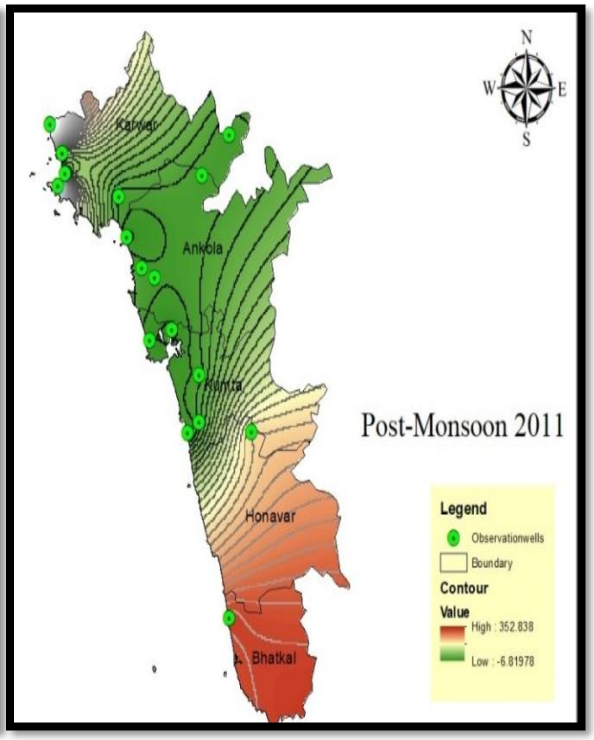
(c)



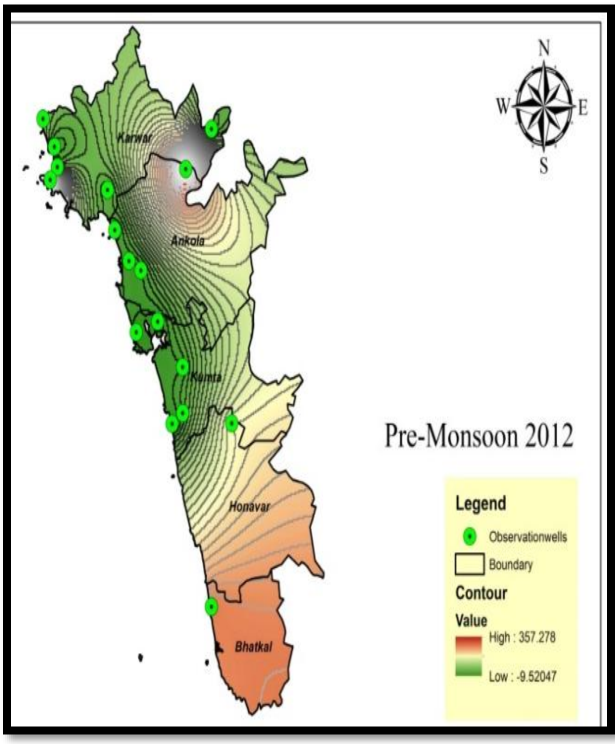
(d)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Pre-Monsoon 2011
Legend
Observationwells
Boundary
Contour
Value
High : 358.902
Low : -7.07088

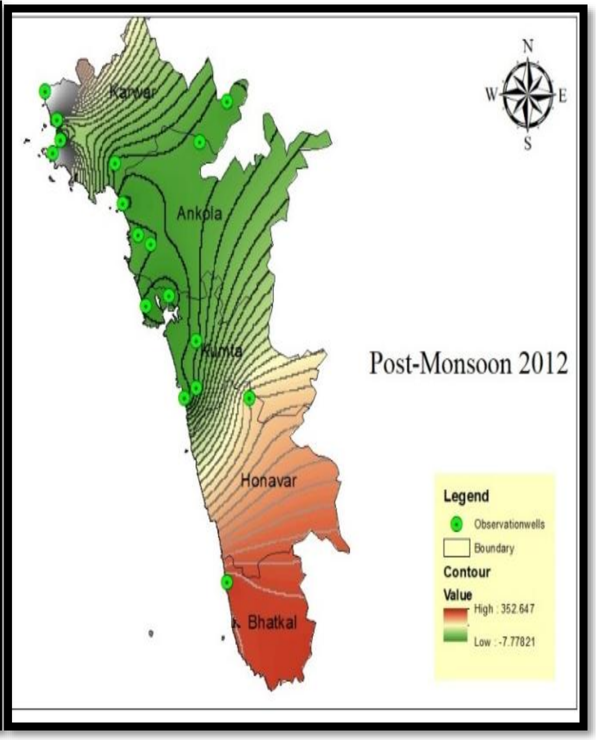
(e)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Post-Monsoon 2011
Legend
Observationwells
Boundary
Contour
Value
High : 352.838
Low : -6.81978

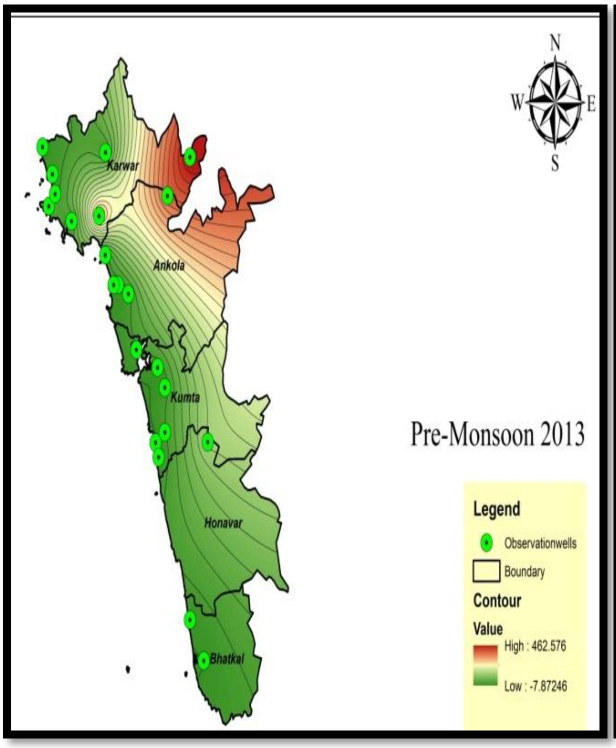
(f)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Pre-Monsoon 2012
Legend
Observationwells
Boundary
Contour
Value
High : 357.278
Low : -9.52047

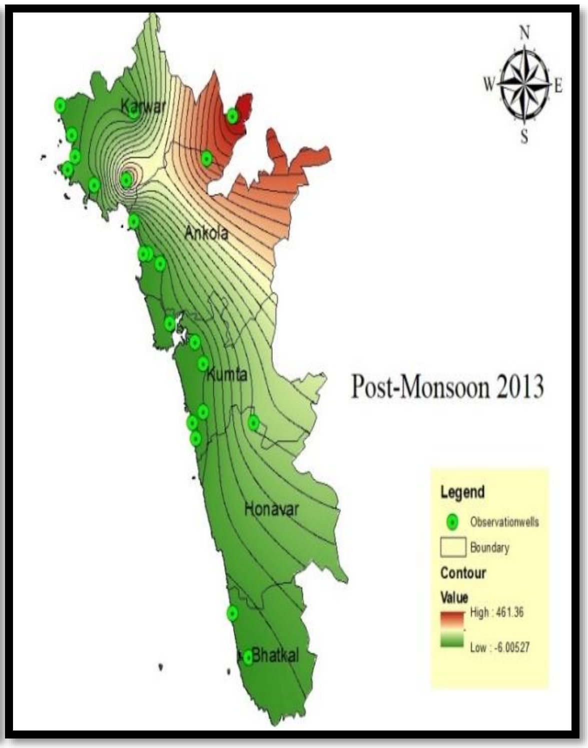
(g)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Post-Monsoon 2012
Legend
Observationwells
Boundary
Contour
Value
High : 352.647
Low : -7.77821

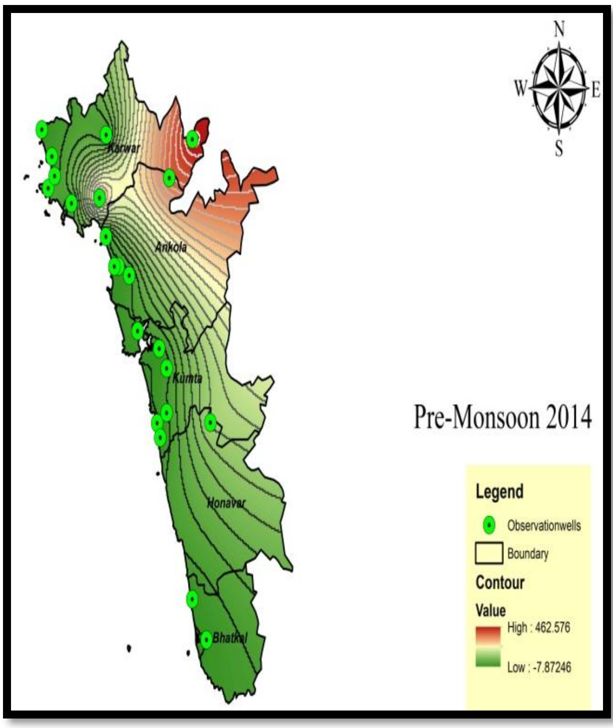
(h)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Pre-Monsoon 2013
Legend
Observationwells
Boundary
Contour
Value
High : 462.576
Low : -7.87246

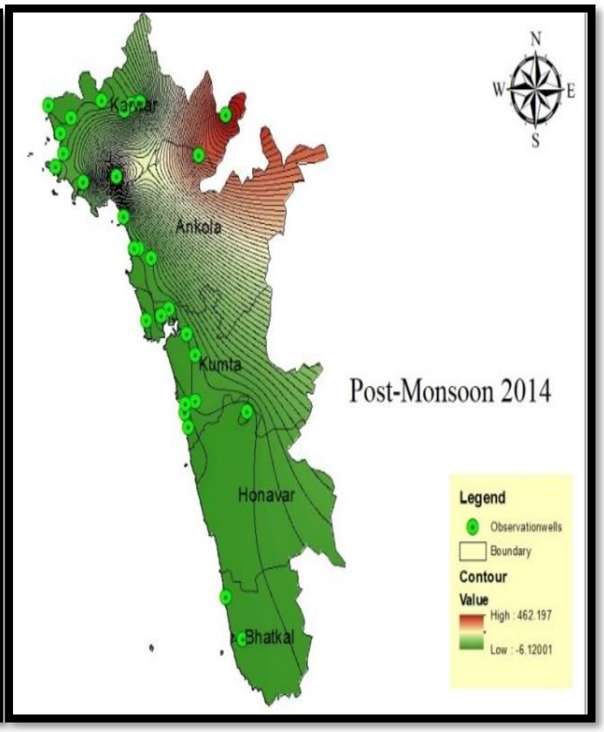
(i)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Post-Monsoon 2013
Legend
Observationwells
Boundary
Contour
Value
High : 461.36
Low : -6.00527

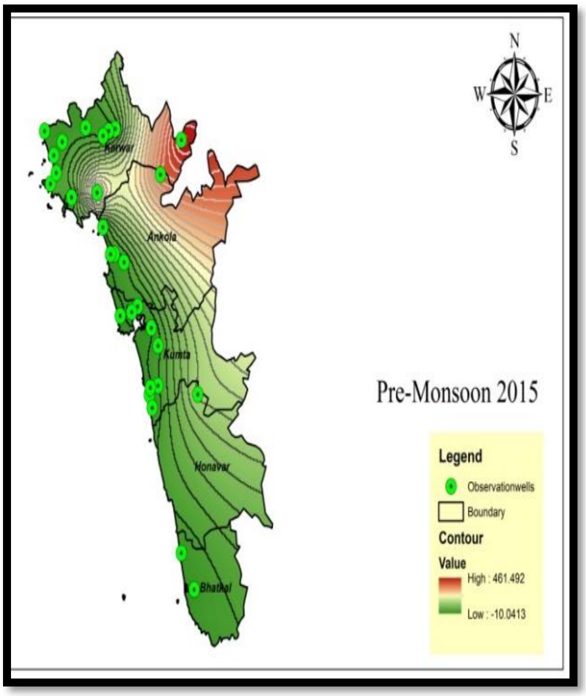
(j)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Pre-Monsoon 2014
Legend
Observationwells
Boundary
Contour
Value
High : 462.576
Low : -7.87246

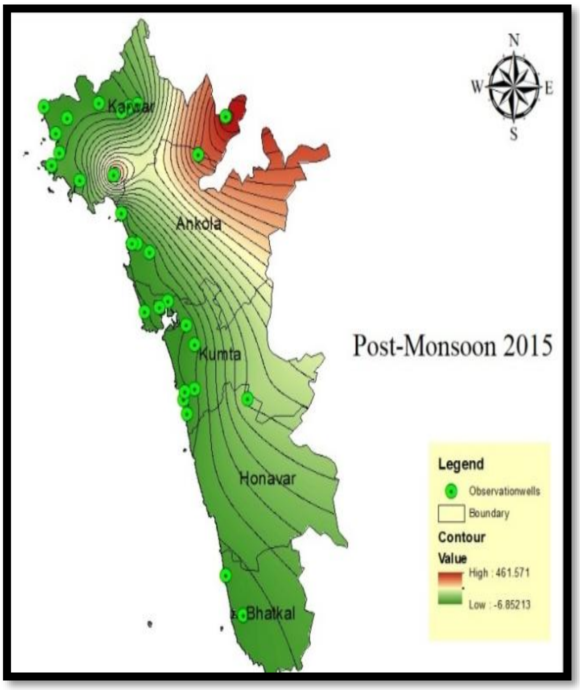
(k)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Post-Monsoon 2014
Legend
Observationwells
Boundary
Contour
Value
High : 462.197
Low : -6.12001

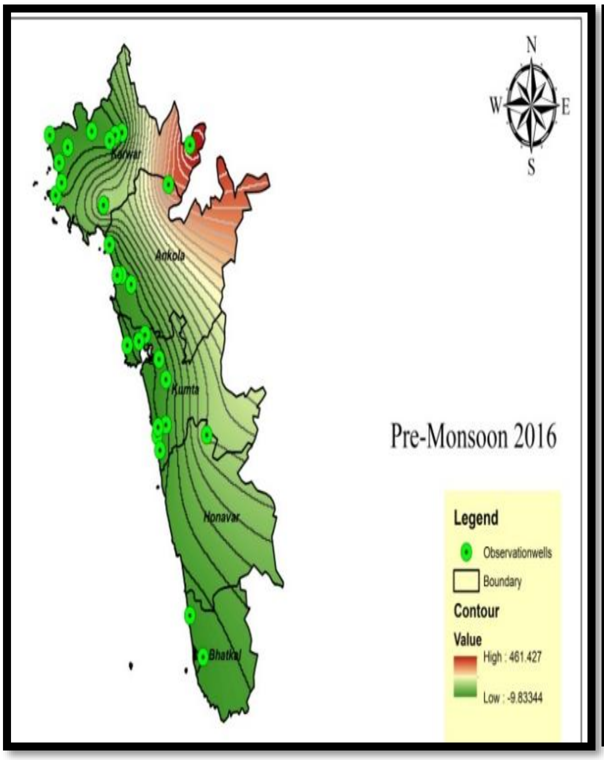
(l)


N
W
E
S
Ankola
Kumta
Honavar
Bhatkal
Pre-Monsoon 2015
Legend
Observationwells
Boundary
Contour
Value
High : 461.492
Low : -10.0413

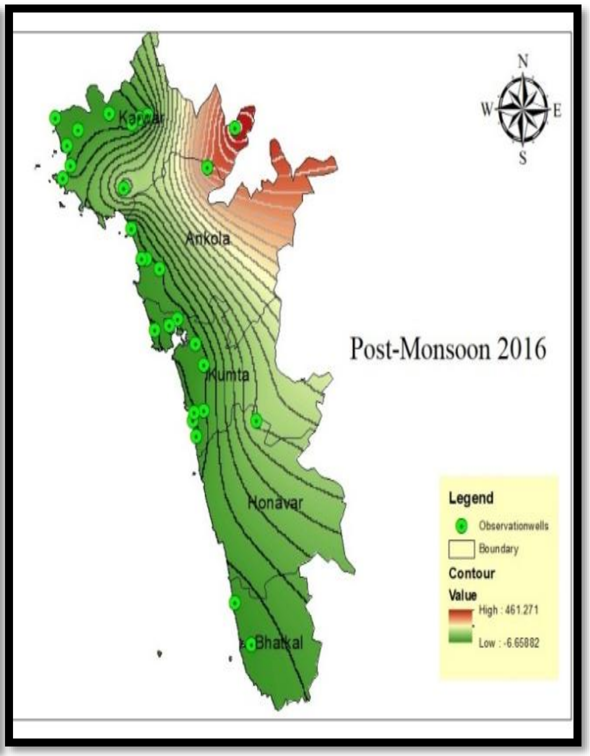
(m)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Post-Monsoon 2015
Legend
Observationwells
Boundary
Contour
Value
High : 461.571
Low : -6.85213

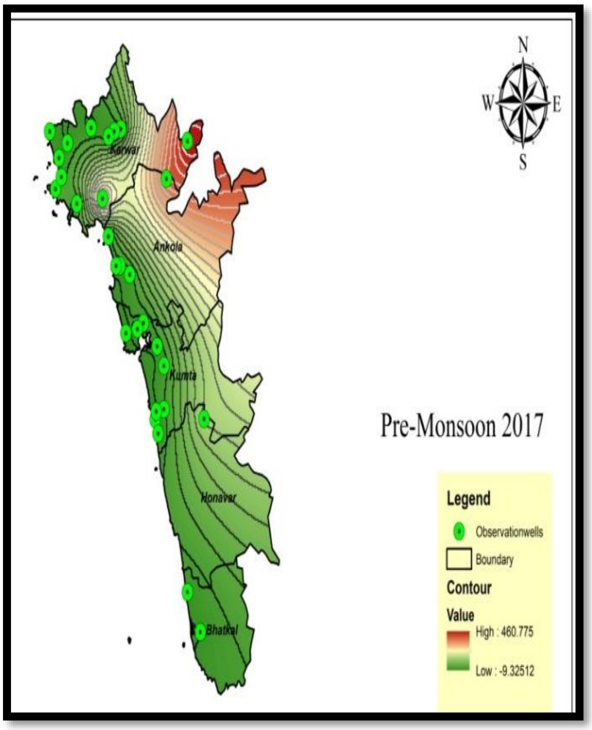
(n)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Pre-Monsoon 2016
Legend
Observationwells
Boundary
Contour
Value
High : 461.427
Low : -9.83344

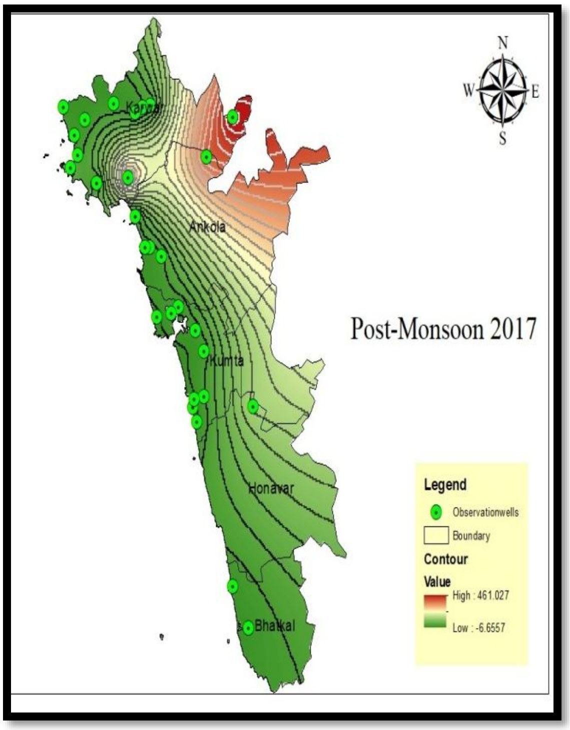
(o)


N
W
E
S
Karwar
Ankola
Kumta
Honavar
Bhatkal
Post-Monsoon 2016
Legend
Observationwells
Boundary
Contour
Value
High : 461.271
Low : -6.65882

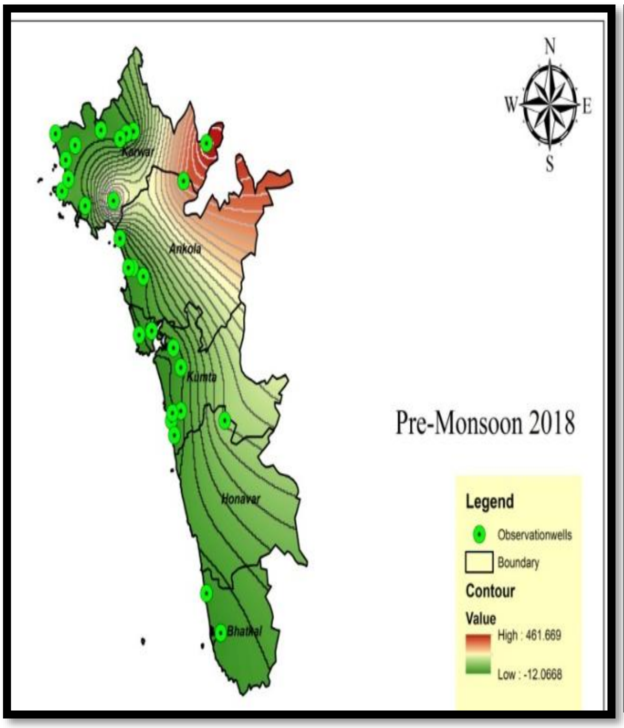
(p)



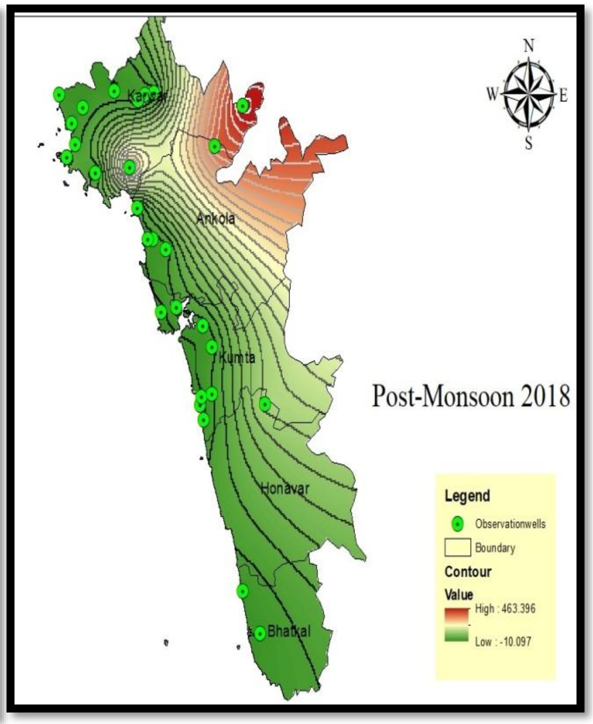
(q)



(r)



(s)



(t)

Figure 9: Groundwater levels of Uttara Kannada district

4.5 Groundwater level fluctuations

The frequency of water-level measurements is one of the most important aspects of a water quality monitoring system. While this may be influenced by economic factors frequency measurements should be considered as far as possible in relation to the expected variability of water level fluctuations in viewing sources and data resolution or the amount of data required to fully reflect the hydrologic performance of the aquifer. Groundwater level, either aquifer water of an unconfined aquifer or a piezo metric surface of a closed aquifer, indicates the height of the atmospheric pressure. Differences between the supply and supply of groundwater create volatile levels.

The method of water level fluctuations is based on the acknowledgment that water level rise is due to recharge reaching groundwater. Estimation of the specific yield of the region of fluctuation for applying the method, the ground water level is required. Data pertaining to rainfall a total 18 well water level data collected for a period of eleven-year (2002 to 2012) during pre and post-monsoon season. According to the study, it is found that during the pre-monsoon (**Figure 10**) and post-monsoon (**Figure 11**) (year 2002), the maximum depth of water level was 14.20 mbgl (meter below ground level) and 8.45 mbgl at Ankola district and minimum depth were found 1.46 mbgl and 0.86 mbgl at Amdalli district respectively, In the year 2003 the maximum depth of water level was record 14.88 and 8.8 mgbl at Ankola and minimum was 2.44 mgbl at Amdalli and 0.51 mgbl at Gokarn district during the pre and post monsoon season respectively, In the pre-monsson 2004, the general depth of water level is ranges between 13.3 mgbl (Ankola district) to 2.81 mgbl (Karwar district) and during the post-monsoon it very between 9.82 mgbl (Amdali) to 0.66 mgbl (Madangeri), In 2005, 2007, 2008, 2009 and 2012, the maximum water level was recorded 11.66 (Kumta) , 13.7 (Ankola) , 11.16 (Manki), 13.17 (Ankola) and 14.71 mgbl (Ankola) and minimum was record 1.76 (Bhatkal), 2.68 (Karwar), 2.6 (Sadashvgad), 2.04 (Amdalli) and 2.52 mgbl (Majali) during the pre-monsoon season, respectively and during the post monsoon season the maximum water level was found 9.6, 8.98, 9.1 mgbl at Kumta, 10.9 and 11.31 mgbl at Ankola and minimum were found 0.56 (Amdalli), 0.42 (Karwar), 0.61 and 0.84 mgbl at Amdalli and 1.26 mgbl at Majali district, respectively, During the entire eleven years, In the year 2006, 2010 and 2011 have been major changes in the water level, The maximum water level was found at Ankola district 16.43, 16.45 and 16.6 mgbl and minimum was at Majali district 2.61, 2.57 and 2.58 mgbl during the pre-monsoon season and during the post monsoon season the maximum was 9.24 (Ankola), 9.24 (Kumta) and 16.6 (Ankola), and minimum was found at Amdalli district is 0.28, 0.74 and 0.98 mbgl respectively. **Figure 10 &11** showing ground water level fluctuation during pre-monsoon and post-monsoon season for eleven years (2002 to 2012) in Uttara Kannada district. **Figure 12** (a to l) showing annual (2008 to 2019) groundwater level fluctuation during pre and post monsoon season.

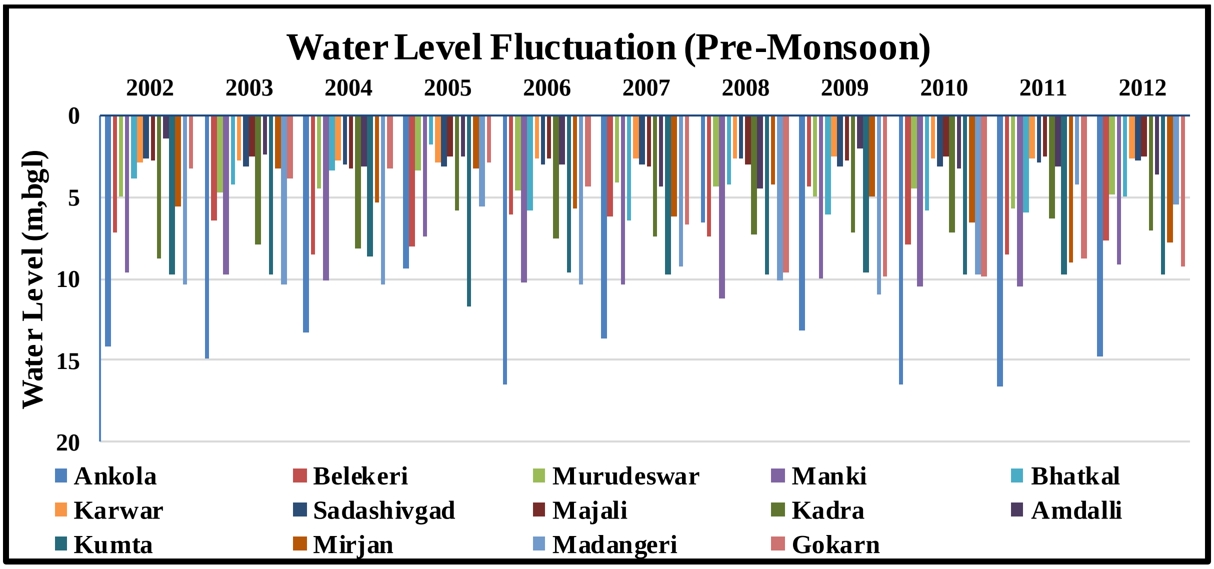


Figure 10: Water level fluctuation (Pre-Monsoon)

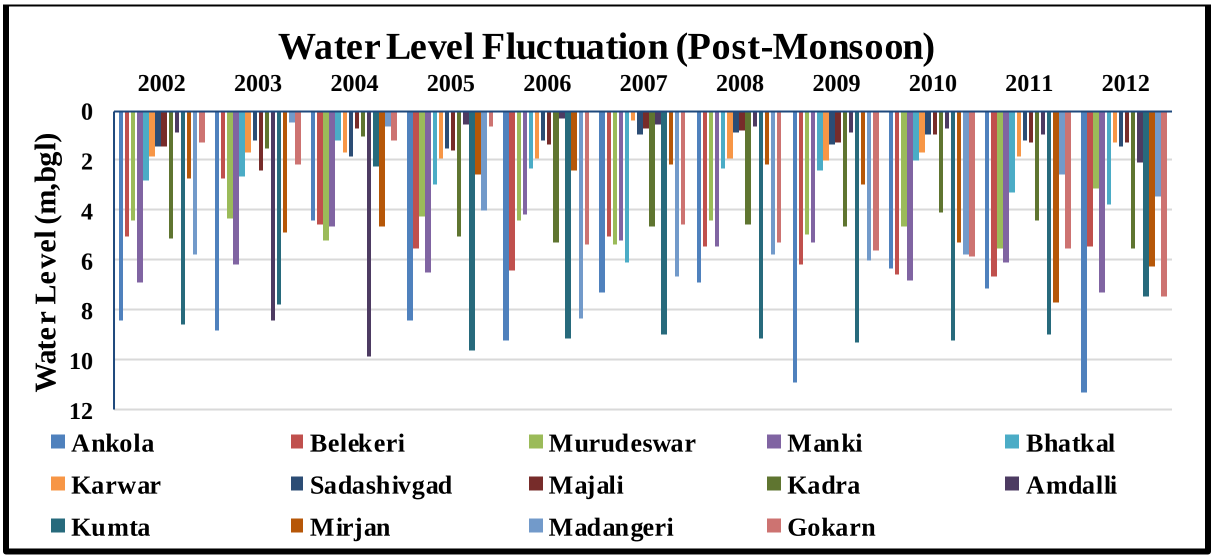
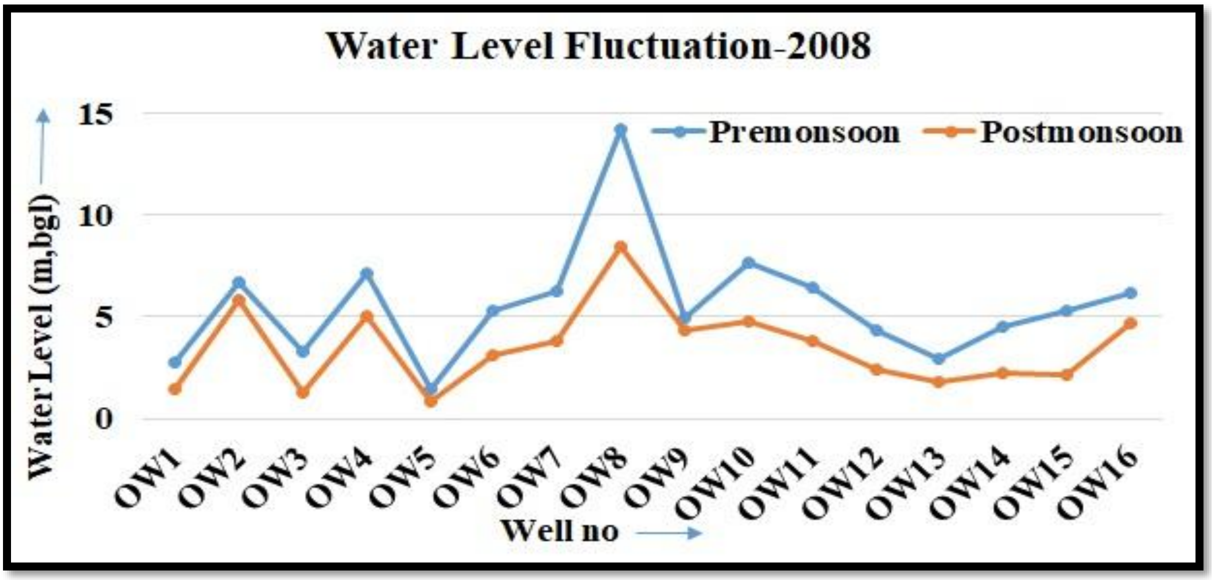
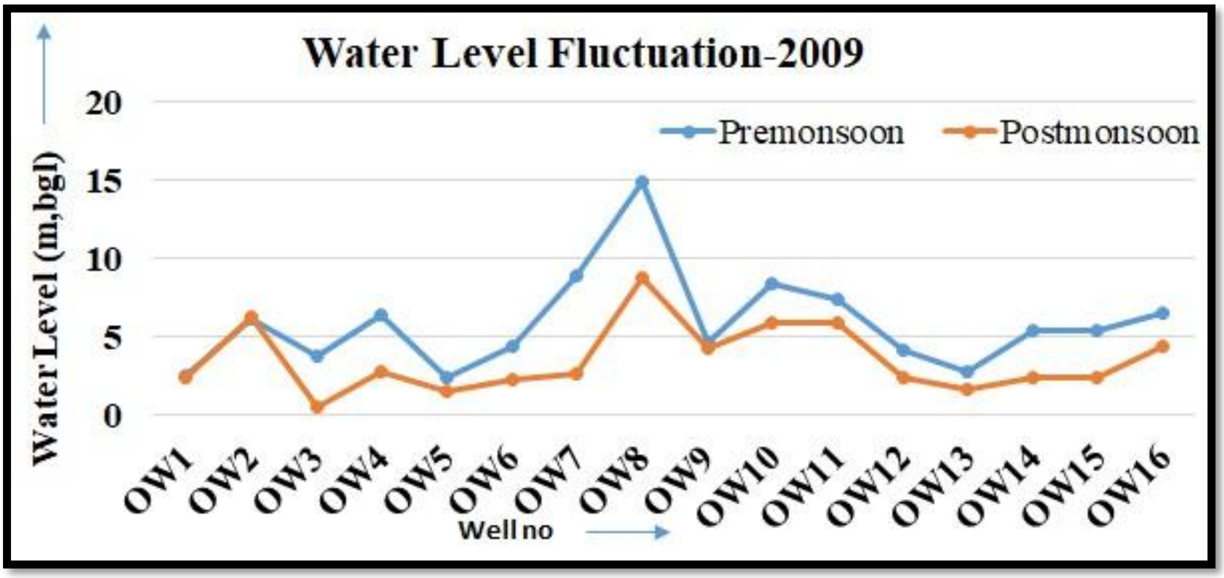


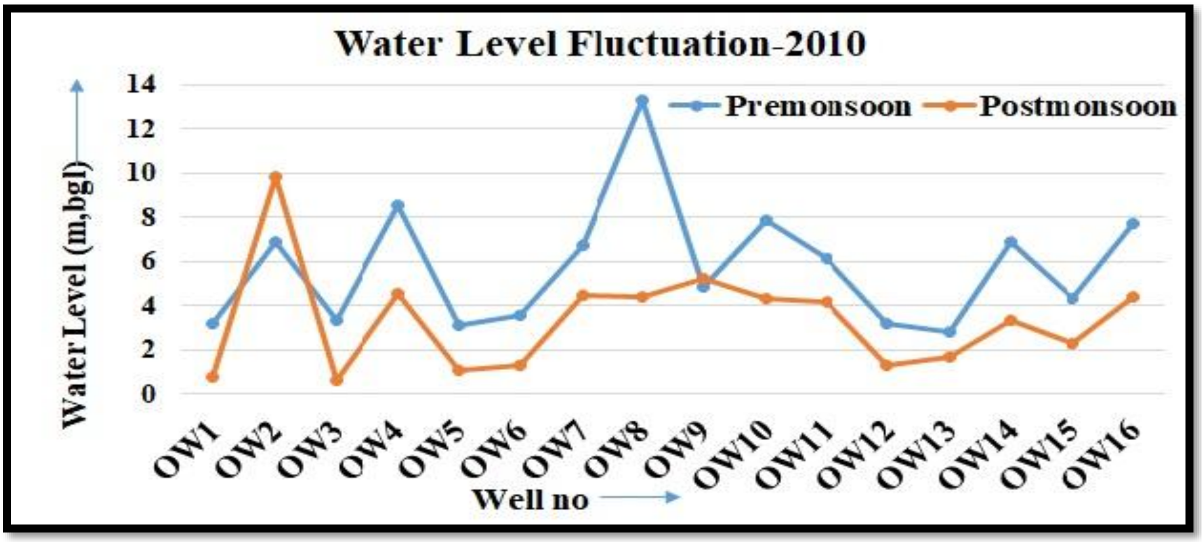
Figure 11: Water level fluctuation (post-monsoon)



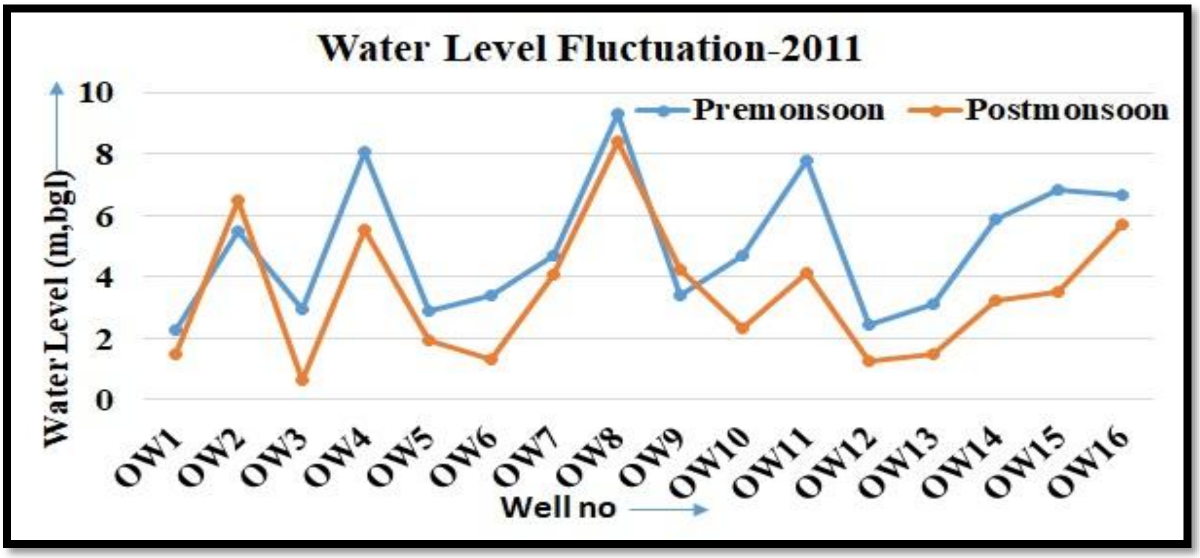
(a)


Water Level Fluctuation-2009
Premonsoon
Postmonsoon
Water Level (m,bgl)
Well no
OW1
OW2
OW3
OW4
OW5
OW6
OW7
OW8
OW9
OW10
OW11
OW12
OW13
OW14
OW15
OW16
0
5
10
15
20

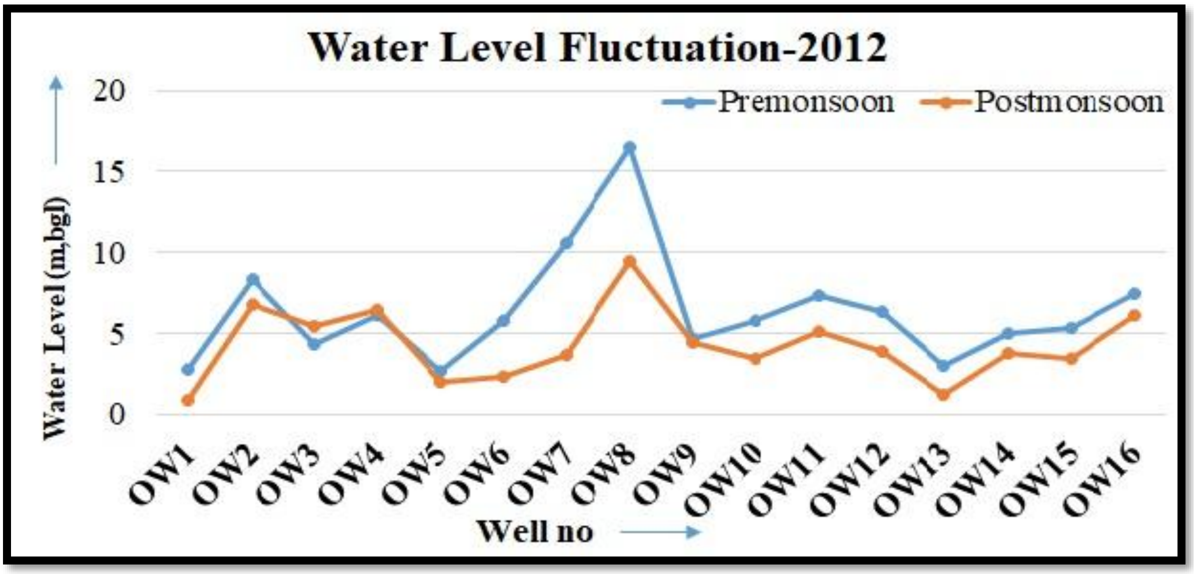
(b)


Water Level Fluctuation-2010
Premonsoon
Postmonsoon
Water Level (m,bgl)
Well no
OW1
OW2
OW3
OW4
OW5
OW6
OW7
OW8
OW9
OW10
OW11
OW12
OW13
OW14
OW15
OW16
0
2
4
6
8
10
12
14

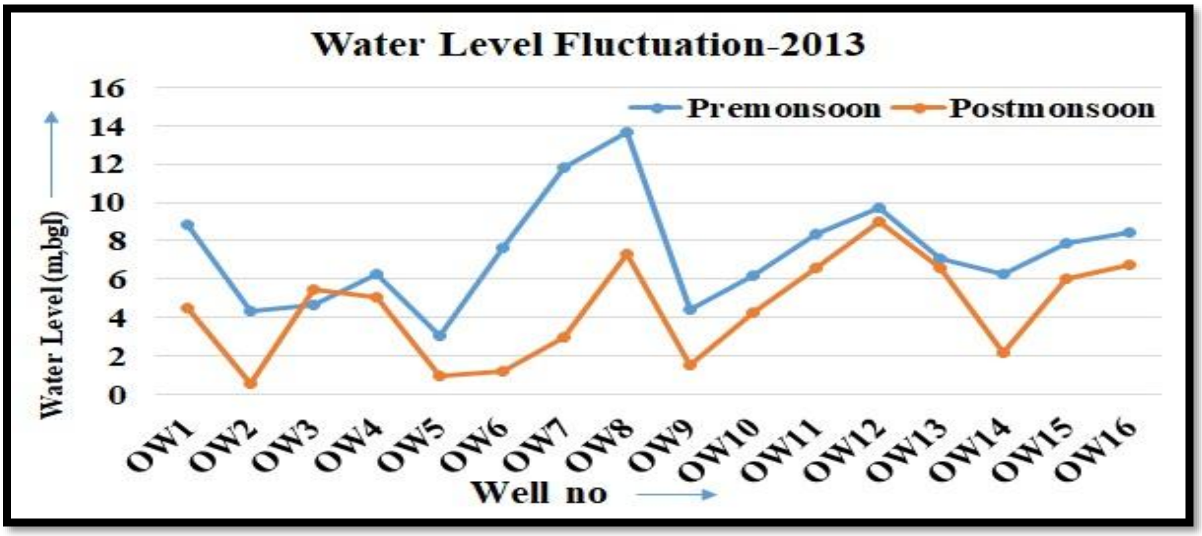
(c)


Water Level Fluctuation-2011
Premonsoon
Postmonsoon
Water Level (m,bgl)
Well no
OW1
OW2
OW3
OW4
OW5
OW6
OW7
OW8
OW9
OW10
OW11
OW12
OW13
OW14
OW15
OW16
0
2
4
6
8
10

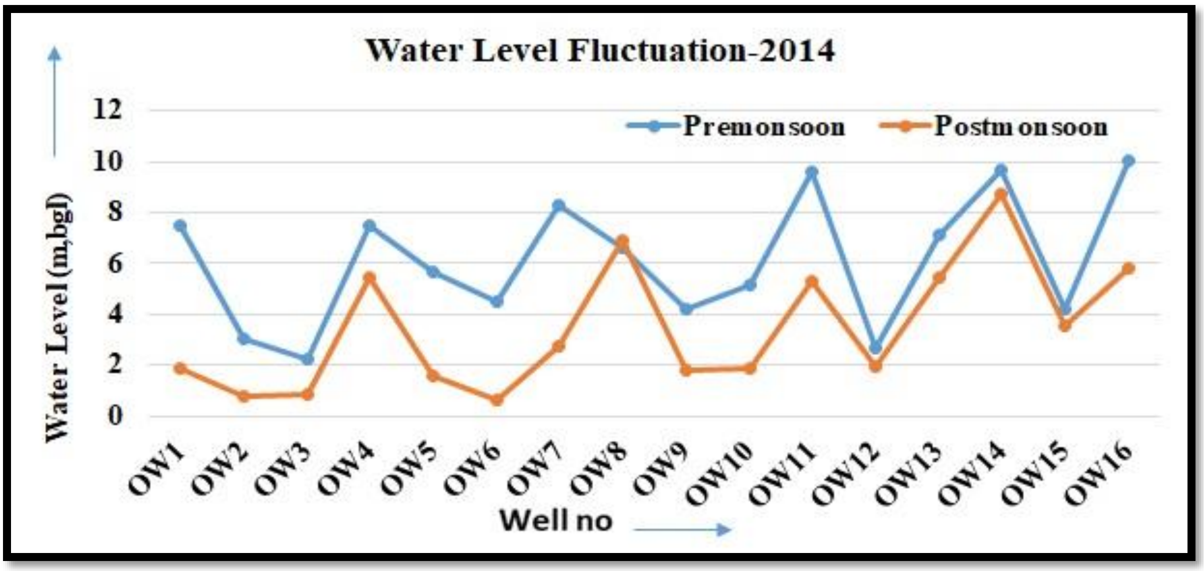
(d)


Water Level Fluctuation-2012
Premonsoon
Postmonsoon
Water Level (m,bgl)
20
15
10
5
0
OW1 OW2 OW3 OW4 OW5 OW6 OW7 OW8 OW9 OW10 OW11 OW12 OW13 OW14 OW15 OW16
Well no

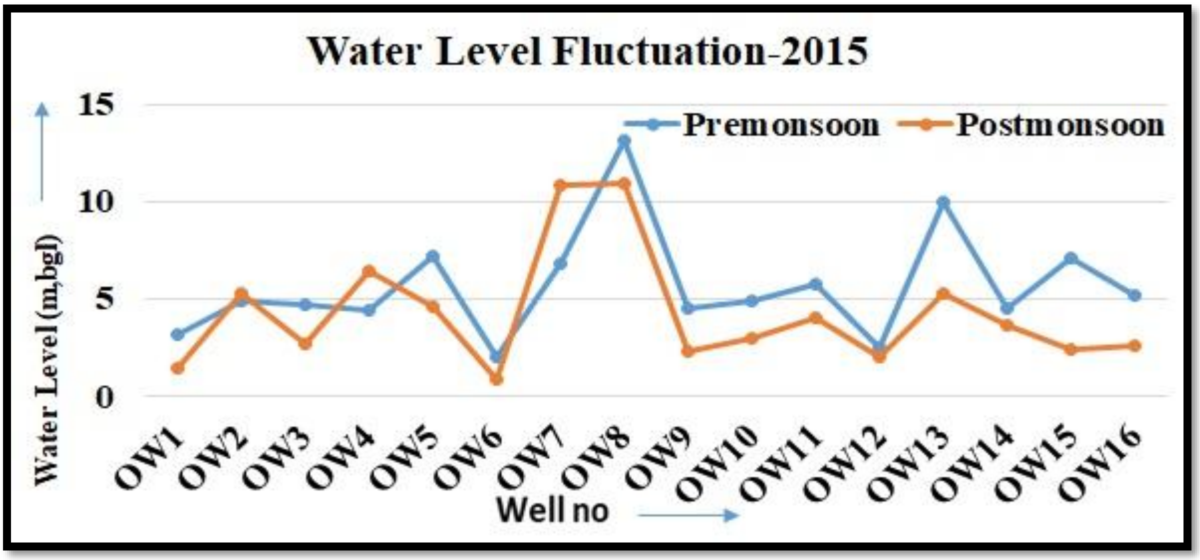
(e)


Water Level Fluctuation-2013
Premonsoon
Postmonsoon
Water Level (m,bgl)
16
14
12
10
8
6
4
2
0
OW1 OW2 OW3 OW4 OW5 OW6 OW7 OW8 OW9 OW10 OW11 OW12 OW13 OW14 OW15 OW16
Well no

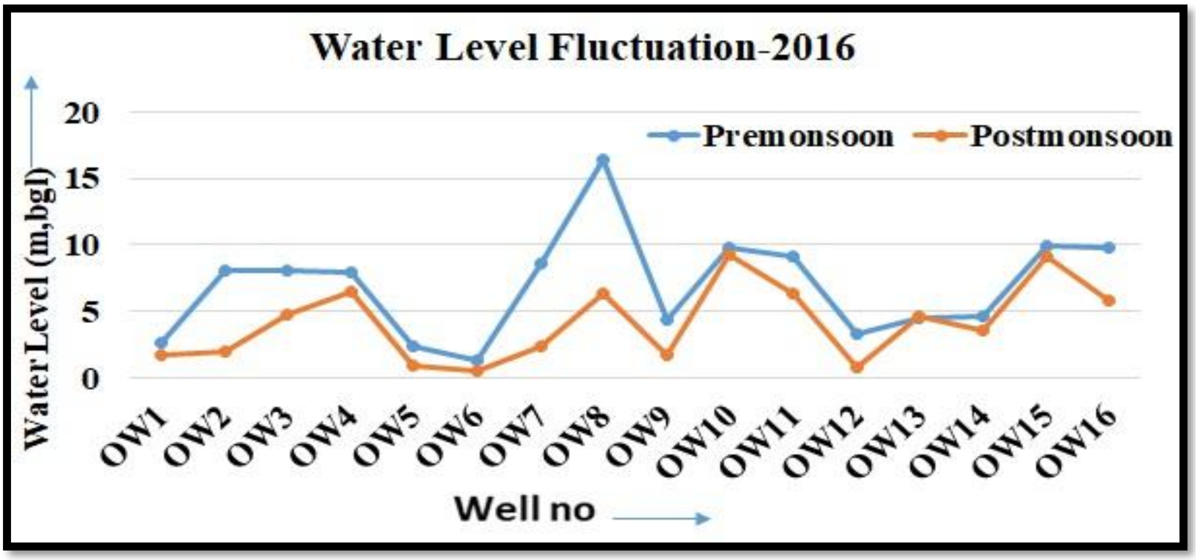
(f)


Water Level Fluctuation-2014
Premonsoon
Postmonsoon
Water Level (m,bgl)
12
10
8
6
4
2
0
OW1 OW2 OW3 OW4 OW5 OW6 OW7 OW8 OW9 OW10 OW11 OW12 OW13 OW14 OW15 OW16
Well no

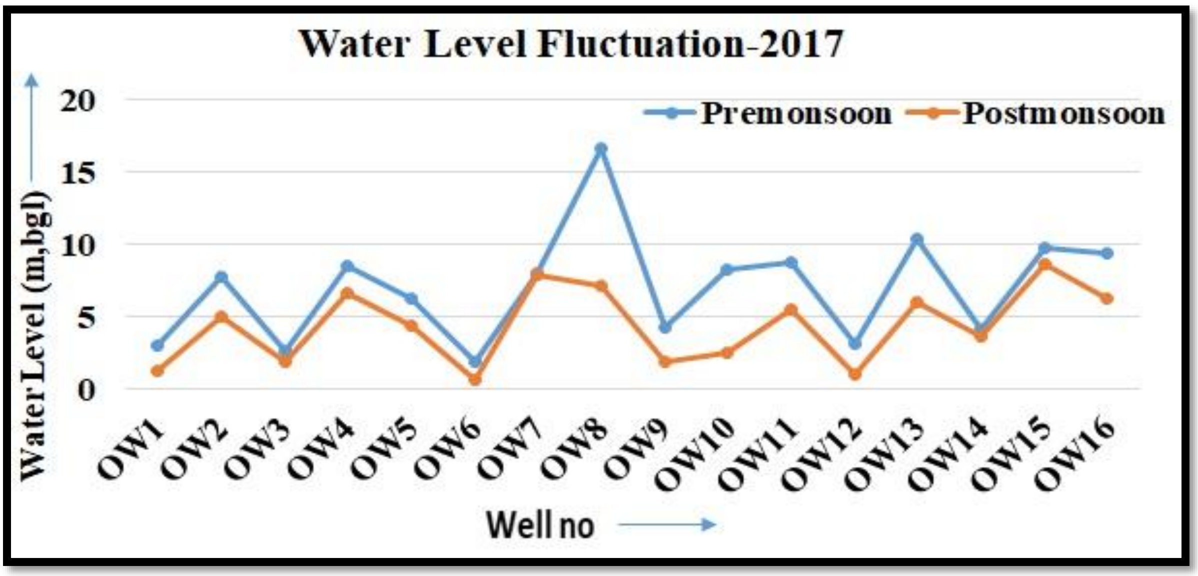
(g)


Water Level Fluctuation-2015
Premonsoon
Postmonsoon
Water Level (m,bgl)
15
10
5
0
OW1 OW2 OW3 OW4 OW5 OW6 OW7 OW8 OW9 OW10 OW11 OW12 OW13 OW14 OW15 OW16
Well no

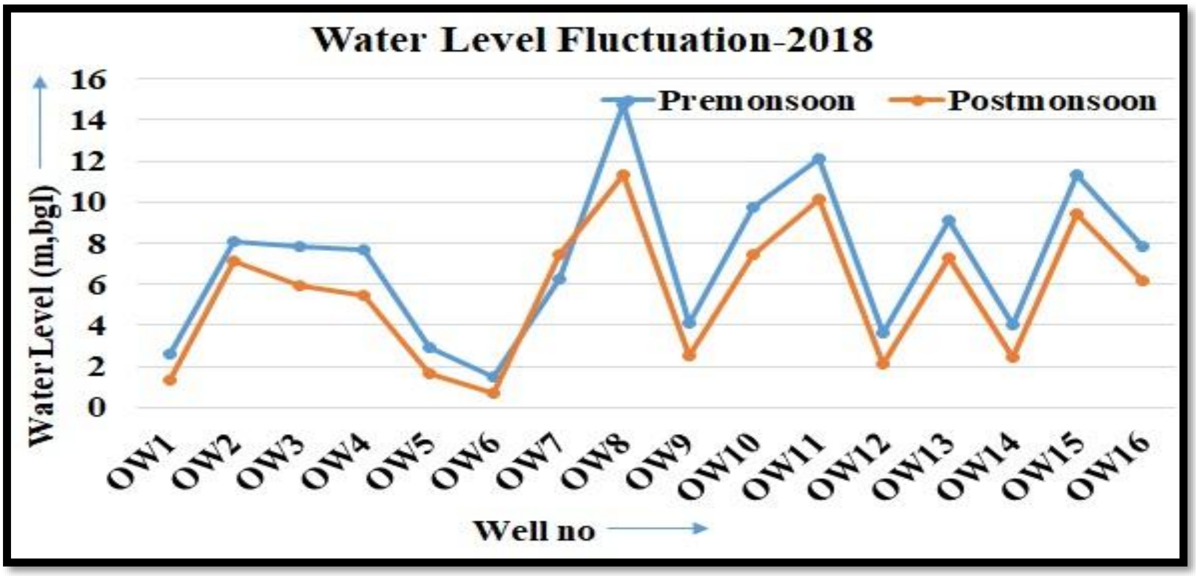
(h)


Water Level Fluctuation-2016
Premonsoon
Postmonsoon
Water Level (m,bgl)
20
15
10
5
0
OW1 OW2 OW3 OW4 OW5 OW6 OW7 OW8 OW9 OW10 OW11 OW12 OW13 OW14 OW15 OW16
Well no

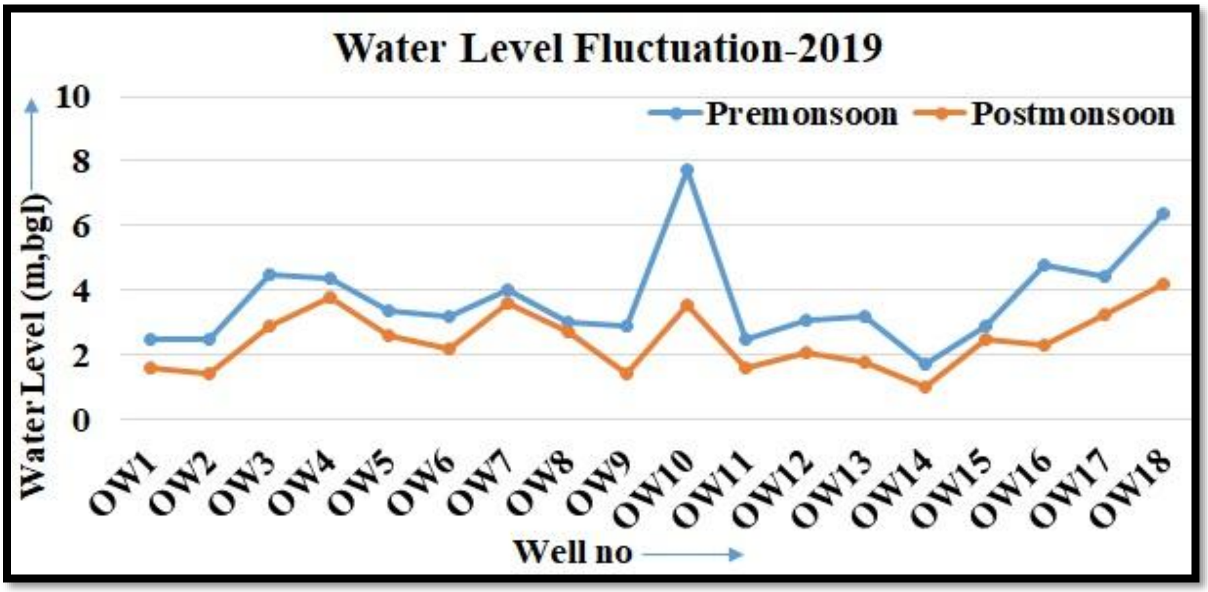
(i)


Water Level Fluctuation-2017
Premonsoon
Postmonsoon
Water Level (m,bgl)
20
15
10
5
0
OW1 OW2 OW3 OW4 OW5 OW6 OW7 OW8 OW9 OW10 OW11 OW12 OW13 OW14 OW15 OW16
Well no

(j)



(k)



(l)

Figure 12: Annual groundwater level fluctuation graph

4.6 Rainfall analysis

The average annual rainfall of 11 years (2002-2012) is considered for study. It is noticed that the maximum rainfall occurred in the year 2007 (1827.6. mm) and the minimum rainfall was observed during the year 2010 (4668.8 mm). Out 11 years, 2002, 2003 and 2004 showed the rainfall much lower than the yearly average rainfall. **Figure 13** shows the rainfall variation from 2002 to 2012.

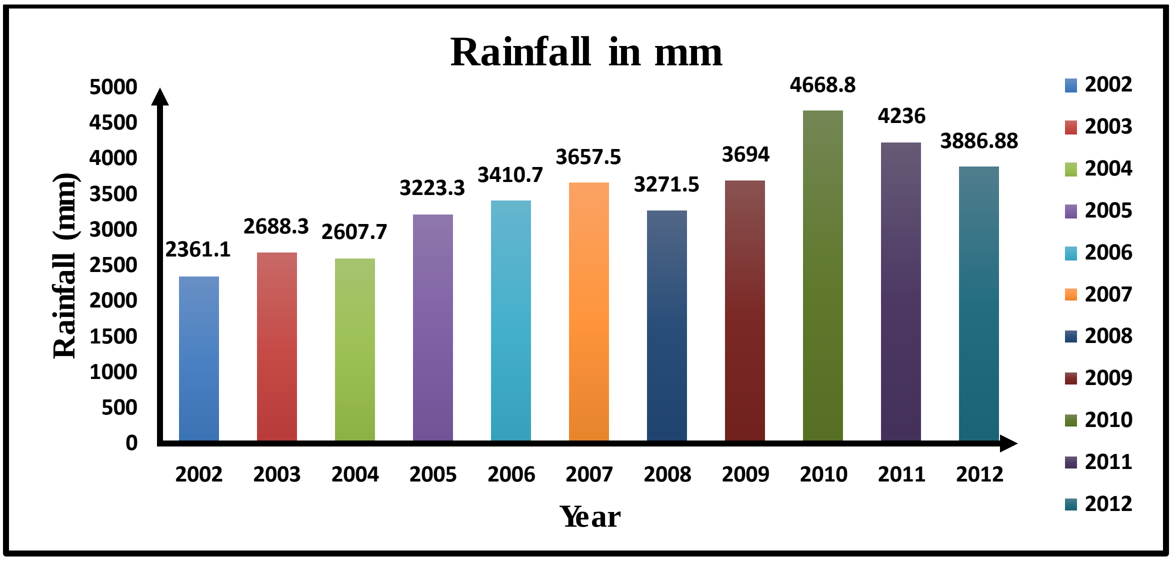


Figure 13: Rainfall pattern from 2002-2012

4.7 Groundwater quality evaluation

Groundwater samples were collected during pre-monsoon and post-monsoon seasons of year 2019. Some of the field conditions and sampling sites are presented in **Figure 14 to 16**. Sixty-two sites have been identified for water sampling and tested for physical parameters. Among the collected samples, based on the site characteristics, detailed analysis for both major anions and cations were carried out. Statistical summary of the analysis is presented **Table 3**.

Table 3: Physico-chemical analysis of groundwater during pre-monsoon & post-monsoon

Parameters	Minimum		Maximum		Mean		Std. Deviation	
	PRE	POM	PRE	POM	PRE	POM	PRE	POM
pH	6.03	6.35	7.84	7.75	6.9022	7.0228	.50519	.459
EC	54.7	32.0	5060	3025	842.87	569.77	1207.69	683.32
TDS	31.6	17.0	2430	1739	411.90	302.83	571.37	393.27
HCO3	70.0	46.0	520	414	180.22	144.11	131.47	113.28
Cl	19.0	10.0	1116	700	190.05	135.77	275.27	175.63
Ca	17.0	10	244	166.0	130.16	103.555	68.49	49.453
Mg	5.00	6.00	56.0	25.00	26.94	14.22	13.43	4.57
Na	0.00	0.00	85.5	81.00	10.15	8.78	19.05	18.196
P	.46	.37	1.82	1.60	.9911	.7939	.408	.36165
CaCO3	22.00	16.0	260	186.0	157.11	117.77	72.78	51.44
Acidity	4.00	4.00	26.0	18.00	10.8889	8.3333	6.40670	4.13023
Salinity	.02	.03	2.48	1.65	.6467	.4033	.60696	.36230

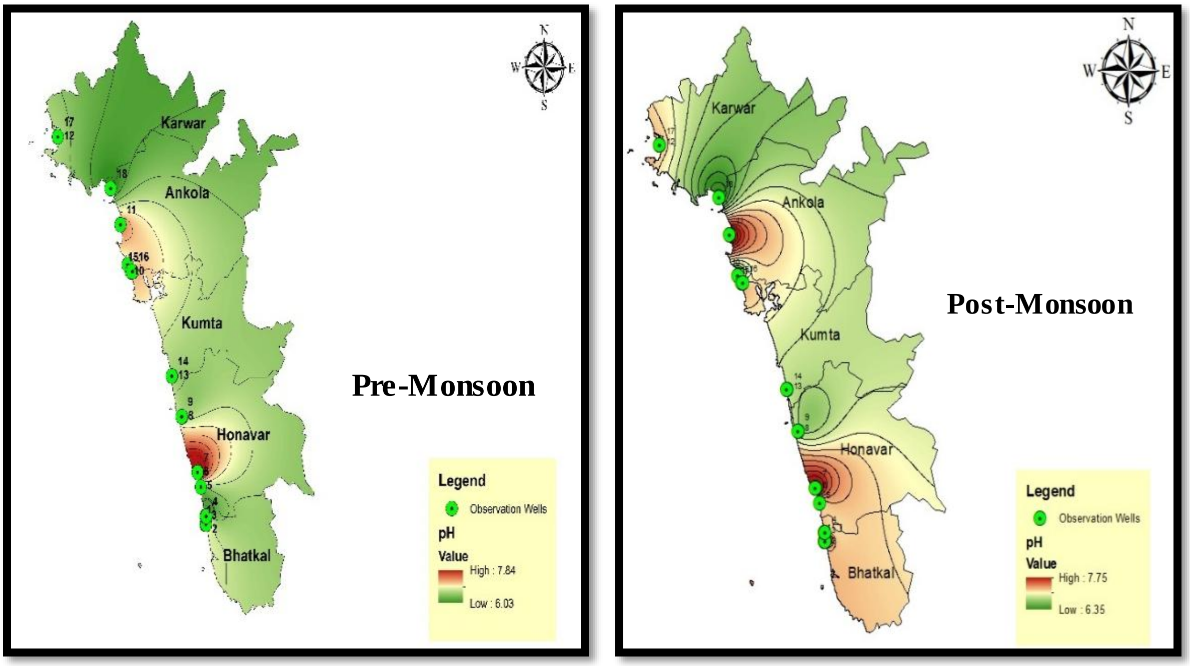
Figure 14: View of observation wells close to open sea.

Figure 15: Sampling site near the coastal region of Uttar Kannada district.

Figure 16: Dry wells close to open sea in the Uttara Kannada district.

pH

pH indicates the strength of the water to react with the acidic or alkaline material present in the water. It controls by carbon dioxide, carbonate and bicarbonate equilibrium (Hem 1985). The combination of CO2 with water forms carbonic acid, which affects the pH of the water. The permissible limit of pH is 6.5–8.5. The pH in the wells is varied between 6.49-7.70 (**Figure 17**a) during pre-monsoon and 6.50-7.53 (**Figure 17**b) during post-monsoon.



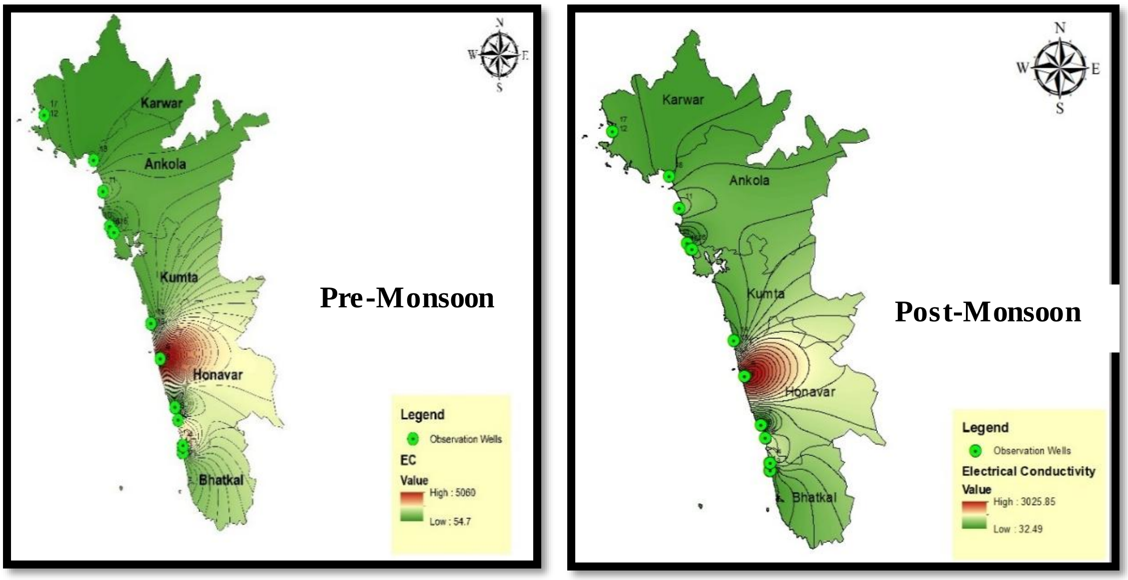
(a) (b)

Figure 17: Spatial variation of pH during pre-monsoon and post-monsoon season

Electrical Conductivity

Electrical conductivity is a measure of water capacity to convey the electrical current. The most desirable limit of EC in drinking water is prescribed as 1,500 lS/cm. The EC values varied between 54.7 µmhos/cm and 5060 µmhos/cm during the pre-monsoon and 32 µmhos/cm to

3025 µmhos/cm during the post-monsoon (**Figure 18**). EC measures the ability of a material to conduct an electric current such that the higher EC indicates enrichment of salts in the groundwater. Thus, the EC can be classified as type I, if the enrichments of salts are low (EC<1,500 µS/cm) type II, if the enrichment of salts are medium (EC: 1,500 and 3,000 µS/cm) and type III, if the enrichments of salts are high (EC>3,000 µS/cm (Sarath Prasanth et al. 2012). According to the classification of EC, 94% of the total groundwater samples are falling under the type I (low enrichment of salts), except for one sample which is falling under type III indicating high enrichment of salts.

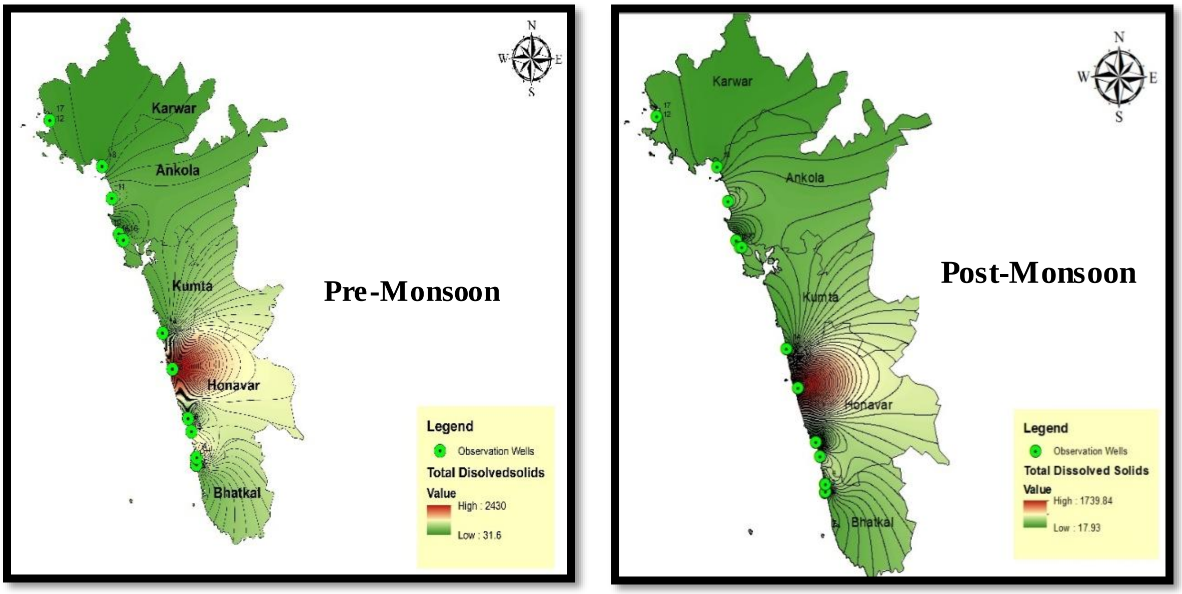


(a) (b)

Figure 18: Spatial variation of EC during pre-monsoon and post-monsoon

Total Dissolved Solids

Total dissolved solids showed a significant correlation with EC. During pre-monsoon, TDS values varied from 31.6 mg/l to 2430 mg/l and the EC values varied from 17 mg/l to 1739 mg/l during post-monsoon (**Figure 19**). Degree of groundwater quality can be classified as fresh, if the TDS is less than 1,000 mg/l; brackish, if the TDS is between 1,000 and 10,000 mg/l; saline, if the TDS is varied from 10,000 to 1,000,000 mg/l and brine, if the TDS is more than 1,000,000 mg/l (Todd 1980). From the analysis it clearly states that all the collected water samples have low TDS which indicates the influence of rock–water interaction in relation to recharge water expect for one well.

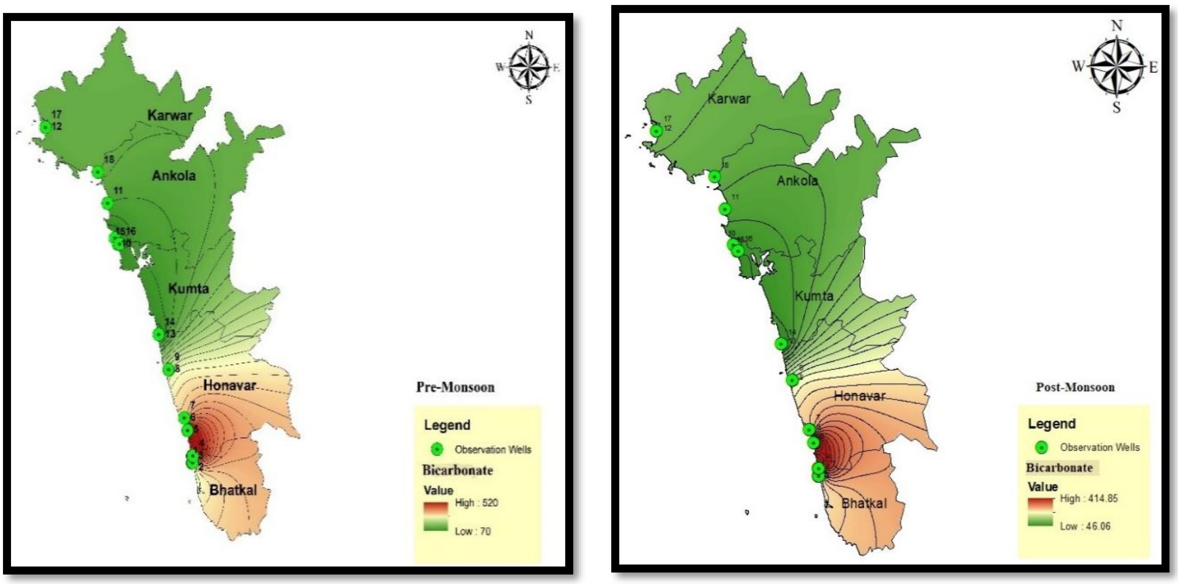


(a) (b)

Figure 19: Spatial Variation of TDS during pre-monsoon and post-monsoon

Bicarbonate (HCO_3)

The concentration of carbonates in natural waters is a function of dissolved carbon dioxide, temperature, pH, cations and other dissolved salts. The concentration of bicarbonate is observed from 70 to 520 mg/l during pre-monsoon and 46 to 414 mg/l during post-monsoon (**Figure 20**).



(a) (b)

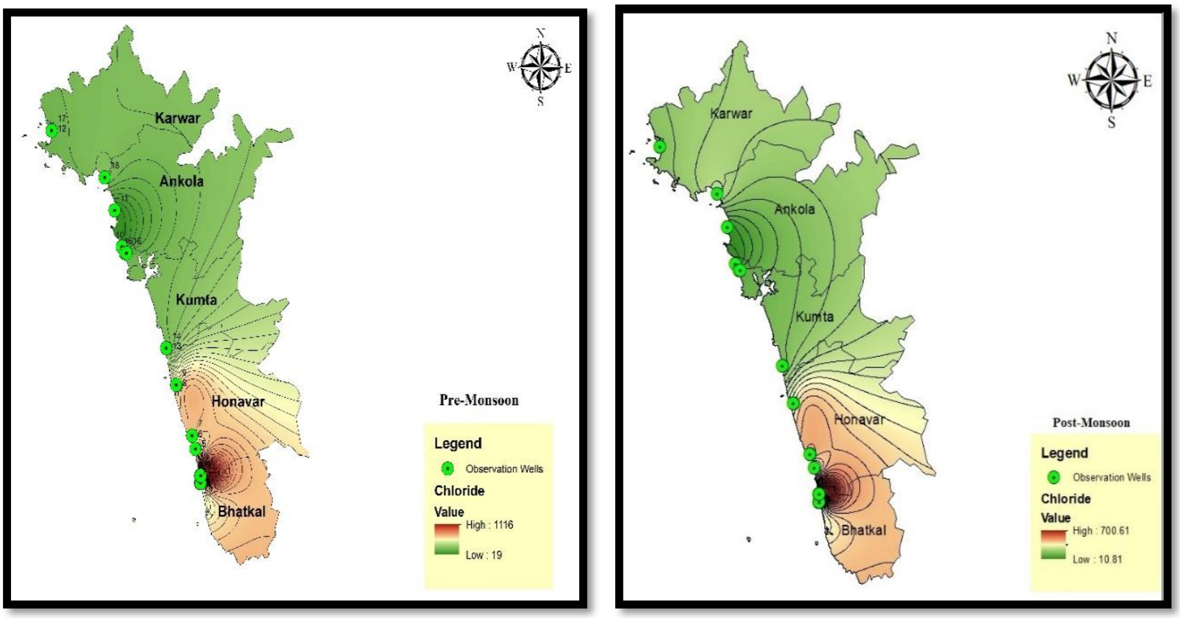
Figure 20: Spatial Variation of HCO_3 during pre-monsoon and post monsoon

Chloride

The chloride ion is the most predominant natural form of the element chlorine and is extremely stable in water. The chloride in groundwater may be from diverse sources such as weathering, leaching of sedimentary rocks and soil, domestic and municipal effluents (Sarath Prasanth et al. 2012). The range of chloride is found to vary between 19 and 1116 mg/l for water samples collected during pre-monsoon and the values varied from 19 to 700 mg/l during post-monsoon (**Figure 21**). As per (World Health Organization 2011) and Indian standards (BIS, 1991) the desirable limit for chloride is 250 mg/l. 83.3 % of the groundwater samples collected from the study area is having chloride concentration within the permissible limit whereas remaining 16.6 % of the collected samples are exceeding the permissible limits.

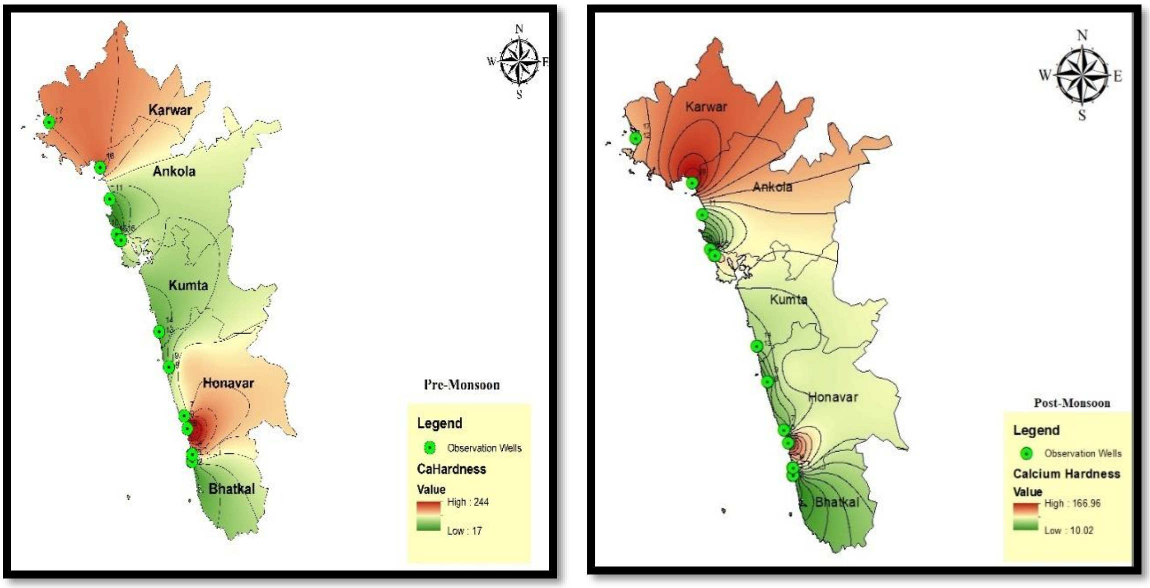
Calcium and magnesium (Ca and Mg)

The calcium and magnesium in waters are generally used to classify the suitability of water. Calcium and magnesium are directly related to hardness of the water and these ions are the most abundant elements in the surface and groundwater and exist mainly as bicarbonates and to a lesser degree in the form of sulphate and chloride. The concentration of Ca is between 17 mg/l and 244 mg/l, and concentration of Mg is varied from 5 mg/l and 56 mg/l during pre-monsoon and the concentration of Ca is between 10 mg/L to 166 mg/l, and concentration of Mg is varied from 6 mg/l to 25 mg/l during post-monsoon. The maximum concentration of calcium ions can cause abdominal ailments and is undesirable for domestic purposes as it causes encrustation and scaling. From the analysis it clearly states that the calcium and magnesium concentration is within the permissible limits (**Figure 22 & 23**).



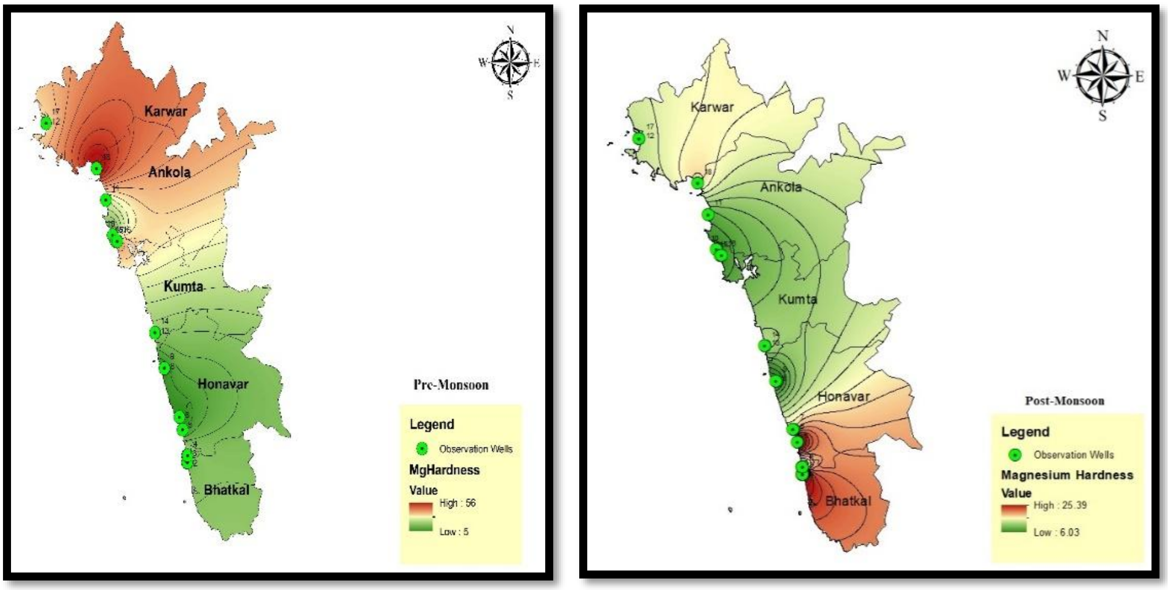
(a) (b)

Figure 21: Spatial variation of chloride during pre-monsoon and post-monsoon



(a) (b)

Figure 22: Spatial variation of Ca during pre-monsoon and post-monsoon

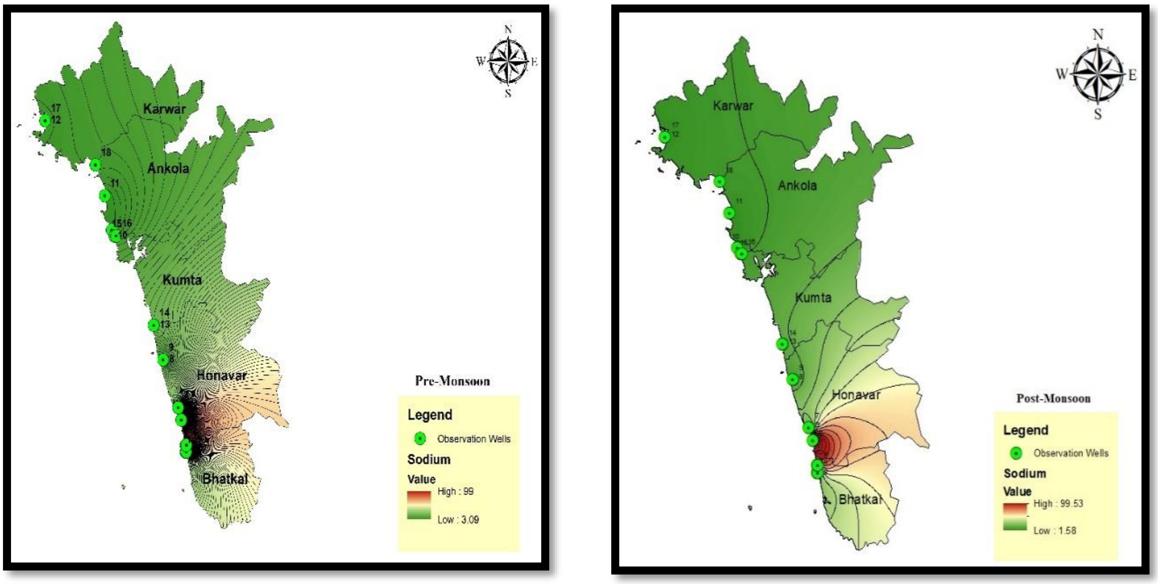


(a) (b)

Figure 23: Spatial variation of Mg during pre-monsoon and post-monsoon

Sodium

The concentration of Na is varied from 3.09 to 85.5 mg/l during pre-monsoon and 0 to 81 mg/l during post-monsoon (**Figure 24**). In general case, the Na is the dominant ion among the cations and is present in most of the natural waters, which contributing approximately 53 to 69 % of the total cations. This is because of the silicate weathering and/or dissolution of soil salts stored by the influences of evaporation, anthropogenic activities, agricultural activities and poor drainage conditions.

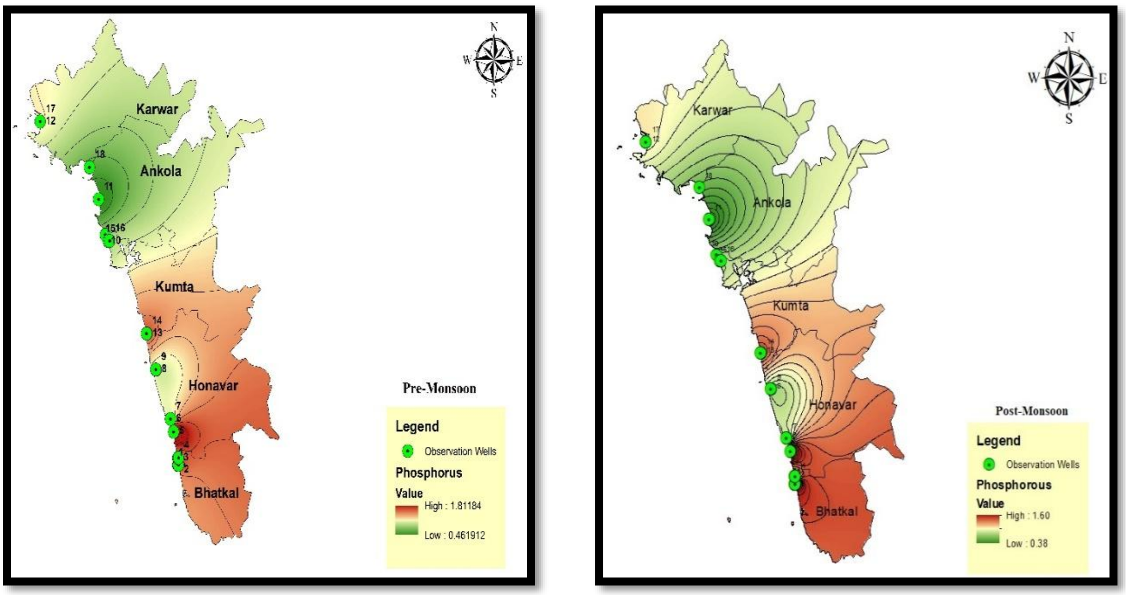


(a) (b)

Figure 24: Spatial variation of Na during pre-monsoon and post-monsoon

Phosphorous

Phosphorous content observed during pre-monsoon varied between 0.46 mg/l and 1.82 mg/l. Analysis of post-monsoon water quality data showed that the concentration varies from 0.37 mg/l to 1.60 mg/l (**Figure 25**). The water quality samples are found to be within the permissible limit.



(a) (b)

Figure 25 Spatial variation of Phosphorous during pre-monsoon and post-monsoon

Total Hardness ($CaCO_3$)

Water rich in calcium and/or magnesium is called as Hardness. Almost certainly most general difficulty recognized by means of groundwater quality i.e. hardness. Majority of the water samples falls under moderately hard to hard category during both pre-monsoon and post-monsoon. The hardness values range from 22 mg/l to 260 mg/l with an average value of 157.1 mg/l during pre-monsoon. Similarly, during post-monsoon, the hardness values range from 16 mg/l to 186 mg/l with an average value of 117.7 mg/l. The maximum allowable limit of TH for drinking purpose is 600 mg/l and the most desirable limit is 200 mg/l as per the BIS standard. Groundwater exceeding the limit of 300 mg/l is considered to be very hard (Sawyer and McMcartly 1967).

Salinity

Salinity is the total amount of inorganic solid material dissolved in any natural water, and water salinization relates to an increase in TDS and overall chemical content of water. The salinity concentration in the study area ranges between 0.02 and 2.48 mg/l during pre-monsoon and 0.03 to 1.65 during post-monsoon.

Sodium Adsorption Ratio

SAR is a measure of alkali/sodium hazard to crops that's why it is significant feature in categorizes water for irrigation. When sodium reacts with soil, it reduces soils permeability and cultivation becomes difficult. The SAR content observed during pre-monsoon and post-monsoon is within the permissible limit i.e., all the collected water samples belong to excellent category (**Table 4**). The analytical data plotted on the US salinity diagram (Richards 1954) suggest that groundwater samples (**Figure 26 & 27**) fall in the domain C1S1, C2S1, indicating water of low-medium salinity and low sodium, which can be utilized for irrigation in all types of soil with slight cause of exchangeable sodium. One of the sample falls in the domain C4S1 indicating high salinity and low alkalinity hazard. This water is desirable for plants having good salt tolerance and its restrains its suitability for irrigation, especially in soils with poor drainage. A few samples fall in the C3S2 domain. The groundwater of the study area in general falls into the categories of good to moderate during both pre-monsoon and post-monsoon.

Permeability index

Based on the permeability index (PI), a water suitability classification for irrigation water was developed by Doneen (1964). The PI values in the study area vary from 18.65 to 345.92 during the pre-monsoon period. Similarly due post monsoon it was observed that the PI values varied between 25.28 and 253.672 (**Table 4**). According to the permeability index values, 88.88 % of the samples falls under the class 1(PI >75) and 11.11 % of the samples fall under class 3 (PI< 25 %) during the pre-monsoon period. Furthermore, during post monsoon 2016 the PI values were accordingly, 33.33 % of the samples falls under class 3(PI >75) and 66.66 % belong to class 2 (PI ranged between 25 and 75 %).

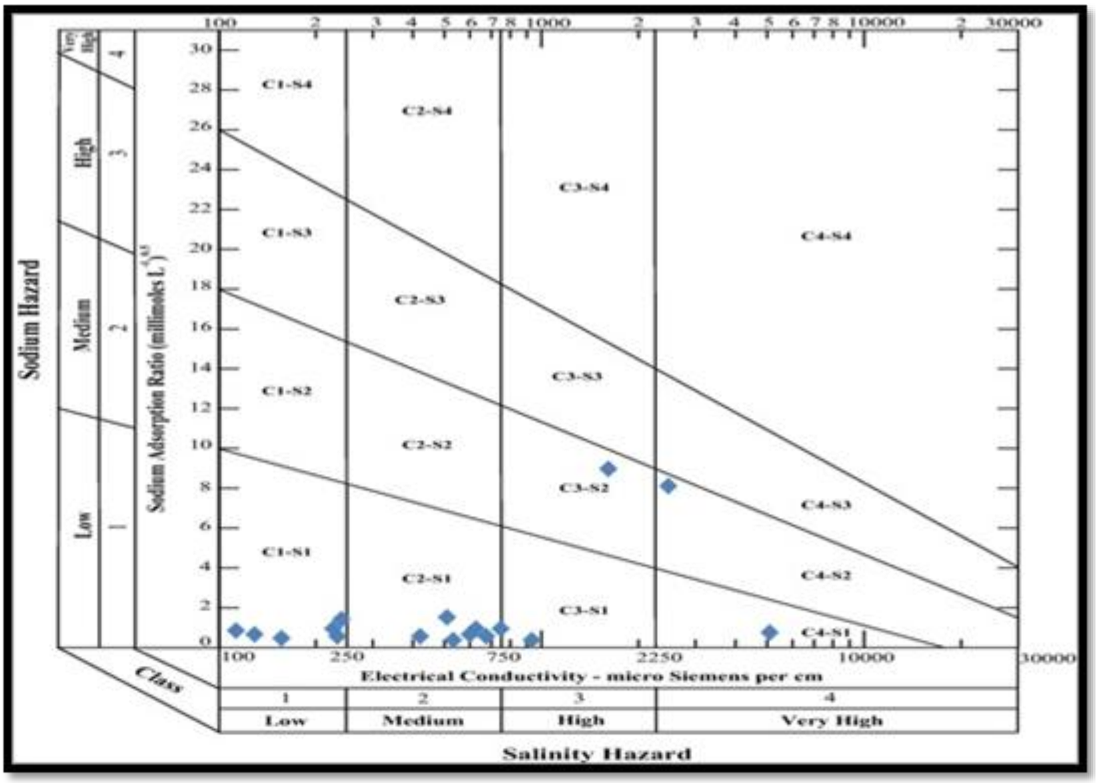


Figure 26: Pre-monsoon: USSL Chart (Open Well)

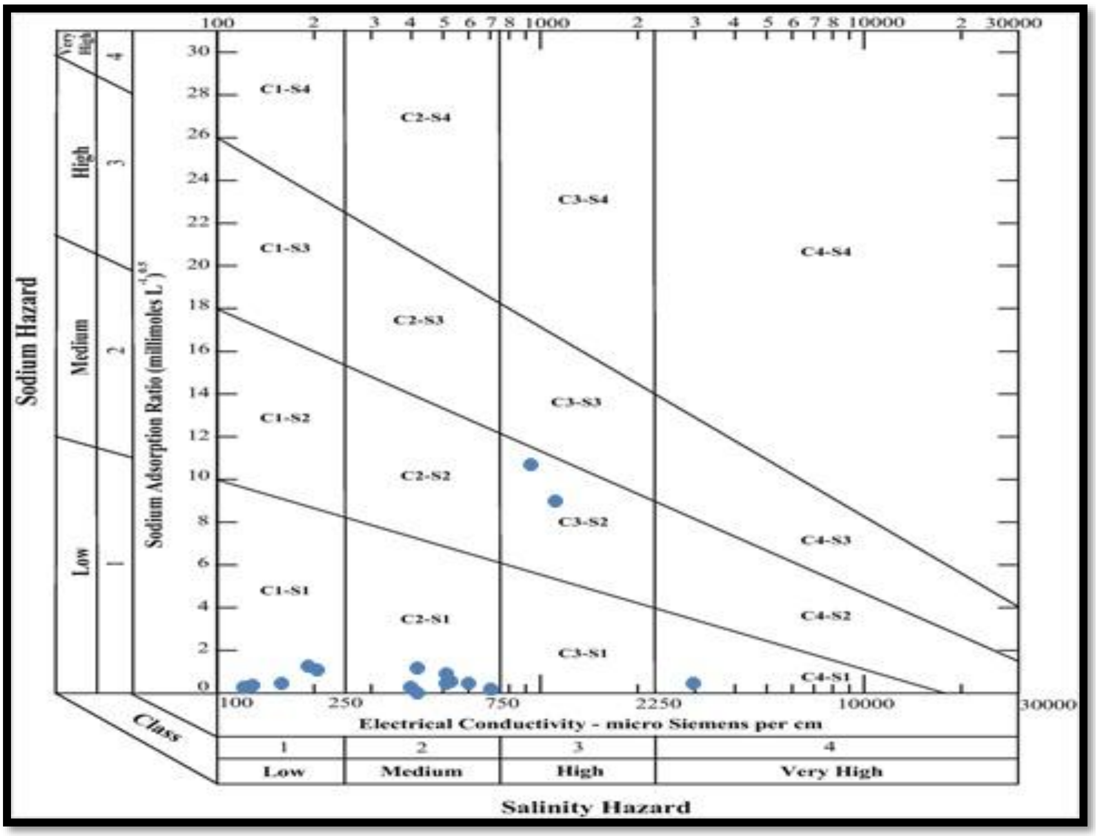


Figure 27: Post-monsoon: USSL Chart (Open Well)

Magnesium hazard

In most waters calcium and magnesium maintains a state of equilibrium. A ratio namely index of magnesium hazard was developed by Paliwal (1972). In the study area the magnesium hazard values fall in the range of 9.75 to 49.41 (**Table 4**) during pre-monsoon the values ranges from 11.65 to 49.72 during post monsoon. In the study area, all the samples collected shows MH ratio <50 % (suitable for irrigation) during pre-monsoon and post monsoon.

Kelley Ratio

KR more than one is a sign of an excess level of sodium in waters. If KR less than one then water is suitable for irrigation. If it is more than one then unsuitable for irrigation. All the water samples (**Table 5**). collected during pre-monsoon and post-monsoon are less than one indicating water suitable for irrigation.

Residual Sodium Carbonate

The sum of bicarbonate and carbonate in groundwater over sum of Ca and Mg also influences incompatibility of groundwater for irrigation. All the water samples collected during pre-monsoon and post-monsoon are less than 1.25 epm indicating water is safe (**Table 4**).

Table 4: Computed values of RSC, SAR, PI, MH and KI in the study area.

Well nos	RSC		SAR		PI		MH		KI	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	-3.681	-2.025	0.170	1.014	136.286	89.047	35.463	27.740	0.046	0.059
2	-3.285	-2.506	0.106	0.522	234.012	77.042	22.282	42.835	0.031	0.030
3	-3.360	-2.045	0.139	0.480	183.481	77.235	49.415	22.132	0.042	0.033
4	-3.895	-2.151	1.493	8.786	18.651	75.367	17.223	12.888	0.300	0.394
5	-6.936	-4.191	1.675	10.370	20.956	57.245	9.755	18.109	0.322	0.435
6	-1.936	-1.700	0.119	0.584	290.480	70.399	35.463	36.782	0.047	0.045
7	-5.938	-3.290	0.131	0.728	111.672	86.095	10.535	17.968	0.026	0.033
8	-8.528	-5.665	0.130	0.659	121.323	58.837	16.306	12.206	0.025	0.029
9	0.707	0.679	0.175	1.432	345.930	253.672	32.653	49.726	0.110	0.177
10	-3.633	-2.700	0.090	0.432	305.223	53.725	23.294	24.135	0.029	0.029
11	-5.558	-4.468	0.071	0.349	254.927	43.352	31.701	16.795	0.018	0.019
12	-7.695	-7.524	0.061	0.172	284.136	28.430	17.880	14.787	0.014	0.008
13	-6.688	-6.087	0.263	1.185	116.191	25.281	23.896	18.790	0.065	0.059
14	-5.651	-4.824	0.279	1.287	121.502	27.120	30.866	17.697	0.075	0.072
15	-6.000	-4.229	0.156	0.671	148.680	34.344	48.337	16.085	0.041	0.040
16	-10.87	-7.292	0.101	0.587	156.345	26.045	28.056	11.651	0.020	0.027
17	-9.705	-3.678	0.110	0.587	146.889	58.219	32.816	17.386	0.022	0.033
18	-10.99	-7.859	0.100	0.496	144.976	28.967	34.926	14.002	0.019	0.022

Ionic Ratios

High EC of groundwater is not sufficient to prove the occurrence of seawater as suggested by Revelle (1941). However, the salinity ingress from the sea can be confirmed by analysing the shifts in molar ratios of ions. Many researchers (Kim et al. 2003; Moujabber et al. 2006) have used the ionic ratios to evaluate seawater intrusion in coastal areas in order to identify the source and nature of the salinity present. In the present study, Cl/(HCO3+CO3), Ca/Mg and Na/Cl are used to delineate region affected by seawater intrusion.

Cl/(HCO3+CO3)

Moujabber et al. (2006) explained the Simpson Ratio, namely Cl/(HCO3+CO3). The ratio is divided into five classes: first is good quality (< 0.5); second, is slightly contaminated (0.5 – 1.3); third, moderately contaminated (1.3 – 2.8); fourth, highly contaminated (2.8 – 6.6); and fifth, extremely contaminated (6.6 – 15.5). The majority of the samples collected from the study area are falling under good to highly contaminated except for 2 samples falling under extremely contaminated class during pre-monsoon and post-monsoon (**Table 5**).

Table 5: Groundwater characterization using ionic ratios (pre and post-monsoon 2019)

Well Nos	$Cl/(HCO_3+CO_3)$		Ca/Mg		Na/Cl	
	PRE	POM	PRE	POM	PRE	POM
1	1.618	1.412	1.820	2.605	0.060	0.069
2	0.387	0.369	3.488	1.335	0.180	0.170
3	0.330	0.270	1.024	3.518	0.349	0.270
4	3.694	2.910	4.806	6.759	0.118	0.178
5	0.654	0.588	9.251	4.522	1.014	1.274
6	0.473	0.287	1.820	1.719	0.245	0.432
7	2.410	2.144	8.493	4.566	0.021	0.025
8	2.957	2.335	5.133	7.193	0.025	0.031
9	0.273	0.219	2.062	1.011	0.259	0.480
10	0.731	0.672	3.293	3.143	0.147	0.155
11	0.430	0.761	2.155	4.954	0.162	0.105
12	1.463	1.721	4.593	5.763	0.047	0.029
13	2.402	3.412	3.185	4.322	0.142	0.133
14	1.699	2.021	2.240	4.651	0.239	0.265
15	2.582	1.849	1.069	5.217	0.100	0.124
16	1.541	1.889	2.564	7.583	0.082	0.103
17	1.212	1.411	2.047	4.752	0.096	0.066
18	1.683	2.399	1.863	6.142	0.069	0.055

Ca/Mg

The ratio of Ca/Mg can also be used as an indicator, where if it is >1, it means that sea water intrusion is taking place. All the samples collected during pre-monsoon and post-monsoon are showing the indication of seawater intrusion taking place as all values are >1 (**Table 5**).

Na/Cl

Some researchers have explained that when calculating the Na/Cl ratio, if the result is smaller than 0.86, it means that the groundwater has been contaminated by seawater; meanwhile, if the ratio is >1, it means the groundwater is contaminated by anthropogenic source (Vengosh and Rosenthal 1994). During pre-monsoon and post-monsoon, 94.4% of the samples showed values <0.86 and 5.5% of the samples showed values >1. Similarly, during pre- and post-monsoon (**Table 5**).

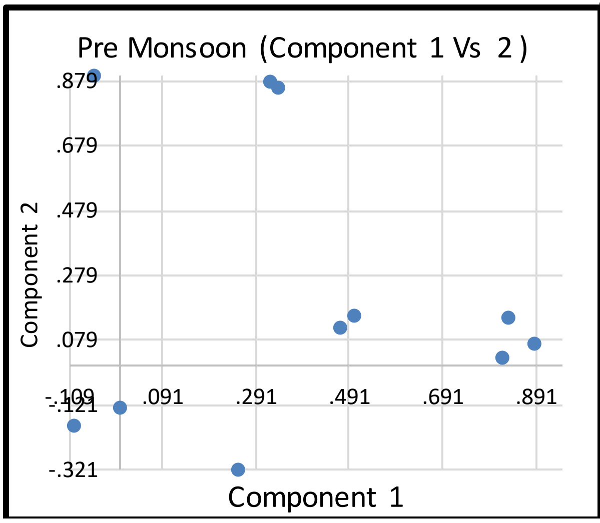
4.8 Factor Analysis

The rotated component matrix, sometimes referred to as the loadings, is the key output of principal components analysis. It contains estimates of the correlations between each of the variables and the estimated components. The purpose of factor analysis is to reduce the problem's dimensionality; but, the conclusions can be difficult to understand at times. To make the interpreting process easier, rotational procedures are used. In the current study, Kaiser's varimax rotation was employed to obtain a basic structure. The positive, no-contribution, and negative contributions of corresponding variables to total variance have been rotated (varimax rotated) so that all of their components are closer to +1, 0 and -1, respectively. The factor loadings explain how a factor affects a variable and how a variable affects a factor. **Table 6** discusses the specific details of the factor analysis performed during the study period.

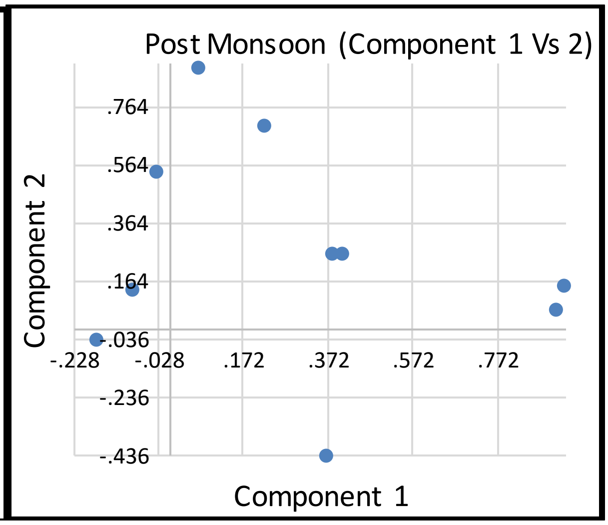
Table 6: Factor pattern of seasonal groundwater quality of shallow aquifers in the year 2019

Parameters	Pre-monsoon				Post-monsoon			
	Rotated Component				Rotated Component			
	1	2	3	4	1	2	3	4
pH	**0.82**	0.03	0.39	0.12	-0.03	0.54	0.26	**0.66**
Cl	**0.83**	0.15	0.41	-0.13	0.22	0.7	0.44	0.17
EC	0.47	0.12	0.7	0.39	0.38	0.26	0.6	0.55
TDS	0.5	0.15	**0.75**	0.23	0.41	0.26	0.54	0.57
HCO_3	0	-0.13	-0.01	**0.94**	-0.09	0.14	**0.84**	0.06
TH	**0.95**	0.25	0.07	0.02	0.25	**0.91**	0.14	0.26
Ca	0.32	**0.88**	0.26	0.16	**0.93**	0.15	0.02	0.24
Mg	0.34	**0.86**	0.29	0.17	**0.93**	0.16	0.02	0.24
Na	-0.11	0.24	**0.82**	-0.1	0.37	-0.44	0.6	0.16
K	-0.1	-0.19	-0.16	-0.64	-0.17	-0.04	0.24	-0.83
SO_4	**0.89**	0.07	-0.15	0.03	0.07	**0.90**	-0.05	0.02
NO_3	0.25	-0.32	0.54	-0.59	-0.23	0.13	**0.81**	-0.32
Eigen value	-0.05	0.9	-0.04	-0.05	0.91	0.07	-0.07	-0.06
% total variance	5.54	2.24	1.71	1.48	5.2	2.54	1.95	1.17
Cumulative %	42.6	17.2	13.17	11.35	39.98	19.55	15.03	8.98

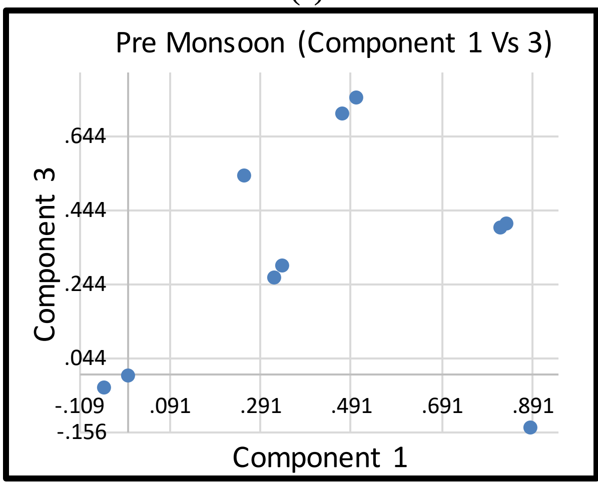
Parameter loading for the year 2019 is shown in **Table 6**. Factor 1, contributed a loading variance of 33.33% and showed higher positive loading during the pre-monsoon season of 2019, which is mostly related to pH (0.82), chloride (0.83), TH (0.95), sulphate (0.89). The loading variance of Factor 2 is 16.66 percent, and the major positive loading factors are Ca (0.88) and Mg (0.86). Factor 3, has a loading variance is also 16.66 %, with TDS (0.75) and Na (0.82). Factor 4, has a loading variance is 8.33%, with HCO_3 (0.94) being the major loading factors. During the post-monsoon season of 2019, Factor 1 contributed 16.66 % of the loading variance and demonstrated higher positive loading, with Ca (0.93) and Mg (0.93). The loading variance of Factor 2 is also 16.66 %, and the major positive loading factors are TH (0.91), SO_4 (0.90). Factor 3 has a loading variance of 16.66 %, and HCO_3 (0.84) and NO_3 has a significant loading factor. Factor 4 is also 8.33 %, and the major positive loading factors are pH (0.66). The plot of factor loadings graphs between rotated Component 1, 2, 3 and 4 are presented in following **Figure 28** (a) to (j) during pre-monsoon and post-monsoon 2019.



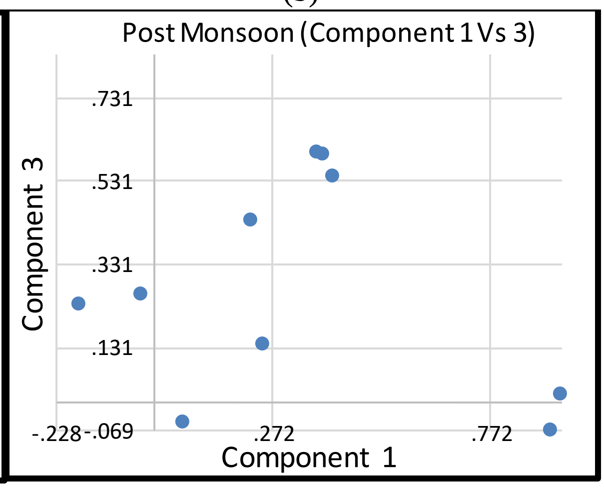
(a)



(b)



(c)



(d)

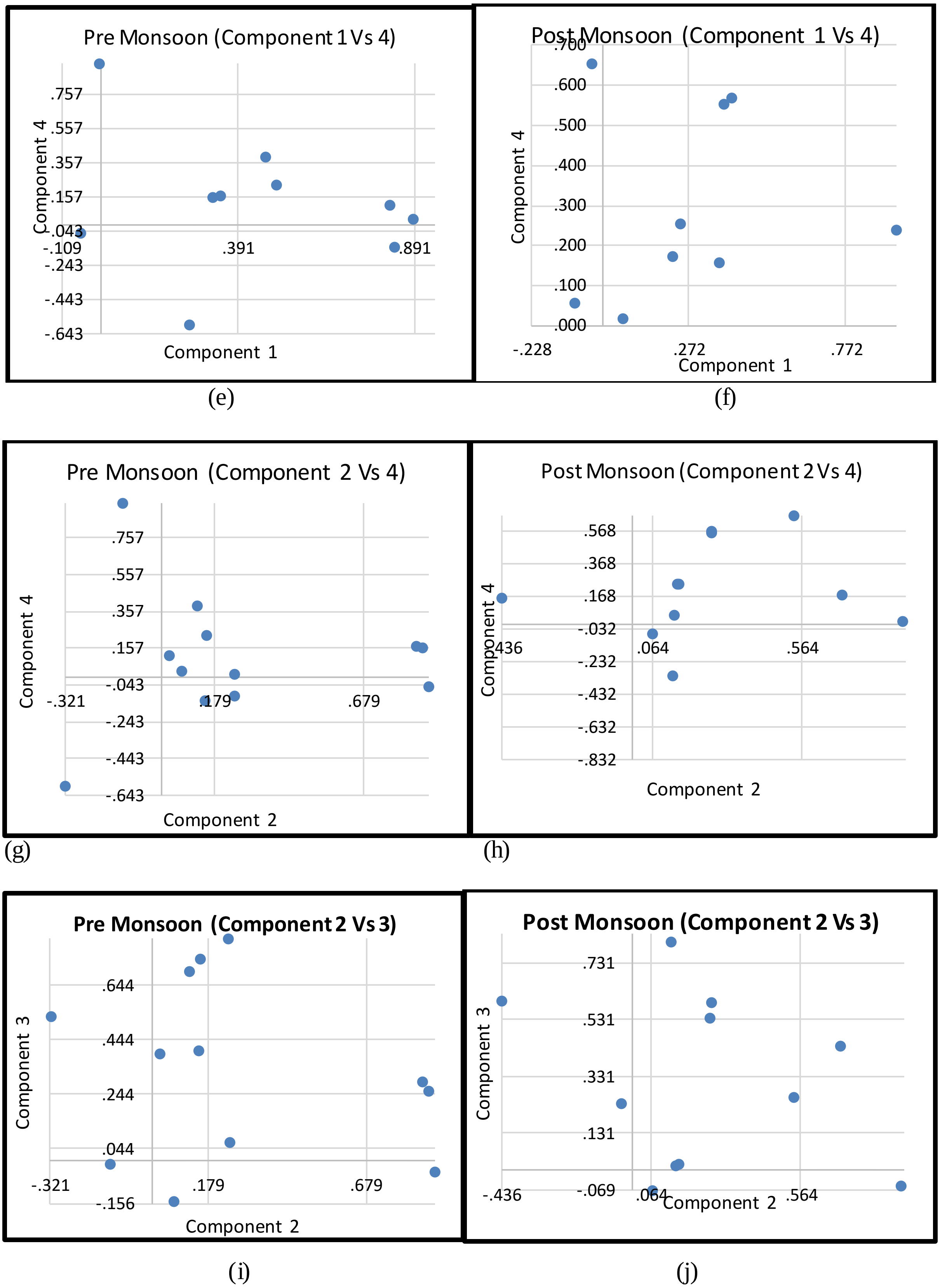


Figure 28: Factor loadings of component 1, 2, 3 and 4 during pre- and post-monsoon 2019.

4.9 Isotopic Analysis

In order to understand the contribution of recharge from various sources, GMWL (Global Meteoric Water) and LMWL (Local Meteoric Water Line) were estimated by the method suggested by Kumar et al., (2010), and shown in **Figure 29&30**. The LMWL of March and May 2019 followed a similar pattern, and they were divided into three groups for easy interpretation. The group I are isotopically, lighter, and the majority of samples fall closer to the LMWL and are found to obtained from rainfall recharge. The samples in Group II, are from wells with depths ranging from 8 to 17 m. These samples are classified as mixed water, which means they contain a mix of groundwater derived from rainfall and seawater. Water formed in Group III originates from wells closer to the sea and fall between the LMWL and the evaporation enrichment line. Both seawater intrusion and evaporation enrichment of recharging water have an effect on these samples. Rainwater is the primary recharge source for the region's groundwater and surface water for the Uttara Kannada coast of Karnataka. An attempt was also made to develop a regression plot between δD and $\delta^{18}O$ to understand the relationship between different sources (**Figure 31**).

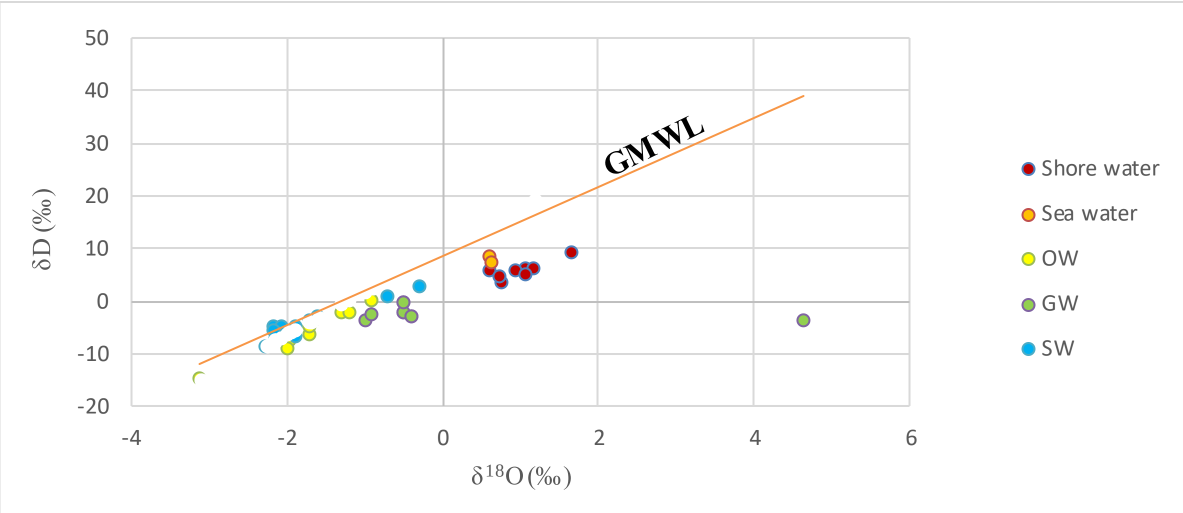


Figure 29: Distribution pattern of δD and $\delta^{18}O$ with reference to GMWL

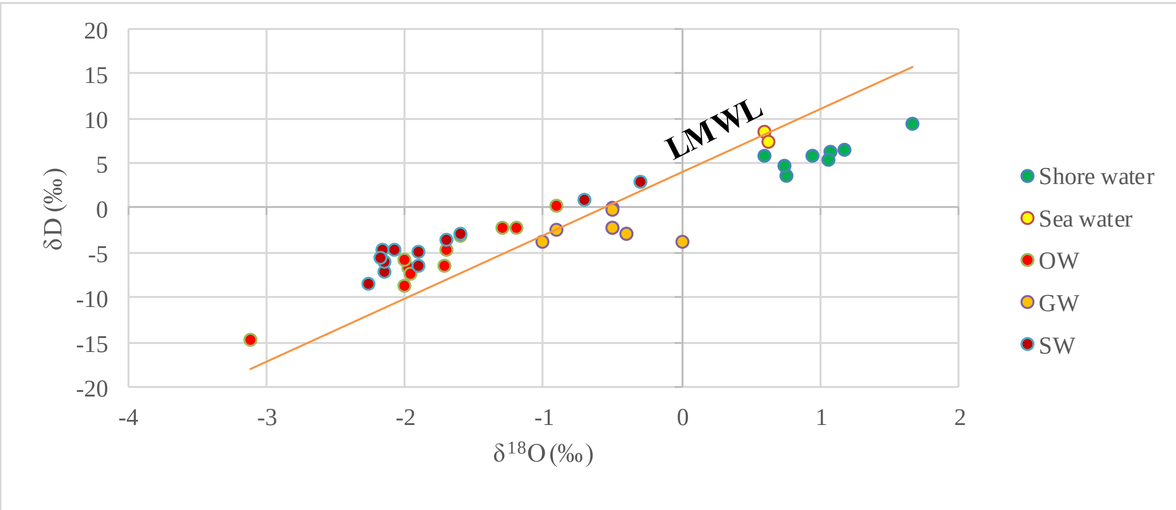


Figure 30: Distribution pattern of δD and $\delta^{18}O$ with reference to LMWL

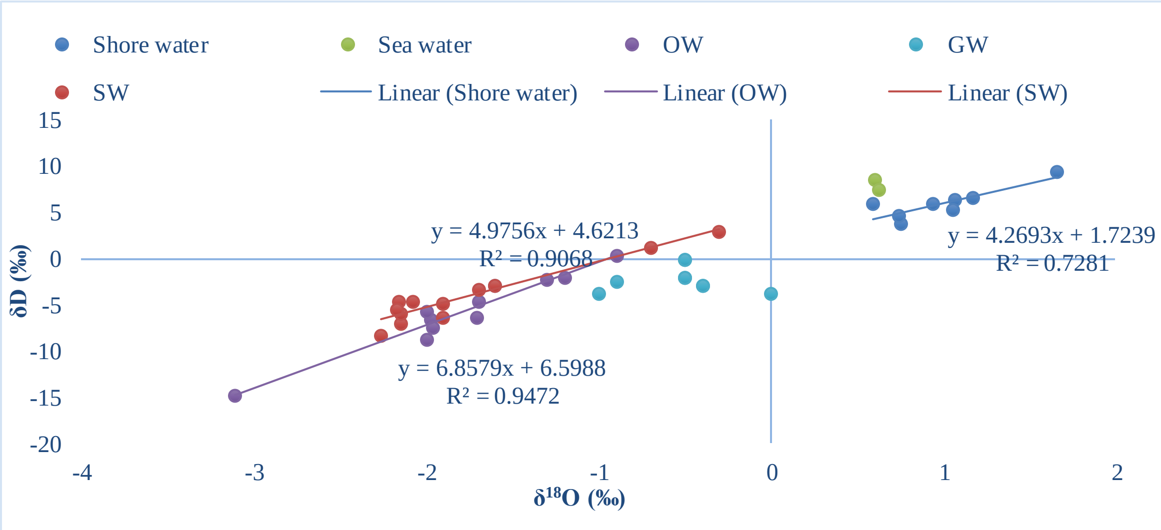


Figure 31: Isotope values of groundwater, seawater, shore water, well and surface water

A secondary parameter derived from evaporative enrichment of heavier isotopes in a water body is deuterium excess (d-excess). **Figure 32** depicts the mean d-excess in the water samples drawn from different sources of Uttara Kannada district coast. In all five categories of samples, the average d-excess value is <4. The low d-excess levels in groundwater samples could be due to a variety of factors. Results indicated that fresh water exhibited relatively higher and positive d-excess values, whereas seawater (close to zero) and shore water (negative) behaved differently from that of fresh water. Admixture of seawater in groundwater can lower d-excess. Low d-excess in shallow aquifers can be caused by seawater infiltration through back waters or salinity ingression caused by pumping of shallow aquifers in coastal zones. In cases of higher evaporation, d-excess will be less than 10 ‰. Accordingly, the present observation indicates the enrichment of denser isotopes due to evaporation.

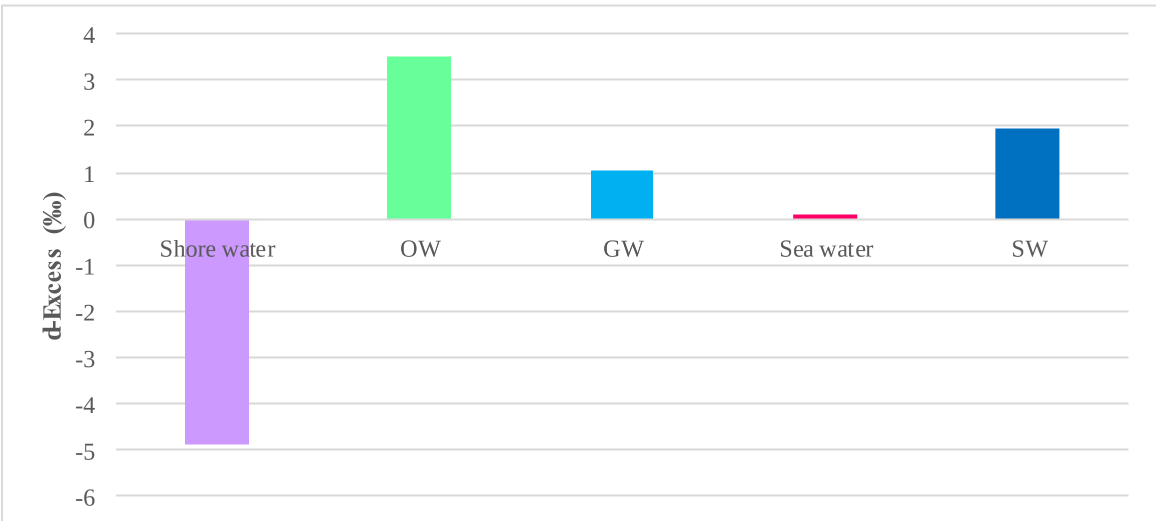


Figure 32: Mean d-excess values in the different water resources of the area

4.10 Seawater Mixing Index (SMI)

Park et al. (2005) proposed the seawater mixing index (SMI) principles to quantify the relative degree of brackish water mixing with freshwater (index greater than one, is considered as SMI. The determined SMI is classified into four groups as represented in **Table 7**.

Table 7: Classification of SMI in groups

Groups	Values	Description
Group I	0-0.5	Low saline groundwater
Group II	0.5-0.75	Moderate saline groundwater
Group III	0.75-1	High saline groundwater
Group IV	>1	Seawater mixing

It is observed that during the post-monsoon season of 2019, all wells had SMI values less than one, indicating that no seawater mixing occurred, whereas during the pre-monsoon season of 2019, only one wells, well no 4 had SMI greater than one and the remaining wells had SMI less than one. The SMI value for all seashore water sample (Post monsoon) is greater than one (**Figure 33**). From the estimated SMI, it is revealed that well number 4 may be impacted by seawater or that the aquifers are not adequately recharged (Diamantis and Petalas 1989).

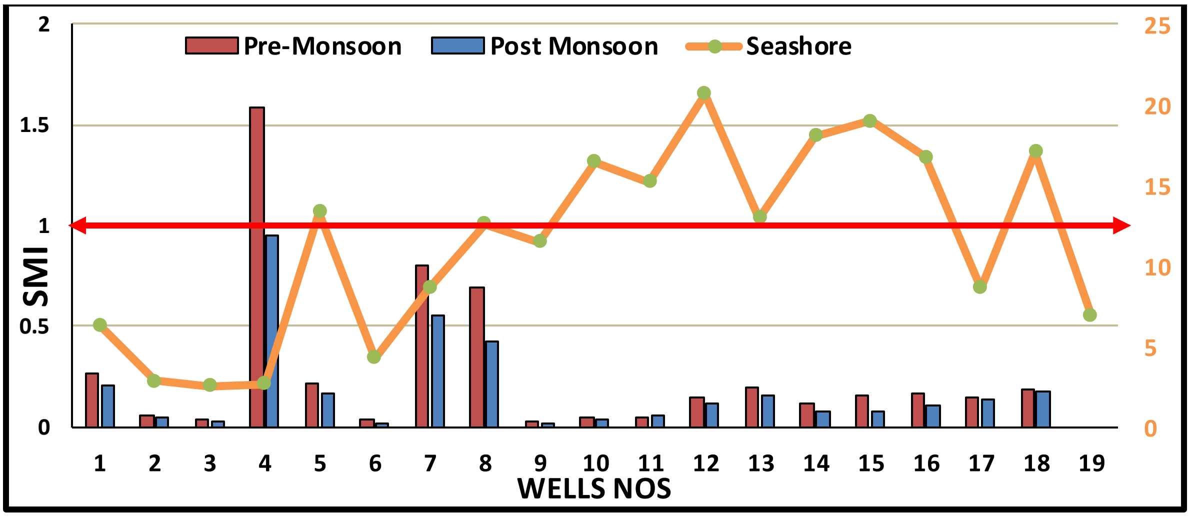


Figure 33: Seawater Mixing Index (pre and post-monsoon 2019)

4.11 Possible SGD zones

Submarine groundwater discharge (SGD) is a hydrological process, which commonly occurs in coastal areas. It is described as submarine inflow of fresh and brackish groundwater from land into the sea. Hydrogeological investigations have shown that the coastal aquifers of Uttara Kannada do not show any signature of seawater intrusion as observed during the study period. From the study, it is understood that the recharge to groundwater is very high (15-20% of annual rainfall) due to which, the possibility of seawater intrusion become rare. However, there are chances of temporary phenomena which occur mainly due to advancement of sea towards the land during heavy monsoon causing enormous losses due to coastal erosion and fishery resources.

River flow characteristics of some of the rivers have been analyzed based on the discharge data. Base-flow estimated indicate that, SGD occurs **(Figure 34)** during dry seasons mainly due to high rainfall (average rainfall more than 3000 mm) and high groundwater recharge. The estimated saturated hydraulic conductivity showed that the soils are highly permeable in lateritic areas, particularly below the top soil due to which the infiltrated water flows to sea continuously. From the present study, a rough estimate of about 0.15% to 0.18% of rainfall quantity enter the sea as submarine ground discharge from March to May. This is mainly based on monthly moisture trend which were observed at three sites and found a reasonably high moisture content in three locations namely, Murudeshwar, Kumta and north of Karwar taluks. Wetness percentage shown below (**Figure 35**). Groundwater quality investigations carried out in more than thirty wells all along the coast also demonstrated that, the coastal aquifers are safe for drinking, irrigation and domestic purposes.

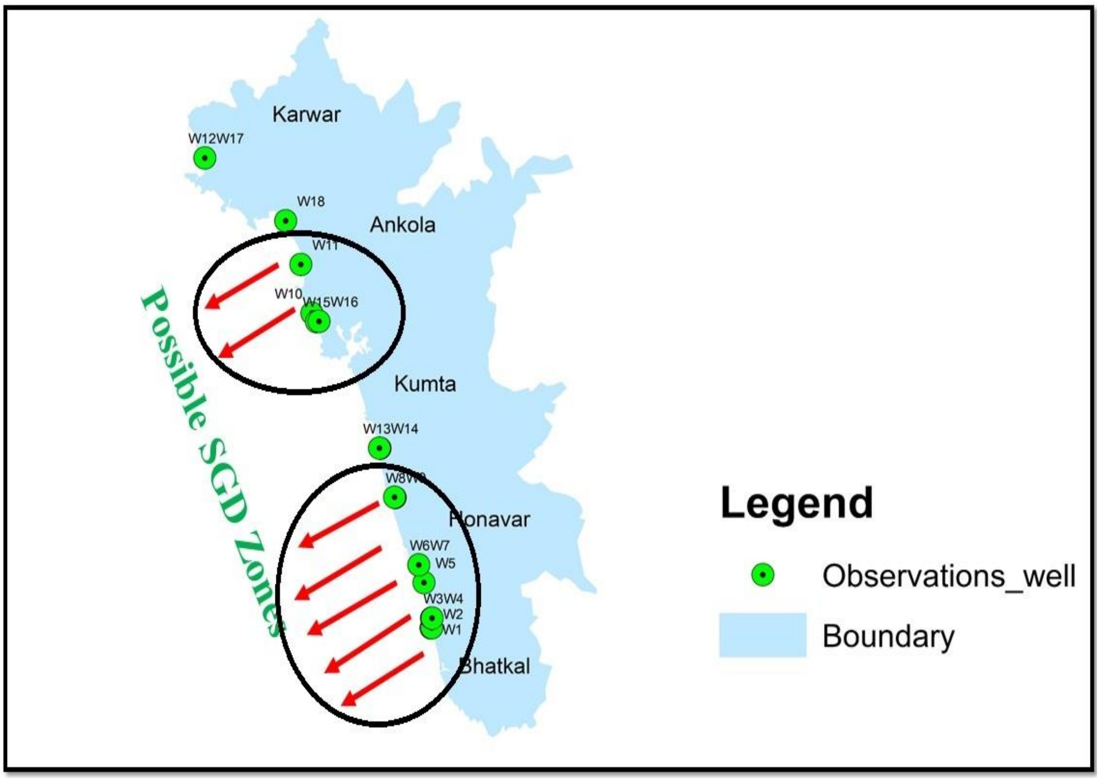


Figure 34: Possible SGD zones of Uttara Kannada district

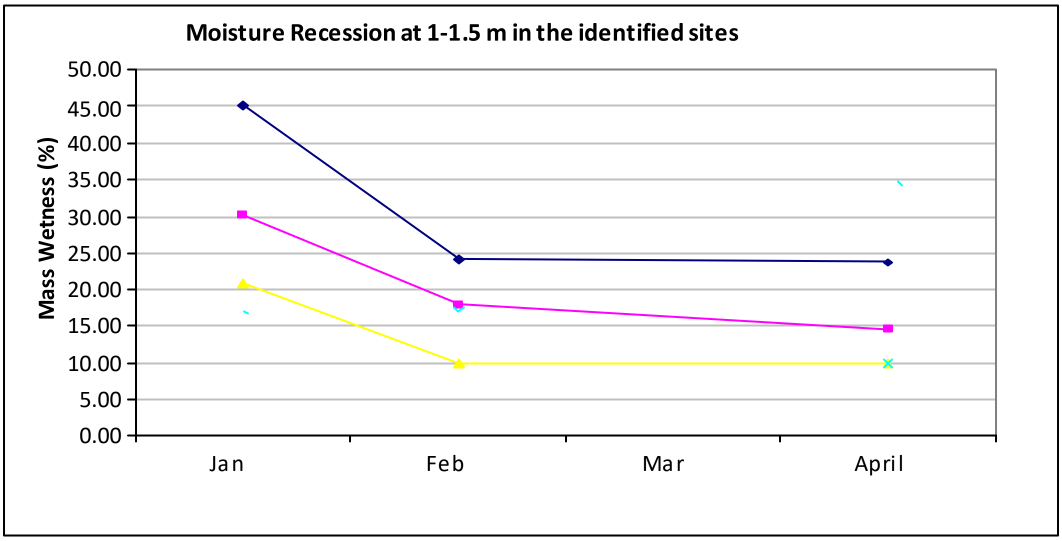


Figure 35: Depth wise moisture variation below the surface during non-monsoon season

4.11.1 Hydraulic properties of soil strata

An estimation of saturated hydraulic conductivity with depth is shown below (**Figure 36**). It is evident that there is an increase in hydraulic conductivity in the above sites which may influence the seaward flow of groundwater (**Figure 36**).

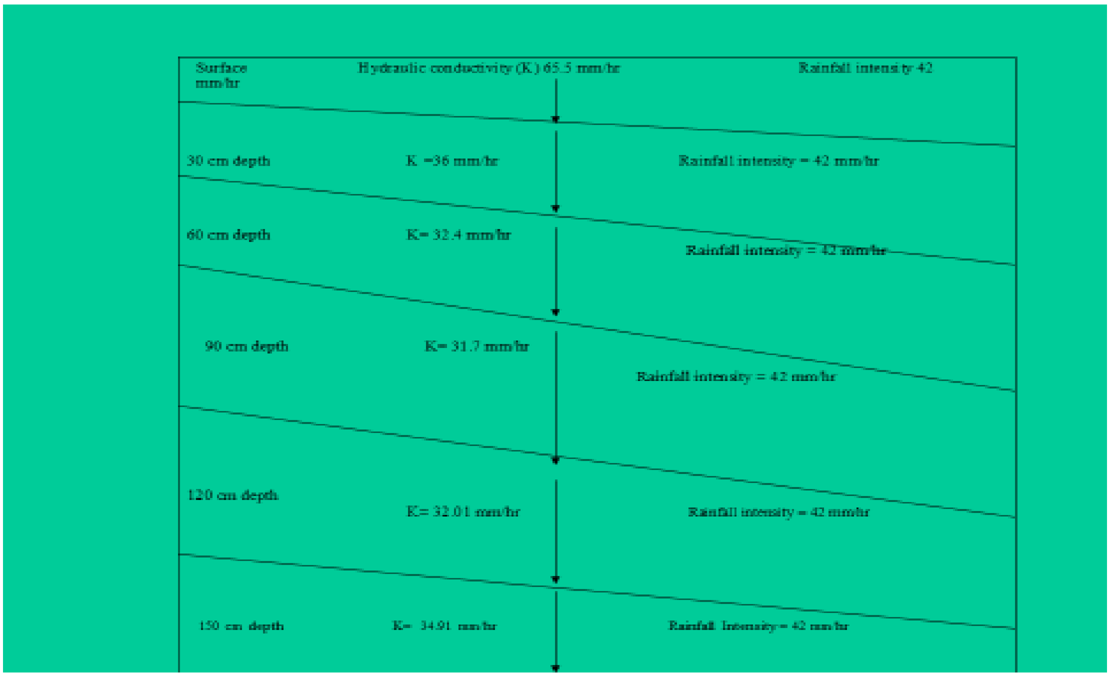


Figure 36: Saturated hydraulic conductivity at different depths

4.11.2 Ground water recharge

Water balance components were estimated by using calibrated SWAT model (SWAT 2007) (**Table 8**). Model was run for a representative watershed available in each taluka. It is observed that, the runoff estimated is higher for Kumta region whereas minimum was observed in

Ankola. Groundwater recharge (shallow) was also found to be maximum in Ankola and Karwar tauka in comparison to other three taluks (Bhatkal, Honnavara and Kumta). Variation in runoff and recharge could be presumed due to increased deforestation followed by urbanization and conversion of forest land to agriculture (however, to conclude specific investigation is required). In all watershed of each taluka showed high lateral flow which is attributed highly porous lateritic soils below moderately weathered laterites. Recharge values estimated by SWAT model was also compared with that obtained from using empirical methods. Chaturvedi (1973) and Rao (1970) formulae showed significant correlation between each other (**Table 9**).

Table 8: Water balance components estimated using SWAT Model

Water Balance Components	Bhatkal	Honnavar	Kumta	Ankola	Karwar
Surface Water	45.170	45.996	46.849	37.749	39.758
Groundwater	18.218	18.680	17.862	23.536	23.956
Lateral flow Q	4.503	3.917	3.471	4.128	4.513
Evapotranspiration (ET)	29.405	29.415	28.858	28.894	28.706

Table 9: Groundwater recharge characteristics of the catchment area

Year	Rainfall, mm	GWR, mm	% Recharge By SWAT	% Recharge (Chaturvedi)	% Recharge (Khosla)
2002	2361.1	457.34	19.37	18.17	18.07
2003	2688.30	491.42	18.28	15.76	19.53
2004	2607.7	455.82	17.48	17.24	19.74
2005	3223.30	597.92	18.55	19.22	22.01
2006	3410.7	657.58	19.28	15.94	21.86
2007	3657.50	495.59	13.55	23.22	15.90
2008	3271.5	654.95	20.02	19.86	22.46
2009	3694.0	606.92	16.43	14.83	20.75
2010	4668.8	905.28	19.39	19.57	18.28
2011	4236	832.37	19.65	17.57	22.65
2012	3886.88	673.98	17.34	16.90	19.27

4.11.3 Groundwater levels and water quality

Evaluation of groundwater levels and groundwater quality parameters showed some positive trends for the identification of SGD. However, the present observations are quite insufficient and need detailed investigations and observations based on piezometers and also by carrying out the study of aquifer parameters. With the use of such data, then we can proceed for Radon analysis and seepage meter studies.

5. CONCLUSIONS

As the ongoing study is not in a conclusive stage an attempt has been made to derive preliminary conclusions based on the following:

5.1 Conclusions

- The soil profile up to 5m depth with a very low resistivity in range of 0.2 to more than 4000 Ωm has been observed which indicate the presence of the top soil and sand within the clay formation. The high resistivity values could be attributed to the extension of lateritic plateau in the deeper layer.
- Isotope results indicated that fresh water exhibited relatively higher and positive d-excess values, whereas seawater (close to zero) and shore water (negative) behaved differently from that of fresh water close to zero. Admixture of seawater in groundwater can lower d-excess. Low d-excess in shallow aquifers can be caused by seawater infiltration through back waters or salinity ingression caused by pumping of shallow aquifers in coastal zones. In cases of higher evaporation, d-excess will be less than 10 ‰. Accordingly, the present observation indicates the enrichment of denser isotopes due to evaporation.
- Seawater mixing index (SMI) is an indication of seawater intrusion, Accordingly, 95% of the water samples collected from the open wells are showing values <1 indicating no seawater intrusion, similarly the samples collected from the seashore are indicating seawater intrusion (>1).
- The groundwater quality of shallow aquifer beyond 350m of the coast is found to be suitable for both domestic and irrigation purposes.
- Permeability index value shows, 88.88 % of the samples falls under the class 1(PI >75) and 11.11 % of the samples fall under class 3 (PI< 25 %) during the pre-monsoon period. Furthermore, during post monsoon 2016 the PI values were accordingly, 33.33 % of the samples falls under class 3(PI >75) and 66.66 % belong to class 2 (PI ranged between 25 and 75 %), the results samples shows that MH ratio is less than 50% (suitable for irrigation), All values of Kelly Ratios are less than one, Residual sodium carbonate values are less than 1.25 epm indicating the water is safe and Percentage of sodium values varies from 1.12 to 30.57 shows good to excellent during pre and post-monsoon indicating water suitable for irrigation.

- From pore water analysis there is an active interaction between seawater and freshwater, Therefore, seawater is likely to encroach the boundary of the beach with land area.
- The average annual rainfall of Uttara Kannada district is 3427.80 mm obtained from period 2002-2012 out of which max. is 4668.80 and min. is 2361 mm. Mean is 3427.79. Standard deviation is 703.66.
- The groundwater recharge estimated showed that the recharge is maximum in 2008 is about 20.02% and minimum in 2007 is 13.55% by SWAT model. By Chaturvedi formulae, the maximum recharge were observed in 2007 is 23.22% and minimum recharge in 2009 is 14.83%. By Khosla formulae, the maximum recharge were observed in 2011 it is 22.65% and minimum recharge in 2007 is 15.90%. According to the SWAT analysis, the surface runoff is found 1754.25 mm, Lateral flow is 136.78 mm, Recharge to deep aquifer is 55.53 mm, Precipitation and evapotranspiration is 3492.3 mm and 490.8 mm, respectively.
- It is observed that during the post-monsoon 2007, the general depth of water level is ranges between 0.42 to 8.98 m-bgl, which is very low.
- Hydrogeological investigations have shown that the coastal aquifers of Uttara Kannada do not show any signature of seawater intrusion as observed during the study period. From the study, it is understood that the recharge to groundwater is very high (15-20% of annual rainfall) due to which, the possibility of seawater intrusion become rare. However, there are chances of temporary phenomena which occur mainly due to advancement of sea towards the land during heavy monsoon causing enormous losses due to coastal erosion and fishery resources.
- River flow characteristics of some of the rivers have been analysed based on the discharge data. Base-flow estimated indicate that, submarine groundwater discharge occurs during dry seasons mainly due to high rainfall and high groundwater recharge. The estimated saturated hydraulic conductivity showed that the soils are highly permeable in lateritic areas, particularly below the top soil due to which the infiltrated water flows to sea continuously. From the present study, a rough estimate of about 0.15% to 0.18% of rainfall quantity enter the sea as submarine ground discharge from March to May. This is mainly based on monthly moisture trend which were observed at three sites and found a reasonably high moisture content in three locations namely, Murudeshwar, Kumta and north of Karwar taluks. Groundwater quality investigations

carried out in more than thirty wells all along the coast also demonstrated that, the coastal aquifers are safe for drinking, irrigation and domestic purposes.

5.2 Recommendations

1. It is recommended that the proper provision of rainwater harvesting and groundwater recharge schemes can be implemented in the possible SGD zones and its catchment areas where the sustainable fresh groundwater can be obtained in the coastal regions.
2. Groundwater recharging by artificial method should be taken up priority basis first in district where rainfall is less.
3. It is also recommended that Radon analysis, seepage meter, Nutrient fingerprint and Additional field visits can be made in the identified SGD zones and detail investigation can be taken for further development of groundwater resources in the coastal areas of Uttara Kannada.
4. Groundwater levels and water quality evaluation of groundwater levels and groundwater quality parameters showed some positive trends for the identification of submarine groundwater discharge. However, the present observations are quite in sufficient and need detailed investigations and observations based on piezometers and also by carrying out the study of aquifer parameters.

5.3 Limitations

Field data collection was not able to carried out exactly at 1 km due to local conveyance and adverse field conditions. Due to COVID-19 pandemic, additional field visits have not been carried out in the study area. In addition, there are restrictions in the coastal areas of Uttara Kannada where the area is dominated by mangrove areas (Forest) and coastal ports (harbors). These limitations may result slight differences in the actual estimates of the possible SGD zones where analysis is solely based on archival groundwater data analysis (In case of coastal regions of Uttara Kannada districts). This has to be taken into consideration.

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