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GROUNDWATER DEVELOPMENT IN HARD ROCKS - A GIS APPROACH

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ABSTRACT

In this study, an attempt is made to identify some of the factors that affect deep groundwater quality and extractable quantity. The potential areas for future deep groundwater development for drinking purposes of the rural community in Beliatta area were demarcated. GIS and remote sensing techniques were used as the principal tools for data processing.

Using GIS application software packages, overlay operations were performed on available data to identify the attributes of lineaments, fractures, axial traces of folds, lithology and water bodies that will influence the yield of deep tube wells. The maps showing the distribution of electrical conductivity, fluoride, pH, hardness, total iron, calcium and total alkalinity of deep ground water were prepared. The effect of the presence of fractures, faults, folds and geology on water quality was analyzed manually. A simplified map showing the distribution of quality of deep groundwater in the area was compiled.

It has been established that deep groundwater development potential in most parts of the area is high or moderate. Deep groundwater with or without treatment can be used for medium and small scale pipe-borne water supply schemes covering around 50-200 households.

Keywords: deep groundwater, hard rock, GIS modelling

INTRODUCTION

Water, being one of the basic needs for living, plays a vital role in the life of people. Rural village community of Beliatta area has a duty to perform every day in the dry season- that is to collect water for drinking. As the dry season approaches, the hand-dug wells in the area gradually go dry and people have to walk several kilometres to the nearest tube well to satisfy their water requirements. Drinking water supply facility in the area is poor due to three main reasons viz, localized confinement of surface water, drying up of hand dug wells in the overburden soil and undesirable taste of shallow groundwater due to iron and chloride concentration.

Groundwater studies of Sri Lanka in the past have been focused mainly on the sedimentary terrains. Although nine-tenths of the country are underlain by hard crystalline metamorphic rocks, fewer studies have been done to identify the nature of deep fractured aquifers. Deep groundwater is extracted from fractures found in the hard crystalline rocks which are massive without intergranular primary porosity. A secondary porosity has been created by the process of weathering and fracturing. The process of fracturing in rocks depends mainly on tectonics that causes deformation. It is a common practice to identify geological structures that have resulted from deformation, when selecting suitable locations for extraction of deep groundwater.

Identification of factors that affect the yield of deep tube wells was done using remote sensing methods, namely, aerial photography and satellite imagery interpretation. These factors were determined at a reconnaissance level prior to ground surveys. Building of models has not been of interest to many field hydrogeologists in the past as handling spatial data manually was a time-consuming and difficult task. However, with the introduction of GIS tools, the

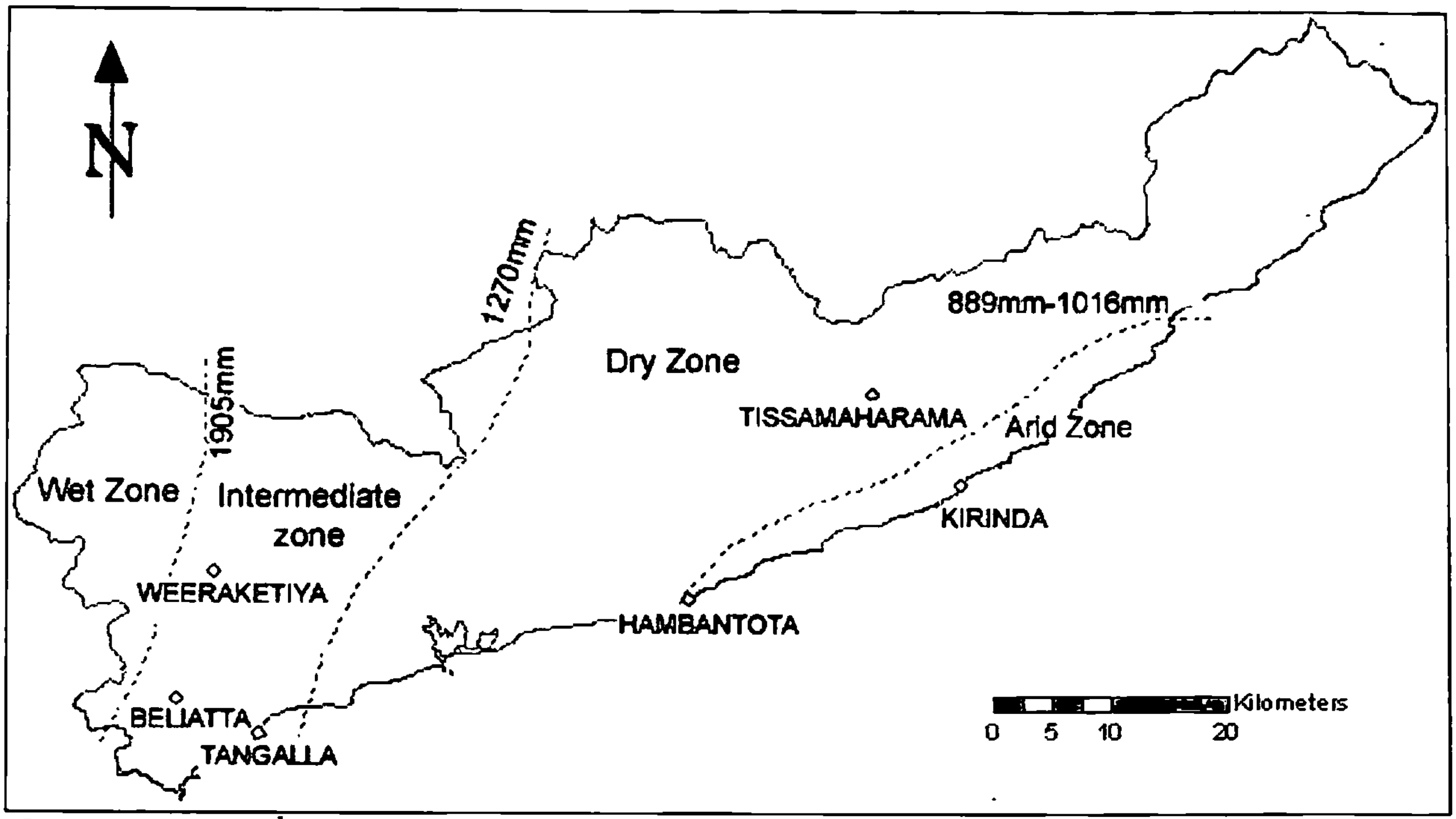

Figure 1: Climatic zones of Hambantota District. The dotted lines indicate the boundary between different zones.

spatial modelling has become more effective. GIS modeling is defined as the use of GIS in the process of building models with spatial data. The basic requirement in modeling is the modeler's interest and knowledge of the system to be modeled. This is why many models are discipline-specific models. GIS can assist the modeling process in several ways. First, GIS is a tool that can integrate different data sources including maps, Digital Elevation Models (DEM), GPS data, images and tables. These data sources can be displayed together and dynamically linked. GIS is therefore useful for modeling related tasks such as exploratory data analysis, data visualization and database management.

The study area is located in the south western part of Hambantota District in the coastal peneplain of Sri Lanka with the elevation ranging between 50m and 120m above MSL. Most of the area consists of gentle slopes. The northern part of the area is hilly and has a higher elevation while the southern part slopes gently towards the coast.

There are two streams in the study area. The main stream is Kirama Oya and has a catchment area of 225 square kilometres. The upper catchment of Kirama Oya is located outside the study area and very few perennial tributaries contribute to its flow within the study area. The stream Seenimodara Ara has a catchment area of 65 square kilometres and the entire catchment is found within the study area. An interesting feature of this basin is the occurrence of several perennial springs which emerge at the surface, feeding this stream throughout its course (Kodippili, 1988). The drainage pattern is mainly dendritic and is greatly influenced by the geological structure of the area. The path of Kirama Oya follows the regional thrust fault and the Seenimodara Ara is found to be associated with a shear zone. Several small tanks are located in the topographic lows of the area and almost all of them are drying up during dry season.

Three main climatic zones are recognized in the Hambantota District based on average annual rainfall. The area where the average annual rainfall is greater than 1905mm is named wet zone; intermediate zone has an average annual rainfall between 1905mm and 1270mm, whereas the dry zone has an average annual rainfall less than 1270 mm. This dry zone has an arid zone where the average annual rainfall is between 889mm and 1016mm. The study area of Beliatta lies in both wet and intermediate zones. However, a greater part of the area lies within the intermediate zone (Figure 1). No rain gauge stations are located in the area and therefore, the average annual rainfall of the nearest gauging station which is at Tangalle is assumed to be applicable to the area. The average annual rainfall recorded in Tangalle area has been 1181mm for the last 20 years. The average daily temperature is recorded as 26.9 ^{0}C. During the months of June and July the maximum temperature of 30.9 ^{0}C is recorded while the minimum temperature of 22.7 ^{0}C is recorded during the month of December.

The study area was selected in such a way that rainfall and topography do not show much variation. Geological structure, lithology and the presence of surface water are considered as factors that affect the quantity and quality of deep groundwater of the area.

GEOLOGY AND STRUCTURE

Geology

The study area which lies within the Highland Complex is made up mainly of garnet sillimanite biotite gneiss and charnockite (Figure 2). Garnet sillimanite biotite gneisses, formally called "Khondalites", contain up to 30% large red garnet grains. Charnockites are coarse grained with characteristic green, greasy appearance and they often form ridges. Quartzofeldspathic gneisses are found in the southwest quarter of the study area. Charnockitic gneisses interbanded with charnockitic biotite gneisses are observed in the northern part of the study area. Hornblende biotite gneisses and granitic gneisses are also found in the northern part. (Figure 2).

The rocks generally trend east-west and show 15° to 40° southward dips. Higher dips between 45 ° to 70 ° south are found only in the north-west side of the study area characterized by topographic highs.

Structure

The structural pattern in the area is dominated by a series of large east west trending overturned synforms and antiforms, and crosscutting shear zones. A major thrust fault trending east west dissects the area into two blocks (Geological Survey and Mines Bureau, 2001). The major shear zones that run either sub-parallel or oblique to the regional strike dissect the study area into three blocks. Getamanna overturned antiform plunges east while the Denagama-Bedigama Antiform is double plunging east and west. Denagama-Bedigama Antiform separates the study area into two parts in the northern side while the overturned Galagama Synform which plunges west separates the study area into two parts in the south.

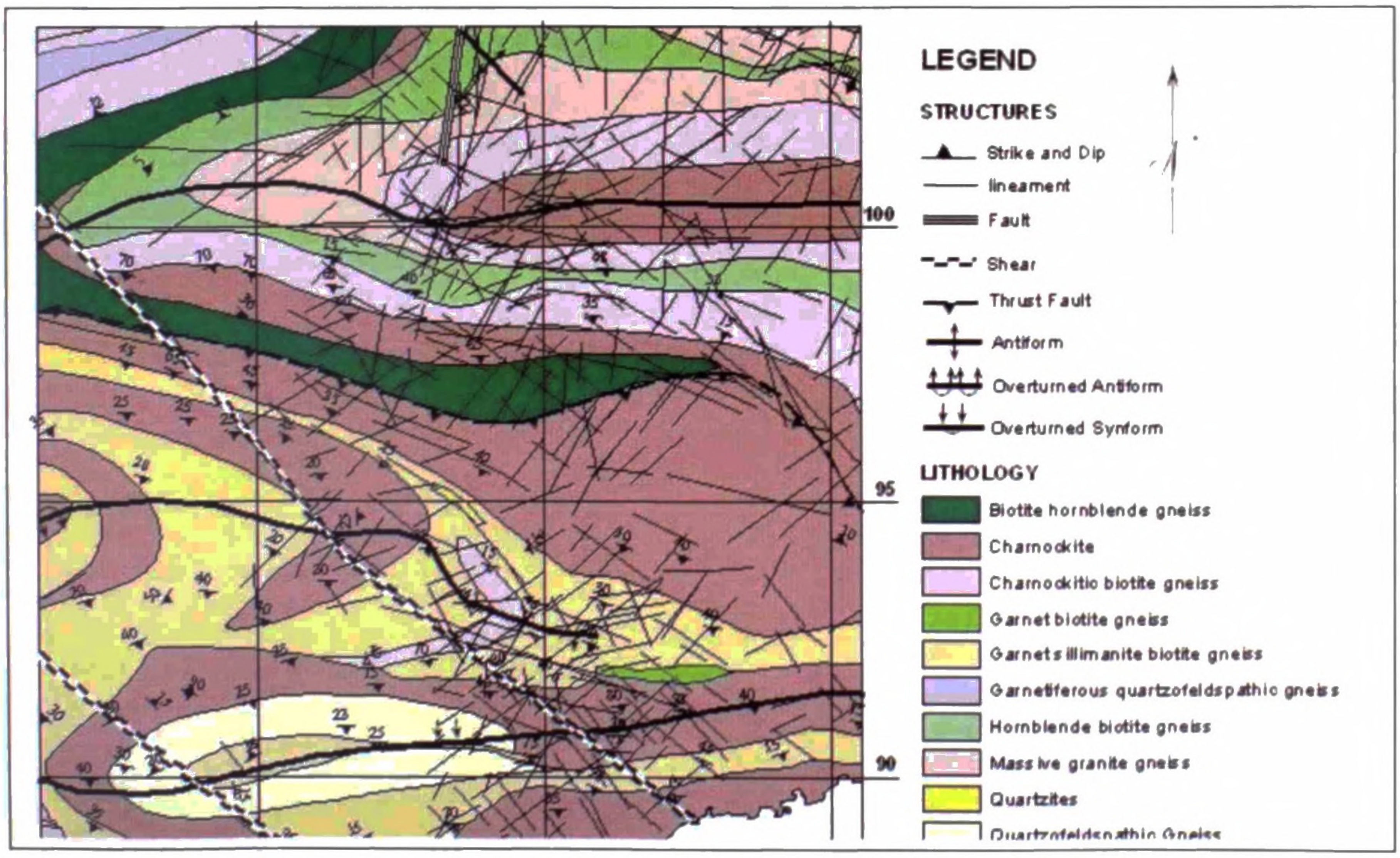

Figure 2 Regional geology of the study area (Source: Geological Survey and Mines Bureau, 2001, Provincial Map Series)

YIELD OF DEEP TUBE WELLS - EFFECTS OF DIFFERENT FACTORS

Fracture Density

Yields of deep tube wells were plotted against the fracture density and a linear trend line is drawn to identify the relationship between yield and the fracture density (Figure 3). The best fit linear trend line has the equation

$$y = 87.847x - 123.72$$

Where y is the yield of the deep tube well and x is the fracture density and R^2 value of the equation is 0.1572. R^2 which is the coefficient of determination is a measure of the proportion of variation that is explained by the independent variable x in the linear regression model.

The results show that the yield of the deep tube well increases with the fracture density. However, only 15% of the variation in the yield of the deep tube wells can be explained by the variability in the fracture density.

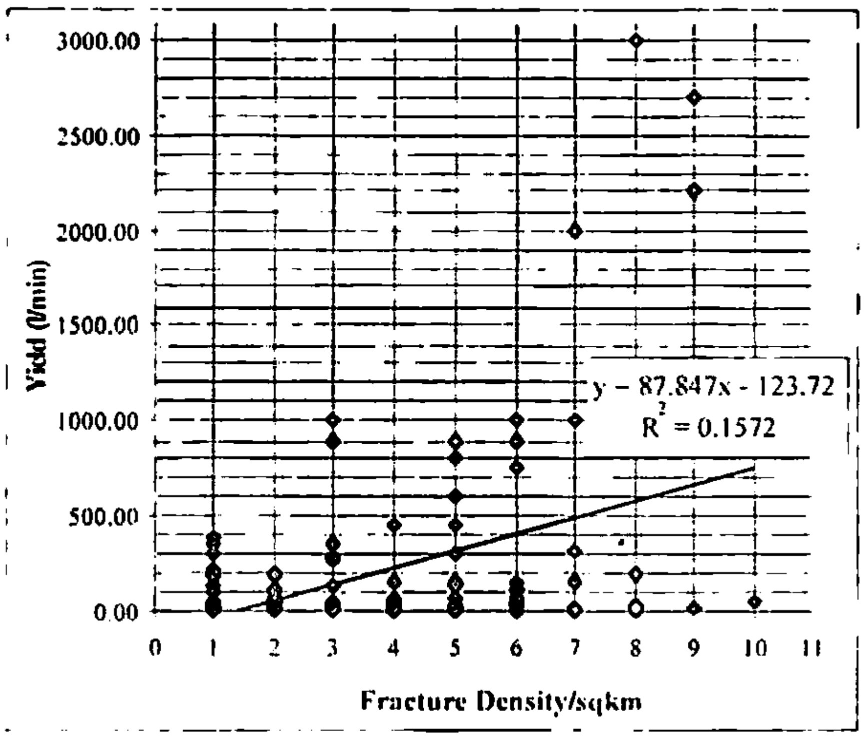

Figure 3: Fracture density vs. yield of deep tube wells

Shear Zones

Yields of only 16 wells located within 600m distance from the shear zones follow a linear pattern which gives the equation;

$$y = -2.6416x+1417.9$$

Where y is the yield of deep tube well and the x is the distance from the shear zones, and has the R^2 = 0.2177 (Figure 4). The results show that the general trend of the effect is decrement to the distance from shear zones. Only 21.7% of the variation in the yield of the deep tube wells can be explained by the variability in the distance from the shear zones.

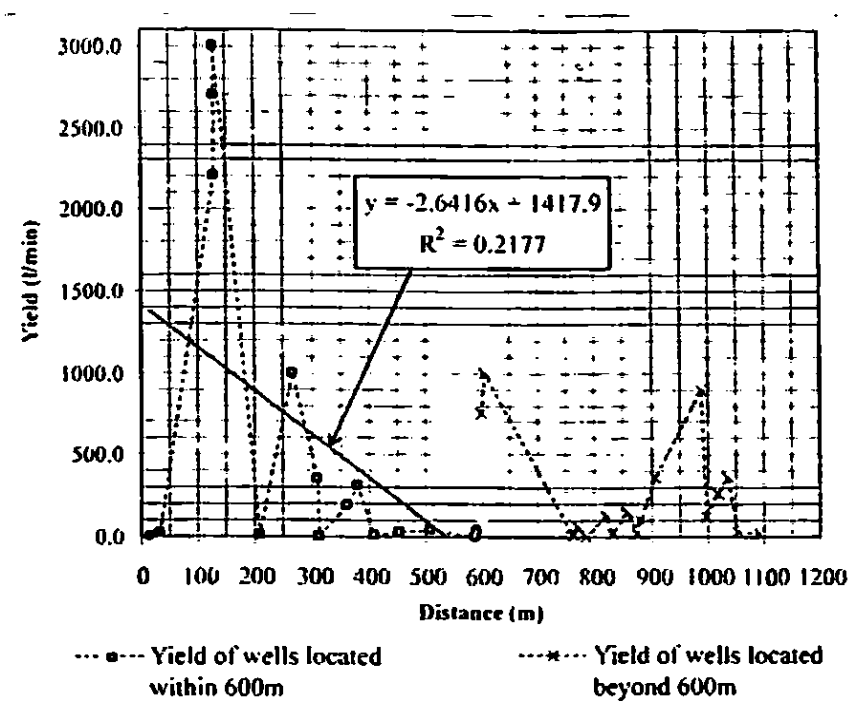

Figure 4: The distance from the shear zones vs. yield of deep tube well

Fault

Yields of 6 wells located within 1,400m distance from the fault seem to follow a linear pattern which gives the equation y = -0.4705x + 618.45 (Figure 5) where y is the yield of deep tube wells and the x is the distance from the fault. The linear regression model has the R^2 = 0.498 showing that about 49.8% of the variation in the yield of the deep tube wells can be explained by the variability in the distance from the fault.

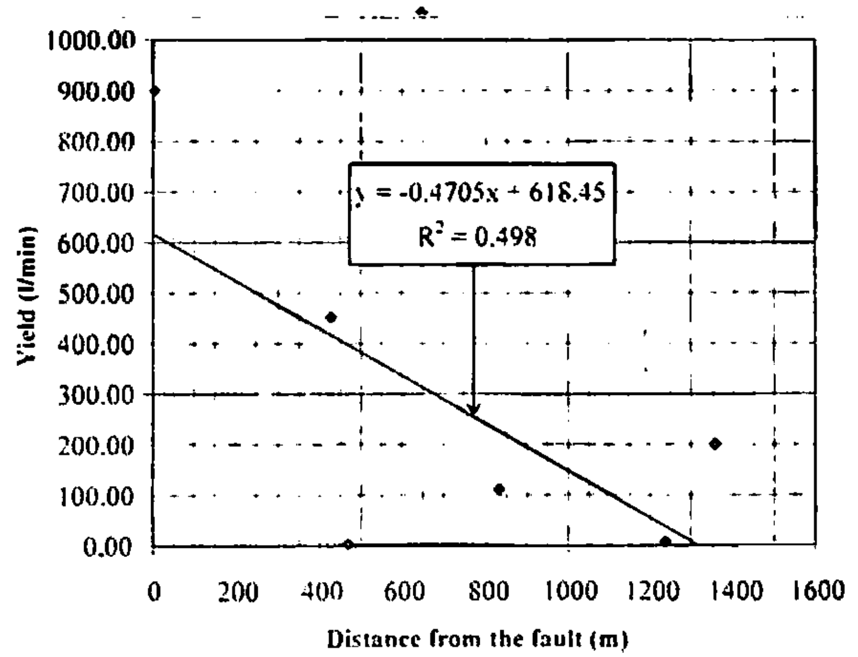

Figure 5: The distance from the fault vs. yield of deep tube wells. Distinct negative relationship of yield with the distance from the fault is indicated by the graph.

Thrust Fault

Yields of twenty deep tube wells located within 2,000m from the thrust fault to the North seem to follow a linear pattern which gives the regression equation:

$$y = -0.0401x + 87.96$$

and the linear regression model has R^2 = 0.2087 (Figure 6). Yields of 16 wells located within 2,000m from the thrust fault to the South seem to follow a linear pattern which gives the equation:

$$y = -0.4487x + 779.03$$

and has $R^2 = 0.2682$. In both equations, y is the yield of deep tube wells and x is the distance from the thrust fault.

About 20.8% of the variation in the yield of the deep tube wells in the North of the thrust fault can be explained by the variability in the distance from the thrust fault whereas the southern side shows a slightly higher percentage which is 26.8%.

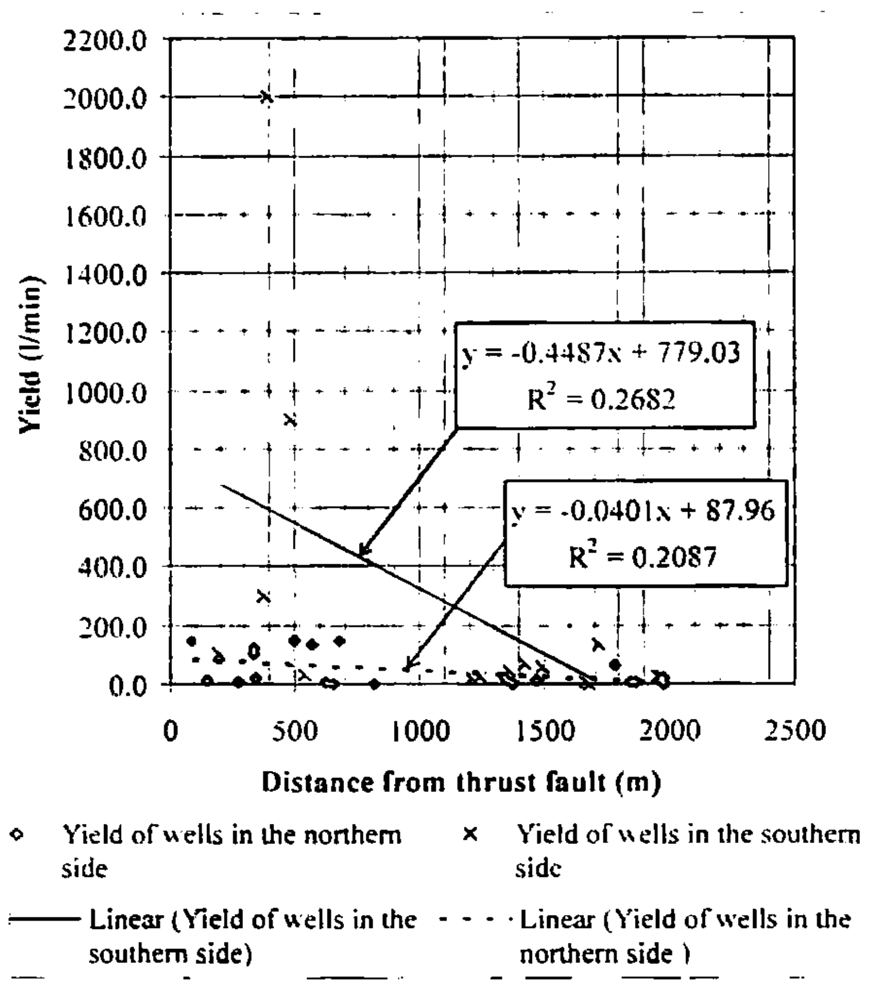

Figure 6: The distance from the thrust fault vs. yield of deep tube wells. Yields of deep tube wells located on either side of the thrust fault show negative trend with the distance from the thrust fault though the correlation coefficient is low.

Overturned Synform

Yields of 11 deep tube wells located within 600m from the axial trace of the Galagama Synform to the north, follow a linear pattern having the equation:

$$y = 0.4348x + 81.855$$

Where y is the yield of the deep tube wells and x is the distance from the axial trace of the synform to the north (Figure 7). The linear regression model has $R^2 = 0.0803$. The increment effect of the yield with the distance from the axial trace is probably due to reaching of the area under the influence of Getamanna Antiform.

Yields of 11 deep tube wells located within 766m from the axial trace of the Galagama synform to the south follow a linear pattern which gives the equation:

$$y = 1.3245x - 141.81$$

and $R^2 = 0.1122$ where y is the yield of the deep tube wells and x is the distance from the axial trace of the synform to the south.

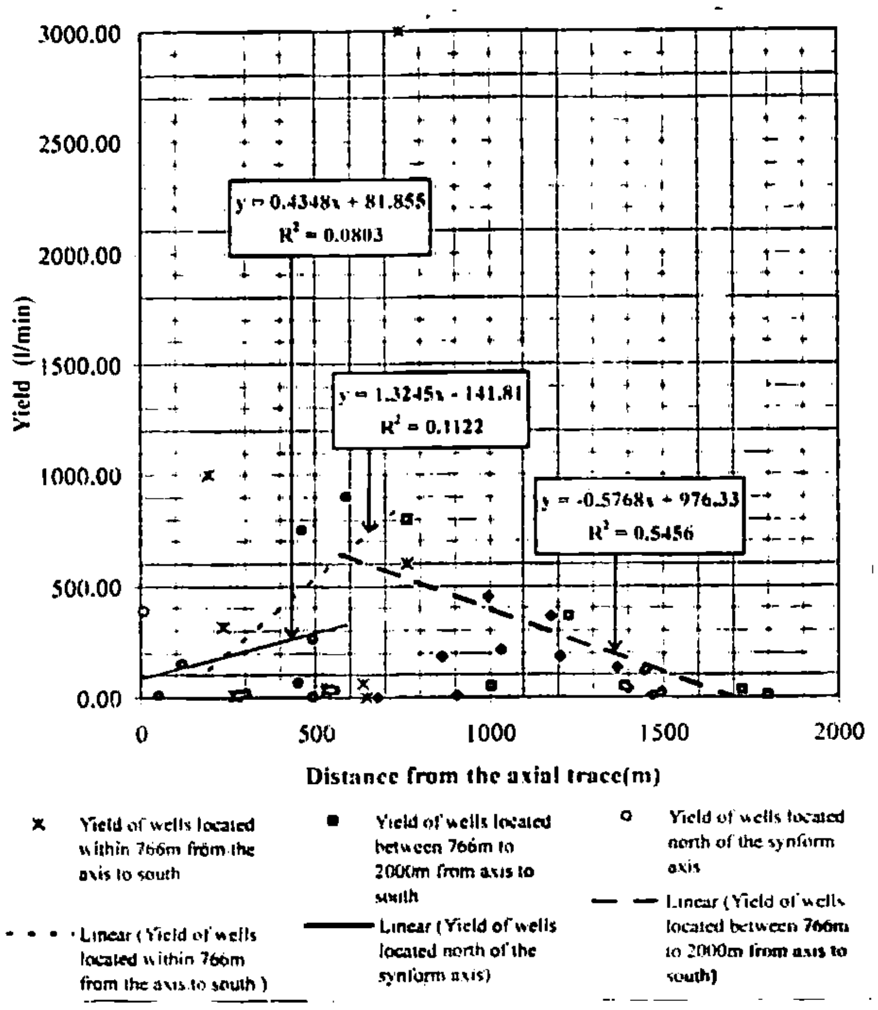

Figure 7: The distance from the axial trace of the Galagama overturned synform vs. yield of the deep tube wells.

Yields of another 5 wells located between 766m and 2,000m on the same side follow a different linear pattern having the equation:

$$y = -0.5768x + 976.33$$

and $R^2 = 0.5456$. The low yields of deep tube wells located closer to the axial trace may be due to the weathering and eroding away of the fracture zone associated with the axial trace of the synform.

Denagama -Bedigama Antiform

A total of 15 wells are located within 1,500m from the axial trace of the Denagama-Bedigama Antiform to the south. They follow a linear pattern which gives the linear regression equation:

$$y = -0.0535x + 71.88$$

and $R^2 = 0.2455$ where y is the yield of the deep tube wells and x is the distance from the axial trace of the antiform to the South (Figure 8).

A total of 6 wells located within 1,204m from the axial trace of the Denagama-Bedigama Antiform to the North, seem to follow a linear pattern which gives the equation $y = 0.0615x - 4.6607$ and $R^2 = 0.2177$ where y is the yield of the deep tube wells and x is the distance from the axial trace of the antiform to the North. A limiting distance for the effect of the antiform on well yield to the north of the axial trace cannot be identified due to lack of data. The increase in the well yield may be due to reaching another geological structure beyond the study area.

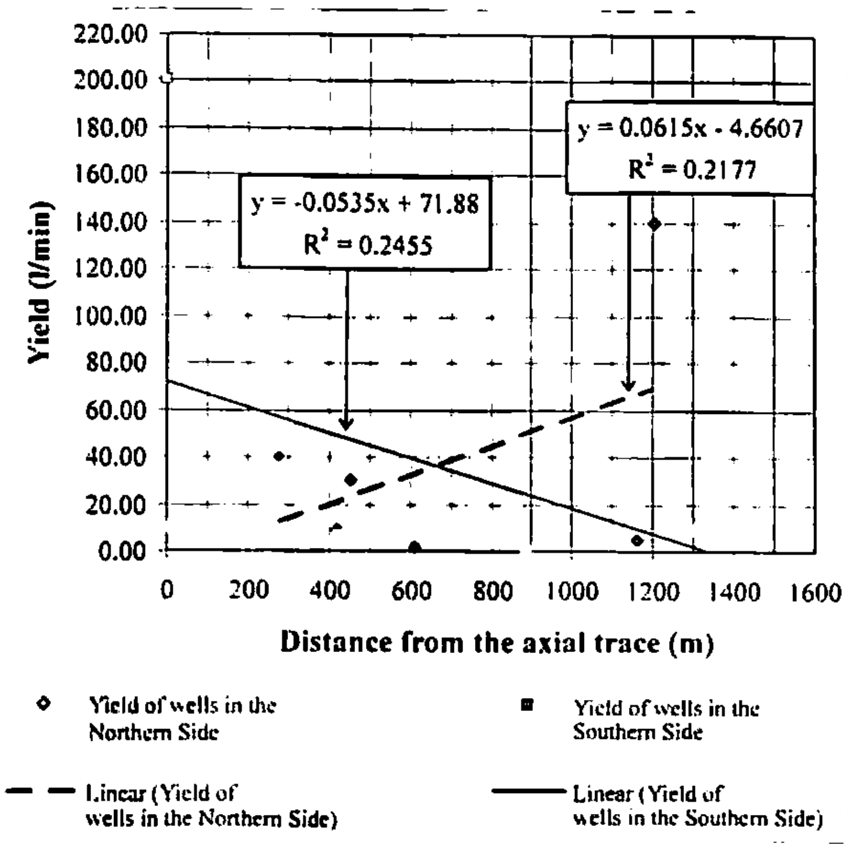

Figure 8: The distance from the axial trace of the Denagama - Bedigama Antiform vs. yield of deep tube wells.

Getamanna Overturned Antiform

Yields of 15 wells located within 1500m from the axial trace of the Getamanna antiform to the north, follow a linear pattern giving the linear regression equation:

$$y = -0.0254x + 49.219$$

and has the $R^2 = 0.0968$ where y is the yield of the deep tube wells and the x is the distance from the axial trace of the antiform to the North (Figure 9). Total of 12 wells located within 700m from the axial trace of the Getamanna antiform to the South, seem to follow a linear regression model which has the equation:

$$y = 2.9733x - 16.512$$

and $R^2 = 0.3404$. Yields of another 3 wells located between 700m and 1500m on the same side seem to follow a different linear pattern which gives the equation:

$$y = -1.1725x + 1518.2$$

and $R^2 = 0.8901$. In both cases, y is the yield of the deep tube wells and the x is the distance from the axial trace of the antiform to the South.

Presence of surface water

Yields of only 21 deep tube wells located within 300m distance from the surface water body seem to follow a linear pattern which gives the linear regression equation:

$$y = -2.6749x + 797.56$$

and $R^2 = 0.0725$ (Figure 10). However, only 7.25% of the variation in the yield of the deep tube wells can be explained by the variability in the distance from the surface water body.

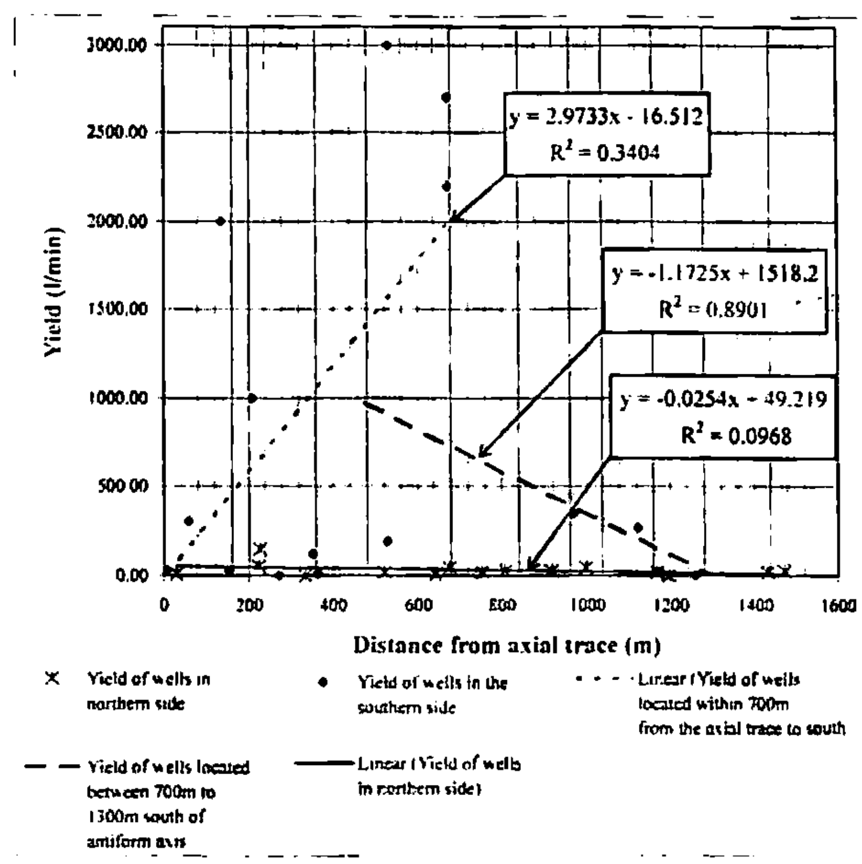

Figure 9: The distance from the axial trace of the Getamanna antiform vs. yield of deep tube wells.

Rock type

None of the specific lithological types is confined to either low yields or high yields except for garnet biotite gneiss where only two wells were drilled and both were low yielding. However, yields of two wells is not sufficient to reach a conclusion.

The analysis is based on the surface lithology only. As wells are drilled deeper, they can encounter different lithological units from the surface lithology. Most of the data found in the data bases are incomplete and do not indicate changes in rock type at depths. From this analysis, it can be interpreted that surface lithology data alone cannot be used to identify a direct relationship with the yield of deep tube wells in the area.

Yield of Deep Tube Wells - Combined Effect of Identified Factors

The identified effects of fracture density, faults, shear zones, thrust fault, overturned antiform, overturned synform, antiform and the presence of the surface water as well as the interpolated yield of existing wells were used for the analysis. Surface lithology was not taken for the analysis as a linear relationship between lithology and well yield cannot be established.

Weights based on the R^2 value of the trend lines were assigned to all the maps showing the identified effects. Weighted sum operation was performed on the maps and resulting raster grid was reclassified. The resultant map shows the distribution of deep groundwater in Beliatta area (Figure 11). It shows a clear low yield zone (<50 l/min) between the north of the thrust fault and the axis of Denagama-Bedigama

Antiform. Another main low yield zone is located at the south eastern corner of the study area. High yield zones (>500 l/min) are found to be associated in the south of the trust fault, south of Getamanna Antiform and shear zone. Another high yield zone is found in the northern part of the study area associated with the mechanical fault. When compared with the ground truth the accuracy of the model is 70%.

Quality of Deep Groundwater - Effect of Different Factors

Geological Structures

Level of electrical conductivity and total hardness in deep groundwater do not show any significant relationship with major structures. Low pH zones are found to be associated with the thrust fault, overturned antiform and overturned synform. However, no specific pattern can be identified.

High iron concentrations can be associated with Getamanna antiform, Galagama synform and the shear zone. Yet, a specific pattern could not be established. High calcium (>200mg/l) in deep groundwater can be associated with Getamanna overturned antiform and its plunging direction. High alkalinity (>400mg/l) in deep groundwater can be associated with Denagama-Bedigama antiform and the shear. These areas occur as isolated patches and a definite pattern cannot be established.

High fluorides (>1.5 mg/l) in deep groundwater can be associated with overturned antiform and the thrust fault. However, a significant relationship of the occurrence of high fluoride with the major geological structures cannot be identified.

Periodic/ seasonal sampling has not been done in the area. Even though seasonal water quality changes have not been reported, it may well happen without changing the taste, odour or colour so that the change may remain undetected by the users. Samples collected at dry periods may show higher concentration of ions and could be the reason for having isolated areas of poor water quality. Furthermore, most of these patches with poor water quality occur in the areas with low fracture densities where the recharging and dilution of ions are limited due to the lack of interconnecting fractures. As a result, higher concentration of undesirable ions may occur in the deep groundwater of these areas.

Surface Lithology

Deep groundwater found in quartzites preserves the maximum desirable drinking water standards of all the analyzed chemical parameters except for iron. Quality of deep groundwater found in quartzofeldspathic gneiss and garnet biotite gneiss falls within the maximum permissible limit of the analyzed parameters except for iron.

For other lithological units, amount of iron and fluoride can be present in a large range, within the maximum permissible limit as well as above that limit.

As such, a definite pattern cannot be identified. Occurrence of high iron may be due to the weathering of red garnet which is present in most of the rock types found in the area, especially garnet sillimanite biotite gneiss.

Total hardness, calcium and total alkalinity amounts present in deep groundwater found in biotite hornblende gneiss and massive granite gneiss is within the maximum permissible limits. Chemical quality of deep groundwater found in charnockites, varies in a wide range, below and above maximum permissible levels. A significant correlation of quality of deep groundwater with charnockite cannot be established.

Reclassification of Quality of Deep Groundwater

Seven maps depicting deep groundwater quality (showing the distribution of electrical conductivity, fluoride, pH, total hardness, total iron, calcium and total alkalinity of deep ground water) were combined using the combine tool. Attribute table of the combined map contains the limits of all the analyzed parameters relevant to each land area. Using the attribute table, the resulting map was reclassified into three main groups namely, good, moderate and poor water quality based on the levels of all the analyzed chemical parameters. The classification criteria are given in Table 1.

The map showing the quality of deep groundwater in Beliatta area is given in Figure 12. Zones with poor water quality do not show any significant relationship to the major structures. However, two patches of such areas are found on the south of both Denagama-Bedigama antiform and Getamanna overturned antiform. Greater part of the area comes under the moderate quality of deep groundwater category.

Occurrence of deep groundwater having analyzed parameters within the SLS drinking water standards is limited to two major zones at the south west corner and the eastern part of the study area. Isolated patches scattered all over the area.

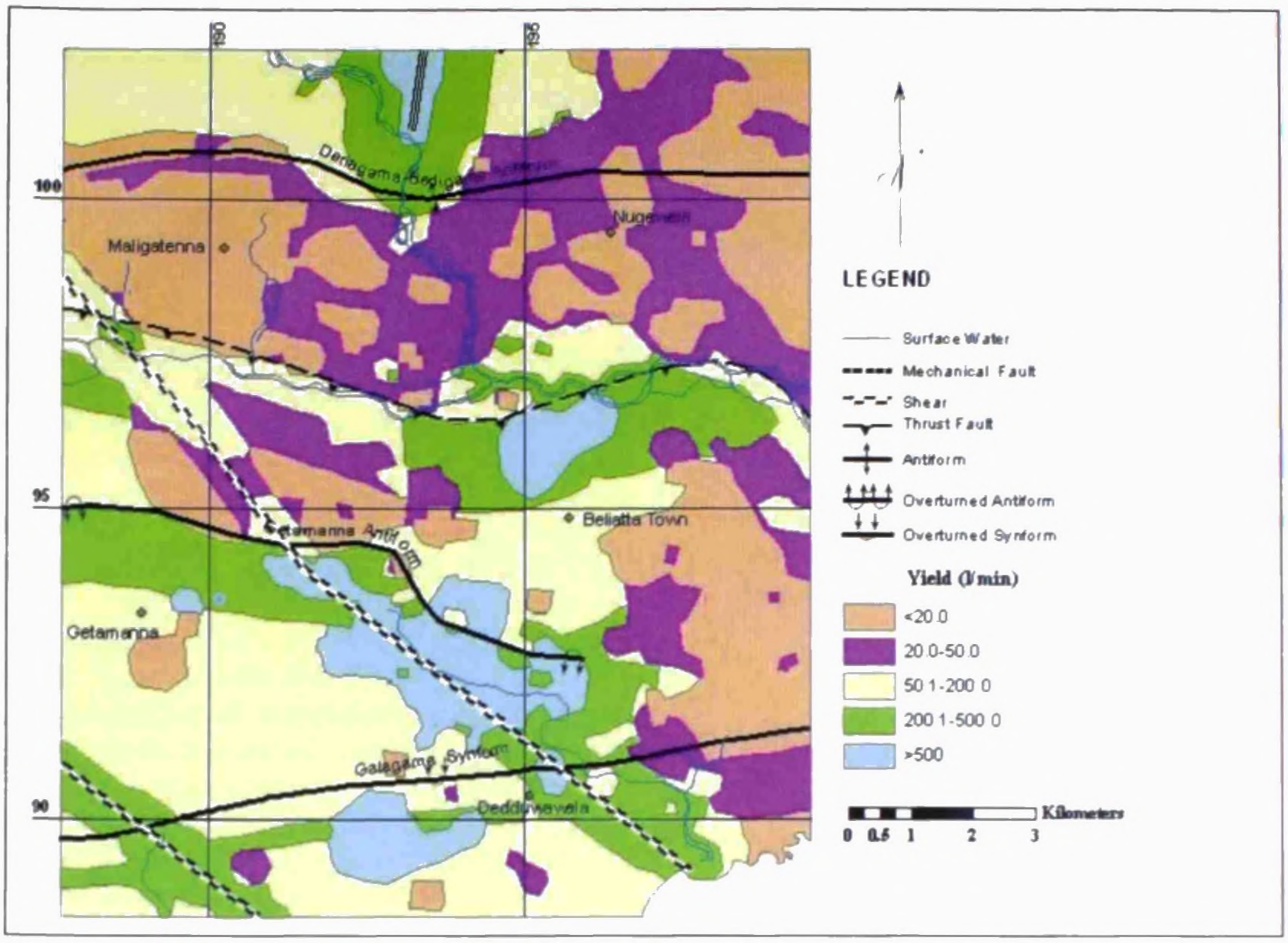

Figure 11: Distribution of deep groundwater in Beliatta area

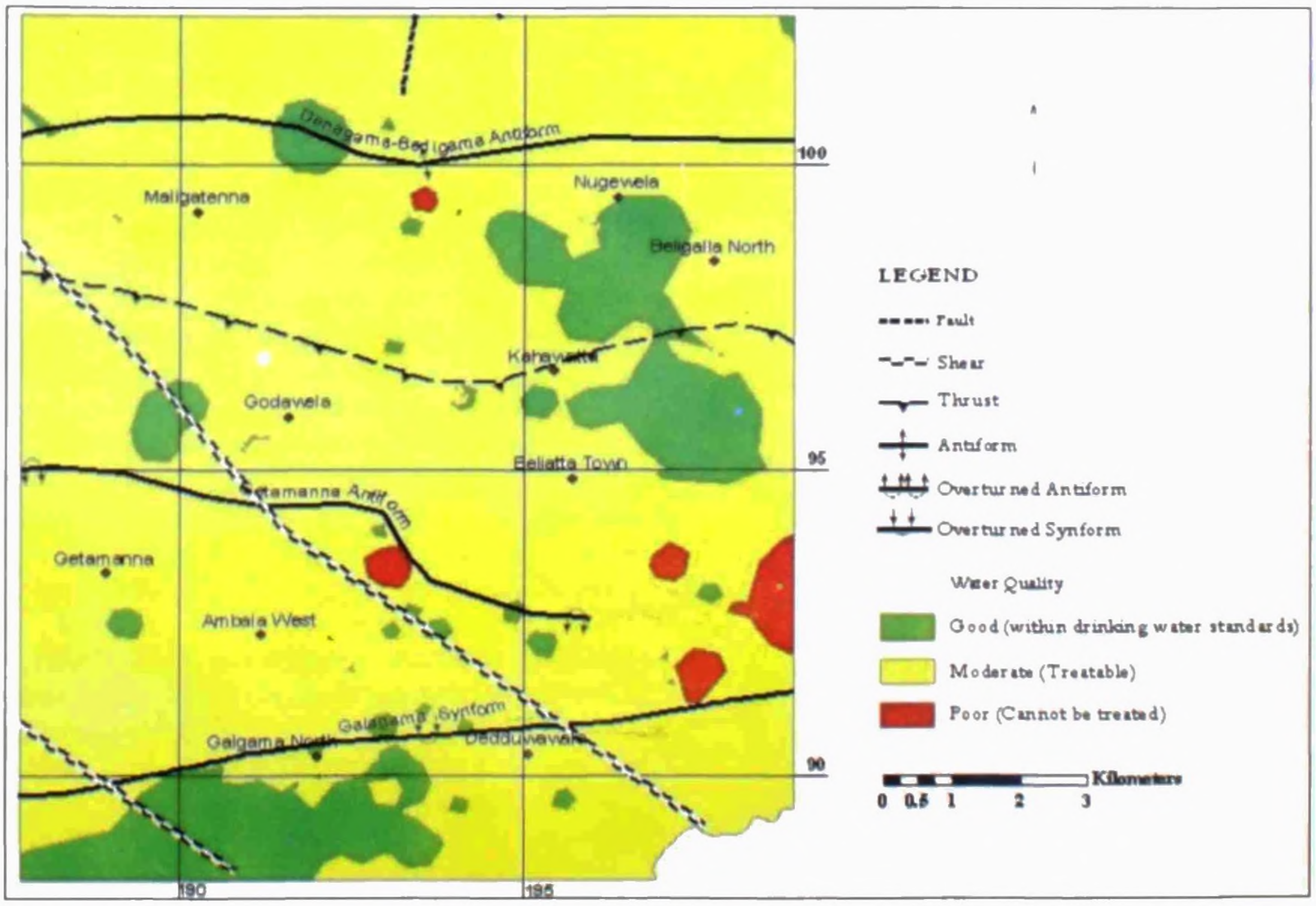

Figure 12: Distribution of deep groundwater quality in Beliatta area

Table 1: Classification of deep groundwater quality

Class	Deep Groundwater Quality	Description
1	Good	All the analyzed chemical parameters are within the SLS drinking water standards permissible level
2	Moderate	At least one chemical parameter or all the chemical parameters are within the treatable range
3	Poor	At least one chemical parameter is within the untreatable range

DEMARCATION OF POTENTIAL

Areas for Deep Groundwater Development

Maps showing the occurrence of deep groundwater and the distribution of quality of deep groundwater were overlaid and analyzed using the intersection tool. Resultant map was reclassified into five types of development potential areas: namely, very high, high, moderate, poor and very poor. Deep groundwater development potential was categorized into above five groups considering the service capacity (180 liters per capita demand per day) which depends on the extractable quantity of deep groundwater in the area and the quality of it. The classification is given in Table 2. The reclassified map (model) showing the deep groundwater development potential in Beliatta area is given in Figure 13. Table 3 Shows the total land area coming under each category of deep groundwater development potential.

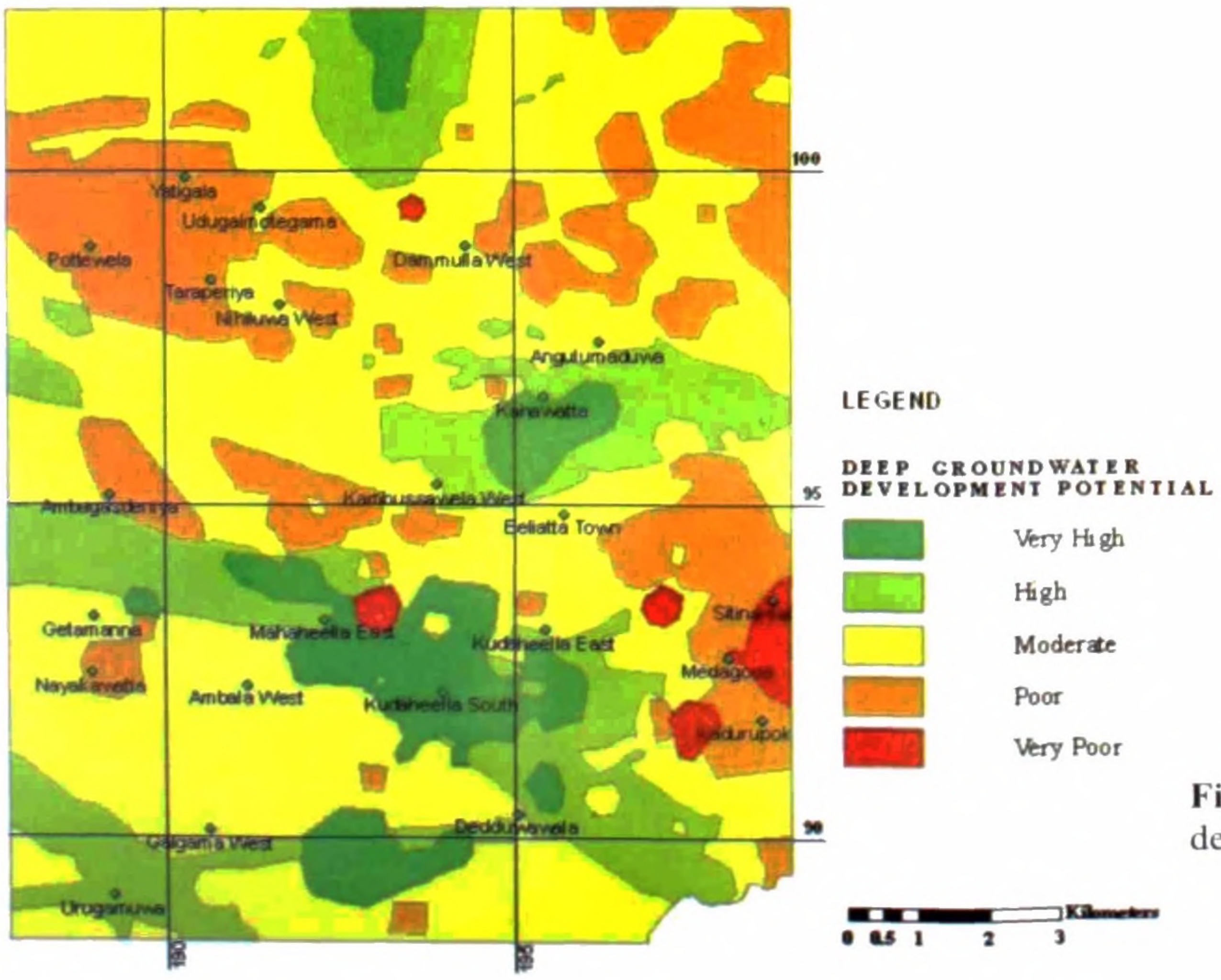

Figure 13: Deep groundwater development potential in Beliatta area

Table 2: Classification of deep groundwater development potential

Development Potential	Service Capacity
Very High	Deep groundwater can be used for large scale pipe borne water supply schemes covering more than 200 households with or without treatment
High	Deep groundwater can be used for medium scale pipe borne water supply schemes covering around 100-200 households with or without treatment
Moderate	Deep groundwater can be used for Small scale pipe borne water supply schemes covering around 50-100 households or pumping wells for individual households with or without treatment
Poor	Deep groundwater can be used for hand pump tube wells serving as point sources
Very Poor	Deep groundwater cannot be used for drinking purpose due to poor quality and/or low yield

Table 3: Land area coming under each category of deep groundwater development potential.

Deep Groundwater Development Potential	Land Area (km^2)
Very High	12.8
High	28.2
Moderate	58.9
Poor	33.4
Very Poor	2.3

CONCLUSIONS

Of all the geological structures present in the area, fracture density together with the Getamanna Antiform exerts the highest positive impact on the yield of deep tube wells. Statistical analysis shows that the correlation with the real factors and the productivity of the deep tube well is not significant. This is because, in hard rock terrains, the influence of the selected factors can be complex, sometimes interconnected, individual or retarding. Electrical conductivity, total iron, fluoride, total hardness, calcium, pH, and alkalinity in deep groundwater are influenced by the geological structures and lithological type in the area. Overall quality of deep groundwater in most parts of Beliatta area can be considered as moderate. i.e. Water can be made potable by treatment.

The model prepared by the combination of all the identified effects of geological structures and surface water bodies has the accuracy of 70%. Eventhough the individual contribution of influencing factors are less significant, weighted overlaying can compensate for the results and increase the accuracy of the model. Deep groundwater can be used to cater the drinking water demand of the rural community of the Beliatta area. Deep groundwater development potential in most of the area is high or moderate.

The study reveals that remote sensing surveys using satellite imagery and aerial photographs and application of GIS on compilation of hydrogeological maps, from which approximations of the deep groundwater occurrence can be made. ,

Remote sensing techniques and application of GIS software are very effective tools in hydrogeological investigations and modeling which can drastically reduce the cost of groundwater development programmes in the hard rock areas of Sri Lanka.

RECOMMENDATIONS

It is recommended to conduct detailed field hydrogeological surveys in more promising areas and field test the model to validate. It is economical to identify high potential areas using GIS and remote sensing techniques prior to the field surveys.

Further improvements to the model incorporating the depth and elevation data are recommended.

The understanding of hydrogeological characteristics of any hard rock terrain is not a simple task. The task becomes impossible when the relevant data is not compiled properly and the access to the data is restricted. It is recommended to implement a national level deep tube well data compilation programme from which free access to data is permitted.

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REFERENCES

Bakker, W. H., Janssen, L.L.F., Weir. M.J.C. and Gorte, B.G.H., 2000. Principles of Remote Sensing, An Introductory Text Book, ITC Publication, 80p.

Chang, K., 2002. Introduction to Geographic Information Systems. Tata McGraw-Hill Publishing Company Limited, New Delhi.

Cooray, P. G., 1984. An Introduction to the Geology of Sri Lanka. Colombo, Sri Lanka, National Museum of Sri Lanka.

Cooray, P. G., 1995. The Geology of Sri Lanka, an overview. Handbook on Geology and Mineral Resources of Sri Lanka. K. Dahanayake (ed.), GEOSAS II, 1-7.

Department of Census and Statistics, 1996. Census of Population and Housing in 1996, Department of Census and Statistics Sri Lanka, Colombo.

Department of Census and Statistics, 2001. Census of Population and Housing 2001, Department of Census and Statistics Sri Lanka, Colombo.

Fernando, A.D.N., 1988. Use of Remote Sensing Methods for Estimating the Groundwater Potential of Sri Lanka. Journal of the Geological Society of Sri Lanka, 1: 93-98.

Gamage, S.J.K., Mendis, L., Gunatilake, A.A.J.K. and Wijewickrama M.I.D.H., 1992. Groundwater Quality in Fold Axes in the Western Vijayan Complex, Kurunegala District. Journal of the Geological Society of Sri Lanka, 2: 65-69.

Geological Survey and Mines Bureau, 2001. Sri Lanka 1:100,000 Geology (Provincial Map Series), Rakwana-Tangalle (Sheet 20).

Heywood, I., Cornelius, S. and Carver, S., 2004. An Introduction to Geographical Inforamtion Systems. Pearson Education, India 120pp.

Kodippili, A.A., 1998. Groundwater Exploration in Fractured Rock Aquifers in Sinimodara Oya Basin, Hambantota. Abs., Fifteenth Annual

Technical Sessions, Geological Society of Sri Lanka, 14.

Kodituwakku, K.A.W., 1998. Extraction and Modeling Spatial Parameters in Groundwater Potential Studies in Hard Rock Terrain, Sri Lanka. Abs., Fifteenth Annual Technical Sessions, Geological Society of Sri Lanka, 15.

Kulathunga, K., 1988. Hydrology of a Metamorphic Terrain; a Case Study from Hambantota, Sri Lanka. Journal of the Geological Society of Sri Lanka, 1: 73-79.

Lahee, L. H., 1987. Field Geology, Sixth Edition, CBS Publishers, India: Chapter 7, 8.

Lapidus, D. F., 1990. Collins Dictionary of Geology, Collins, Glasgow.

Milisenda, C. C., Liew, T.C., Hofmann, A. W., and Kroner, A., 1988. Isotope mapping of age Provinces in Precambrian High-Grade terrains. Journal of the Geological Society of Sri Lanka, 96: 608-615.

Milisenda, C. C. and Hofmann, A. W., 1991. Isotopic Characterization of the High Grade Basement Rocks in Sri Lanka. The Crystalline Crust of Sri Lanka, Part I, A. Kroner (ed.), 258-266.

NWS&DB Project Implementation Unit, 2000. ADB Assisted Third Water Supply and sanitation Sector Project, Hambantota District, Water Resources Planning Preliminary Study, Hambantota District.

Pacific Consultants International, 2003. The Study on Comprehensive Groundwater Resources Development for Hambantota and Monaragala Districts in the Democratic Socialist Republic of Sri Lanaka, Final Report.

Railsback, B., 2008. Geological Diagrams. http://www.gly.uga.edu/railsback/ Geological Diagrams.html (accessed on August 27, 2008).

Twiss, R. J. and Moores, E. M., 1992. Structural Geology, W.H. Freeman and Company, New York, 85pp

Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/wiki/shear_zones, http://en.wikipedia.org/wiki/Thrust_fault, (accessed on July 6 2008),