



Assessment of Groundwater Conditions in the Watershed  
covering Kolhar Industrial Area, Naubad, Bidar,  
Bidar District, Karnataka

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**Assessment of Groundwater Conditions in the Watershed  
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***Executive Summary***

Karnataka State Pollution Control Board (KSPCB), Bangalore requested CSIR-NGRI to carry out groundwater study in the Kolhar Industrial Area for assessment of groundwater pollution and generation of base line hydrogeologic data. NGRI has selected a network of 65 observation wells for groundwater monitoring during April 2012 and January 2013 for ascertaining the groundwater flow direction in the Kolhar industrial Area, Naubad, Bidar District, Karnataka. Depth to groundwater in the industrial area varied from 5 to 15 m (bgl) during the monitoring period in the basaltic terrain. Shallow groundwater condition near the Marar Halla stream could be noticed and the groundwater flow direction is from Kolhar Industrial Area towards the West .

Water quality monitoring has identified four TDS contaminant plumes in the Kolhar Industrial Area reporting elevated concentrations varying from 2000 - 8000 mg/l. Elevated concentration of chloride and Sodium were also observed. There is no fluoride contamination and the concentration of heavy metals are also found within permissible limits. The groundwater monitoring was made mostly in the open wells inside the industrial area in the basaltic terrain suggest that once the groundwater recharge due to rainfall enters the groundwater regime through top laterite layer, it travels along the groundwater flow path depending on hydraulic gradient and groundwater velocity. The water quality database identified four contaminant plumes with regard to elevated TDS concentration and the plumes are migrating towards west of the Industrial area from the eastern boundary. Major contaminants include, TDS, Chloride and Nitrate with little elevated heavy metal presence in the groundwater was noticed during the water quality monitoring. But their concentrations are only slightly elevated along groundwater flow path. Similarly, the heavy metal concentration like Barium, Cobalt, Chromium and Manganese shows elevated in the Obs wells inside the industrial Area only. There is no threat to the public water supply wells or irrigation wells outside the industrial area. Significantly there is no problem encountered with regard to elevated concentrations towards the Air Force Base Station, Bidar. The groundwater quality database of December 2013 from RO, Bidar confirm the four contaminant plumes.

The aquifer characteristics were estimated on 6 open wells and 2 bore wells through pumping tests. The hydraulic conductivity was found varying from 1.5 to 10 m/day in the industrial area and also in the outside. The in situ infiltration rates estimated in the industrial area indicated high values, which is favorable for good groundwater recharge. Thus any surface water contamination from the top surface enters the groundwater regime, it may migrate fast in groundwater with groundwater velocity through advection and mixing through dispersion mechanism. The hydraulic gradient is controlled by pumping within the industrial area as well as pumping by irrigation wells outside.

The resistivity investigations employing Vertical Electrical Soundings indicate that the groundwater regime in the basaltic rocks occurs in weathered and semi-weathered conditions. The thickness of weathered and fracture zone occurring just below the laterite cover is generally varying from 10 – 35 m (bgl) in the industrial Area. The high infiltration rates reported from the industrial area on laterites indicate that the area is vulnerable for groundwater contamination from liquid waste disposal from industries. There is no groundwater contamination in the Air Force Base station adjacent to the Kolhar industrial area as there is no heavy groundwater pumping taking place close to the industrial area.

The groundwater flow and mass transport models were constructed using the above hydrogeologic and water quality data base. The groundwater flow model was calibrated for groundwater conditions of April 2012. The computed groundwater velocity from the groundwater flow model was 30 m/yr. Simulated four identified contaminant plumes with varying concentrations in the mass transport model. The contaminant migration was calibrated for 20 year period during April 2012 and prediction of contaminant plume migration for next 30 years was made in the mass transport model. The mass transport model predictions indicate that the contaminant migration from four contaminant sources is limited to the western boundary of the industrial area. Remedial measures suggested include that no liquid waste disposal may be allowed within the industrial area as in situ infiltration rates of top laterite is high. The industrial area is vulnerable for fast contaminant migration based on large thickness of high permeability of weathered and semi-weathered formations. Industrial Area should have a Common Effluent treatment plant outside the industrial area and all industries should send their partially treated effluents for treatment in the CETP.

## Assessment of Groundwater Conditions in the Watershed covering Kolhar Industrial Area, Naubad, Bidar, Bidar District, Karnataka

### 1.0 Introduction

Kolhar Industrial Area (KIA), Bidar District, Karnataka is considered one of the thickly populated industrial zone in Karnataka. Small and large scale industries were established in the industrial Area during 1980's. Few industries have been closed down and others are carrying out their activity. The working industries include pharmaceuticals and few small scale industries. No Common Effluent treatment plant (CETP) was functioning in the KIA and the untreated effluents are disposed in the stream channels or in open areas. Thus groundwater contamination has been noticed in some parts of the industrial area and at places the groundwater has been found not suitable for drinking or agriculture use.

Karnataka State Pollution Control Board (KSPCB), Bangalore requested CSIR-National Geophysical Research Institute, Hyderabad to assess the groundwater conditions through detailed geohydrological investigations in the watershed covering Kolhar Industrial area, Naubad, Bidar, Karnataka. Based on their request a MOU has been signed between KSPCB, Bangalore and CSIR-NGRI, Hyderabad with an objective to carry out detailed hydrogeological investigations through monitoring of groundwater level, water quality as well as delineation of aquifer geometry. These information generated through these investigations has been used for making groundwater flow and mass transport modeling of the area for predicting migration of contaminant plume in groundwater.

The scope of the investigations includes assessment of groundwater conditions and groundwater quality in the watershed covering KIA. The NGRI, Hyderabad has carried out the following investigations:

- Selection of 57 observation wells during pre-monsoon and 66 wells during post-monsoon period for monitoring of water level

- Assessment of groundwater quality through major ions and heavy metal analyses
- Preparation of groundwater level contours for ascertaining groundwater flow direction
- Vertical Electrical Soundings for delineation of aquifer geometry
- Estimation of Aquifer parameters
- In-situ infiltration test
- Groundwater flow and mass transport modeling studies for assessment of groundwater contaminant plume migration paths and predictions for future.

### **1.1 Kolhar Industrial Area**

The Industrial area is located about 10 km from the Bidar town near Kolhar Khurd village, Naubad taluk, Bidar. The Air Force Base Station, Bidar forms the Eastern Boundary of the industrial area (Fig. 1). Nizampur and Belur villages form the western and southern boundaries. The drainage pattern is sub-dentric and surface water from the industrial area flows in stream joining stream Marar Halla. The industrial area lies on an elevated plateau. The ground elevation in the IA is 662 m (amsl). The ground slopes towards south-Western to South.

### **2.0 Geology**

The watershed consists of Deccan Basalts covered with lateritic capping of varying thickness. Deccan Basalts are grouped under hard rocks, as they have limited inter-granular porosity. The thickness of Laterite capping varies from 20 m to 30 m in the watershed. The laterite are product of intensive and long lasting tropical rock weathering which is intensified by high rainfall and elevated temperatures. Laterite forms potential aquifers along valleys. The occurrence and movement of groundwater in the laterite are mainly controlled by the topography. The porosity and permeability of Basalts varies within individual basaltic flow and also from one flow to another. The weathered zones, jointed and fractured in massive and vesicular Basalts forms the water bearing horizons. Abundance of vesicles with interconnecting nature coupled with joints and horizontal partings in the vesicular basalt make it a good aquifer. No significant major or minor lineaments are passing through the Industrial Area (Fig. 2).

### 3.0 Hydrogeology

Groundwater monitoring was carried out on 56 observation wells including open wells and bore wells during April 2012 (Fig. 3). The topographic elevation varied from 669.94 m (amsl) near Chidri in the North east to 627.5 m(amsl) in the Nizampur village (Fig. 4a). The highest ground elevation of about 663.38 m(amsl) could be found in the Industrial Area on the north east and 651.03 m (amsl) in the southern part. The ground elevation is varying from north east to south west in the industrial area (Fig. 4b).

### 4.0 Groundwater Conditions

Groundwater occurs under water table condition in the shallow aquifers up to a depth of 20 m(bgl) and semi confined to confined condition at depth. The inter-trappean red bole horizon acts as an aquiclude to form a confined aquifer. The weathered zone occurs to a depth of 25 m(bgl) and semi confined condition could be found up to 25 m - 40 m depth. The jointed and fractured formations allow groundwater movement at greater depths. Laterite is highly porous rock formation, which can form potential aquifers along topographic lows. However due to this porous nature, groundwater is drained from elevated places and slopes at shortest duration after monsoon due to which scarcity is experienced in the elevated places and slopes.

The depth of open wells varied from 15 m in the valley parts to 30 m in the industrial area on the ridge part. The depth of the bore wells varies from 90m to 120 m. The yield of the open wells ranges from 50 - 75 m<sup>3</sup>/day, whereas bore wells yield ranges from 5 to 6 m<sup>3</sup>/hr. The depth to groundwater was measured in 57 selected observation wells during pre monsoon season (April 2012) (Fig. 5 & Table 1). A Differential Global Position System (DGPS) survey was conducted at all observation wells to know absolute elevation with respect to the mean sea level. The depth to groundwater ranged from 6.2 m to 28.29 m (bgl) in the watershed during pre monsoon of 2012. The minimum depth to groundwater was reported from Belur village, whereas maximum depth was found in the industrial area near Kolhar khurd village.

The groundwater level contours of pre monsoon 2012 indicates that groundwater in general flows from central part of the Industrial Area towards West and also from North east to south west in the southern part of industrial area. The highest groundwater elevation reported was 650 m(amsl) from central part of the industrial area



whereas lowest groundwater elevation was found as 618 m near Zamistapur in the southern part (Fig. 6). Groundwater flows from central part of industrial Area passes through Nizampur and later flows towards the Baghchaudi village.

Groundwater level monitoring was carried out for second time with 9 additional wells totaling to number of wells to 66 during post monsoon season i.e., January 2013 (Figs. 7 & 8 & Table 2). The lowest depth to groundwater was reported as 4.27 m (bgl) in the Belur well whereas the deepest groundwater was reported depth of 51.29 m (bgl) in obs. no. K60 in M/s. Surya kala Laboratories Pvt Ltd premises. The groundwater level contours of January 2013 indicate that similar flow directions as indicated during pre monsoon season (Fig. 9). In general the groundwater flow follows the topographic elevations.

## 5.0 Groundwater Quality

Groundwater quality was assessed during April 2012 as well as during January 2013 for major ions at all observation wells. The water quality was assessed for the major ions including pH, TDS and  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{HCO}_3^-$ ,  $\text{CO}_3^{3-}$  and  $\text{Cl}^-$  by volumetric method and Na and K by flame photometer and  $\text{F}^-$  by ion electrode,  $\text{NO}_3$  as  $\text{NO}_3$  by double beam spectro-photometer,  $\text{SO}_4^{2-}$  by a turbidity meter, pH by a pH meter, total dissolved solids by gravimetric method and conductivity by conductivity meter. The heavy metal analyses for B, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni and Pb were carried out during April 2012 and the occurrence of Al, Ag, As, Ba, Be, Cd, Co, Cr, Cu, Fe and Mn were analyzed during January 2013 samples.

The water quality analysis for major ion concentrations were reported during April, 2012 and January 2013 respectively were presented in Tables 3 & 4 whereas the heavy metal concentrations during April 2012 and January 2013 were presented in Tables 5 & 6 respectively. Potable nature of Drinking water was ascertained by comparing the water quality of various parameters determined with respect to World Health Organization (WHO, 1984) and Bureau of Indian Standards (BIS, 1991) (Table 7). The groundwater quality data during 2013 in Kolhar Industrial area was provided by RO, KSPCB, Bidar and no additional TDS plumes could be identified (Annexure I).

### 5.1 Major Ions Concentrations

#### 5.1.1 pH

The pH is an important variable in water quality assessments as it influences many biological and chemical processes within a water body and all processes

associated with water supply and treatment. When measuring the effects of an effluent discharge, it can be used to help determine the extent of the effluent plume in the water body. At a given temperature, pH (hydrogen ion activity) indicates the intensity of the acidic or basic character of a solution and is controlled by the dissolved chemical compounds and biochemical processes. In unpolluted waters, pH is principally controlled by the balance between the carbon dioxide, carbonate and bicarbonate ions as well as other natural compounds such as humic and fluvic acids. The natural acid-base balance of a water body can be affected by industrial effluents and atmospheric deposition of acid forming substances. The pH value of groundwater in the Industrial area is varying from 4.22 at Obs well No. K5 adjacent to the boundary of IA and to a maximum of 8.57 during the pre-monsoon (April 2012) (Fig. 10a). Low pH values were reported from K7, K5, K58 and K63 wells varying from 2- 4.1 during January 2013 (Fig. 10b). The low pH value may be attributed to liquid waste disposal practices around these wells.

### 5.1.2 Total Dissolved Solids (TDS)

TDS concentration in groundwater reported varied from lowest of 45 mg/l in observation wells no. K32 in Belur village whereas highest concentration of 10560 mg/l was reported in Obs well no. K15 in front of Satwik Drugs Pvt Ltd in the Industrial Area during April 2012 (Table 3 & Fig. 11a). It has been observed that most of the samples analyzed have TDS concentrations less than the prescribed limit with the drinking water standards and few samples have shown elevated concentration from the wells in the industrial Area. TDS concentration of groundwater during January 2013 ranged from 110 - 8620 mg/l (Table 4 & Fig. 11b). The lowest and highest concentration reported locations being same. Generally the post monsoon average TDS concentration in groundwater was reported slightly elevated compared to pre monsoon value. TDS concentration reported > 500 mg/l were in 20 samples (WHO, 1984) whereas > 2000 mg/l was found in 7 locations. Elevated TDS concentration was reported from industrial wells whereas the wells located outside have reported normal TDS concentration. High TDS (>1000 mg/l) exceeding the limit of portable water standard and causes gastro-intestinal irritation.

### 5.1.3 Sodium

Sodium (Na) was found in all natural waters, since the salts are highly soluble in water and it is one of the most abundant elements on earth's crust. **WHO (1984)** guide

limit for Sodium in drinking water is 200 mg/l. Many surface waters, including those receiving wastewaters, have levels well below 50 mg/l. However groundwater concentrations frequently exceed 50 mg/l. Sodium concentration varied from 1.79 -2174 mg/l with average values 104 mg/l for pre-monsoon period, whereas it ranged from 2.5 - 2018 mg/l with an average of 146.21 mg/l during post-monsoon period (Figs. 12a & 12b). The reported Sodium concentration was found exceeding the permissible limit of 200 mg/l in 12 samples during pre monsoon and post monsoon. The elevated concentrations are mostly found within the industrial area during January 2013.

#### 5.1.4 Potassium

Potassium ( $K^+$ ) is found in low concentration in natural waters since rocks which contain potassium are relatively resistant to weathering. However, potassium salts are widely used in industry and in fertilizers for agriculture and enter freshwaters with industrial discharges and runoff from agricultural land. Potassium concentrations found in natural waters are usually less than 10 mg/l. Potassium concentration in groundwater has been found to be varies from 0.06-144 mg/l with average of 5.82 mg/l in the pre monsoon period. During post-monsoon period the it is varies from 0.5-155 mg/l with average concentration of 5.30 mg/l (ref. Tables 3 & 4).

#### 5.1.5 Calcium

Calcium is present in all waters as  $Ca^{2+}$  and is readily dissolved from rocks rich in Calcium minerals, particularly as carbonates, Sulphate, especially limestone and gypsum. The elemental cation is abundant in surface and groundwater. The salts of calcium, together with those of magnesium are responsible for the hardness of water. Industrial water and wastewater treatment, processes also contribute calcium to surface waters. Acidic rainwater can increase the leaching of calcium from soils. Calcium concentrations in natural waters are typically less than 15 mg/l. For waters associated with carbonate rich rocks, levels may reach 30-100 mg/l. The calcium concentration in groundwater has been found to vary from 8-960 mg/l with average value of 84 mg/l in the pre-monsoon period and it is varies from 12-866 mg/l with average concentration of 90 mg/l in post-monsoon period in the watershed (Figs. 13a & 13b).. Calcium is another important element for classification of water irrigation uses. Elevated calcium concentrations are only noticed in the industrial area.

### 5.1.6 Magnesium

Magnesium is common in natural waters as  $Mg^{2+}$  and along with calcium, is a main contributor to water hardness. Magnesium arises principally from the weathering of rocks containing Ferro-magnesium minerals and from some carbonate rocks. Magnesium occurs in many organo metallic compounds and in organic matter, since it is an essential element for living organisms. Natural levels of magnesium in freshwater may range from 1 to 100 mg/l, depending on the rock types within the catchment area. The magnesium concentration has been found to vary from 0-291.72 mg/l with average value of 22.45 mg/l in the pre-monsoon period and 1-112 mg/l with an average of 10.71 mg/l during post-monsoon period respectively (Figs. 14a & 14b). The computed plumes indicate that industrial area wells possess slightly elevated magnesium concentration.

### 5.1.7 Carbonates and Bicarbonates

The presence of carbonates ( $CO_3$ ) and bicarbonates ( $HCO_3^-$ ) influences the hardness and alkalinity of water. The inorganic carbon component ( $CO_2$ ) arises from the atmosphere and biological respiration. The weathering of rocks contributes carbonate and bicarbonate salts. The relative amounts of carbonates, bicarbonates and carbonic acid in pure water are related to the pH. Bicarbonate is the dominant anion in most surface waters. Carbonate is uncommon in natural surface waters because they rarely exceed pH 9, whereas groundwater can be more alkaline and may have concentrations of carbonate up to 10 mg/l. The concentration of carbonates in pre-monsoon period varies from 0-100 mg/l with average value of 8.42 mg/l. Similarly, bicarbonates in groundwater have been found varying from 3.5 - 275 mg/l with average values of 75.06 mg/l. During post-monsoon period the bi-carbonate concentration were ranges from 10-380 mg/l with average of 107.79 mg/l (ref. Tables 3 & 4).

### 5.1.8 Chloride

Most chlorine occurs as chloride (Cl) in water. Higher concentrations can occur near sewage and other waste outlets, irrigation drains, saltwater intrusions, in arid areas and in wet coastal areas. As chloride is frequently associated with sewage, it is often incorporated in the assessments as indication of possible fiscal contamination or as a measure of the extent of the dispersion of sewage discharge in water bodies. In the study area Cl concentration varies from 5-5570 mg/l in the pre-monsoon period with average value of 284.39 mg/l, while during post-monsoon period it is varies from 3-3890

mg/l with average value of 282.47 mg/l (Figs. 15a & 15b). Elevated chloride concentrations during post-monsoon period were found in 17 samples and the plume size has reduced due to dilution with groundwater recharge during post monsoon season.

### **5.1.9 Sulphate**

Sulphate is naturally present in surface waters as  $\text{SO}_4^{2-}$ . It arises from the atmospheric deposition of oceanic aerosols and the leaching of sulphur compounds, either Sulphate minerals such as gypsum or Sulphate minerals such as pyrite, from sedimentary rocks. It is the stable, oxidized form of sulphur and is readily soluble in water (with the exception of lead, barium and strontium sulphates which precipitate). Industrial discharges and atmospheric precipitation can also add significant amount of sulphate to surface water. Sulphate can be used as an oxygen source by bacteria which convert it to hydrogen sulphide ( $\text{H}_2\text{S}$ ,  $\text{HS}^-$ ) under anaerobic conditions. Sulphate concentrations in natural waters are usually between 2 and 80 mg/l, although levels may exceed 1000 mg/l near industrial discharges or in arid regions where sulphate minerals (eg gypsum) are present. High levels of sulphate (>400 mg/l) may make water unpleasant to drink. In the study area  $\text{SO}_4$  concentration varies from 0.20-300 mg/l with average values of 27.61 mg/l during pre-monsoon period. During post-monsoon period it is varies from 0.4-743 mg/l with average value of 52.42 mg/l. Elevated Sulphate concentrations are found in 4 obs wells and are within industrial area (Figs. 16a & 16b).

### **5.1.10 Nitrate as Nitrate**

Natural sources of nitrate to surface water include igneous rocks, land drainage and plant and animal debris. Natural levels which seldom exceed 0.1 mg/l  $\text{NO}_3^-$ - $\text{NO}_3^-$ , may be enhanced by municipal and industrial wastewaters, including leachate from waste disposal sites and sanitary landfills. In rural and suburban areas the use of inorganic nitrate fertilizers can be a significant source. The nitrate as nitrate concentration in groundwater during pre-monsoon was found to be ranging from 0 - 27.5 mg/l with average value of 3.86 mg/l whereas it ranged from 0.3 -398 mg/l with average concentration of 23.06 mg/l during post monsoon(Figs. 17a & 17b). High concentrations of Nitrate were found more than permissible limit in 5 samples.

### 5.1.11 Fluoride

The fluoride concentration in the groundwater during post-monsoon period was ranging from 0.18-3.06 mg/l with average concentration of 0.46 mg/l. High concentration of fluoride was found in 3 samples only which are attributed to local geology rather than industrial impact. There is no elevated Fluoride concentration found in rest of the area.

## 5.2 Heavy metals

Heavy metal analyses like B, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni and Pb were analyzed for April 2012 (pre-monsoon) samples (Table 5) and Al, Ag, As, Ba, Be, Cd, Co, Cr, Cu, Fe and Mn were analyses for January 2013 (post-monsoon) period (Table 6) respectively in the watershed covering 5 km radius of Kolhar Industrial Area. The results of some of the trace elements like Ba, Be, Cd, Co, Cr, Cu, Fe and Mn were discussed below.

### 5.2.1 Barium

The Barium concentration during pre-monsoon (April 2012) were ranges from 0-1368 µg/l with average value of 78.77 µg/l. The maximum concentrations of 1368 µg/l were found in the dug well sample collected in front of Swatik Drug Ltd (K-14). During post-monsoon (January 2013) the barium concentration were ranges from 0.816-505.6 µg/l with average value of 42.39 µg/l (Figs. 18a & 18b). The plumes are only indicative of extrapolation feature rather than pollution impact.

### 5.2.2 Beryllium

Beryllium concentrations during pre-monsoon were ranges from 0-6.193 µg/l with average value of 0.80 µg/l. During post-monsoon season the concentration were ranges from 0.001-2.213 µg/l with average concentration value of 0.041 µg/l (Tables 5 & 6). No elevated concentrations of beryllium were found in the water.

### 5.2.3 Cadmium

The Cadmium concentration during pre-monsoon were ranges from 0-29.61 µg/l with average value of 0.96 µg/l, while during post-monsoon the concentration were

ranges from 0.004-0.139 µg/l with average value of 0.025 µg/l (Figs. 19a & 19b). The cadmium plumes are located inside the industrial area only.

#### **5.2.4 Cobalt**

During pre-monsoon season the Cobalt concentration were ranges from 0-828 µg/l with average value of 20.30 µg/l. The maximum values of 828 µg/l were found in the sample No. 5 near boundary of Air Force station. During post-monsoon season the cobalt concentration were ranges from 0-153.6 µg/l with average value of 3.55 µg/l (Figs 20a & 20b).

#### **5.2.5 Total Chromium**

The total Chromium concentration were ranges from 0-27.69 µg/l with average value of 6.37 µg/l during pre-monsoon season, while during post-monsoon season the concentration chromium ranges from 0-1.51 µg/l with average value of 0.42 µg/l. No elevated concentrations of total chromium were found in groundwater in the watershed (Figs. 21a & 21b).

#### **5.2.6 Copper**

The copper concentration in groundwater ranged from 0-265.8 µg/l with average value of 12.83 µg/l during pre monsoon season whereas it was varied from 0 to 27.04 µg/l with average value of 1.19 µg/l during post monsoon. No elevated concentrations of copper were found in water samples in the watershed (Figs. 22a & 22b).

#### **5.2.7 Iron**

Iron concentration during pre-monsoon season was varying from 0 to 869.4 µg/l with average value of 59.61 µg/l, whereas it is ranged from 12.68 to 13660 µg/l with average value of 669.60 µg/l during post monsoon. During post-monsoon Elevated iron concentration was found in four samples at K4 (13660 µg/l), K63 (10429 µg/l), K14 (5895 µg/l) and K58 (1857 µg/l). The elevated concentrations of iron may be due to leaching of iron from Laterite soil/rock during monsoon season.

### 5.2.8 Manganese

The Manganese concentration was found ranging from 0 to 31570 µg/l with average value of 1591.9 µg/l during pre-monsoon (April 2012). The maximum concentration of 31570 µg/l (K-14), 31000 µg/l (K-5), 9867 µg/l (K15), 3340 µg/l (K-11) and 528.4 µg/l (K-8) samples respectively during pre-monsoon season. During post-monsoon (January 2013) the manganese concentration were ranges from 0.753-7961 µg/l with average value of 352.02 µg/l. Elevated concentrations of manganese were found in six samples viz., K5 (7961 µg/l), K14 (3936 µg/l), K58 (3782 µg/l), K1 (1591 µg/l), k5 (794.6 µg/l) and K18 (506.6 µg/l) during this period.

## 6.0 Geophysical Investigations

### 6.1 Vertical Electrical Soundings (VES)

Vertical Electrical Soundings (VES) were carried out using Schlumberger Configuration with half current electrode separation 100-200 m to locate potential zones for groundwater exploration and delineation of aquifer geometry. Electrical resistivity technique makes use of variation in electrical resistivity of the ground. The resistivity of material is defined as the resistance offered by a unit cube when a unit current passes normal to its surface. The units are expressed in Ohm-m. Usually, different formations have different resistivity. The resistivity of a formation undergoes a change with the presence of water and its quality. In addition to the resistivity contrast, thickness of the layers together with the depth of occurrence plays an important role in the detection of subsurface layers. The resistivity of different subsurface formations is measured with the help of a resistivity meter having current and potential measuring devices. The resistivity is computed by passing electric current of a few milli-amperes into the ground through two electrodes (iron stakes) and measuring the potential drop resulting from the resistance offered by the ground by two other potential electrodes placed collinearly and symmetrically about the center of the electrode arrangement (sounding point). Non-polarizable electrodes are used for potential measurements in order to eliminate the polarization potential. The most commonly used Schlumberger configuration was employed in the present survey.

The apparent resistivity is given by:



$$\rho_a = K \frac{\Delta V}{I}$$

Where K is a geometrical factor,

$\Delta V$  is the potential in milli-volts and 'I' is the current in milli amperes

The geometrical factor K for Schlumberger configuration is:

$$K = \frac{\pi}{2} \left( \frac{L^2 - l^2}{l} \right)$$

Where L is one half of the current electrode separation in meters, and l is one half of the potential electrode separation in meters.

Initially interpretation of the sounding curves made through conventional curve matching technique in which the field curve is matched with the theoretical master curve (Orellana and Mooney, 1966). The theoretical curve that best fits the observed sounding curve specifies the layer thickness and resistivity of the field curve. The results thus obtained were used as initial model for final interpretation by an inversion algorithm in which the layer parameters are adjusted until minimum root mean square error is obtained between the field and computed curves. The computer software RESIST was used for this purpose (Jupps and Vozoff, 1975).

## 6.2 Interpretation of VES

The Vertical Electrical Soundings (VES) were made at 45 locations in the Kolhar Industrial area with maximum half-current electrode separation of 100-200 m (Fig. 23a). The resistivity interpretation of VES has indicated presence of three to five geo-electric layers in the watershed (Table 8). The minimum resistivity reported for the top layer was 4 Ohm-m in the VES No. 10 representing clay soil and maximum resistivity of 10099 Ohm-m was encountered in the VES No. 38 representing very hard and compact nature of laterite rock, whereas the minimum thickness of top layer reported was 0.4 m in few VES locations and a maximum thickness of 10.8 m was encountered in the VES No. 18. The Resistivity values found in the Kolhar Industrial area indicate that below the laterite occurs a potential groundwater zone in weathered and fractured media of basaltic rocks (Fig. 23b). Any contamination entering through top laterite would move fast through the weathered and fractured media which is having low resistivity. Thus the industrial area is vulnerable for groundwater contamination from waste disposal practices.

Five geo electrical profiles were selected for representing resistivity along different cross sections to represent the nature of aquifer geometry as well as variation of different layers in and around the Kolhar Industrial area in the watershed ( ref. Fig. 23). The geo-electrical cross section along A-A' passing through eastern part of Industrial area was drawn with VES No. 3, VES No. 5 and VES No. 22. The cross section represents occurrence of thick semi-weathered zone between overlying and underlying laterite (Fig. 24a). The cross section B-B' was passing in the northern part of the industrial area with VES No. 7, VES No. 11, VES No. 1 and VES No. 5 (Fig. 24b). Occurrence of 30 m thickness of weathered zone in the northern part of the industrial area is evident from the geoelectric cross section. The occurrence of 30 m thickness of semi-weathered zone underlain with weathered zone could be seen in the cross section C-C' is passing through the southern part of the Industrial area (Fig. 24c). The presence of semi weathered /weathered zone could be seen in the central part of industrial area is traversed by the cross section D-D' (Fig. 24d). The northwestern part of the industrial area is covered by geo-electrical cross section E-E'. Here also the occurrence of semi weathered and weathered zone could be seen underlying the top laterite formations (Fig. 24e). The above described geo-electric vertical cross sections represents the behavior of aquifer (i.e. highly weathered/weathered/semi-weathered) in and around the Kolhar Industrial Area.

## 7.0 Estimation of Aquifer Parameters

Short duration Pumping tests were carried out on existing 6 open wells and 2 bore wells to characterize the aquifer parameters viz., Transmissivity (T), Hydraulic Conductivity (K) and Storativity (S) in and around Kolhar Industrial Area (KIA) in the watershed during January 2013 (Fig. 25). The duration of pumping test varied from 20 to 50 minutes and recovery of water table was observed for 43 to 90 minutes in all the tests (Table 9a). The discharge of groundwater from the pumping wells varied from 171 l/min to 342 l/min whereas the reported maximum drawdown was ranged from 1.84 m to 3.86 m. The static groundwater level measured before the start of the pumping test in the open/ bore wells varied from 10.18 m (bgl) to 12.18 m(bgl). The estimation of aquifer parameters from the pumping test was made through Aquifer Test software using Theis, Newman & Huntush and Jacob methods for all the pumping wells (Table 9b).

### 7.1 Pumping Test No. 1

The pumping test No.1 was carried out in the open well of the Silkworm Culture Office Campus on the northeastern part of Kolhar Industrial area (ref. Fig. 25). The size of the open well 3.7 m x 3.7 m and the static groundwater level observed was 21.12 m (bgl) prior to the pumping test. The pumping duration was 40 minutes with a constant discharge @ 1.15 l/sec. The pumping has created a drawdown of 0.288 m from the static water level and more than 90% recovery could be observed during next 85 minutes. The time-drawdown curve and the estimation of transmissivity, hydraulic conductivity and Storativity by Theis method were 85.8 m<sup>2</sup>/day, 10.7 m/day and 1.50 x 10<sup>-1</sup> respectively (Fig. 26a & 26b). The transmissivity and hydraulic conductivity computed by Neuman method were 84.8 m<sup>2</sup>/day, 10.6 m/day respectively and the hydraulic conductivity estimated by Hantush & Jacob method was 10.7 m/day. The estimated hydraulic conductivity indicates that the aquifer is having a good groundwater potential and is under highly saturated condition.

### 7.2 Pumping Test No. 2

The pumping test No.2 was carried out in the dug well of Dhaneswari Industry (Rice Mill) in the northwestern part of industrial area (ref. Fig. 25). The static groundwater level reported prior to the pumping test was 14.825 m (bgl) and the size of square well was 2.5 m x 2.5 m. The groundwater from the well was pumped with constant discharge @ 1.30 l/sec for 87 minutes and the reported drawdown of 1.99 m was observed. About 90% of recovery was reported during next 80 minutes after stoppage of pumping from the well. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by the Theis method found as 12.4 m<sup>2</sup>/day, 1.56 m/day and 2.18x10<sup>-2</sup> respectively (Figs. 26a & 26b). The transmissivity and hydraulic conductivity estimated by the Neuman method was 12.6 m<sup>2</sup>/day and 1.57 m/day respectively, whereas the hydraulic conductivity estimated by the Hantush & Jacob methods was 1.52 m/day. The estimated hydraulic conductivity indicates that the well yield is poor.

### 7.3 Pumping Test No. 3

The Pumping test No.3 was carried out inside Surgical Industries dug well in the central part of the Industrial Area (Fig. 25). The static groundwater level observed prior

to start of pumping test was 16.10 m (bgl). The diameter of the open well was 6.33 m. The groundwater was pumped for 90 minutes duration with a constant discharge @ 0.635 l/sec and it had created a drawdown of 0.138 m. More than 90% of recovery of groundwater in the well was observed during next 140 minutes. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by the Theis method were 72.2 m<sup>2</sup>/day, 12 m/day and 2.20x10<sup>-1</sup> respectively (Figs. 28a & 28b). The estimated transmissivity and hydraulic conductivity by the Neuman method was 72 m<sup>2</sup>/day, 12 m/day respectively and the hydraulic conductivity estimated by the Hantush & Jacob method was 12 m/day. The well is having a good groundwater potential with high hydraulic conductivity in the central part of the industrial area.

#### 7.4 Pumping Test No. 4

The pumping test No.4 was carried out in the dug well situated inside Gorak Machendranath Temple, Belur Village outside the industrial area in the south eastern part (ref. Fig. 25). The diameter of the bore well was 5.15 m. The static groundwater level observed prior to the pumping test was 4.248 m (bgl) and groundwater was pumped for 160 minutes from the well with a constant discharge @ 8.835 l/sec. The pumping has created a drawdown of 0.402 m from the observed static water level. More than 90% recovery was reported in a short duration of 30 minutes. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by Theis method was 19.9 m<sup>2</sup>/day, 24.9 m/day and 1.01x10<sup>-1</sup> respectively (Figs. 29a & 29b). The transmissivity and hydraulic conductivity computed by Neuman method were 19.7 m<sup>2</sup>/day, 2.46 m/day respectively and hydraulic conductivity estimated by Hantush & Jacob method was 2.43 m/day. The well is located on the stream course in the downstream of a surface water body.

#### 7.5 Pumping Test No. 5

The pumping test No.5 was carried out in the bore well of Govt. Nursery, Bidar-Balky Road, Naubad village outside industrial area in the northern part (ref. Fig. 25). The diameter of the bore well was 0.25 m. The static groundwater level observed prior to the pumping test was 10.35 m (bgl) and the well was pumped for 35 minutes duration with constant discharge @ 1.028 l/sec. The pumping has reported a drawdown of 16.42 m from the static water level. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by Theis method were 1.99 m<sup>2</sup>/day,

0.16 m/day and  $8.58 \times 10^{-4}$  respectively (Figs. 30a & 30b). The transmissivity and hydraulic conductivity computed by Neuman method were 2.02 m<sup>2</sup>/day, 0.168 m/day respectively and the hydraulic conductivity estimated by Hantush & Jacob method was 0.17 m/day.

### 7.6 Pumping Test No. 6

The pumping test No.6 was carried out in a bore well behind Laxmi Temple, Bachudi Village outside industrial area on the western part (Fig. 25). The diameter of the bore well was 0.25 m. The static groundwater level observed prior to the pumping test was 36.07 m (bgl) and the well was pumped for 33 minutes duration with constant discharge @ 1.029 l/sec. The pumping has created a drawdown of 9.63 m from the static water level. The recovery was observed during 40 minutes after stoppage of pumping. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by Theis method were 4.29 m<sup>2</sup>/day, 0.28 m/day &  $6.54 \times 10^{-4}$  respectively (Figs. 31a & 31b).. The transmissivity and hydraulic conductivity computed by Neuman method were 4.27 m<sup>2</sup>/day, 0.28 m/day respectively and the hydraulic conductivity estimated by Hantush & Jacob method was 0.28 m/day.

### 7.7 Pumping Test No. 7

The pumping test No.7 was carried out in the dug well of Mr. Chandrappa Agriculture land, Sikenpur Village outside industrial area on the south western part ( ref. Fig. 25). The diameter of the dug well was 6.2 m. The static groundwater level observed prior to the pumping test was 9.66 m (bgl) and the water from the well was pumped for 62 minutes with constant discharge @ 9.935 l/sec. The pumping has created a drawdown of 2.124 m from the static water level. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by Theis method were 199 m<sup>2</sup>/day, 33.1 m/day and  $1.96 \times 10^{-1}$  respectively (Figs. 32a & 32b). The transmissivity and hydraulic conductivity computed by Neuman method were 196 m<sup>2</sup>/day, 32.7 m/day respectively and the hydraulic conductivity estimated by Hantush & Jacob method was 32.4 m/day.

### 7.8 Pumping Test No. 8

The pumping test No.8 was carried out in the CMC Pump House, Chidri Village outside the industrial area in the eastern part of watershed (ref. Fig. 25). The diameter

of the open well was 7.5 m. The static groundwater level observed prior to the pumping test was 11.03 m (bgl) and the well was pumped for 29 minutes duration with constant discharge @ 9.95 l/sec. The pumping has created a drawdown of 0.299 m from the static water level. Due to power failure the well could not be pumped further and more than 90% recovery was observed during next 30 minutes after stoppage of pumping. The time-drawdown curve and the estimated transmissivity, hydraulic conductivity and Storativity by Theis method were  $420 \text{ m}^2/\text{day}$ ,  $52.5 \text{ m/day}$  and  $5.71 \times 10^{-1}$  respectively (Figs. 33a & 33b). The transmissivity and hydraulic conductivity computed by Neuman method were  $418 \text{ m}^2/\text{day}$ ,  $52.3 \text{ m/day}$  respectively and the hydraulic conductivity estimated by Hantush & Jacob method was  $52.5 \text{ m/day}$ . The highest hydraulic conductivity in the watershed was reported from the well in the Chidri village.

## 8. In-Situ Infiltration Rate Measurement

*In situ* Infiltration tests were carried out with double ring infiltrometer at 18 locations in the Kolhar Industrial Area (KIA) watershed to estimate the in situ infiltration rate (Fig. 34a). The outer infiltration ring was made with diameter of the 60 cm and inner diameter of the ring was 30 cm and height of the ring is 13 cm. The in situ infiltration rates reported were found varying from 0.59 cm/hr to 13.68 cm/hr on the laterite in the Kolhar Industrial Area (KIA) (Fig. 34b & Table 10). Highest infiltration rate was reported from infiltration test No. 8 inside Basavesvara Dal Industries and lowest at infiltration test No. 16 in the Sikenpur village. Thus any surface water leakage from storm water disposal practices from industries is likely to contaminate the groundwater in the Industrial area and the industrial area is vulnerable with regard to the slightly high infiltrate rate reported.

## 9. Groundwater Flow & Mass Transport Modeling

The groundwater flow model in the watershed covering Kolhar Industrial Area, Bidar District was conceptualized as a two layer weathered and fractured aquifer system spread over  $14702 \text{ m} \times 8744 \text{ m}$  and observation wells considered for model calibration (Figs. 36 & 37). The simulated vertical cross sections along Row 22, Row 24 & Column 33 indicates that the weathered zone has a thickness of about 32 m, which is underlain by a fracture zone of about 8 m thickness (Fig. 38a & 38b). The groundwater flow model has 44 rows and 46 columns of rectangular cells of varying sizes of  $374 \text{ m} \times 226 \text{ m}$  and  $187 \text{ m} \times 113 \text{ m}$  (ref. Fig. 36). Fine grid cells are used in

the groundwater flow model for the industrial area. These vertical cross sections of Rows and Column pass through the Kolhar industrial area. The highest permeability of saturated basaltic rocks are found in the valley fill zone and accordingly maximum permeability of 4.0 m/day was assigned along the stream courses and slightly lower permeability of 3.0 m/day was assigned to adjoining cells. The rest of the area covering the industrial area was assigned a permeability of 2.0 m/day. Higher permeability values of 8.0 m/day and 6.0 m/day assigned on the Eastern boundary and in south western part are based on pumping test estimates. The permeability of second layer covering the fracture zone was assigned uniform permeability of 2.0 m/day (ref. Figs. 37a, 37b & 37c). The permeability has been assumed to be one tenth of the horizontal permeability in the vertical direction.

The Kolhar watershed is spread over about 96 sq km is a closed watershed with no flow boundary all along except Marar halla stream as outlet. Constant head boundary condition was simulated at the outflow the watershed with a groundwater head of 620 m (amsl). The Marar Halla stream was simulated with a river boundary condition with appropriate stream stages and stream bed elevations. The intervening hydraulic conductance of stream bed between the Marar Halla and aquifer has been varying from 80 to 100 m<sup>2</sup>/ day (Fig. 38).

The Bidar district receives about 650 -700 mm of rainfall mostly during south west monsoon period and natural groundwater recharge to the groundwater regime was assumed as 60 mm/year all over the watershed. Slightly higher groundwater recharge could enter the groundwater regime from open areas in the Air force Base Station adjacent to industrial area on the east and it was assumed as 90 mm/yr. The water utilization in the Kolhar Industrial Area may further contribute for additional recharge and as the Industrial area is situated on ridge part with good infiltration characteristics, it was assumed as 120 mm/yr (Fig. 40). The groundwater pumping is varying from 20 -60 m<sup>3</sup>/day depending size of the dug well and also from irrigation wells. The groundwater pumping centers and pumping rate assigned in the model varies on an average 20 -40 m<sup>3</sup>/day (Fig. 41).

## Flow and Transport Processes

The process of groundwater flow is generally assumed to be governed by the relations expressed in Darcy's law and the conservation of mass. The purpose of Mass transport model in groundwater is to compute the concentration of a dissolved chemical species in an aquifer at any specified time and place. The theoretical basis for the equation describing solute transport has been well documented in the literature (Bear, 1979). Changes in chemical concentration occur within a dynamic groundwater system primarily due to four distinct processes:

- Advective transport, in which dissolved chemicals are moving with the flowing groundwater
- Hydrodynamic dispersion, in which molecular and ionic diffusion and small-scale variations in the flow velocity through the porous media cause the paths of dissolved molecules and ions to diverge or spread from the average direction of groundwater flow
- Fluid sources, where water of one composition is introduced into and mixed with water of a different composition and
- Reactions, in which some amount of a particular dissolved chemical species may be added to or removed from the groundwater as a result of chemical, biological, and physical reactions in the water or between the water and the solid aquifer materials or other separate liquid phases.

## Governing Equations

The subsurface environment constitutes a complex, three dimensional heterogeneous hydrogeologic setting. The variability strongly influences groundwater flow and transport, and such a reality can be described accurately only through careful hydrogeologic practice. The mathematical equations that describe groundwater flow and transport processes may be developed from the fundamental principle of conservation of mass of fluid or of solute. Given a representative elementary volume (REV) of porous medium, a general equation for conservation of mass for the volume may be expressed as:

$$\text{Rate of mass inflow} - \text{rate of mass outflow} + \text{rate of mass reduction/}$$



$$\text{Consumption} = \text{rate of mass accumulation} \quad (1)$$

The statement of conservation of mass may be combined with a mathematical expression of the relevant process to obtain a differential equation that describes flow or transport.

$$q_i = -K_{ij} \frac{\partial h}{\partial x_j} \quad (2)$$

A general form of the equation describing the transient flow of a compressible fluid in a non-homogeneous anisotropic aquifer may be derived by combining Darcy's law with the continuity equation. A general groundwater flow equation may be written in Cartesian tensor notation as:

$$\frac{\partial}{\partial x_i} \left( K_{ij} \frac{\partial h}{\partial x_j} \right) = S_s \frac{\partial h}{\partial t} + W^* \quad (3)$$

Where  $S_s$  is the specific storage,  $L^{-1}$ ;  $t$  is time,  $T$ ;  $W^*$  is the volumetric flux per unit volume (+ for outflow and – for inflow),  $T^{-1}$ ; and  $x_i$  are Cartesian coordinates,  $L$ . Darcy's law applies (and gradients of hydraulic head are the only driving force), and fluid properties (density and viscosity) are homogeneous and constant. Aquifer properties can vary spatially, and fluid stresses ( $W^*$ ) can vary in space and time.

If the aquifer is relatively thin compared to its lateral extent, it may be appropriate to assume that groundwater flow is aerially two-dimensional. This allows the three-dimensional flow equation to be reduced to the case of two dimensional aerial flows, for which several additional simplifications are possible. Advantages include less stringent data requirements and shorter computation time to achieve numerical solutions.

For confined aquifer case,

$$\frac{\partial}{\partial x_i} \left( T_{ij} \frac{\partial h}{\partial x_j} \right) = S \frac{\partial h}{\partial t} + W \quad (4)$$

Where  $T_{ij}$  is the transmissivity,  $L^2T^{-1}$ ;  $T_{ij} = K_{ij} b$ ;  $b$  is the saturated thickness of the aquifer,  $L$ ;  $S$  is the storage coefficient (dimensionless) and  $W = W^* b$  is the volume flux per unit area  $LT^{-1}$ .

When equation 4 is applied to an unconfined aquifer system, it must be assumed that flow is horizontal and equipotential lines are vertical, that the horizontal hydraulic

gradient equals the slope of the water table, and that the storage coefficient is equal to the specific yield ( $S_y$ ) (Anderson and Woessner, 1992). Note that in an unconfined system, the saturated thickness changes as the water table elevation (head) changes. Thus, the transmissivity also can change over space and time (i.e.  $T_{ij} = K_{ij} b$ , where  $b(x,y,t) = h - h_b$  and  $h_b$  is the elevation of the bottom of the aquifer).

The cross-product terms of the hydraulic conductivity tensor drop out when the coordinate axes are aligned with the principal axes of the tensor; i.e.  $K_{ij} = 0$  when  $i \neq j$ . Therefore, the only hydraulic conductivity terms with possible nonzero values are  $K_{xx}$  and  $K_{yy}$ . The eq 4 may be simplified to

$$\frac{\partial}{\partial x} \left( T_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( T_{yy} \frac{\partial h}{\partial y} \right) = S \frac{\partial h}{\partial t} + W \quad (5)$$

In some field problems, fluid properties such as density and viscosity may vary significantly. When the fluid properties are heterogeneous and (or) transient, the relations among water levels, hydraulic heads, fluid pressures, and flow velocities are neither simple nor straightforward. In this situation, the flow equation is written and solved in terms of fluid pressures, fluid densities, and the intrinsic permeability of the porous media (Konikow and Grove, 1977).

### Groundwater Velocity

The migration and mixing of chemicals dissolved in groundwater will obviously be affected by the velocity of the flowing groundwater. The actual seepage velocity of groundwater is computed as

$$V_i = \frac{q_i}{\varepsilon} = - \frac{K_{ij}}{\varepsilon} \frac{\partial h}{\partial x_j} \quad (6)$$

Where  $V_i$  is the seepage velocity and  $\varepsilon$  is the effective porosity of the porous medium.

### Mass Transport Equation

An equation describing the transport and dispersion of a dissolved chemical in flowing groundwater may be derived from the principle of conservation of mass by considering all fluxes into and out of a representative elementary volume (REV). A generalized form of the solute transport equation, in which terms are incorporated to represent chemical reactions and solute concentration both in the pore fluid and on the solid surface, as:

$$\frac{\partial(\varepsilon C)}{\partial t} = \frac{\partial}{\partial x_i} \left( \varepsilon D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (\varepsilon C V_i) - C' W^* + \text{CHEM} \quad (7)$$

Where CHEM equals one or more of the following:

$$- \rho_b \frac{\partial \bar{C}}{\partial t} \text{ for linear equilibrium controlled sorption or ion-exchange reactions}$$

$$\sum_{k=1}^s R_k \text{ for } s \text{ chemical rate-controlled reactions, and (or)}$$

$$- \lambda \left( \varepsilon C + \rho_b \bar{C} \right) \text{ for decay}$$

and where  $D_{ij}$  is coefficient of hydrodynamic dispersion (a second order tensor),  $L^2 T^{-1}$ ,  $C'$  is the concentration of the solute in the source or sink fluid,  $C$  is the concentration of the species adsorbed on the solid (mass of solute/mass of solid),  $\rho_b$  is the bulk density of the sediment  $ML^{-3}$ ,  $R_k$  is the rate of production of the solute in reaction  $k$ ,  $ML^{-3} T^{-1}$ , and  $\lambda$  is the decay constant  $T^{-1}$ .

The first term on the right hand side of equation (7) represents the change in concentration due to hydrodynamic dispersion. This expression is analogous to Fick's law describing diffusive flux. This Fickian model assumes that the driving force is the concentration gradient and that the dispersive flux occurs in a direction from higher towards lower concentrations. The coefficient of hydrodynamic dispersion is defined as the sum of mechanical dispersion and molecular diffusion (Bear, 1979). The mechanical dispersion is a function both of the intrinsic properties of the porous medium (such as heterogeneities in hydraulic conductivity and porosity) and of the fluid flow. Molecular diffusion in a porous medium will differ from that in free water because of the effects of tortuous paths of fluid connectivity in porous media. These relations are commonly expressed as

$$D_{ij} = \alpha_{ijmn} \frac{V_m V_n}{|V|} + D_m \quad i, j, m, n = 1, 2, 3 \quad (8)$$

Where  $\alpha_{ijmn}$  is the dispersivity of the porous medium (a fourth order tensor),  $L$ ;  $V_m$  and  $V_n$  are the components of the flow velocity of the fluid in the  $m$  and  $n$  directions, respectively,  $LT^{-1}$ ,  $D_m$  is the effective coefficient of molecular diffusion,  $L^2 T^{-1}$ ; and  $|V| = \text{sq root } V_x^2 + V_y^2 + V_z^2$  (Bear, 1979, Domenico and Schwartz, 1990). The dispersivity of an isotropic porous medium can be defined by two constants. These are

the longitudinal dispersivity of the medium  $\alpha_L$  and the transverse dispersivity of the medium  $\alpha_T$ . These are related to the longitudinal and transverse dispersion coefficients by  $D_L = \alpha_L|V|$  and  $D_T = \alpha_T|V|$ . Most of the reported transport models of groundwater problems relate to the conventional formulation, even for cases in which the hydraulic conductivity is assumed to be anisotropic.

Although conventional theory holds that  $\alpha_L$  is generally an intrinsic property of the aquifer, it is found in practice to be dependent on and proportional to the scale of the measurement. Most reported values of  $\alpha_L$  fall in a range from 0.01 to 1.0 times the scale of the measurement, although the ratio of  $\alpha_L$  to scale of measurement tends to decrease at larger scales (See Anderson, 1984, Gelhar et al. 1992). Field dispersion (macro dispersion) results from large scale spatial variations in hydraulic properties. Representing a transient flow field by a mean steady state flow field, as is commonly done, inherently ignores some of the variability in velocity and must be compensated for by using increased values of dispersivity (primarily transverse dispersivity). Over all, the more accurately a model can simulate the true velocity distribution in space and time, the less of a problem will be the uncertainty concerning representation of dispersion processes.

The mathematical solute –transport model requires at least two partial differential equations. One is the equation of flow, from which groundwater flow velocities are obtained, and the second is the solute transport equation, whose solution gives chemical concentration in groundwater. If the properties of water are affected significantly by changes in solute concentration, as in a seawater intrusion problem, then the flow and transport equations should be solved simultaneously ( iteratively). If the properties of the water remain constant, then the flow and transport equations can be decomposed and solved sequentially, this is simpler numerically.

The numerical approaches for solving mass transport equations are based on computer-based particle tracking methods. They are approximate forms of the advection-dispersion equation (5) as a system of algebraic equations or alternately simulating transport through the spread of a large number of moving reference particles. Second step is to provide boundary condition at a large number of node points and assign values of concentration or loading rates defining various boundary conditions for

all nodes located along boundary of the domain. Continuity consideration of numerical solutions of solute transport requires a smooth and accurate representation of velocity field, which was obtained by simulation of groundwater flow model. Velocity values are computed from calculated hydraulic heads and porosity values by applying Darcy's equation. The transport model was coupled to the flow model by velocity terms. The water level configuration of particular time period will be considered for solving groundwater flow equation under steady state and thereby a single velocity field determined for the mass transport simulation for all times. With a small time step, this particle motion traces a pathline through the system (Konikow and Bredehoeft, 1978). Dispersion was accounted for in the particle motion by adding to the deterministic motion a random component, which is a function of the dispersivities. The mean concentration for each grid block was calculated as the sum of the mass carried by all the particles located in a given block divided by the total volume of water in the block. The head solution is obtained using visual MODFLOW (McDonald and Harbough, 1988).

The computed groundwater level contours in the groundwater flow model has been showing groundwater flow direction towards the Marar Hall stream and following closely the trend of observed water level contours during April 2012 (Fig. 42a). The computed vs. observed hydraulic heads at 35 observation wells in the watershed have been found matching closely (Fig. 42b). The groundwater velocity field has been computed from the flow model by assuming an effective porosity of 0.1. The computed groundwater velocity field represents maximum groundwater velocity > 40 m/year.

### **9.1 Mass Transport Model**

Using the computed velocity field from the groundwater flow model, a mass transport model was simulated using the MT3D software. The source concentration was assigned at 4 locations in the Kolhar Industrial Area based on the reported maximum concentration during groundwater quality monitoring of April 2012 and January 2013. The initial concentration of groundwater was assumed as 600 mg/l and the source concentrations varied from 2000 – 8000 mg/l during last 20 years (Fig. 43). The computed TDS plumes indicate the migration of contaminant in groundwater originating from the sources. The predicted TDS concentration in groundwater for

different years presents that the TDS plume migration is limited to four clusters within the Kolhar Industrial area and is towards the south western part from Eastern boundary (Figs.44a to 44h). The computed TDS concentration plume for the year 2012 was used for calibration of the mass transport model during last 20 years. The mass transport model was later used for making prediction during next 30 years up to 2042. The mass transport model predictions indicate that significantly TDS concentration plumes are extending towards Western boundary of the Kolhar Industrial Area, but not crossing the boundary of industrial area (Figs. 45a to 45h). Major contaminant TDS plume could be seen emanating from Obs well no. 15 on the Eastern boundary. There is no migration of contaminant TDS plume towards the Air Force Base Station as there is no heavy pumping taking place outside along eastern boundary of the Kolhar Industrial Area. Further as the industrial area is situated on high ground sloping towards west, the contaminant migration if any through storm water disposal would be towards the western boundary of industrial area.

The migration of TDS concentration plume along vertical direction was predicted along Row -22 and Column 33 for different years to understand the dispersion pattern of contaminant within the Kolhar Industrial Area during next 50 years ( Figs. 46a to 46 i & Figs 47a to 47i). The vertical migration of TDS concentration from other two sources in the industrial area with depth along Row -20 & Row-24 indicate very low concentrations (Figs. 48a & 48b). The groundwater flow and mass transport modeling has only demonstrated extent of likely migration of TDS contaminant plume from Eastern boundary towards the Western boundary in the northern part of the Kolhar Industrial Area. Further it is confirmed that contaminant plumes movement will be towards the western boundary. The plume can move fast as ground surface possess good infiltration characteristic. It is suggested to monitor the groundwater quality rigorously in all the observation wells for reporting elevated TDS in groundwater in the industrial area. The liquid waste disposal should be made by sending the treated effluent to a Common Effluent Treatment Plant.

## 10. Conclusions

Groundwater level and water quality monitoring was carried out in 57 observation wells during April 2012 and January 2013 for ascertaining the groundwater flow direction and water quality in the Kolhar industrial Area, Bidar. The groundwater

flow direction is from Kolhar Industrial Area towards the Marar Halla stream on the west. Four TDS contaminant plumes were identified through water quality monitoring within the Kolhar Industrial Area reporting concentrations varying from 2000 - 8000 mg/l. The open wells monitored in the basaltic terrain suggest that once groundwater recharge enters the groundwater table through the top laterite it migrates with groundwater velocity along the groundwater flow path. The aquifer characteristics as well as the infiltration rates determined in the industrial area indicated that the area is a favorable region for groundwater recharge. Hence any pollution from top surface enters the groundwater regime and it migrates with groundwater velocity with dispersion properties of the medium. The hydraulic gradient is controlled by pumping within the industrial area as well as neighboring irrigation well pumping in the watershed. Further groundwater quality data during December 2013 provided by RO, KSPCB, Bidar was examined and found that both NGRI and KSPCB data sets confirm similar contaminant plume configurations in the industrial area.

The observed groundwater quality database also suggests that the contaminant plumes with regard to TDS are moving towards west of the Industrial area from eastern boundary. The ground surface is also sloping towards the west. Major contaminants include, TDS, Chloride and Nitrate as nitrate with slightly elevated heavy metal presence in the groundwater was noticed during the water quality monitoring. But the concentrations are only slightly elevated along the groundwater flow path. Similarly, the trace elements concentration for Barium, Cobalt, Chromium and Manganese shows elevated concentration in the wells inside the industrial Area only. There is no threat to the public water supply wells or irrigation wells outside the industrial area. Significantly there is no problem encountered with regard to elevated concentrations towards the Air Force Base Station, Bidar.

The resistivity investigations employing Vertical Electrical Soundings indicate that the groundwater regime in the basaltic rocks occurs in weathered and semi-weathered conditions. The thickness of weathered and fracture zone occurring just below the laterite cover is generally varying from 10 – 35 m (bgl) in the industrial Area. The pumping test results also indicated that the aquifer characteristics with regard to hydraulic conductivity is varying from 1.2 to > 25 m/day indicating presence of potential groundwater zones at shallow depth. The results further point out that avoiding surface water contamination in the industrial area will maintain groundwater quality in the Kolhar Industrial Area. The high infiltration rates reported from the industrial area on

laterites indicate that the area is vulnerable for groundwater contamination from liquid waste disposal on ground surface from industries. There is no groundwater contamination in the Air Force Base station adjacent to the Kolhar industrial area as there is no heavy groundwater pumping taking place close to the industrial area. Water harvesting structures are not recommended as they may aid faster migration of groundwater contamination, if any, in the industrial area.

It is recommended that KSPCB may procure Visual MODFLOW and MT3D suite model software and use it at the Head Quarters for comparison of future groundwater quality data base with the model predictions. The software will be an asset for KSPCB, which could be fruitfully utilized for simulation of groundwater contamination assessment studies elsewhere in other parts of Karnataka state. NGRI will be pleased to offer training of KSPCB Officers for operation of the software at NGRI on the Kolhar IDA groundwater flow and mass transport model.

### **11.0 Remedial Measures**

- The industrial area should have a common effluent treatment plant (CETP) to process the liquid effluent from different industries and it is recommended to set up a CETP in the industrial area for effluent treatment.
- Most of the unused open wells in the industrial area need to be protected from surface water contamination during rainy season through diversion of storm water runoff. The unused wells may be thoroughly cleaned by groundwater pumping to arrest migration of contaminant in the downstream area.
- Stagnation of storm water should be avoided in the industrial area otherwise it may drive nascent elevated concentrations to the downstream areas.
- Periodical monitoring of groundwater quality for compliance and detection of contaminant migration if any in the industrial area is suggested.
- It is imperative to order closing of unused open wells by individual industries so as to prevent the industries using them for disposal of industrial waste water in the industrial area.

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