J. Ind. Geophys. Union (March 2018)
v.22, no.2, pp: 163-170

Hydrogeological and Geophysical Characteristics of Northern Parts of Eastern Ghat Khondalitic Aquifers

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ABSTRACT
In this study various concepts pertaining to khondalitic (Garneti Ferrous Sillimanite gneiss) aquifers and their kaolinisation in the Vijayanagaram district of Andhra Pradesh, India is attempted. The hydrogeological and geophysical studies on these aquifers inferred that the khondalites in this region are sedimentary in origin but later metamorphosed and became hard rocks. These rocks were subjected to intense weathering, faulting, fracturing and folding giving way to accumulation of ground water in two different layers mainly in weathered layer and fractured layer with hydraulic continuity among them. Beneath the streams and low-lying areas most of the khondalite became kaolinised and turned out to be low ground water potential zones. This kaolin, which is essentially clay, is acting as a barrier for the ground water movement towards the stream and forcing it to accumulate in the upland areas between the streams and naturally became groundwater potential zones whenever the formation is fractured and intruded with quartz veins. Lack of resistivity contrast between highly weathered khondalite and fractured khondalite has been noticed in the Vertical Electrical Sounding data at few places. This called for Two-Dimensional (2D) and Three-Dimensional (3D) resistivity imaging surveys to delineate the kaolinised zones to avoid well failures. The extended deeper kaolinisation of the aquifer is responsible for failure of wells in this terrain. At failed wells, kaolinisation is not only deeper but also followed by the basement characteristics either with very thin or no aquifer layer immediately below the kaolinised layer. At successful wells not only kaolinised layer is thinner but also aquifers are thicker resulting in presence of basement characteristics only at deeper depths. Layers having resistivities between 25 - 65 Ohm-m are identified as aquifer layers, which are composed of moderately weathered and fractured khondalitic suite of rocks. Layers with resistivities greater than 65 Ohm-m are interpreted as granite gneissic basement, while the layers with resistivities less than 25 Ohm - m are interpreted as kaolinised layer. The quality of the ground water in this region is generally good and suitable for both drinking and irrigation purposes except at few pockets where Fluoride and Nitrate is present in excess of permissible limits. Similarly, in downstream areas of major streams high salinity is present.

Key words: Khondalite, Aquifer, Kaolinisation, Resistivity, Groundwater potential

INTRODUCTION

Khondalitic suite (garneti ferrous sillimanite gneiss) of hard rocks occurring in Eastern Ghats of India (Figure 1) constitutes nearly one-eighth of the hard rock areas of the country. The Khondalites are named after 'Khonds', the tribesmen living in the mountain jungles of Eastern Ghats (Walker, 1902). Khondalites forming the lower Precambrian group are extensive in the districts of Srikakulam, Vizianagaram, Visakhapatnam and in the upland areas of East Godavari, West Godavari and Krishna districts of Andhra Pradesh, India.

The hydrogeological properties of Khondalitic aquifers in northern parts of Eastern Ghats of Andhra Pradesh are to an extent different from those present in southern parts. For instance the soil and weathered thickness is much higher in the southern parts (about 20m to 30m) compared to the northern parts (about 10 m to 20 m). Similarly, ground water availability in fractured rock of Khondalite is at 50 m in southern parts compared to 30 m in the northern parts. In this region assured surface water supplies are minimal. The limited surface water facilities are getting depleted slowly as 1/5th out of the average annual rainfall of around 1000 mm goes as recharge to ground water. Since there is no assured surface water supplies, majority of the farmers solely depend on ground water for drinking and irrigation purposes. Since dependence on ground water is increasing systematic ground water exploration and exploitation studies and planned groundwater development have become essential in the region. As a part of such an organized ground water development initiative, natural recharge and modeling studies have been carried out by researchers. Many modeling studies have indicated presence of the natural recharge of 14% to 18% of rainfall in Khondalitic terrain. Since the natural recharge of ground water is not encouraging organized ground water development assumes greater significance in the region, by identifying not only shallower but deeper aquifers. In the present paper, the views of various researches on khondalitic aquifers situated around Vizianagaram and Visakhapatnam are presented in the form a review, covering more than hundred years of research work.

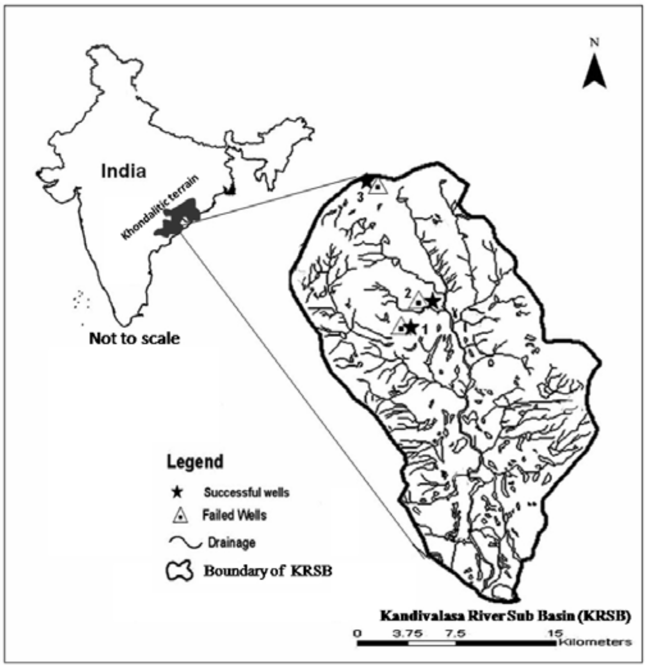

Figure 1. Location map of the study area.

Geology and Tectonics

In view of the presence of Manganese and bauxite ores in the region, most of the early researchers evinced interest on petrological and minerological aspects but not on the hydrogeological aspects. Some of the opinions of early workers on the origin of the khondalitic formation are presented here.

Fermor (1909) was probably the first scientist to make an observation that the manganese ores in this area owed their origin to the alteration and concentration of manganese rich igneous rocks. Cross (1914) questioned the validity of the igneous nature of the local rock type and instead suggested a hybrid origin for them. Subsequent works by Fermor (1915) and Prabhakara Rao (1950) have shown that the rocks were indeed hybrid and the manganese ore was sedimentary in origin. Krishna Rao (1952) confirmed the sedimentary origin of khondalites. He stated that they were paragneisses representing metamorphism of original arenaceous, argillaceous and calcareous sediments, the arenaceous constituents giving rise to quartzites, the argillaceous matter to quartz-garnet-sillimanite gneiss and the calcareous sediments to calc granulites. Krishnan (1968) opined that the rocks of Eastern Ghats are the result of high-grade metamorphism of sedimentary rocks.

Later investigations have revealed that the rocks are products of re-crystallisation of a complex series of sediments (Dey, 1968). The typical khondalite is a rock constituting of silimanites, garnets, feldspar and quartz. The idea that khondalites have been derived from high alumina clays that are fairly high in iron is confirmed by the existence of bauxite and iron deposits (Sarma, 1982). The main khondalitic rocks are associated with charnockites, which is a bluish grey granular granitic rock named after Job Charnock. His tomb was constructed by this rock. These rocks are observed to have an intrusive character in the khondalitic country (Sarma, 1982).

Geological investigations carried out by Rao (1964) and Sriramdas and Rao (1979) have indicated the existence of faulting, folding, cross-folding and domal structures in the region. Narayanaswamy (1975) has explained the structure and tectonics of Eastern Ghats. According to him khondalites and leptinites (garnetiferrous quartzofelspathic gneiss) belong to the khondalitic suite of rocks in Eastern Ghats. The charnockitic suite is the basal zone overlain by khondalitic suite. He further pointed out that Eastern Ghats have undergone at least two periods of deformations marked by intense folding, shearing and faulting of khondalites. Kanungo and Murthy (1981) have presented the structural features of khondalites and associated rocks and established a structural superposition of various rock types present, namely, charnockitic gneisses, quartzites, khondalites, calc granulites, granites and granitic veins in that order. Chetty et al., (2002) have studied the shear zones and lineaments in the Eastern Ghat Mobile Belt (EGMB) and found that the lineament patterns are distinct in the contrasting geologic terrains. The presence of shear zone network is strikingly restricted to the EGMB.

Hydrogeology

Probably Mahadevan (1929) was the first scientist to postulate a hydrogeological concept of this region and has pointed out that due to the action of water the khondalites are altered in to two different forms. On the surface the rock changes into a lateritic soil and the subsurface formation when acted upon by water alters itself into kaolin. Sarma (1967) has conceived a four layer system in the khondalitic terrain i.e., the top soil zone underlain by talus zone in foot hill areas, which in turn is underlain by weathered kaolinised portion that merges into a fractured and fissured zone and followed further by basement material. He has further observed that ground water occurs in weathered kaolinised zone and in the fractured and fissured zone. Where the weathered and kaolinised zone consists of sandy clay with sufficiently large permeability, the water table continues into the fractured and fissured zone. But at places where the weathered zone is completely kaolinised and clayey in nature, any well located in it shows water at the bottom of this layer, when it touches the fractured zone the water table eventually rises to some extent offering semi-confined conditions. Venkateswara Rao (1994) also found that weathered and fractured zones have hydraulic continuity. This is proved by the fact that whenever the bore well was drilled near by the open well, the open well yield is considerably reduced and even became dry. Nooka Raju and Jaganmohan Rao (1990) have confirmed the earlier findings that the area is occupied by khondalites intruded by charnockites and quartz veins. The khondalites show a general strike direction of NE-SW and the foliation dips vary from 45^o to 75^o due SE. Their investigation has revealed that the discharges are higher in khondalites intercalated with quartz veins and fractured quartz felspathic gneisses, than in felspathic gneisses and weathered khondalitic suite of rocks.

Later investigation carried out by Venkateswara Rao and Briz-Kishore (1990) in Cheepurupally region of vizianagaram district has shown that flat upland areas are yielding better than low lying areas near the streams. It is found subsequently by Venkateswara Rao (1998b) that at low lying areas, i.e., beneath the streams the khondalite must have transformed itself into kaolin and having more thickness than in the flat uplands. In fact the kaolinisation process is observed from low lands to high lands at a depth of 10 m to 20 m and its thickness is varying from 20 m to 10 m, respectively. This kaolin is acting as a barrier evidently preventing lateral movement of ground water towards the stream. At many places in the khondalitic terrain the kaolinised layer is acting as an aquitard or semi-confining stratum atop the main aquifer of fractured khondalite. The aquitard's contributions to the total well yield in many cases is substantial, a point that underscores the need to seek ways and means of tapping it. (Venkateswara Rao and Ramadurgaiah, 1996). However, if the kaolinisation is too strong and extends to greater depths of more than 20 m., the yields of the wells are low leading to well failures (Venkateswara Rao et al., 2013). Another important observation is that many successful wells are located in areas of considerable quartzisation hinting at the possibility that the appearance of a quartz vein or quartz pebbles on the ground surface probably related to ground water occurrence (Venkateswara Rao, 1994). Central Ground Water Board (CGWB) investigations have revealed that the depth of weathering ranges from 10 m to as high as 40 m. Higher degree of weathering in Khondalites results in the formation of kaolinite, causing less porosity and permeability (Sudarshan and Rao, 2004).

Hydrogeomorphology

Aerial photo studies by Prudhvi Raju and Vaidhyanadhan (1981) particularly applicable to khondalitic terrain has shown the existence of fractured zones. Raghavaswamy (1981) described the landforms, land systems and geographical synthesis of the area. According to Sarma (1982), Eastern Ghats have well-developed basins and sub-basins in their watersheds and act as independent ground water basins. This character is responsible for ground water to be available at all levels throughout the Eastern Ghat ranges in spite of their steeply slopping nature. The slopes of the hills vary from 1 in 85 to about 1 in 400. Ramana (1980) has undertaken morphometric analysis of the five river basins in the area, namely, Sarada, Narova, Peddagadda, Gostani and Champavati. The dominating pattern of the tributaries is dendritic. Miller and Miller (1961) have pointed out that homogeneity of formations has given rise to dendritic drainage. The dominance of khondalitic formation in the area has clearly indicated the above point.

The hydrogeomorphological investigations in Kandivalasa River Sub-Basin (KRSB) of Viziangaram district (Figure 1) by Venkateswara Rao (1998b) revealed that lineaments are fault zones along which stream courses were developed. Ground water potential areas are located on shallow buried pediplains and wash plains in such a way that they are located on gently sloping uplands situated between the lineaments. Non potential areas are those, which are low-lying areas, near the streams and high slope areas near the hillocks.

Geohydrology

The seasonal fluctuation of water table was observed by Subba Rao (1974), Prasad (1980), Narayanaswamy (1980) and Ramana (1980) in different parts of Eastern Ghats. On the average the maximum fluctuation seems to be 3 m. The water table rise is observed to be linearly related to the amount of rainfall. About a third of the rainfall percolates through the soil surface to recharge the ground water (Sarma, 1982). The average non-capillary porosity of the surface layer is 33%. The water level fluctuations are found to follow the physiography. It is observed that an increase in terrain elevation by one metre results in a fluctuation of 0.5 metre in the ground water level Sarma et.al. (1983). Subba Rao and Krishna Rao (1984) have noted that bore-wells tap ground water in the aquifer while dug wells penetrate only the overlying aquitard. CGWB investigations have revealed that dug wells in these rocks have yields varying from 40 to 12 m^3/day in winter months to 10 to 30 m^3/day in summer months (Sudarshan and Rao, 2004). The bore well yields in the KRSB is varying from as low as 0.5 m^3/hour to high as 27 m^3/hour (Venkateswara Rao, 1994).

Venkateswara Rao (2003) has observed the pre monsoon and post monsoon water levels in KRSB of Vizianagaram district and found that ground water potential areas have less fluctuations of water levels than in non-potential areas. This point can be used as a good ground water prospection tool. The groundwater fluctuation studies by Siva Prasad (2017) have indicated that there is 10 m depletion of groundwater levels in the KRSB basin between the years 1993 to 2014. Siva Prasad and Venkateswara Rao (2015) have estimated Transmissivity (T) and Storage Coefficient (S) values of KRSB and found that T values are varying between a minimum of 37.2 m^2/day to a maximum of 304.3 m^2/day, while S values are varying between a minimum of $2.91x10^{-4}$ to a maximum of $91.5x10^{-4}$. They have also observed that T and S values are minimum at the main stream of the basin where aquifers have been kaolinized to maximum extent. The T and S values are maximum at flat uplands where the aquifers are subjected to minimum kaolinisation. Siva Prasad (2017) has estimated the groundwater recharge in the KRSB and found that about 12 per cent of the total rainfall in the basin goes as groundwater recharge. Groundwater flow model of this basin has indicated that hydraulic conductivity of the weathered layer is varying from 1.6 - 1.9 m/day while that of the fractured layer below it is varying from 1.6 to 2.3 m/day. Groundwater flow modeling studies by Radhika et al., (2000) in Mallavaram basin of East Godavari district covered by khondalitic terrain have shown that the average ground water recharge is of the order of 16% of the total rainfall. Well logging investigations by Venkateswara Rao et al., (2017) have revealed that the aquifer porosity is of the order of 28% in the KRSB. According to the CGWB (2013) report, the stage of development of groundwater for the three mandals of the study area namely Cheepurupalli and Garividi in the Vizianagaram district is nearly 70% which is higher in the Vizianagaram district. The modeling studies in the KRSB by Siva Prasad (2017) have indicated that there is a 100% development of groundwater in the basin and if the present withdrawal continuous, there will be development of dewatering of aquifers in certain pockets in the next few years. Modelling studies indicated that at least 50% of the groundwater usage has to be curtailed by adopting micro irrigation techniques.

Hydrogeophysical Studies

Sarma (1961) has published the results of the resistivity survey conducted in the neighbourhood of Gostani River. His studies of resistivities of core samples from a bore hole indicated that the resistivities obtained from the surveys served to obtain clearly the resistivity contrasts among different formations though actual correspondence in magnitude was not obtained. Bhaskara Rao and Sarma (1962) have reported the results of geophysical survey carried out near Visakhapatnam Oil Refinery. They observed that the topsoil has resistivity of 200 ohm-m to 500 ohm-m, water saturated rock has 200 ohm-m to 250 ohm-m and unsaturated rock over 500 ohm-m. Sarma (1977) delineated four distinct sub-surface horizons having resistivity ranges of 100 to 160 ohm-m, 12.8 to 68 ohm-m, 360 to 680 ohm-m and 1100 ohm-m, representing the top soil zone, weathered kaolinised khondalite, fissured and fractured zone and hard rock, respectively. The narrow strip of coastal zone between the northern part of Eastern Ghat ranges and Bay of Bengal is also found to be a good source of ground water (Sarma, 1965). Extensive geoelectrical surveys carried out in this area have indicated the possibility of obtaining fresh water at depths extending to 35 m (Prasad, 1980).

Venkateswara Rao and Briz-Kishore (1991) noticed that for a good yield, the thickness of the weathered and fractured layers must not be too high. In fact the higher the weathered depth, the more will the well be susceptible for failure. Further investigations by Venkateswara Rao (1998c) in the KRSB of Vizianagaram district have revealed that there are four distinct subsurface layers: (i) top soil zone with an average thickness of 3 m, (ii) highly weathered khondalite (kaolinised layer) with an average thickness of 16 m, (iii) moderately weathered and fractured khondalite, which is the principal aquifer layer with an average thickness of 20 m and (iv) basement of granite gneiss (Figure 2). Interpretation of geoelectrical data fails to reveal a sharp contrast between the second and third layer at many places as shown in Figure 2. First layer resistivities in the range of 150 ohm-m and more are associated with the occurrence of quartz vein on the ground surface and quartzisation in sub-surface layers leading to good yields from bore wells. The optimum range of resistivity of potential aquifer layer is 25-65 ohm-m. Lower ranges of resistivity are indicative of increasing degree of kaolinisation and higher than 65 ohm-m range represents increasing degree of basement characteristics. There are two ranges of optimum depth to the electrical basement, one is at the 20-30 m range and other is at the 40-45 m range. Depth smaller than 20

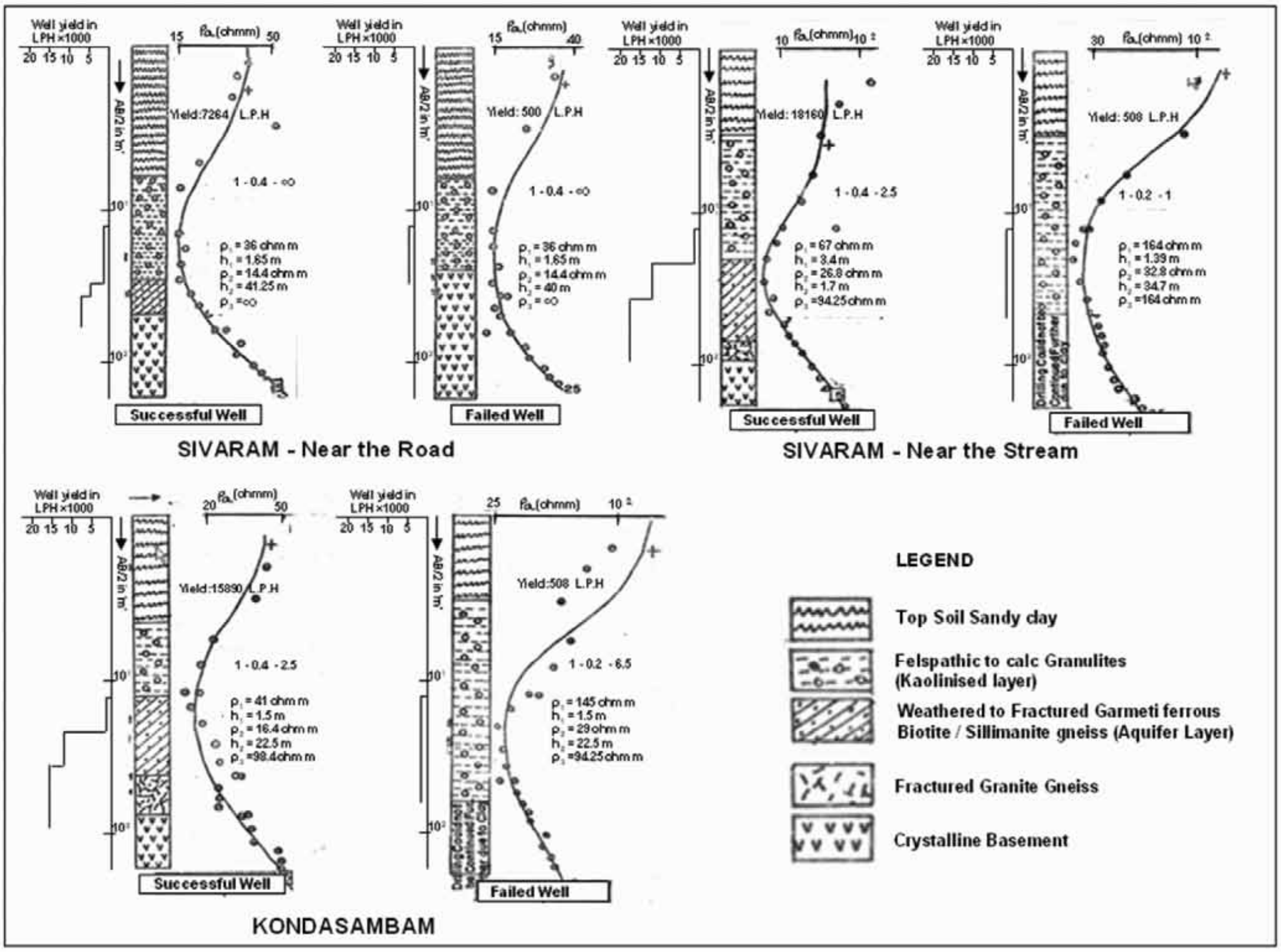

Figure 2. Vertical Electrical Sounding curves, Yield logs and Lithologs of adjacent success and failed wells in KRSB (Venkateswara Rao et al., 2013).

m are inadequate to hold a reasonable quantity of ground water and if the depth is more than 45 m there is likely hood of a deeper and more intensively weathered kaolinised layer to occur in the system. Venkateswara Rao (2002) has further analysed the resistivity data of the KRSB basin with the multivariate statistical analysis. It is inferred that high yielding wells are characterized by an average value of transverse resistance of 1227 ohm-m^2 and an average value of aquifer resistance of 1093 ohm-m^2 with the aquifer resistivity ranging between 23-43 ohm-m and its thickness varying in the range of 27- 48m.

Venkateswara Rao et al., (2011) have conducted multi-geophysical techniques at successful and failed wells of KRSB (Figure 1). They found that to produce a good well yield, fracture system must be extended in all the four directions, which is identified with high values of coefficient of anisotropy while the unidirectional fracture system may not produce good well yield, which is identified with less value of coefficient of anisotropy. Shallow seismic refraction method and very low frequency electromagnetic method could not be of much help to find the fracture zones. Venkateswara Rao et al., (2013) and Venkateswara Rao and Siva Prasad (2015) have conducted 2D and 3D resistivity imaging at successful and failed wells (Figure 1) in the KRSB and found that at failed wells, kaolinization is not only thicker (> 20 m.) but also followed by the basement characteristics either with thin or no aquifer layer immediately below the kaolinised layer. At successful wells, not only the kaolinised layer is thinner (<20 m.) but also aquifers are thicker (> 20 m.). Siva Prasad (2017) has found that kaolinized layers are having low chargeability compared to the other fractured khondalitic formations.

Hydrogeochemistry

Sarma, (1982) has observed that in the Eastern Ghat basins a regular increase in the total dissolved salt content increased with a decrease in elevation. It is also observed that a few pockets of high conductivity zones exist in the area. The highly conductive zones are associated with areas of the lowest elevation, where, due to absence of movement of ground water, maximum Base Exchange process takes place. Water quality maps of Visakhapatnam basin have been prepared by Sarma et al., (1980) with the help of Piper classification. They observed a general predominance of secondary alkalinity and neutral water with secondary salinity and high dissolved salt content in low elevation areas.

Sarma and Narayana Swamy (1986) have given a hydrogeochemical approach to the interpretation of ground water movement in the unconfined condition of the region. They observed that in general, as the topography sloped down along the hill ranges to the plains, the sequence of bicarbonate-chloride water is followed by chloride-bicarbonate water, again followed by chloride-sulphate water confirming the fact that in general ground water movement follows topography. Subba rao and Krishna Rao (1991) have concluded that in Visakhapatnam basin, wells are undesirable at topographic lows (below 15 m contour line) and desirable at topographic highs (above 15 m contour line) as the former contain water with heavy concentrations of total dissolved solids, total hardness, bicarbonates, chlorides and sulphates associated with corrosion and incrustation of wells, while the latter is free from them.

Hydrogeochemical investigations in the Kandivalasa River Sub Basin by Venkateswara Rao (1998a) have revealed that upland areas of this basin are having neutral quality of water while in the lowland areas, the water is having secondary alkalinity in upstream portion and primary salinity in down stream portion. Studies on Total Dissolved Salts (TDS) and topography across the main stream have shown that the TDS follows the topography i.e., at the flanks the TDS is more and gradually decreases towards the main stream. This may be due to the fact that more salts must have been dissolved in the ground water while it is percolating down greater over burden thickness in reaching water table at the flanks of the basin than that at the main stream where there is less over burden thickness. Along the main stream TDS has gradually increased towards the downstream, a fact that confirms the general belief of identity in the movement of surface and sub surface waters. However, Fluoride is a recent observation by Siva Prasad (2017) who has reported more than 1.5 ppm in some parts of the KRSB. Similarly, he has also observed that Nitrate is another important chemical constituent in groundwater and found to be exceeding the permissible limit of groundwater in more than 50 per cent of the samples collected from KRSB, due to use of more fertilizers in the basin. CGWB has noticed the nitrate values more than 100 mg/L at Vijayanagaram, Cheepurupalli, Payakapadu, Gharbam and Kanimetta stations in the Vizianagaram district. Chemical pollution by way of applying nitrogenous fertilizers in the agriculture sector is the root cause of high nitrate content in the groundwater (CGWB, 2013).

CONCLUSIONS

Northern parts of Eastern Ghat Khondalites are sedimentary in origin but later metamorphosed and became hard rocks. The basement is granitic gneiss. In general charnokites and quartzites have intrusive character in khondalites. These rocks were subjected to intense weathering, faulting, fracturing and folding giving way to accumulation of ground water in two layers mainly in weathered layer and fractured layer with hydraulic continuity among them. Streams followed the fault zones and fractured zones giving rise to dendritic pattern of drainage owing to the homogeneity of khondalitic formation. Beneath the streams and low-lying areas most of the khondalitic formations became kaolonised and turned out to be low potential zones suitable only for open wells. This kaolin, which is essentially clay is acting as a barrier for the ground water movement towards the stream and forcing it to accumulate in the upland areas between the streams and naturally became groundwater potential zones for high yielding borewells whenever the formation is fractured and intruded with quartz veins. Lack of resistivity contrast between highly weathered khondalite and fractured khondalite with Vertical Electrical Sounding data at few places calls for applying 2D and 3D Resistivity Imaging where in more data points and their inversion are revealing the kaolinisation phenomena in the subsurface to avoid well failures. The extended deeper kaolinisation of the aquifer is responsible for failure of wells in this terrain. At failed wells, kaolinisation is not only deeper but also followed by the basement characteristics either with very thin or no aquifer layer immediately below the kaolinised layer. At successful wells not only kaolinised layer is thinner but also aquifers are thicker and basement characteristics are found only at deeper depths. Layers having resistivities between 25-65 Ohm-m are identified as aquifer layers, which are composed of moderately weathered and fractured khondalitic suite of rocks. Layers with resistivities greater than 65 Ohm-m are interpreted to have basement characteristics belonging to the granite gneiss, while the layers with resistivities less than 25 Ohm-m are interpreted as kaolinised. Transmissivity values are varying between a minimum of 37.2 m^2/day to a maximum of 304.3 m^2/day, while Storage coefficient values are varying between a minimum of $2.91x10^{-4}$ to a maximum of $91.5x10^{-4}$. Groundwater flow model of KRSB basin has indicated that hydraulic conductivity of the weathered layer is varying from 1.6 - 1.9 m/day, while that of the fractured layer below it is varying from 1.6 to 2.3 m/day. The aquifer porosity is of the order of 28% in the KRSB. The quality of the ground water in this region is generally good and suitable for both drinking and irrigation purposes except at few pockets where Fluoride and Nitrate is present in excess of permissible limits. Similarly, in downstream areas of major streams, high salinity is present.

In view of the increased abstraction of the groundwater, there will be development of dewatering of aquifers in certain pockets in the next few years. Modelling studies have indicated that at least 50% of the groundwater usage has to be curtailed by adopting micro irrigation techniques in the agriculture, enhancing of surface water storage by rainwater harvesting and increasing the groundwater recharge with flood waters.

ACKNOWLEDGEMENTS

Thanks are due to Dr.P.R.Reddy, Chief Editor for his continued support, objective evaluation of the manuscript and apt editing.

Compliance with Ethical Standards:

The author declares that he has no conflict of interest and adheres to copyright norms.

REFERENCES

Bhaskara Rao, V., and Sarma, V.V.J., 1962. A Case History of Geophysical Prospecting for Water in Visakhapatnam Area, Bulletin of the National Institute of Science, India, no.22, pp: 102-114.

CGWB (Central Ground Water Board), (2013) Ground Water Yearbook.

Chetty, T.R.K., Vijay, P., Vijaya kumar, T. and Suresh, B.V.V., 2002. GIS and the Tectonics of the Eastern Ghats, India, GIS Development, v.6, no.12, pp: 21-24.

Cross Whitman, 1914. The position of the Kodurites in Quantitative Classification, Journal of Geology, v.22, pp: 791-806.

Dey, A.K., 1968. Geology of India, National Book Trust, New Delhi, India, pp: 178.

Fermor, L.L., 1909. Manganese Ore Deposits of India, Mem. of G.S.I., v.37, and Rec.35, pp: 1046-1115.

Fermor, L.L., 1915. Rec. Geological Survey of India, v.XLV, pp: 102.

Kanungo, D.N. and Murthy, D.S.N., 1981. Structural Features of Khondalites and Associated Rocks Between Vizianagaram-Garividi in Eastern Ghats Belt of India, Geophysical Research Bulletin, v.19, no.1, pp: 35-50.

Krishnan, M.S., 1968. Geology of India and Burma, Higgin Bothams (P), Madras, India, p: 555

Krishna Rao, J.S.R., 1952. The Geology of Chipurupalle Area, Visakhapatnam District with Special Reference to the Origin of Manganese Ores, Geological Society of India, v. XXVI, no.1, pp: 36-45.

Mahadevan, C., 1929. Geology of Vizag Harbour Area, Quar. Jour. Geol.Min. Metal. Soc. India, v.2, no.4.

Miller C.V., and Miller, C.F., 1961. Photogeology, Mc Graw Hill Book Co., New York, pp: 215.

Narayanaswamy, A., 1980. Geohydrology of Visakhapatnam Basin, Ph.D. Thesis, Andhra University, India. pp: 192.

Narayanaswamy, S., 1975. Proposal for Charnockite Khondalite System in the Archean Shield of Peninsular India, In: Precambrian Geology of Peninsular Shield, Geological Survey of India, Miscellaneous Publications, no.23, Part.1, pp: 1-16.

Nooka Raju, D., and Jaganmohan Rao, D., 1990. Augmentation of Ground Water Yield Through in Well Bores in Hard Rock Terrain in Vizianagaram district – An Appraisal, Procs. Of the Seminar on Ground water Resources Development and Management in Andhra Pradesh S.G.W.D., A.P., pp: 173-174.

Prabhakar Rao, G., 1950. The Geology of Manganese bearing rocks of Garividi and Garbham, Visakhapatnam District, Quart. Jour. eol.Min.Met.Soc. of India, v.22, no.2, pp: 25-42.

Prasad, N.V.B.S.S., 1980. Geohydrological and Geophysical Investigations along Visakhapatnam-Bhimilipatnam Coast, Ph.D. Thesis, Andhra University, India, pp: 250.

Prudhvi Raju, K.N., and Vaidhyanadhan, R., 1981. Fracture Pattern Study from Landsat Imagery and Aerial Photos of a part of the Eastern Ghats in Indian Peninsula, Journal Of The Journal of Geol.Soc. of India, v.22, no.1, pp: 17-21.

Radhika, K., Venkateswara Rao, B., Gurunadharao, V.V.S., and Dhar, R.L., 2000. Coupled Recharge and Groundwater Flow Model in Mallavaram Watershed in East Godavari District, A.P., Procs. Of the National Seminar on Geophysical Exploration Retrospect and Prospect conducted by Department of Geophysics , Andhra University at Visakhapatnam, pp: 57.

Raghavaswamy, V., 1981. Landforms and Systems and Geographical Synthesis of Visakhapatnam Tract in the East Coast Plain of India, Ph.D Thesis, Andhra University, India. pp: 285.

Ramana T.V., 1980. Geohydrological Characteristics of the Ground Water Basins of Khondalitic terrain of Eastern Ghats, Ph.D. thesis, Andhra University, India. pp: 201.

Rao, G.V., 1964. Structural Control and Origin of the Manganese Ore Deposits in Visakhapatnam Manganese Belt, Andhra Pradesh, International Geological Congress, Part V, pp: 215-227.

Sarma, V.V.J., 1961. Resistivity Investigations along Gostani River, Bulletin of the National Institute of Science, India, no.22, pp: 77-93.

Sarma, V.V.J., 1965. Preliminary Investigations on the Occurrence of Fresh Water Wells along Visakhapatnam Beach, Andhra Pradesh, India, Jourl. Ind. Geophy. Uni., v.2, no.4., pp: 197-207.

Sarma, V.V.J., 1967. Hydrogeology of Visakhapatnam Region of Eastern Ghats, Jour. Ind.Geophy Union, v.4, no.2, pp: 422-431.

Sarma, V.V.J., 1977. A Case History of the Application of the Geoelectrical Sections of Khondalitic Zones of Eastern Ghats, Geophysical case Histories of India, AEG, Hyderabad, India, v.1, pp: 211-118.

Sarma, V.V.J., 1982. Ground Water Resources of Northern Eastern Ghats, Procs. Of the Seminar on resources Development and Environment in the Eastern Ghats, Visakhapatnam, pp: 69-75.

Sarma, V.V.J., and Narayanaswamy, A., 1986. Regional Ground Water Flow Investigations in Visakhapatnam Basin, Andhra Pradesh, Journal of Geological Society of India, v.27, pp: 386-391.

Sarma, V.V.J., Prasad, N.V.B.S.S and Rajendra Prasad, P., 1983. A study of Water Level Fluctuations and Estimation of Recharge and Recession along the Coastal Strip of Visakhapatnam-Bhimilipatnam, Journal of Association of Exploration Geophysicists, v.4, pp: 49-65.

Sarma, V.V.J., Ramana, T.V. and Narayanaswamy, A., 1980. Water Table and Water Quality Studies in Visakhapatnam, Jour. Of the Institution of Engineers (India), v.60, pp: 312-316.

Siva Prasad, Y., 2017. Geohydrological and Groundwater Modelling Studies of a Khondalitic Aquifer, a Ph.D. thesis, Submitted to JNT University Hyderabad.

Siva Prasad. Y., Venkateswara Rao, B., 2015. Geohydrologcal Investigations of a Typical Khonalitic Terrain of Vizianagaram District of Andhra Pradesh, India, Proceedings of the 32nd & 33rd AHI Annual convention and National Seminar on "Water Resources"

Sriramdas, A., and Rao, A.T., 1979. Charnockites of Visakhapatnam A.P., Jour. Of. Geol. Soc. Of India, v.20, pp: 512-517.

Subba Rao, C., 1974. Studies on Some Aspects of Hydrogeology of Chandrampalem Basin, Ph.D. Thesis, Andhra University, India, pp: 220.

Subba Rao, N. and Krishna Rao, G., 1984. Dug Wells and Bore Wells in Hard Rock Aquifers of Visakhapatnam District, Andhra Pradesh – A Comparative Study, Journal of Association of Exploration Geophysicists, v.4, no.4, pp: 11- 18.

Subba Rao, N., and Krishna Rao, G., 1991. Ground Water Chemistry for Location of Wells in Visakhapatnam area, Andhra Pradesh, Bhujal News, v.10, pp: 7-10.

Sudarshan, G., Rao, P.N., 2004. Ground Water in Andhra Pradesh, unpublished report, CGWB.

Venkateswara Rao, B., and Briz-Kishore, B.H., 1990. Influence of topography over the Yields of Bore Wells in a Typical Khondalitic Formation, Procs. Of the Seminar on Ground Water Resources Development and Management in Andhra Pradesh, Hyderabad, India, pp: 43-50.

Venkateswara Rao, B., and Briz-Kishore, B.H., 1991. A Methodology for Locating Potential Aquifers in a Typical Semi-Arid Region in India Using resistivity and Hydrogeologic Parameters, Geoexploration, v.27, pp: 55-64.

Venkateswara Rao, B., and Ramadurgaiah, D., 1996. Comparative Analysis of Geoelectric and Lithologic Data in a Typical Khondalitic Terrain, Procs. of the 2nd International Seminar and Exhibition on Geophysics Beyond 2000 conducted by AEG, Hyderabad. pp: 403-405.

Venkateswara Rao, B., 1994. Integrated Studies for Evaluation of Ground Water Potential in a Typical Khondalitic Terrain, a Ph.D. thesis in Water Resources submitted to JNT University, pp: 284.

Venkateswara Rao, B., 1998a. Hydrogeochemical Characteristics of a typical Khondalitic Aquifer". Procs. of the National Seminar on Conservation of Eastern Ghats, held at Visakhapatnam by ENVIS centre EPTRI, Hyderabad pp: 154-167

Venkateswara Rao, B., 1998b. Hydromorphogeological Investigations in a Typical Khondalitic Terrain Using Remote Sensing Data, Photonirvachak, Journal of the Indian Society of Remote Sensing, v.26, no.1 & 2, pp: 77-93.

Venkateswara Rao, B., 1998c. Geoelectrical Characteristics of a Typical Khondalitic Aquifer, Bhu-jal News a quarterly journal of CGWB, Ministry of Water Resources, Govt. of India v.13, no.3 & 4 , pp: 21-30.

Venkateswara Rao, B., Subramanyam, K., Murthy, E.S.R.C., Varalakshmi, V., and Satyanarayana, B., 2011. Problems and Prospects of Geophysical Methods in identifying Ground Water Potential Zones in Typical Hard Rocks of India, Hydrology Journal, v.34, no.3 & 4, pp: 85-95.

Venkateswara Rao. B., Siva Prasad, Y., and Srinivasa Reddy, K., 2013. Hydrogeophysical Investigations in a Typical Khondalitic Terrain to Delineate the Kaolinised Layer using Resistivity Imaging, the Journal of Geological Society of India, v.81, pp: 521-530.

Venkateswara Rao, B., Siva Prasad, Y., 2015. Delineation of Kaolinised Zones by using Three Dimensional Resistivity Imaging in a Typical Khondalitic Terrain to Contain Water Well Failures, Journal of Geophysics, v.XXXVI, no.4, pp: 197-209

Venkateswara Rao, B., Siva Prasad, Y., and Narasaiah, V., 2017. Field work information of SERB sponsored research project, unpublished.

Received on: 15.9.17, Revised on: 27.10.17; Accepted on: 10.11.17