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RESEARCH ARTICLE

Seasonal variation of water table and groundwater quality of the karst aquifer of the Jaffna Peninsula-Sri Lanka

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Abstract: The Miocene limestone bedrock of the Jaffna Peninsula of Sri Lanka extends below the sea level and is an excellent aquifer. The North-East Monsoonal rainfall infiltrates into the soil and forms a layer of freshwater in the limestone above the seawater. This freshwater is in the form of a convex lens, which thins out towards the coast and the lower part of the lens is a transitional zone where the freshwater becomes increasingly brackish with depth. The thickness of the lens diminishes continuously due to the outflow of freshwater into the lagoon/sea along the coastline. Even with this outflow, the freshwater in the lens is able to sustain irrigation and domestic usage till the end of the dry season. The groundwater has an abundance of calcium and bicarbonate ions, the varying concentrations of which affects the pH, causing it to vary from neutral to slightly alkaline. The concentrations of chloride ions increase with the depth of the transition zone as well as towards the coast. The nitrate contents of the well water are higher in the urban areas due to contamination from septic tanks and also in intensively cultivated farm areas where high amounts of nitrogen fertilizers are used. In some wells, both the chloride and nitrate concentrations do exceed the WHO standards for safe drinking water. Thus, the quality of well water is site specific depending on the depth of wells in relation to the transition zone and the surrounding environment.

Keywords: Groundwater, limestone aquifer, water quality, water table.

INTRODUCTION

The Jaffna Peninsula, which forms the northernmost part of Sri Lanka, has an area of about 1100 km^2 and is about 70 km long and 10 to 36 km wide (Figure 1). The Peninsula could not have been the permanent habitat of an ancient population but for the existence of good quality groundwater, which is available throughout the year for both intensive agriculture and domestic use. Considering the extensive presence of shallow and rocky soils in the peninsula, it is only the relatively easy availability of good groundwater from the underlying sedimentary limestone aquifer that makes agriculture a profitable enterprise. Farmers have used innovative and context-appropriate methods to reclaim rocky and shallow lands and adopted irrigation practices that make intensive agriculture a reliable source of livelihood income.

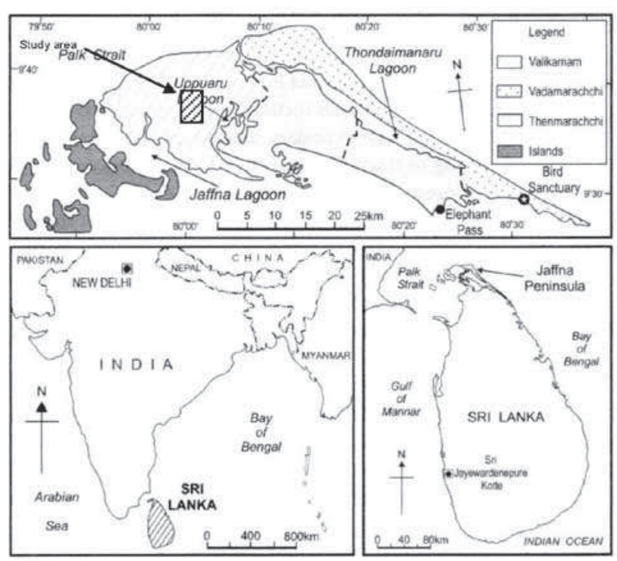

Figure 1: Map showing the study area in relation to Jaffna Peninsula, Sri Lanka, India and the regions around

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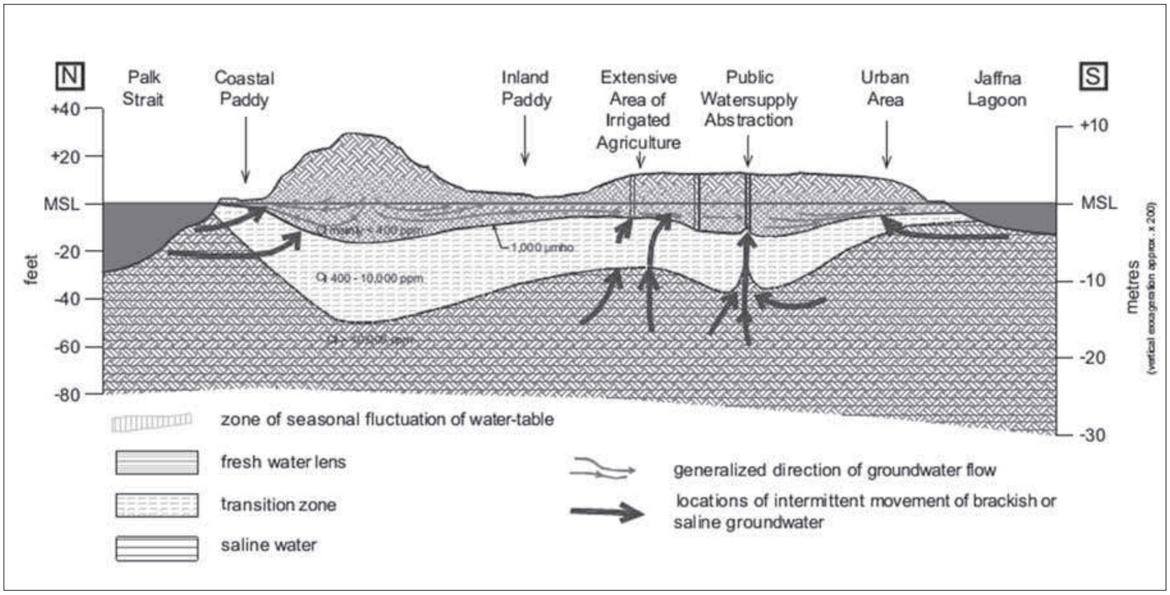

Figure 2: Schematic diagram of the landform and groundwater of a section of Jaffna Peninsula (Source: Jaffna Rehabilitation Project, by GTZ, Sri Lanka)

The limestone bedrock, which extends below sea level functions as an excellent aquifer. It is charged annually by the North-East Monsoonal rains that average 950 mm between October and January. The rainwater percolates downwards through the soil and moves into the pores and cavities of the limestone. The percolated fresh rainwater floats on top of the heavier sea water that is already present in the aquifer at sea level. According to the Ghyben-Herzberg Principle (Carlson, 1963), the weight of the freshwater pushes down the heavier sea water so that the overlying freshwater is in the shape of a convex lens (Figures 2 & 5) within the aquifer and the freshwater - seawater interface extends below mean sea level (MSL). The lower part of the lens above the interface is actually a transitional zone, where the salinity level of the groundwater increases gradually with depth from freshwater to that of the sea water at the interface (Balendran, 1969). The freshwater-table is above the mean sea level (MSL).

Studies have been carried out since 1938 on the occurrence, quantity and quality of the groundwater of the Jaffna Peninsula. The quality of investigations and the inferences were according to the facilities and information available at that time. From these studies, it was generally recognized that the karst limestone and the deep sand aquifers recharged annually by rainfall were the source of the freshwater in the peninsula. Although the porosity of the Miocene limestone was low, the macro-pores, channels and large cavities that had developed through dissolving of the limestone were able to store an adequate quantity of freshwater to support the population. In 1965, systematic hydrological investigations were initiated to study the quantity, quality and the overall groundwater balance of the whole peninsula. Over four hundred representative observation wells were selected to obtain data on water levels, and water samples were collected for chemical analysis. The concentrations of chloride, calcium carbonate and total dissolved solids were determined from the water samples. Using data from four consecutive years, a preliminary report was published (Arumugam,1970) giving estimates of average freshwater storage above MSL due to recharge from monsoon rains, draw off and depletion during the dry season and the salinity status of groundwater in different regions of the Jaffna Peninsula. Although the investigations continued for a few more years, the raw data, especially the coordinates and elevations of the well sites related to this study are presently not available. Without such information further interpretation of the available data or more studies on the same sites cannot be undertaken unless a costly re-survey is conducted. However, all previous studies and the main properties of the aquifer of the peninsula are well documented (Panabokke, 2007).

The measurements of nitrate N in some selected well water samples (Rajeswary & Mahalingam, 1983) indicate that wells located in lands without agricultural activity have lower nitrate-N contents than those in agricultural lands. Most of the latter wells have nitrate-N higher than the WHO safe upper limit of 10 ppm for drinking water. The authors concluded that the higher levels of nitrate-N in these wells were from the leaching of fertilizers into the groundwater by excess irrigation and rainfall.

Nagarajah *et al*. (1988) did a systematic study of the quality of well waters in the peninsula. The electrical conductivity (EC), pH, sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), phosphorous (P), and nitrate (NO^{-}_{3}) were measured in water samples collected monthly for one year. Only the averages of the twelve samples from each well were reported. The salinity estimated from electrical conductivity was found to be high in more than 90 % of the wells sampled and was above the United States Department of Agriculture (USDA) suitability standard for irrigation waters. However, despite the high salinity levels, irrigated plants did not show any adverse effects of salinity. Sodium, calcium and magnesium were in amounts such that the sodium adsorption ratios were well below the critical limit for adverse effects of alkalinity. Potassium and phosphorous were also in very low concentrations in these well waters. On one hand, 79 % of the farm wells sampled showed nitrate-N above the WHO permissible level for drinking water of 10 ppm. Domestic wells on the other hand had low nitrate-N levels. Here again the high levels of nitrate in well waters were attributed to the leached nitrogen fertilizers used in the intensive agriculture practised in the peninsula.

Nanthini *et al*. (2001) studied the physico-chemical characteristics of groundwater in some selected water supply wells in the Jaffna Peninsula. The study was mainly directed towards assessing the water for human consumption with respect to colour, turbidity, chloride, iron, sulphites, pH and electrical conductivity. Jayaruba and Thushyanthi (2009) studied the quality of water in 68 farm wells in relation to their respective land use around the wells. The well waters were sampled monthly and analysed for pH, electrical conductivity, chloride and nitrate-N. Only the average values for each well were reported and evaluated for drinking and irrigation purposes. The pH, conductivity and the chloride contents were well within the suitability limits for drinking and irrigation use, and statistically there was no correlation between these parameters and the different land uses. However, there was significant correlation between nitrate-N and mixed cropping, whereas no significant correlation was found with banana or paddy cropping. Based on these findings, the authors inferred that the high levels of fertilizer used in mixed cropping caused the high nitrate in well water as leachate from the soil. Although this inference is probable, there is no direct evidence given in any of the studies so far to show that the nitrates in well water originate from the fertilisers used in the farms.

The objective of this investigation was to study the seasonal variations in the quantity and quality of the groundwater obtained from wells in two topo-sequences from the highest elevation towards the Upparu and the Jaffna lagoons in the peninsula.

METHODS AND MATERIALS

A set of 20 wells in each of the two topo-sequences were selected for the study. One set was from Kopay towards the Jaffna lagoon and the other was from Kopay along the Kaithady road towards the Upparu lagoon. The wells were identified by GPS for their latitude and longitude and were numbered from 1 to 40 (Figure 3). The elevations of the wells above mean sea level (MSL) were determined from a two-foot contour map of the area by interpolation. However, there may be small errors in the elevation values arising from this method of estimation.

Well water sampling

The well waters were sampled fortnightly for 12 months from April 2005 on the 1^{st} and the 15^{th} day of each month up to December and on January 10^{th}, February 10^{th} and March 5^{th}, 2006. Sampling was done after making sure that the time lapse after any irrigation from the well was sufficient for the water level to recover to the natural water table level. The water samples were taken at the mid point between the surface of the water and bottom of the well with a special sampler. The water was then transferred to glass containers after rinsing them with the same sampled water. Before each sampling, the depth of water in the well was measured from a reference point at a known height from the land surface. Daily rainfall data was obtained from the Department of Agriculture meteorological station located within the area of this study and the fortnightly totals are shown in Figure 4.

Water analyses

The following analyses were carried out on the water samples within 24 h from the time of sampling: pH and electrical conductivity (EC) were determined by glass electrode and conductivity bridge, respectively. Chloride was determined by Mohr's method and nitrate was measured colorimetrically by Brucine method (Ranney & Bartlett, 1972).

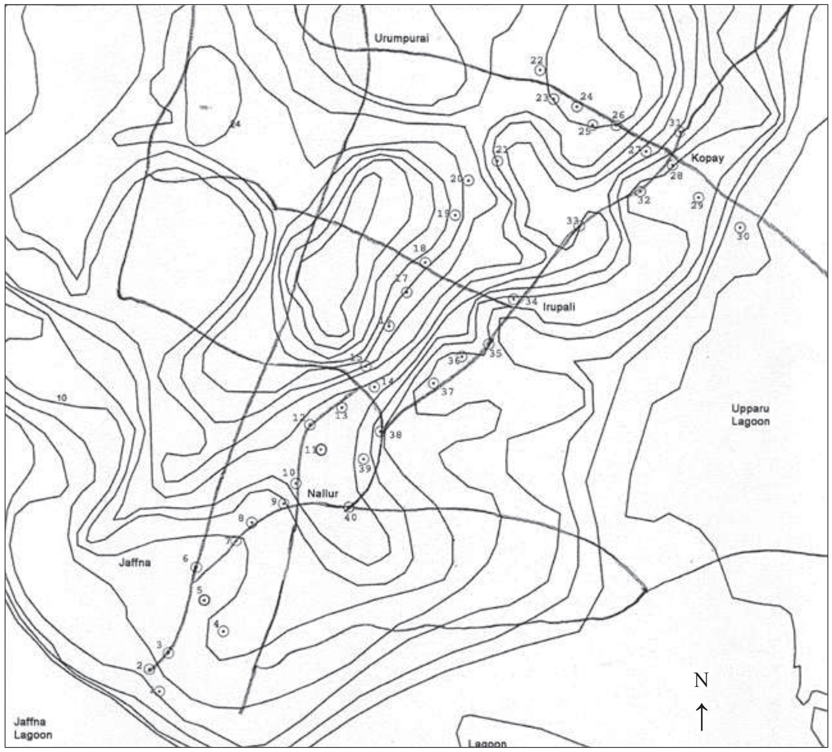

Figure 3: Study area – showing contours (feet) and well locations with identification numbers

RESULTS AND DISCUSSION

Interpretation of the data is done by using the results from all forty wells but the detailed results are presented only for well numbers 1, 3, 16, 19, 22 and 29. These wells are selected as representative wells for the whole area from the coast to the highest point in the topography (Figure 3).

Hydrodynamics of the aquifer

The hydraulic pressure differences and water movement determine the behaviour of the water table and the quality of the freshwater in the aquifer. Except within the transition zone, the overlying freshwater remains salinity free due to a continuous outflow of fresh groundwater into the lagoon/sea along the coast line (Figure 2). The outflow is caused by the existing outward hydraulic gradient within the freshwater lens. As a result, numerous freshwater springs are observed along the coastline around the Jaffna peninsula. This dynamic equilibrium is essential to keep the freshwater and sea water separate, without mixing completely within the aquifer. As a consequence of this outflow, the thickness of the freshwater lens gradually decreases during the period when recharge of the aquifer is absent. This decrease is further exacerbated through freshwater extraction from wells for domestic and agricultural use. Thus, the freshwater-table goes down and the freshwater-sea water interface rises during the dry season. If there is excessive extraction of freshwater in any well, there will be a rise of salt water in the shape of a cone below the well to balance the hydraulic pressure between the freshwater and the salt water (Figure 5). If the cone enters the well, the water in the well will become brackish. On the other hand, irrespective of the depth of the well, if the well intercepts one or more solution channels from the freshwater layer, the well water will be less brackish or even fresh. Therefore, at any point of time, the quality of the well water (whether fresh or brackish) in the peninsula, can be explained by whether the bottom of the well is in the freshwater layer, the transition zone or in the salt water layer (Figure 5).

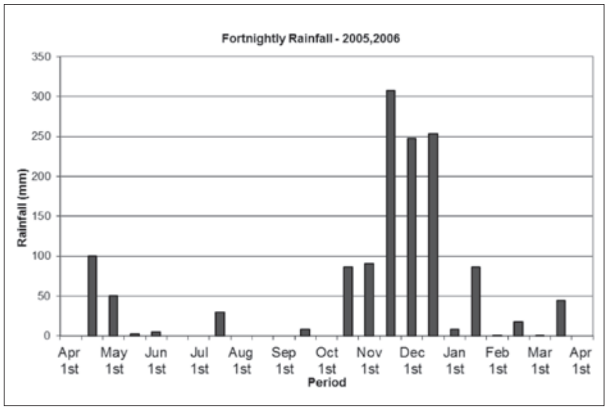

Figure 4: Fortnightly rainfall amounts in the study area from April 1st 2005 to April 1st 2006

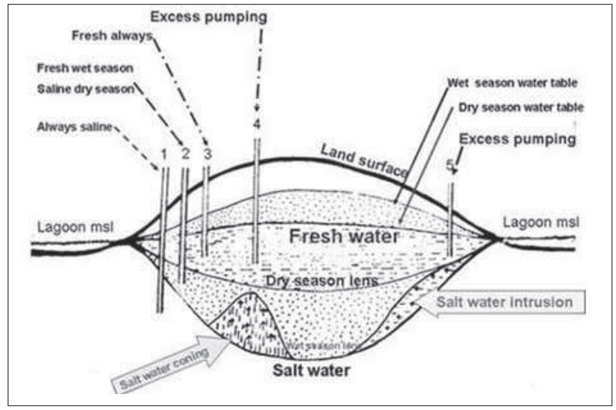

Figure 5: Schematic diagram showing positions of bottom of wells in relation to the changing thickness of the fresh water lens and the resulting quality of well water

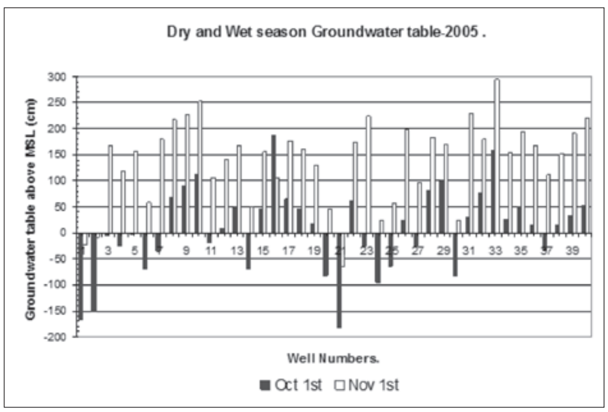

Figure 6: (a) Groundwater table in all the wells in October (dry season) and November (wet season) in 2005

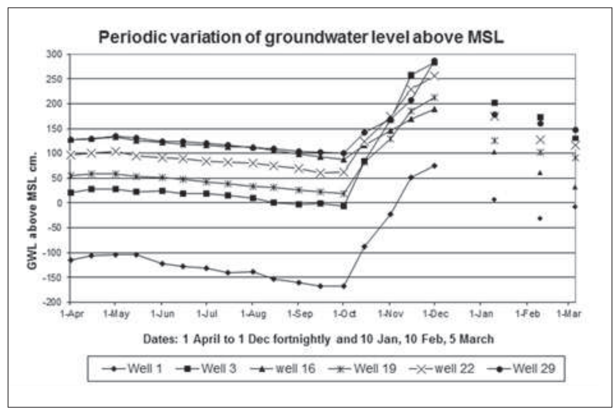

Figure 6: (b) Fortnightly variation of groundwater table in the selected wells from April 2005 to March 2006

Water table and groundwater storage

Since there was a possibility of small errors in the estimation of the elevation of ground level, no attempt was made to evaluate the hydraulic gradient and the direction of water flow within the aquifer. However, data on the relative variation of water table within each well can be used to evaluate the changes in storage of the aquifer and help to explain the changes in quality of the groundwater.

Figure 6a shows the level of the groundwater table above mean sea level (MSL) of all the wells on two dates in the dry and wet seasons. Some wells show a recorded water table below MSL, which is theoretically not possible. This discrepancy can possibly be attributed to errors in estimation of the elevation of the land surface, and in a few cases to a delay in the water table recovering to its equilibrium state.

Figure 6b shows the periodic variations of the water table in the selected wells on the sampling dates shown. Water table measurements were not taken on the 15th of December, even though there was a rainfall of 250 mm between the 1st and the 15th of December. Therefore the data points after the December 1st are shown simply as points without the line joining them because there would have been an increase in the water table on the 15th. Water table variations are best explained in relation to the rainfall distribution as shown in Figure 4. The changes in water table in all the wells follow the same trend. A very slight rise in the water table is observed in response to the usual short rain spell in April-May followed by a steady gradual decrease during the dry season up to October. The lowering of the water table is caused by the continuous outflow to the sea under the existing hydraulic gradient and to the extraction of groundwater for irrigation and domestic use.

With the onset of the monsoon rains during the first fortnight in October, the water table rises sharply and continues to rise till the 15th December. With the end of the heavy rains in mid December, the water table drops rapidly during the following first three to four months (Figure 6b) by about 60 - 70 % of the maximum storage. Earlier studies also have reported a rapid drop of the same magnitude in the water table soon after the end of the monsoon rainy season (Wijesinghe, 1973). During the initial stages of the rains, the high infiltration rate of the dry soil causes most of the rain to percolate into the ground with little or no runoff resulting in the sharp rise of the water table. As the water table rises, the hydraulic gradient towards the coast within the freshwater lens also rises causing an increase in the rate of outflow into the sea. At the end of the rainy season, the prevailing high hydraulic gradient causes a rapid decrease of the water table. Eventually by April, the water table drops to a level when the outflow becomes slow and gradual.

As also seen from earlier studies (Arumugam, 1970; Wijesinghe, 1973), it appears that, irrespective of the maximum aquifer recharge attained in December of any year, the storage at April-May in the following year is always of similar amounts and can be considered as the effective storage for domestic and irrigation purposes during the dry months. Any effort to increase the storage by adopting measures to enhance rainfall infiltration during the North-East Monsoon period, would probably be of no use as it would only increase the initial losses through seepage to the sea due to the additional increase in the hydraulic gradient. Only surface storage of rainwater in tanks (reservoirs) and ponds, which could retain water during at least part of the dry season could be useful in recharging the groundwater through slow infiltration. The best option under the prevailing situation would be to minimise waste and adopt good groundwater management by avoiding over-irrigation and practicing irrigation methods with high water use efficiencies.

Quality of groundwater

pH

Figure 7a shows that the pH of the 40 well water samples varied from 6.80 to 8.54 for the dates on which the highest and the lowest values were recorded. However, most of the well-waters had a pH varying between 7.0 and 8.0. Figure 7b shows the fortnightly variation of pH for the selected wells. The variation of the pH of the water in each well was less than half a unit and random; there was no discernible trend that could be observed with time or location except that with the onset of the monsoon rains, the pH tended to drop slightly by about half a unit. The variation of the pH of well-waters was due to the dynamic equilibrium between the concentrations of the constituent ions in solution; namely calcium (Ca^{2+}), bicarbonate (HCO_3^-), hydrogen (H^+) and hydroxyl (OH^-) ions. This equilibrium is influenced by the amount of dissolved CO_2 and its partial pressure in the system. Increase in the partial pressure of CO_2 results in a decrease in pH of the solution. Based on the equilibrium constants of the reversible reactions between the above ions, the pH of a solution in contact with calcium carbonate and open to the atmosphere can be expected to have a pH of about 8.3. But the waters within the underground aquifer are exposed to higher than atmospheric levels of carbon dioxide due to dissolution of limestone. This

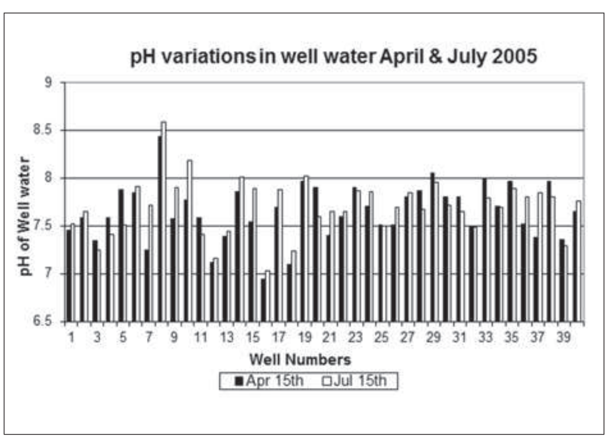

Figure 7: (a) pH of well waters for all the wells on April 15th and July 15th 2005

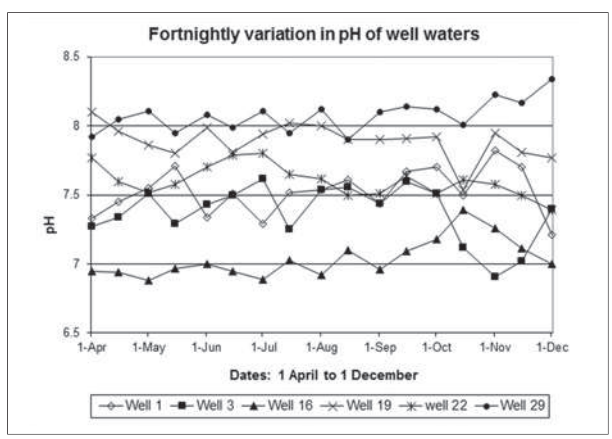

Figure 7: (b) Fortnightly variation of pH of the well waters for the selected wells

results in groundwater pH values of much less than 8.3. Therefore, the observed variation of pH between 6.80 and 8.50 can possibly be attributed to change of pH that occur between the inflow of groundwater into the well and the period of exposure of the well-water to the open atmospheric conditions when sampled. The fact that the well-water with the highest pH of 8.54 was recorded in the well that was not in use at all and most of the other wells with water of lower pH are emptied and replenished frequently during irrigation of home gardens and farms is in accordance with this reasoning.

Electrical conductivity (EC) and total dissolved solids (TDS)

The electrical conductivity of the groundwater is a measure of the electric current carrying capacity of the constituent ions, which are present as solutes. The ions commonly found are Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-} and NO_3^{-}. Based on the conductivity factors of these ions and their usual concentrations in groundwater, the total dissolved solids in mg/L can be approximately estimated by multiplying the EC in microS/cm by a conductivity factor of 0.76. This factor in microS/cm per mg/L differs from the often quoted factor of 0.68 because the actual average measured value of the concentration of sodium chloride of the well waters was used in deriving the factor instead of the usually assumed concentration. The TDS therefore is directly proportional to EC and does not identify individual ionic species nor does it include non-ionisable solutes. The error in TDS thus estimated is considered to be less than 10 % (Lenntech, 1998).

The TDS values of all the well waters (Figure 8a) are below 1500 ppm except for 5 wells, namely numbers 2, 3, 29, 30, and 33, which have higher values, being located near the coast where the fresh water lens is thin. Waters in well numbers 2, 3 and 29 have TDS between 1500 ppm and 4000 ppm. These wells probably intercept the transition zone with brackish water. Waters of well numbers 30 and 33 have TDS of over 40,000 ppm (not shown) indicating that the bottoms of these wells are in or near the sea water layer below. The TDS of waters of the coastal wells are dominated by the high content of sodium chloride in sea water.

Figure 8b shows the general pattern of the variations of TDS from the April 1st to the December 1st of the selected wells. After a slight drop in TDS during the short rain spell in April-May, there was a small gradual increase of less than 200 ppm during the dry months from May to October 1st . With the onset of rains, there is again a slight drop in TDS for the first fortnight in October followed by a small but significant increase thereafter till the end of the rains. The drops in the TDS are probably due to a dilution effect with the attendant rise in water table from the direct infiltration of initial rainfall. The small steady increase in TDS during the dry season could be attributed to the rise in the position of the transition layer and to some solutes coming in with interstitial flow within the aquifer. During the rainy season there is more dissolution of limestone due to increased internal flow caused by higher outward hydraulic gradient and the acidic nature of the rain. This in turn results in the observed increase in TDS.

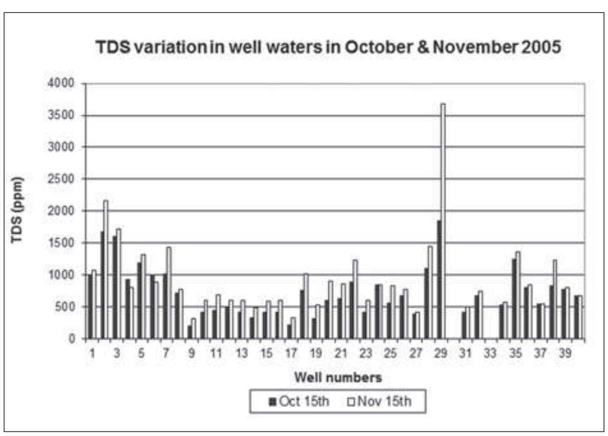

Figure 8: (a) Total Dissolved Solids (TDS) concentrations of well waters for all the wells on October 15th and November 15th 2005

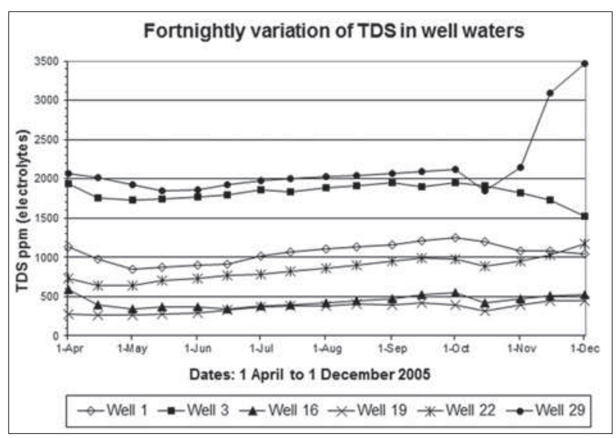

Figure 8: (b) Fortnightly variation of TDS concentrations of well waters for the selected wells

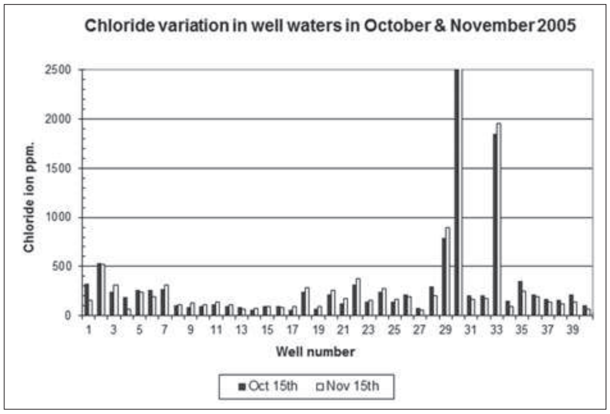

Figure 9: (a) Chloride concentrations of well waters for all the wells on October 15th and November 15th 2005

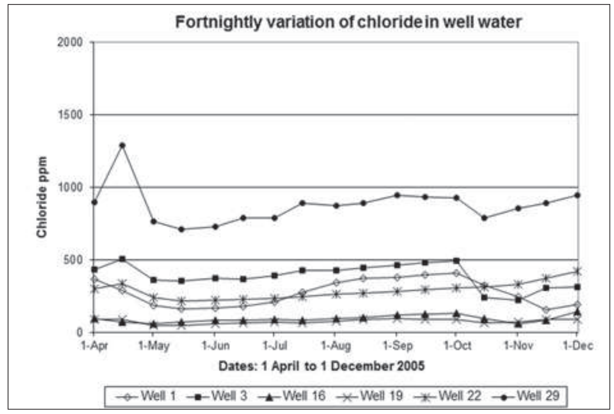

Figure 9: (b) Fortnightly variation of Chloride concentrations of well waters for the selected wells

Chloride ion (Cl^-)

Chloride is an important constituent in the groundwater as it determines the quality of the water for human consumption as well as for irrigation. The main source of chloride in the groundwater is the underlying sea water and to a lesser extent the leachate from fertilizer. The chloride from the transition zone in the freshwater lens accounts for most of the chloride ions by far. Moreover, excessive pumping in wells also can cause localised increases in chloride content due to coning up of the underlying sea water. Thus, the chloride content of the wells is site specific and depends on factors such as (a) rate and amount of water usage; (b) height of water table above MSL; (c) thickness of freshwater lens above the freshwater- seawater interface; and (d) depth of the bottom of the well in relation to the transition zone in the freshwater lens (Figure 5). The deeper the bottom of the well extends into the transition zone, higher will be the chloride concentration. Since chloride ions also contribute to the values of EC and TDS, variations in EC and TDS due to other ions are often masked by the variations in chloride ions if the well waters have high concentrations of chlorides.

Except for the five coastal wells (Figure 9a), chloride contents of the water of all the other interior wells were below 500 ppm, qualifying them as suitable for human consumption. Even in these interior wells, except for the wells that were used for home-garden and farm irrigation, the rest of the wells had chloride ions below 300 ppm. As seen from Figure 9b, seasonal variation of chloride during the dry season was very similar to TDS and for the same reasons. However, with the onset of rains in October, although the initial decrease in chloride was similar to TDS, the subsequent increase of chloride is less than that of TDS suggesting that some "other ions" are contributing to the increase in TDS. Therefore it may be erroneous to suggest that the increase in EC is due to chloride alone.

TDS other than NaCl

Figure 10 shows the variation in TDS other than the Na^+ and Cl^- ions. This was estimated by subtracting the concentration of NaCl from the total TDS assuming that the origin of the chloride ions was from NaCl. It is very clear from Figure 10 that there is a definite increase in TDS other than NaCl with the onset of rains. With the rise in water table and increased flow within the aquifer, the Ca^{2+} and HCO_3^- produced through the dissolution of limestone by the acidic nature of the rainfall in all probabilities results in the increase in TDS.

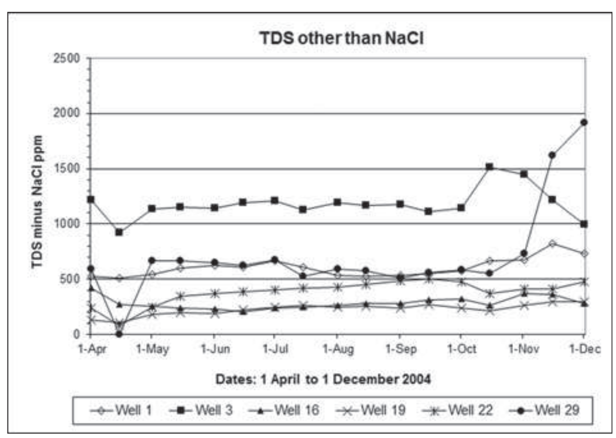

Figure 10: Concentration of total dissolved solids other than sodium chloride – measured concentration of sodium chloride subtracted from TDS as estimated from electrical conductivity for the selected wells

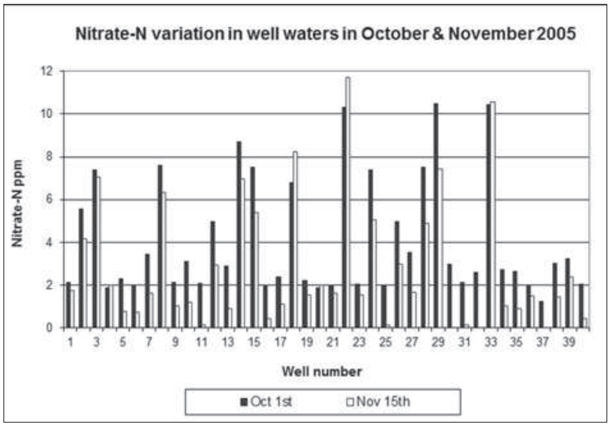

Figure 11: (a) Nitrate-N concentrations of well waters for all the wells on October 1st and November 15th 2005

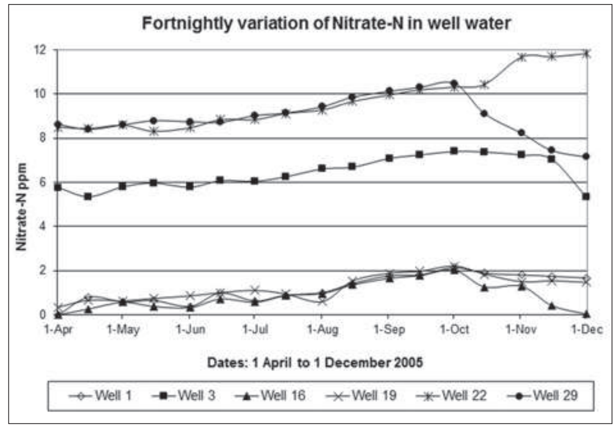

Figure 11: (b) Fortnightly variations of Nitrate-N concentrations of well waters for the selected wells

Nitrate-N

The sources of nitrate contamination of well-waters in the peninsula are mainly leachate of fertilizer through groundwater, surface runoff into unprotected wells and septic tanks and cess pits. Most of the publications cited earlier presume leachate of fertilizer nitrate as the main source without any direct evidence. Of the forty wells investigated, although the irrigated coastal wells have water with relatively higher nitrate content, some interior domestic wells too have higher amounts of nitrates while some interior irrigation wells have lower amounts (Figure 11a). However, except for 3 wells, nitrate-N contents of water from all the other wells are lower than 10 ppm, making them suitable for human consumption based on the WHO standards for drinking water. The nitrate-N contents of the selected wells (Figure 11b) show a gradual but small increase during the dry season irrespective of the actual individual concentrations. The only possible explanation for such an increase could be, as in the case of TDS, the leaching of some soil nitrate and other solutes into the groundwater due to excess application of irrigation water causing deep percolation. Uncontrolled overuse of water had become a common practice in the peninsula after the introduction of water pumps for irrigation.

It is difficult to establish the cause for the nitrate contamination of the water of any well without a detailed investigation of the surrounding environment, usage history of the well and land-use practices such as fertilizer application and irrigation frequency and amounts. The water of well no. 22, which was used for farm irrigation, always had high nitrate-N, which gradually increases to slightly over 10 ppm during the latter part of the dry season. With the onset of rains, the nitrate-N content increases sharply to almost 12 ppm. The cultivated soil close to this well was sampled at 15 cm depth increments, both before and immediately after the rainy season and the water extract was analysed for nitrate-N. As seen from Figure 12, although the soil nitrate-N profile follows a similar pattern before and after the rains, the nitrate-N content after the rains at each depth has reduced considerably and the peak in the nitrate-N profile is also less pronounced and had moved down. The reduction in the soil nitrate-N content and the movement of the peak downwards after the rains and the increase in nitrate-N of the well water with the onset of rains, strongly suggest the leaching of soil nitrate into the well by the rain water.

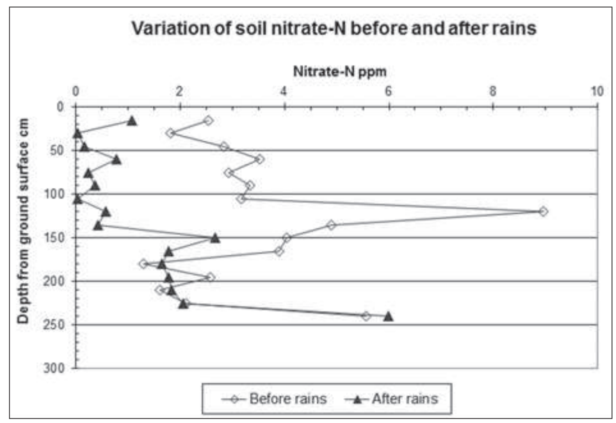

Figure 12: Nitrate content of soil adjoining well No. 22 – before and after the rainy season

CONCLUSION

The annual maximum storage of freshwater attained in the karst aquifer of the Jaffna Peninsula in each rainy season decreases continuously during the ensuing non-rainy periods due to natural outward flow and human use. It is replenished during the following rainy season. The freshwater storage remaining at the beginning of the dry season, even with its gradually decreasing rate of outward flow thereafter, seems sufficient for human use till the beginning of the following North-East monsoon. This was the case when the population of the peninsula was more than 700,000 with intensive irrigated agriculture in the 1960s and 1970s. There are more than six hundred partly silted-up surface storage ponds i.e kulams in the peninsula as natural land depressions or man-made tanks adjoining temples. So far there was no necessity to use them by de-silting or by any other means to enhance recharging the groundwater. The present trend is for the irrigated farms especially in the urban areas and adjoining roads to be converted to residential areas thereby almost halving the water use and reducing the danger of water shortage.

In any event, over-irrigation of crops resulting in deep percolation losses should be avoided. Systematic study of the aquifer should be undertaken to establish a database of the thickness of the freshwater, transition zone and the hydraulic gradients through a network of deep bore holes in the peninsula. Such a database will be useful in deciding on the depth of wells at different locations to ensure good water and for overall better groundwater management. The main sources of nitrates for polluting the groundwater are from septic tanks and over application of nitrogen fertilizers and subsequent over-irrigation. Therefore sources of nitrates should be identified for wells with high nitrates. Remedial measures such as sewage treatment plants in urban areas and controlled irrigation with split application of nitrate fertilizers in agricultural lands would be useful.

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