HYDROLOGICAL MODELING OF THE LAHORE-AQUIFER, USING ISOTOPIC, CHEMICAL AND NUMERICAL TECHNIQUES

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ABSTRACT

Lahore, the capital city of Punjab Province, has about 6 million population. The only water supply to the public is groundwater, pumped through tube-wells. With the increase in population, the demand of water is also increasing accordingly. Radiation and Isotope Application Division of PINSTECH is carrying out hydrological investigations of Lahore aquifer, sponsored by IAEA. For the last three years, 7 samplings have been performed on groundwater of Lahore city area. Natural isotopes of water, such as ^{18}O*, deuterium and tritium, have been analysed from the collected water samples. Major and important chemical ions, such as Ca, Mg, Na, K,* CO_3*,* HCO_3*,* SO_4 *and Cl, have also been analysed. Hydrological data on pumping-wells and soil-characteristics has been gathered from different agencies.*

A conceptual flow model was developed on Lahore aquifer and was calibrated with Visual Modflow. Hydrochemical interpretations were made with the locally developed innovative techniques and diagrams, as well. The groundwaters have been identified as calcium bicarbonate, magnesium bicarbonate and sodium bicarbonate, with the help of Multi-Rectangular Diagram (MRD). A spatial variation of groundwater-quality map has been constructed. Recharge mechanism is addressed by chemical and isotopic techniques. Both shallow and deep aquifers get significant recharge from river Ravi. Simulations have been run on dynamic depression cone, which has emerged as a result of daily abstractions of groundwater after 1960. In the vicinity of Governor House, the water level was 191 m above mean sea level (amsl) in 1989. It has been observed to have gone down to 185 m in 1998. Preliminary numerical simulations predict that the water-table will further lower to 174 m and 171 m in the years 2009 and 2019, respectively.

INTRODUCTION

Good quality potable water is a fundamental requirement for human health and survival. In third-world countries, fast growth of population, poor town-planning and industrialization are causing problems in supplying public services. Supply and sustainability of clean water stands among the most crucial problems. Lahore is the second largest city of Pakistan, covering an area of about 1000 square kilometers (NESPAK, 1991). Its population is increasing at a rapid rate of 3.7 per cent per year. In 1901 the population of Lahore was 0.203 million which, by 1990, has increased to about 5 million. At present, the population is near about 6 million. The sole supply of water to the Lahore City depends upon the abstraction of groundwater. Fast growth of population, progressive migration of people to the area and establishment of numerous industries have resulted in rapid increase in water-demand. The number of wells and, hence, the groundwater abstraction has been increasing in accordance with the growth of population. On the other hand, urbanization and industrialization has reduced the recharge, as a significant part of the land has become impermeable. With the increasing number of tubewells, the groundwater level, which used to exist at about 4.5 m below surface, started declining rapidly. A decline of 15.5 meters in water-table during 1960 to 1991 was noticed in Lahore City (Alam, 1996). At present, the water-table in the central area of the city has gone down to 28 m from the surface level (WASA, 1999). The existence of saline groundwater in the nearby areas of Raiwind and Kasur, in the south of Lahore, is a potential threat to the aquifer under the city. There is a danger of deterioration of the aquifer water-quality if the saline water finds a path to reach the city area. The flushing out of this saline water, if it once enters the aquifer, would then be nearly impossible. It is therefore, imperative to assess the mechanism of groundwater-replenishment, pollution-levels and pollution-sources, for sustainable development and conservation of these resources.

HYDROGEOLOGY

The aquifer under Lahore area is composed of unconsolidated alluvial sediments, consisting of sand, silt and clay in different proportions. The chief constituent minerals are quartz, muscovite,

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biotite and chlorite, in association with a small percentage of heavy minerals. The sediments have been deposited by the present and ancestral tributaries of the Indus River during Pleistocene-Recent age. The sedimentary complex has a thickness of more than 400 meters. The shifting course of the tributaries in the area has impregnated the heterogeneous character to the thick sedimentary alluvium. Therefore, the geological strata have little vertical or lateral continuity. In spite of their heterogeneity, the alluvial sediments constitute a large aquifer, which on regional basis behaves as an unconfined homogeneous aquifer (Greenman et al., 1967). The individual lenses of silt and clay do not impede the flow of groundwater, considering long-term pumping. Lahore aquifer is highly transmissive, with hydraulic conductivity variation between 25 m/day to 70 m/day. In spite of heterogeneous nature of alluvial complex, groundwater occurs under water table conditions.

SAMPLE COLLECTION AND ANALYSES

The study area comprises the city of Lahore and the adjoining areas. Locations of the sampling points are shown in Figure - 1. During the last two years, 7 samplings have been carried out in different seasons. In order to cover the maximum representation, the samples were collected from shallow and deep aquifers, and from canals, river Ravi and sewerage drains. The samples were analyzed for environmental isotopes ^{2}H, ^{3}H, ^{18}O and major chemical ions Ca, Mg, Na, K, HCO_3, CO_3, SO_4, Cl. Physico-chemical parameters like EC, pH and temperature were measured in the field.

RESULTS AND DISCUSSION

Quality Of Chemical Data

It is an imperative step, before any manipulation of chemical data, to ascertain its quality. The reliability of chemical data can be checked by computation of ionic charge-balance error (Mandel and Shiftan, 1981, and Lloyd and Heathcote, 1985). The ionic charge balance equation is defined as:

$$\text{Reaction Error} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum (\text{cations} + \text{anions})} \times 100$$

In this equation, meq/l concentrations of cations and anions are used. If the reaction error of a chemical data-set is more than 10% it makes the quality of analysis questionable. In the present study, the reaction error criteria were applied to chemical analyses of each data-set. Reaction errors are shown in Figure - 2. Almost all the reaction errors are within 10% range, except 6 samples which remain within 20%. Therefore the quality of chemical data is acceptable, according to ionic charge balance criteria.

Groundwater Quality

EC of shallow aquifer (<200 feet depth) is shown in figure - 3a and it has approximately normal distribution. It varies between 250 to 4500 μS/cm. The maximum samples occur at 1200 μS/cm. On the other hand, EC of deep aquifer (300 to 600 feet depth), as shown in figure - 3b, varies between 250 to 1750 μS/cm, with maximum frequency at about 500 μS/cm. It indicates that shallow aquifer is more saline, as compared to deep aquifer. The range of EC for shallow wells is about 2.5 times higher, as compared to that of tube wells. It was also observed during sampling that a tube-well and a hand-pump only 100 feet apart had remarkable difference in EC. This difference of salinity may be due to high contribution of fresh-water recharge to the deeper aquifer from distant hills on the north, while shallow aquifer has higher contribution from local sources of canals and sewerage waters. Spatial distribution of EC is shown by figure - 4 where the radius of the circle is proportional to the EC value. This figure clearly indicates that the shallow wells (hand pumps and motor pumps) have higher values of EC than the counterpart deeper tube wells.

Frequency distributions of major chemical ions have been shown in Figure - 5. Concentrations (mg/l) of Ca, Mg, Na, HCO_3, SO_4 and Cl varies between 20 to 172, 15 to 140, 84 to 964, 140 to 1020, 80 to 672 and 55 to 550, respectively. All the ions have similar distributions except HCO_3 which indicates two populations having their modal classes at 220 and 380 mg/l, respectively. Chloride is considered as conservative anion which once it enters groundwater does not react with other ions and remains in solution form. Cl depicts the interesting behaviour of movement of groundwater in the aquifer. Spatial variation of Cl (Figure - 6) indicates higher values of shallow wells than deeper tube wells in the Bund Road and Hadiara Drain areas, while in the center of the city, Gowal Mandi and Mozang area, both shallow and deep wells show higher values of Cl. This behavior of Cl can be explained: in the south east and north east areas, the waters of shallow and deep aquifers are not mixing efficiently, while in the center of the city (Gowal Mandi, Mozang, Governor House) both shallow and deep groundwaters are mixing in substantial amounts. A three dimensional picture shown in Figure - 7 gives more clear indication of Cl variation. Groundwater from the aquifer has been abstracted heavily after 1960, to meet the increasing demand of water with growing population. It has produced a depression-cone in the center of the city, as shown in Figure 8. The areas having apex of the depression-cone and peak of Cl ion are overlapping in the center of the city. It further supports the mixing of shallow aquifer waters with the deep aquifer in the center of the city, causing deterioration in the quality of water.

Hydrochemical Classification of Groundwater

Groundwater salinity is the result of combined effect of a number of chemical ions. The major chemical ions responsible for the salinity of groundwater are calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate and chloride (Freeze and Cherry, 1979). Among these ions, some are in higher concentration as compared to others, depending upon the chemistry of source water and geochemistry of the rocks met in the way of flowing water. Groundwater samples collected from different locations may be recharged from different sources and will show dominance of particular ions, accordingly. The type of groundwater at a particular location is determined by calculating the percentages of cations and anions, using milli-equivalent per liter (meq/l) concentrations. The ions with highest percentage from cation and anion groups define the type of the groundwater. A number of graphical methods are available in the literature for hydro-chemical classification of groundwaters (Hill, 1940; Piper, 1944; Durov, 1948; Burdon and Mazloum, 1958; Lloyd, 1965 and Ahmad, 1998). Here the chemical analyses are plotted on Piper diagram, which is shown in Figure - 9. This diagram shows that Na is the dominant cation and HCO_3 is the dominant anion from the water-analyses in the study area. A small number of samples are dominant in Ca. It is difficult from this diagram to single out the pairs of dominant cations and anions together. A Multi-Rectangular Diagram developed by Ahmad (1998) takes into account the shortcomings of trilinear Piper diagram. Chemical analyses of water-samples from the study-area have also been plotted on Multi-Rectangular diagram (MRD) shown in Figure - 10. The waters emerge as calcium bicarbonate, magnesium bicarbonate, sodium bicarbonate, sodium sulfate, sodium chloride and calcium sulfate types. Out of 144 samples, 99 qualify for sodium bicarbonate, 27 for calcium bicarbonate, 6 for magnesium bicarbonate, 8 for sodium sulfate, 3 for sodium chloride and 1 for calcium sulfate categories. The waters of Indus River and its tributaries are rich in calcium bicarbonate type. Therefore, calcium bicarbonate and magnesium bicarbonate type of waters indicate fresh recharge or that the recharged water has not moved a long distance from the source area. During the movement of groundwater, the dissolved calcium exchanges with sodium present in the minerals of rock matrix. As a result, sodium becomes dominant over other cations when water covers a long distance from the source. Sodium bicarbonate type of waters may be the result of mainly ion-exchange reaction between calcium and sodium at an appreciable distance from the recharge area. Occurrence of some magnesium bicarbonate type of ground-waters indicates the presence of dolomite mineral in the reservoir formations. Chloride type of ground-waters either emerges directly from industrial activity in the area or indicates very sluggish movement of groundwater, which evolves from bicarbonate through sulfate to chloride (Chebotarev, 1955).

Hydrochemical Facies

The term hydrochemical facies is used to denote the differences in groundwater spatial quality. Generally, the groundwater facies are susceptible to geologic facies to some extent. The hydrochemical processes do not occur within sharp boundaries, rather they possess inherent transition-character within a particular area. The chemistry of groundwater evolves according to the availability of minerals and equilibrium conditions. During the movement of groundwater, its chemistry does not change abruptly until and unless it meets rocks with entirely different character. Identification of areas with a particular type of groundwater helps to manage and maintain the future supply of water. Hydrochemical facies map (Ahmad, 1998) can easily be constructed after the recognition of prevalent groundwater types with the help of MRD. Figure - 11 shows hydrochemical facies in the study area. Groundwater with a particular type is marked with a specific symbol on the map. As a result, the areas with different types of groundwater are highlighted on the map. The area under study is mainly occupied by calcium bicarbonate and sodium bicarbonate type of ground-waters. Calcium bicarbonate type of waters occur in border-areas adjacent to river Ravi and along the Lahore Canal. Other areas, which are away from the river, are occupied by sodium bicarbonate type of groundwater. Magnesium bicarbonate waters occur south east of the study area. Sodium sulfate type of waters occur towards the city, just after calcium bicarbonate type of waters.

Recharge Mechanism

The possible sources of recharge of the aquifer are: River Ravi, irrigation canals passing through the area which originate from River Chenab, and rains. Isotopic data of rivers are already available (Hussain et al., 1993) and their sampling is continued. δ^{18}O and δ^{2}H of River Ravi range from -11 to -6 ‰ and -86 to -40‰ with the mean values of -8.9‰ and -61‰, respectively. All the irrigation canals flowing through the study-area originate from the River Chenab. Their δ^{18}O ranges from -13 to -7.9‰, with mean value of -10.8‰ and δ^{2}H ranges from -86.3 to -56.2‰, with average value of -71.8 ‰. Sajjad (1991) determined the δ^{18}O and δ^{2}H indices (mean values) of river Chenab as -10 and -61‰ with high variability. The δ^{18}O and δ^{2}H indices for rain of the nearby area i.e. -5.5‰ and -32‰ have been used (Sajjad et al., 1991).

Frequency Distribution of δ18O

Frequency-histogram of δ^{18}O of deep water (Figure - 12) shows two populations. One population with modal class of about -6.5 ‰, which matches well with the index of base-flow coming from long distances; this class shows little contribution of local rains, which have δ^{18}O index of –5.5 ‰. The other population is from -9 to -7 ‰ with modal class at -8 ‰ showing significant contribution of river water. Because of significant difference in δ^{18}O values of groundwater sources, the following two-component mixing-equation roughly gives the fraction ‘f’ of river water.

$$F = \frac{\delta^{18}O_{B.F} - \delta^{18}O_{M}}{\delta^{18}O_{B.F} - \delta^{18}O_{R}}$$

where $\delta^{18}O_M$, $\delta^{18}O_{B.F}$ and $\delta^{18}O_R$ are δ^{18}O values of mixed groundwater, base-flow and river water, respectively. Using the above equation, about half of the sampling locations show 30 to 40% contribution of river water. The frequency-histogram (Figure - 13) of δ^{18}O of shallow groundwater also indicates two populations. One population is with modal class at -7.0 ‰, while the second population, which is much smaller than the first one, has modal class at -8.5‰. This distribution indicates that the groundwater-samples having major contribution from the river are much less in number, as compared to those recharged by other sources. The locations influenced by the river have greater fraction of its water, as compared to deep ones. Separation of the second population from the first one means that there is no significant mixing of river water at the locations falling in the second population and, most probably, the dominant lower end component having δ^{18}O = -7.5 ‰ is mixing with the local rains and base-flow.

Spatial Variation of δ^{18}O

As the water-supply wells pump the deep groundwater from the depth of 80m to 200m and private hand-pumps/shallow motor pumps tap upper groundwater up to 50m, so the data of deep and shallow aquifers are treated separately. Considering the spatial distribution of δ^{18}O in deep water (Figure - 14), the areas having δ^{18}O <-8.0‰ show significant contribution of the river. Such areas (marked with blue filled circles) lie along the river and extend towards the Lahore Branch Canal. The area away from the river (red coloured plus symbols) having δ^{18}O > -7 ‰ clearly shows base-flow mainly recharged by the rains. A narrow belt in the center, having δ^{18}O from -8.0 to -7.0‰, indicates mixing of rain and river waters in the recharge of deep groundwater. The original δ^{18}O and δ^{2}H indices of the base-flow were estimated as -6.4‰ and -41.7‰. The local-rain index of δ^{18}O for the study area is about -5.5 ‰, which is a bit more enriched than that of base-flow mainly recharged at relatively higher altitude. Sajjad et al. (1991) found the similar values of base-flow in the North-East area of Lahore. Spatial distribution of δ^{18}O in shallow aquifer (Figure - 15) shows similar trend as in the deep aquifer, but the extent of river-dominated and rain-recharged areas towards the center of the city is relatively less. In this case, large area in the center have mixed type of water. Lateral penetration of the river-water in the shallow zone is low.

Possibly due to high hydraulic gradient

towards the center of the cone of depression, which lie in the central part of the city, the vertical component of river-water flow is dominant. It justifies the smaller contribution of river-water in shallow aquifer than that in deep aquifer in the central part. There are a few locations in the eastern part, which are also away from Lahore canal and have δ^{18}O values from -8 to -9‰, showing high contribution of canal water. These points being near BRBD canal show its large contribution in the recharge.

Study of δ^2H vs. δ^{18}O

In the first and second samplings, water samples were mostly collected from WASA tubewells, tapping deep aquifer (screen: 80m to 200m) along with some private shallow pumps, obtaining water from 25 m to 50 m. Figure - 16 shows the plot of δ^2H vs. δ^{18}O for second sampling. All the points are scattered around LMWL between the river-index and rain-index. It confirms that the aquifer is recharged both by rains and the river. Some of the points being just below the LMWL show considerable evaporation-effect. In the third and onward samplings, a lot of hand-pumps were included. All the three plots of δ^2H vs. δ^8O (Figure - 17 to Figure - 19) pertaining to these samplings (No. 3 to 5) show the evaporation in the shallow aquifer. Departure of the points is not much from the LMWL, which does not show extensive evaporation. Such slopes may be obtained due to mixing of evaporated soil-water with the infiltrating rain (Clark et al, 1987). Moreover, the variation in the range of isotopic values reflects the seasonal variation in the input, which also indicate that the shallow water has sufficient recharge from local sources. The δ^{18}O of 4th sampling ranges up to -6‰, while that of 5th sampling it goes up to -5‰. It shows that contribution of local rain that might have evaporated, increased in the groundwater sampled in the 5th sampling.

Ca-Na Relationship

Calcium and sodium are two important chemical ions, which provide useful information on groundwater-recharge and movement when plotted taking the concentrations of these ions in meq/L percentages out of total cations (Ahmad, 1998). Generally, calcium bicarbonate type of waters indicate fresh recharge, or the recharged water has not moved a long distance from the source area. During the movement of groundwater, the dissolved calcium exchanges with sodium present in the minerals of soil-matrix. As a result, sodium gets dominant over other cations when water covers a long distance from the source area, which gives rise to an inverse relationship between calcium and sodium. Therefore, Ca/Na relationship parallel to isotopes has also been used to identify the recharging sources.

Relationships of Ca/Na for deep and shallow groundwater plotted in Figures - 20 and 21 confirm negative correlation. Three groups of groundwater (based on δ^8O) are represented by different symbols and colours. In case of deep water, data points of the river/canals lie at lower end with high Ca and low Na. Groundwater samples with δ^8O depleted more than -8‰, indicating major contribution from river-system (blue coloured), make a trend which starts from river points and indicates increase of Na with decrease of Ca. This trend confirms the recharge from river-system. The groundwater having δ^8O more enriched than -7‰ (mainly recharged by rainwater), lie in the upper part (high Na and low Ca) and slope of trend becomes slightly high. This type of water evolves after travelling longer distance. It seems the base-flow is mainly recharged by rainwater. The data pertaining to the middle group (mixed type of water) is scattered, showing different contributions of both the sources.

Shallow groundwater also shows similar trend of Na-Ca relationship (Figure - 21) to that of deep water, but the data-points are much more scattered, especially the samples with high δ^8O. It means that shallow groundwater is not recharged in a regular manner like deep groundwater, and various local sources are also contributing.

Modeling Of Lahore Aquifer

The whole municipal supply in the Lahore city area is groundwater. Every year new tube-wells are being installed to meet the demands of the increasing population. Presently, about 316 tube wells (2 to 4 cusecs), installed and being operated by WASA, are used for public supply. Total WASA abstraction of ground-water from the aquifer is 280 to 290 million gallons per day. Private sector is also pumping a substantial amount of water, which is estimated at 150 million gallons per day. Historical abstraction of ground-water from Lahore aquifer is shown in Figure - 22. The water-table is continuously lowering, as a result of heavy abstraction from the aquifer. In order to predict the future conditions of the water-table, a groundwater model of Lahore aquifer has been developed and has been calibrated with Visual Modflow. Visual Modflow is a computer-software, which analyses ground-water flow-dynamics. Hydrological data of WASA tube wells was used only to calibrate the model, as data on private tube wells was not accessible. Therefore, the results of the model could be considered preliminary ones and, to approach realistic values, more refined data is needed. Efforts are underway to collect all the relevant data to correct the model.

Water levels measured in November 1989 were used as initial observation heads (Figure - 23). In this figure, the hydraulic head is at 191 meter above mean sea-level (amsl) in the center of the city at Mozang and Gowal Mandi areas. Giving the required inputs, the model was run for different time-steps. The observed data of each year, from 1989 to 1998, was compared with the simulated results produced from the model. Observed data and simulated results were found in good agreement. Beyond 1998, future water-table conditions were simulated with a number of runs of the model. The water-table levels of 1998, 2009 and 2018 are shown in Figures - 24, 25 and 26, respectively. The observed water level in 1998 was at 185 meter amsl, which is predicted to lower further 12 meters to 173 meter amsl, in 2009. In 2018, the water level is predicted to go down to 170 meters amsl in the center of the city where apex of the depression-cone exists.

CONCLUSIONS

The following conclusions are drawn from the study of Lahore aquifer:

- Due to heavy abstraction of groundwater, the water table is declining rapidly and an irregular shaped depression-cone is formed in the central part of the city. If the abstraction of ground-water continues with the same pumping rate, the depression-cone will further extend south towards Kasur and Raiwind areas. The more saline and polluted waters of Kasur and Raiwind areas are the likely to intrude into the fresh aquifer under Lahore city.

- Development of chloride peak exactly at the place of depression-cone indicates that water of shallow and deep aquifer is mixing rapidly in the center of the city, while in other areas, vertical mixing is not efficient.

- Spatial variation maps of EC and Cl show that shallow aquifer is more saline, as compared to deep aquifer. Deep groundwater has generally low dissolved chemical load, indicating good quality, while shallow water is poor at most of the locations, except the areas near the river and irrigation canals.
- Stable isotopic data show that the deep groundwater in the area from the river Ravi up to the center of the city has major contribution of river-water, while at the locations far from the river it seems to be totally base-flow recharged by rains of distant area in the North-East. Groundwater showing mixed recharge from river and rains is also encountered in the intermediate area.

- The shallow groundwater at the locations near the river is mainly recharged by the river water. River influence is restricted to a smaller area, as compared to that in case of deep zone. In the other areas, different local sources like irrigation canals, sewerage drains, local rain and may be the leaking main supply-lines seem to be contributing.

- The identified compositional types of shallow, as well as deep, groundwater are mainly calcium bicarbonate (19 %) at sampling points near the river Ravi, and sodium bicarbonate (69 %) away from the river in rest of the area, indicating cation exchange process.

- Mixing of shallow and deep ground-water, especially in the center of the city reveals that the aquifer is highly vulnerable to pollution.

RECOMMENDATIONS

- As the aquifer has been found vulnerable to pollution, there is need to study the presence of any kind of pollution such as bacterial, heavy metals like arsenic, lead, chromium, mercury and anions like fluoride, nitrates, etc.
- There is an urgent need to study the temporal position of intruding saline boundary from the south. Unfortunately, if it enters into the fresh aquifer zone, it will be almost impossible to clean the aquifer from this menace. Further lowering of water-table can be stopped by;

  - Artificial recharge at the time of heavy rains;
  - Increasing water-demand be fulfilled not only from exploiting the aquifer, but also use of surface-water from canals/river should be explored
- With the advent of high speed computers, it is quite possible to study the behavior of an aquifer (flow dynamics, transport of pollutants and future predictions). Therefore, modeling of the aquifer should be included as an imperative part of exploration, and management studies. Modeling is very cost-effective, as installation of only one tube-well of about 4 cusecs discharge in Lahore costs about 3 to 4 million Pak. Rupees, while the modeling of the whole aquifer will approximately cost one million Rupees only.
- Development of a data-base is strongly recommended. At present, all data is present in the form of files and reports. Data should be in form ready for its retrieval, to be used in computer-based modeling.
- Conservation of water should be given highest priority, for sustainable utilization of these vital resources.

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FIGURES REFERRED IN THE PAPER

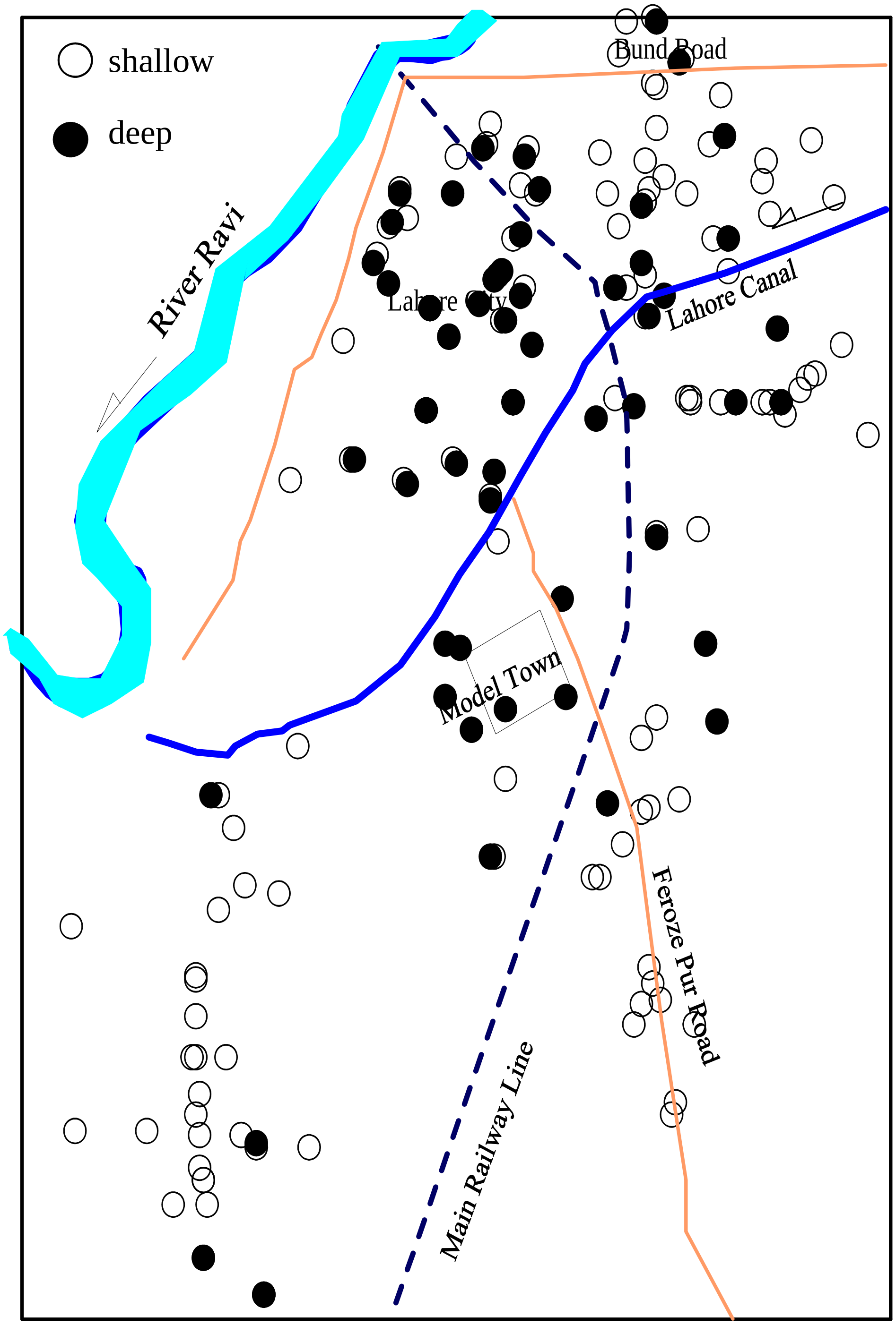

Figure – 1: Map Showing Locations of Sampling Points

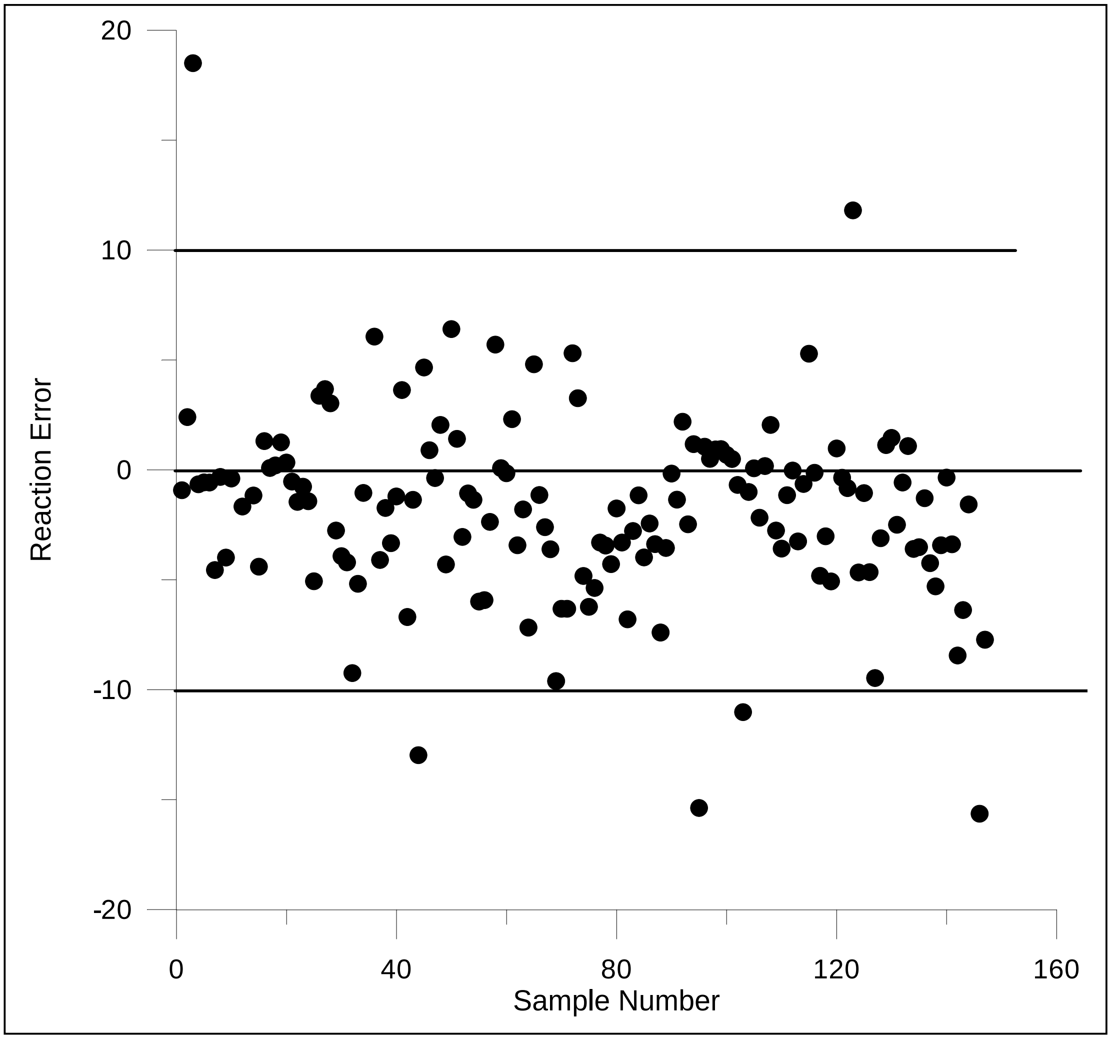

Figure – 2: Ionic Balance Reaction Error

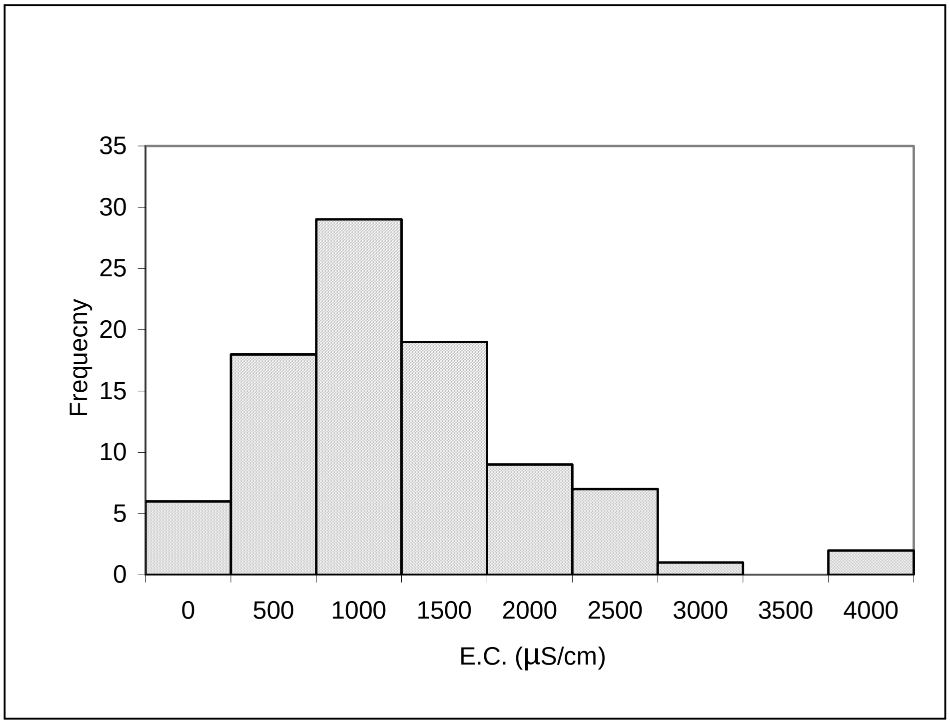

Figure – 3(a): Frequency-Histogram of Shallow Groundwater

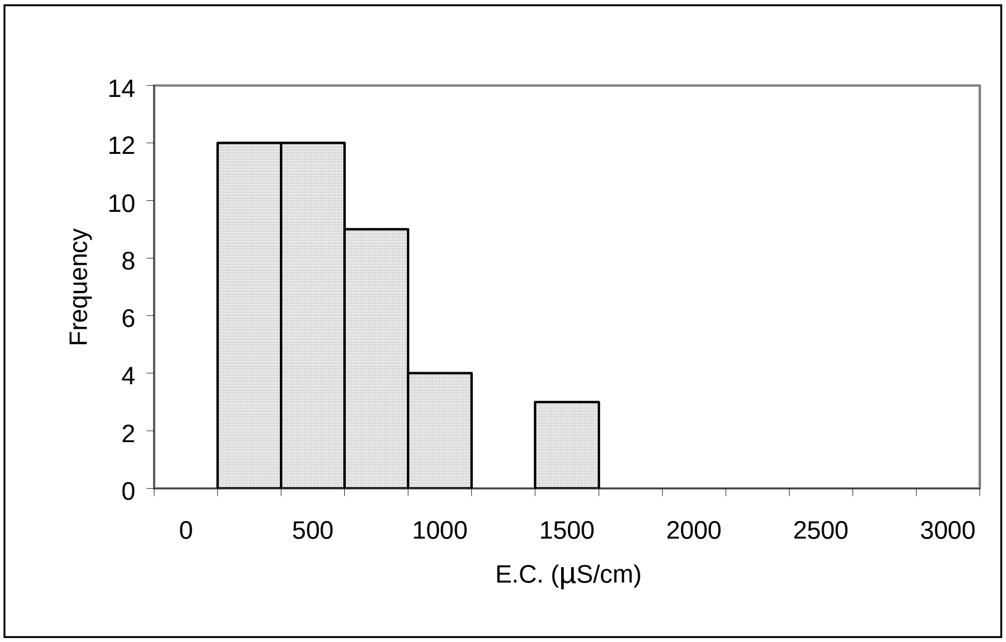

Figure - 3b: Frequency Histogram of Deep Groundwater

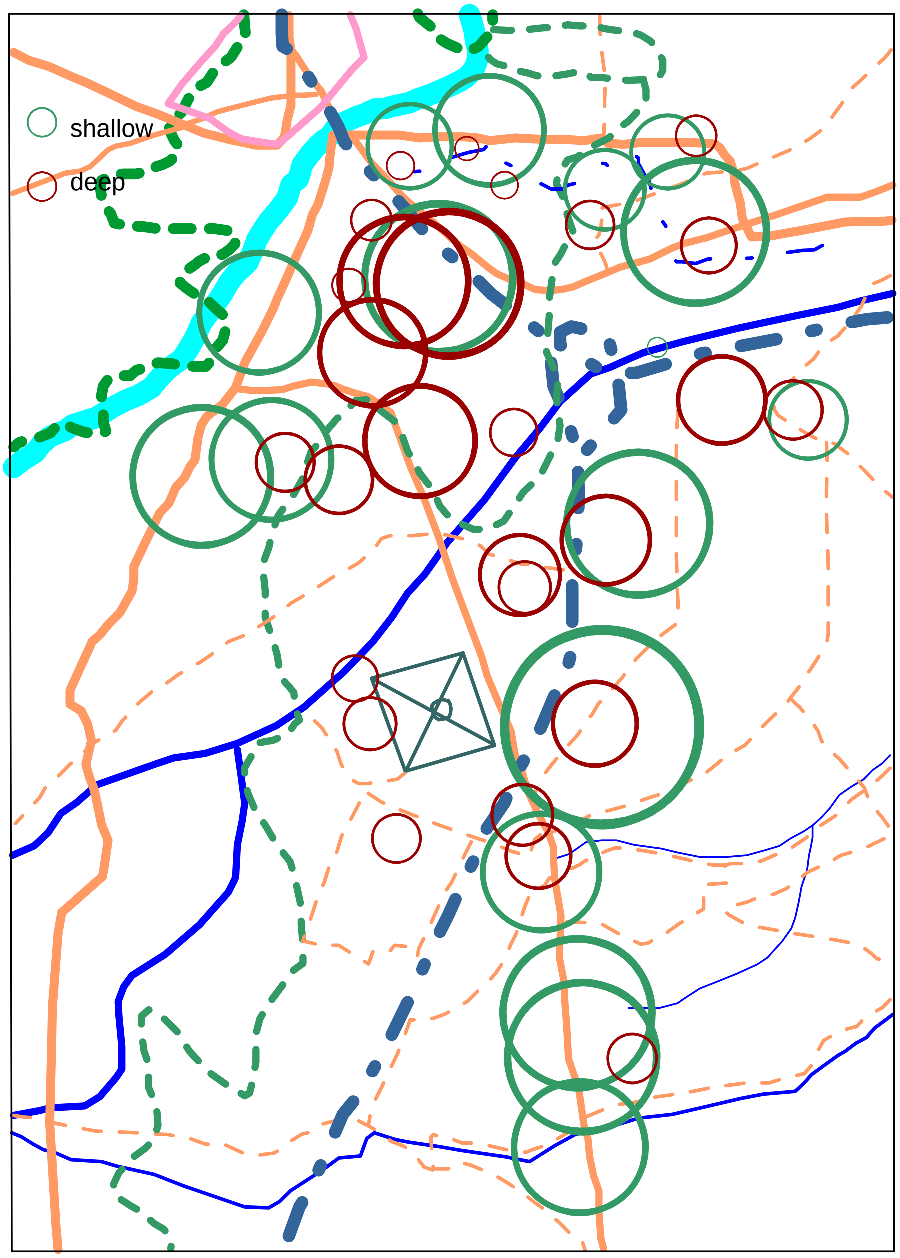

Figure – 4: Spatial Variation of EC

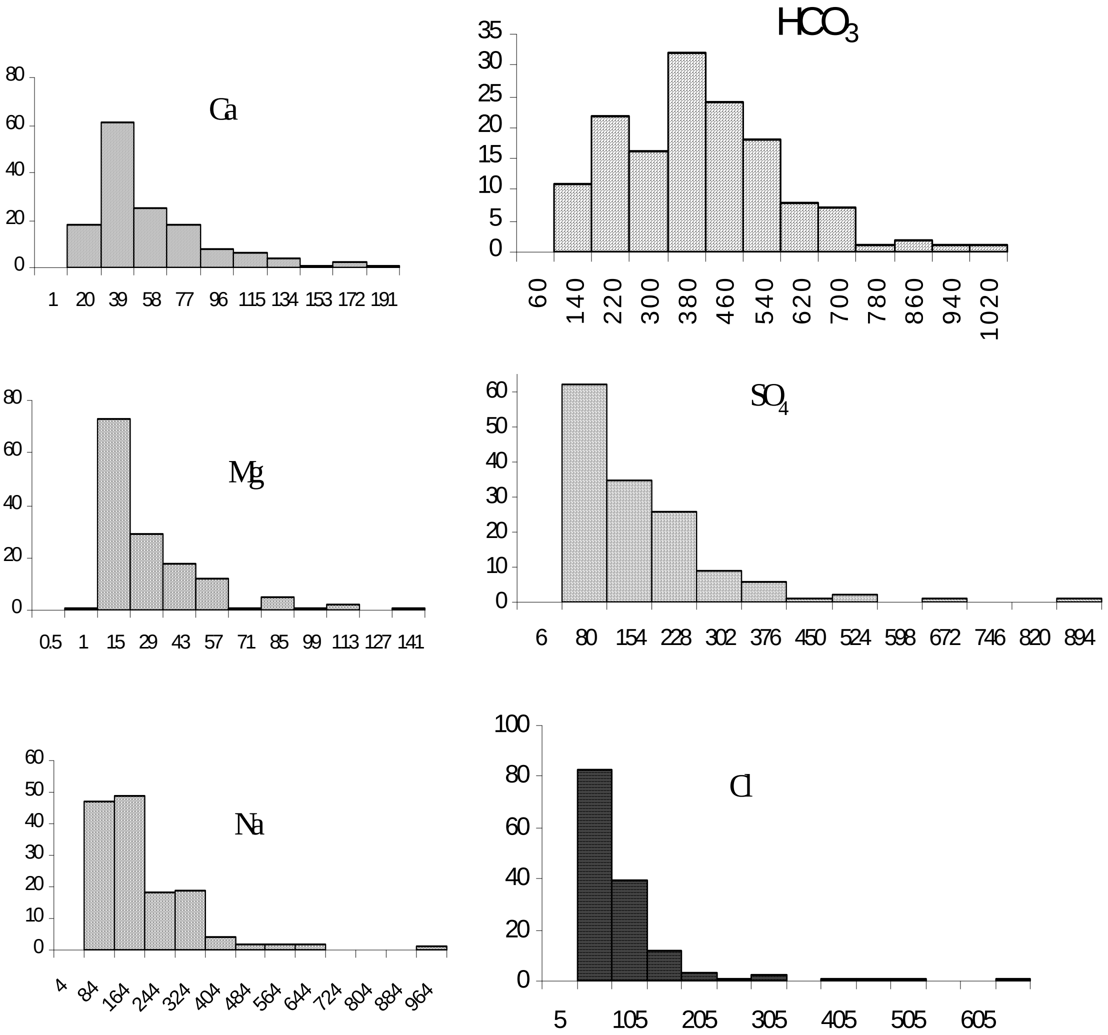

Figure – 5: Frequency-Histograms of Chemical Ions

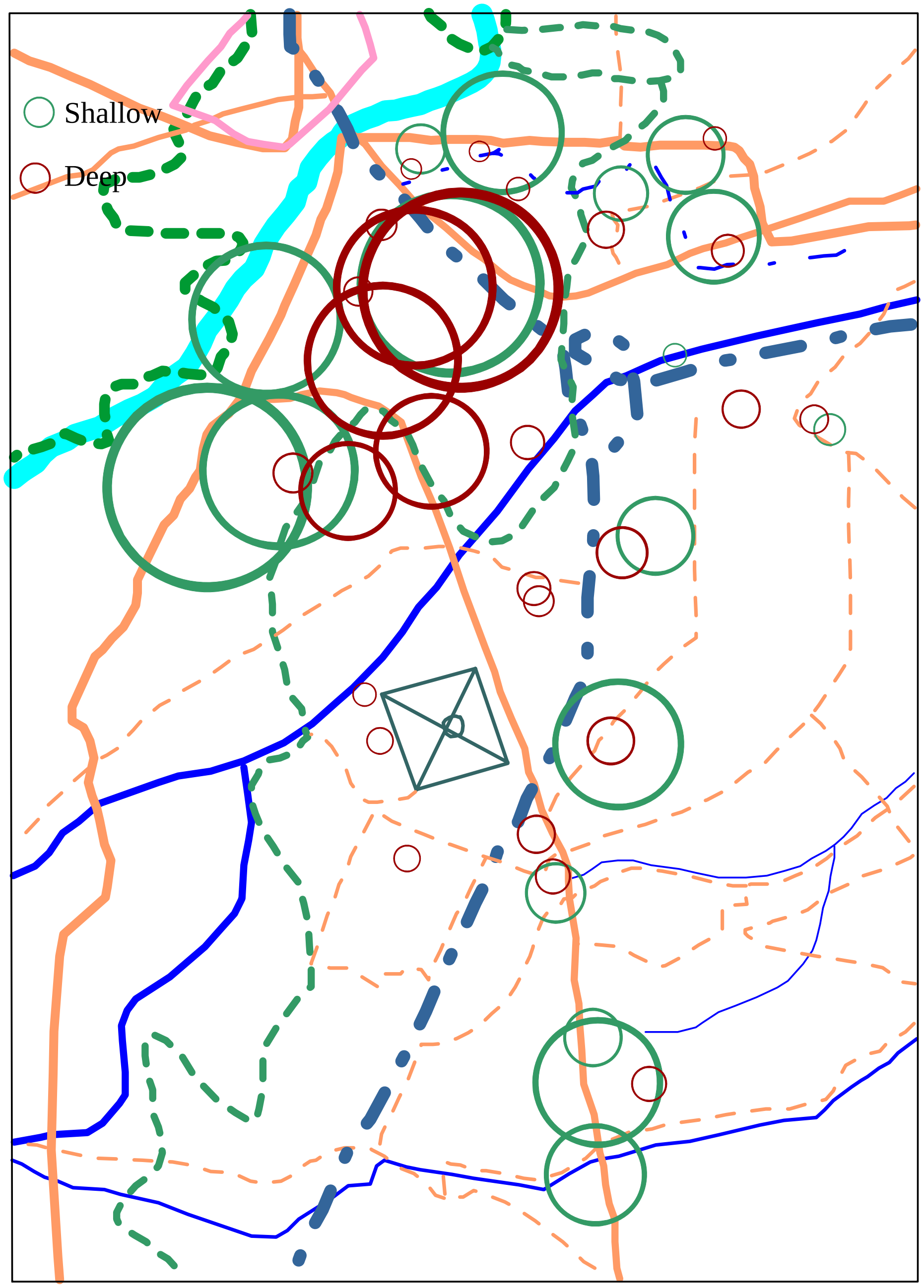

Figure – 6: Spatial Variation of Cl

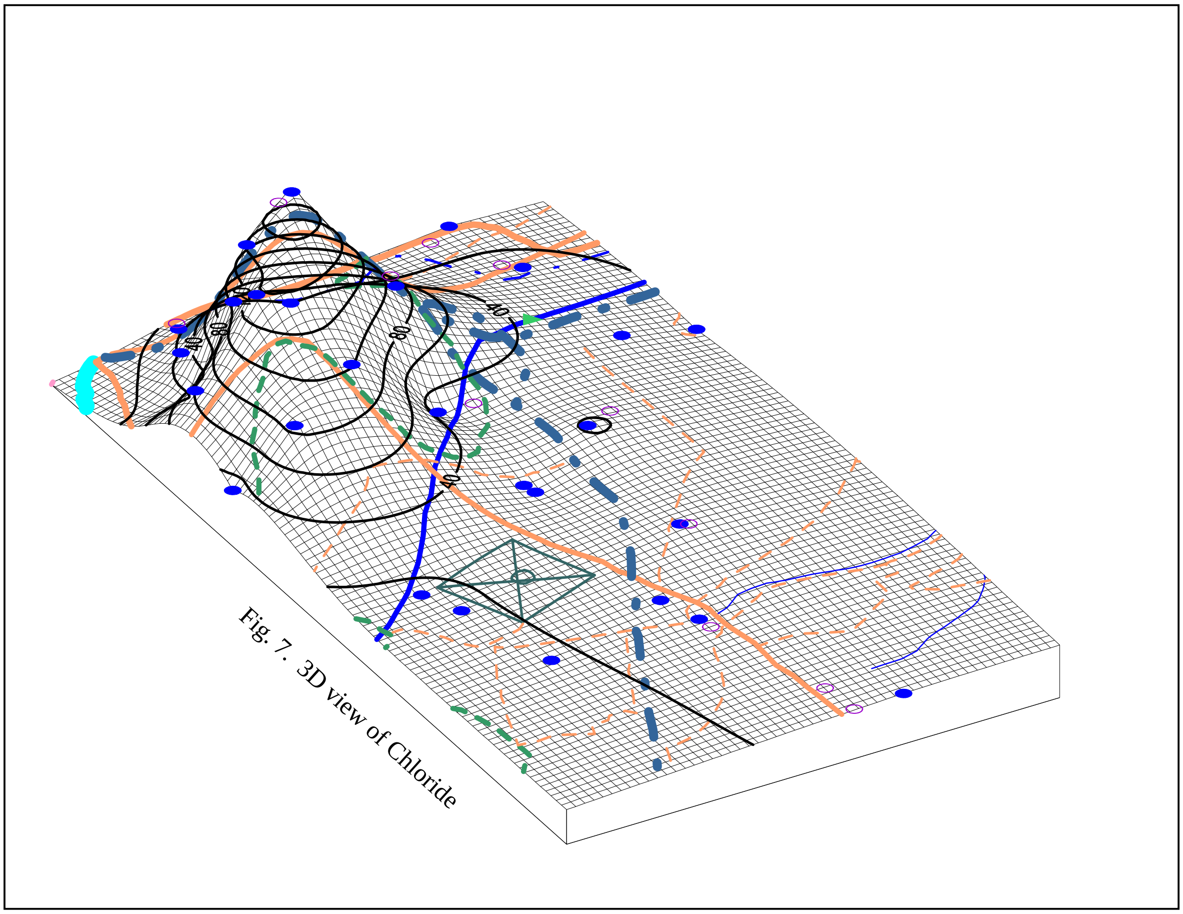

Figure – 7: 3D View of Chloride

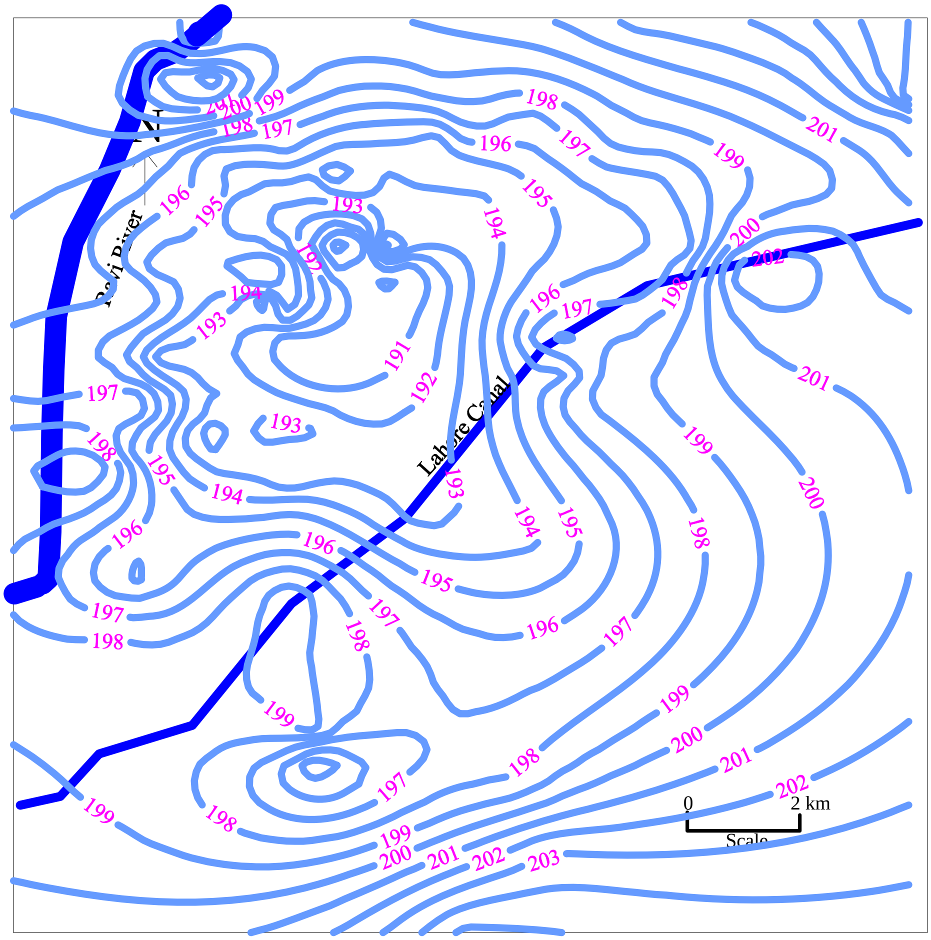

Figure – 8: Contours of Water-Level (Observations in November 1989)

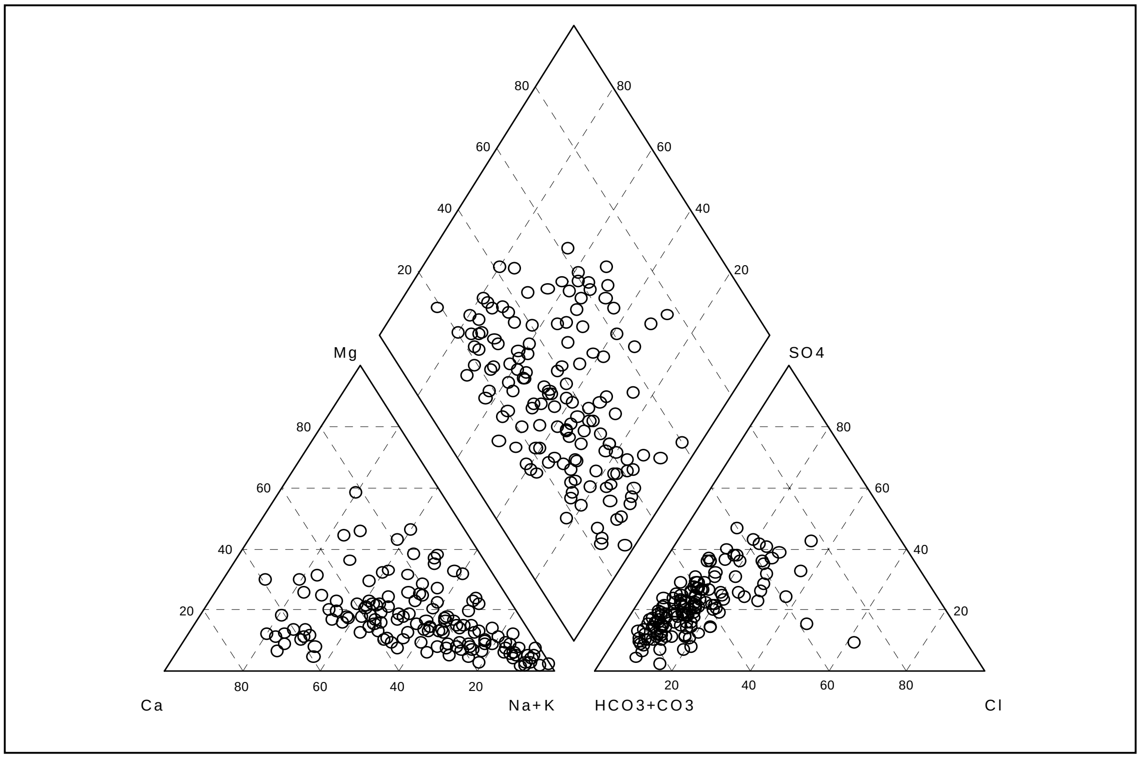

Figure – 9: Plot of Chemical Analyses on Piper-Diagram

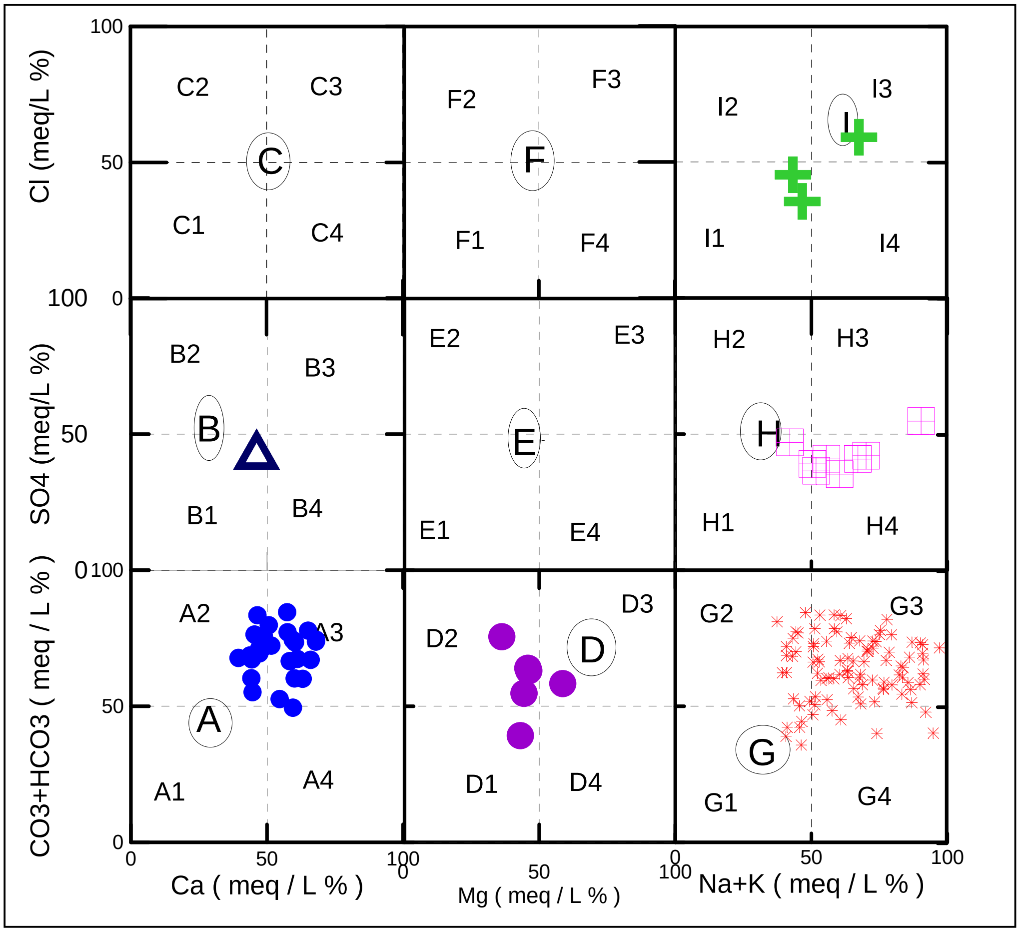

Figure – 10: Classification of Chemical Analyses by Multi-Rectangular-Diagram

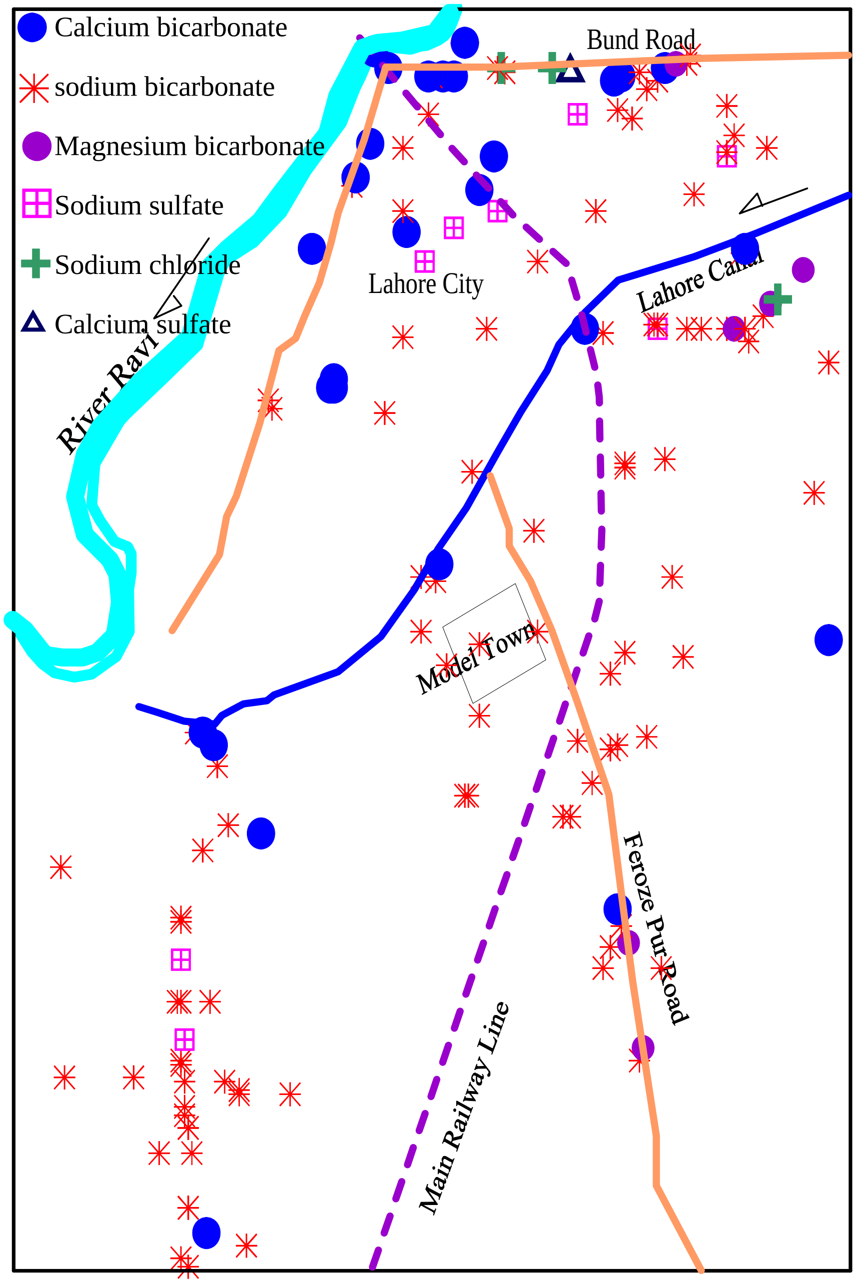

Figure – 11: Map Showing Hydro-Chemical Facies

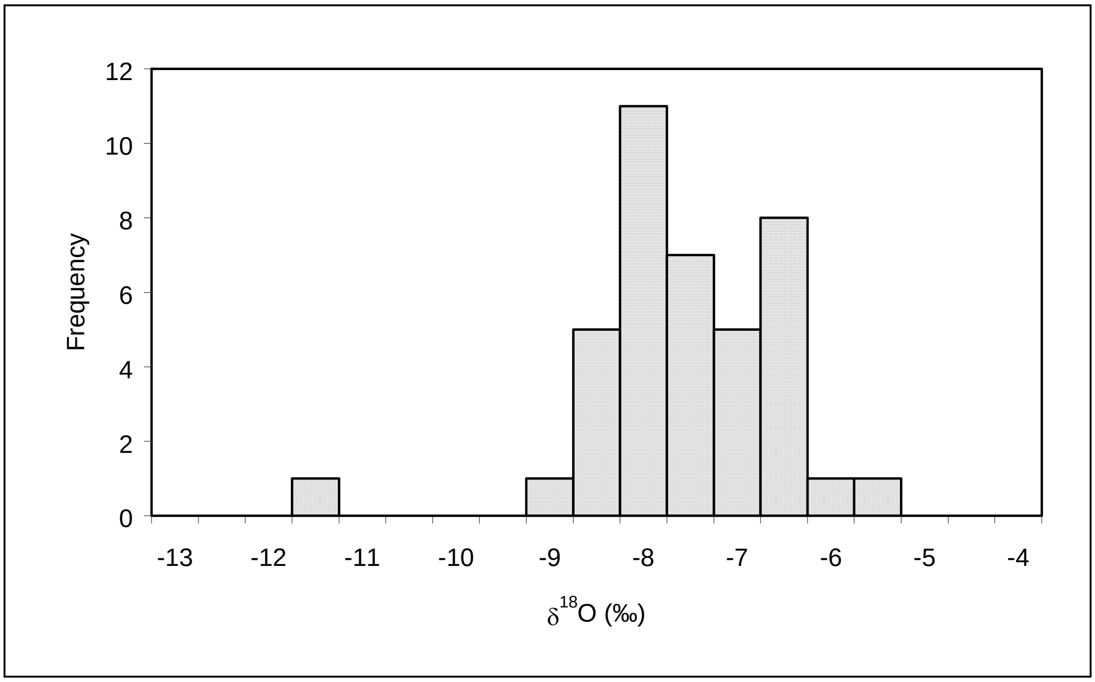

Figure – 12: Frequency-Histogram of $\delta^{18}O$ of Deep Groundwater

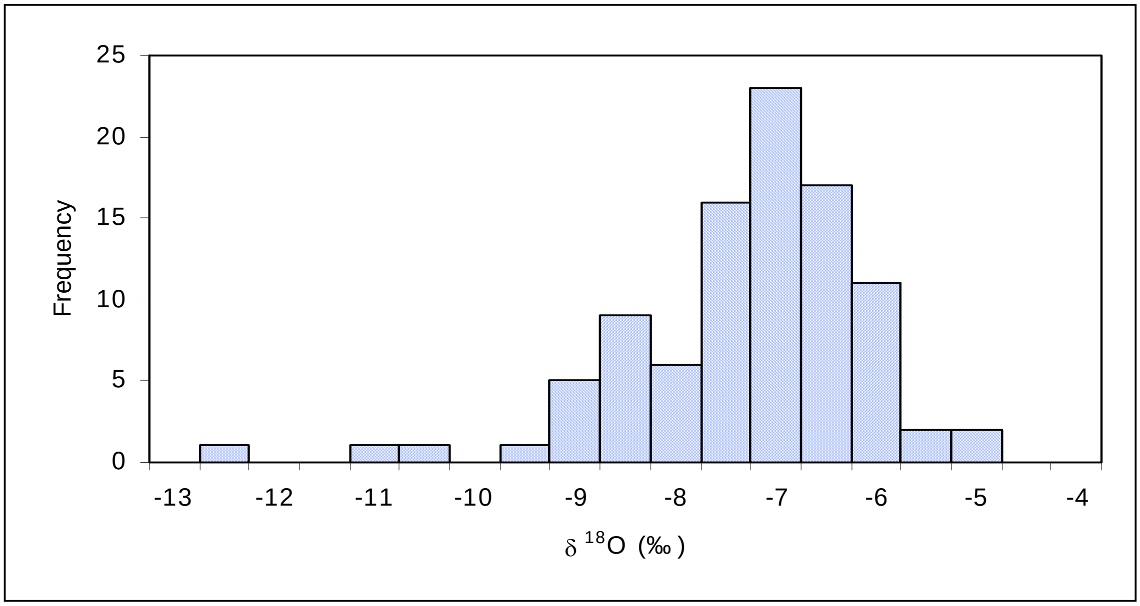

Figure – 13: Frequency-Histogram of $\delta^{18}O$ of Shallow Groundwater

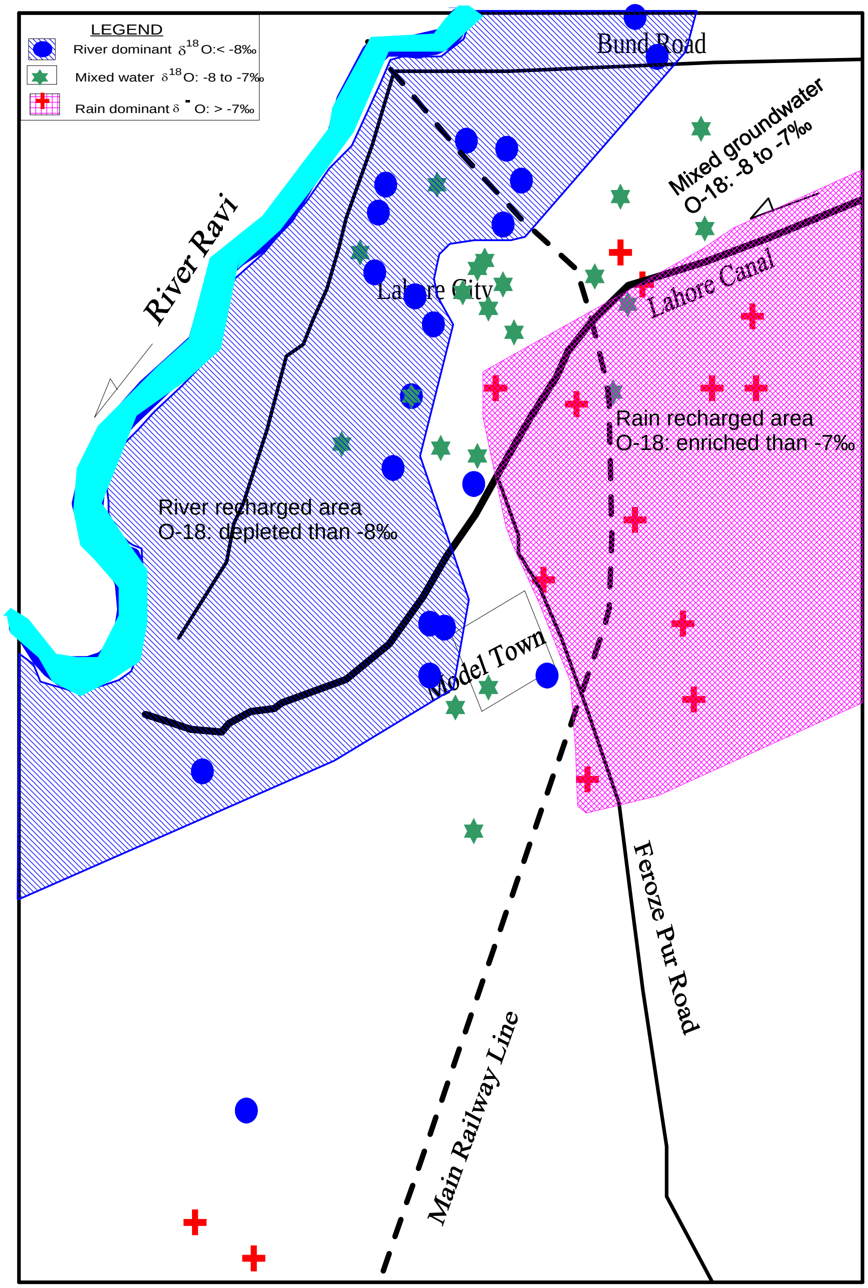

Figure – 14: Spatial Variation of δ ^{18}O of Deep Groundwater

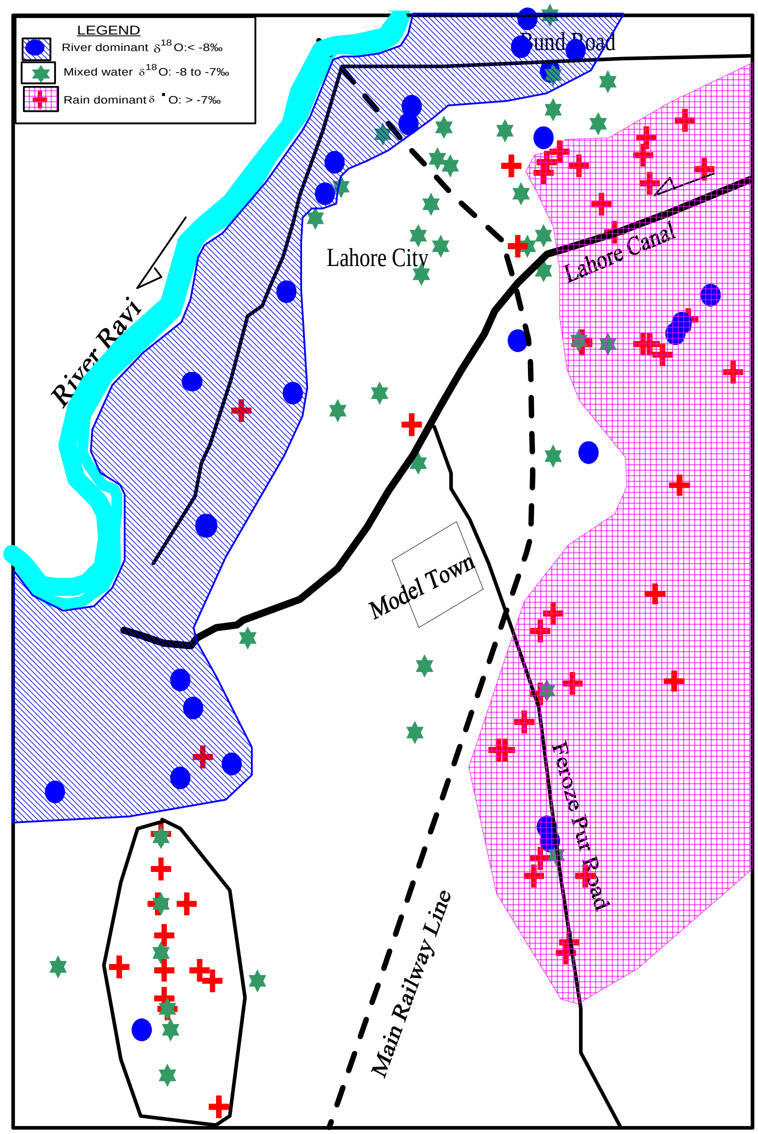

Figure – 15: Spatial Variation of $\delta^{18}O$ of Shallow Groundwater

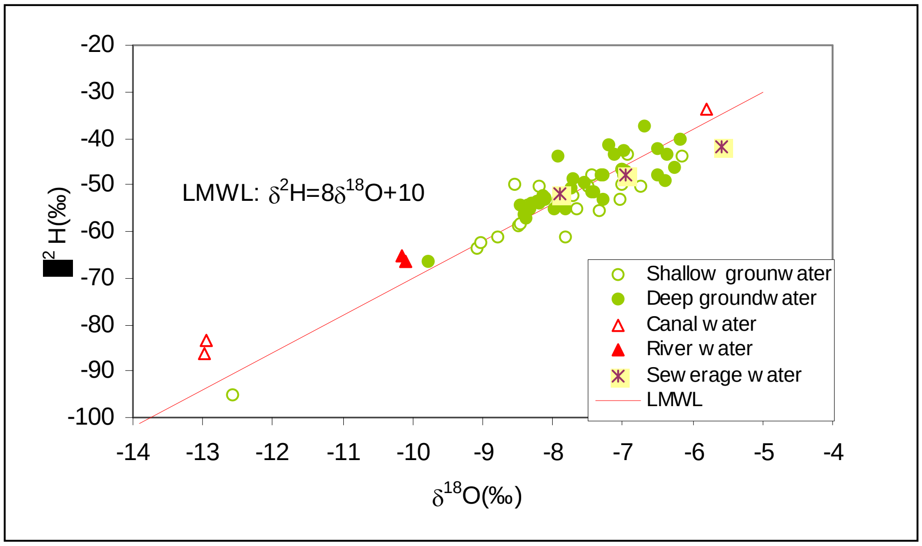

Figure – 16: Plot of δ ^{2}H vs δ^{18}O (2nd Sampling)

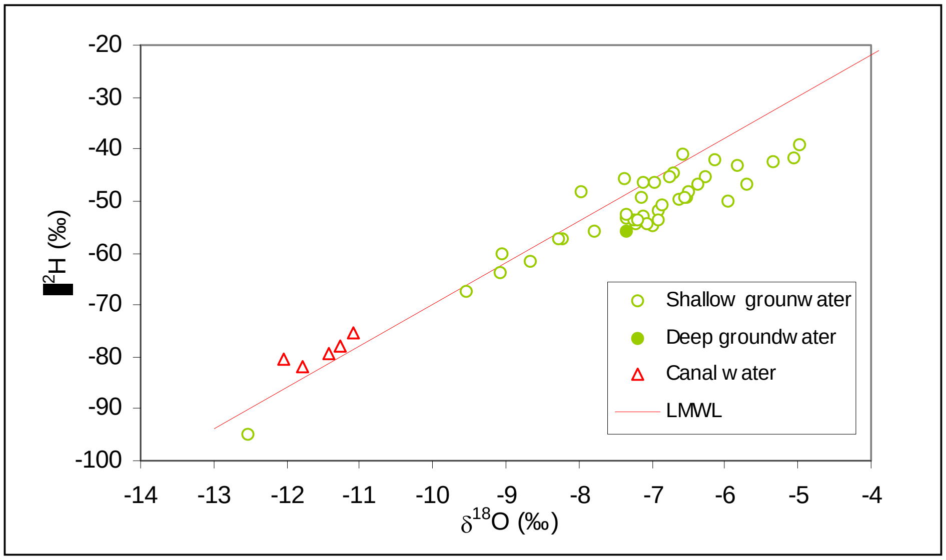

Figure – 17: Plot of δ^2 H vs δ^{18}O (3rd Sampling)

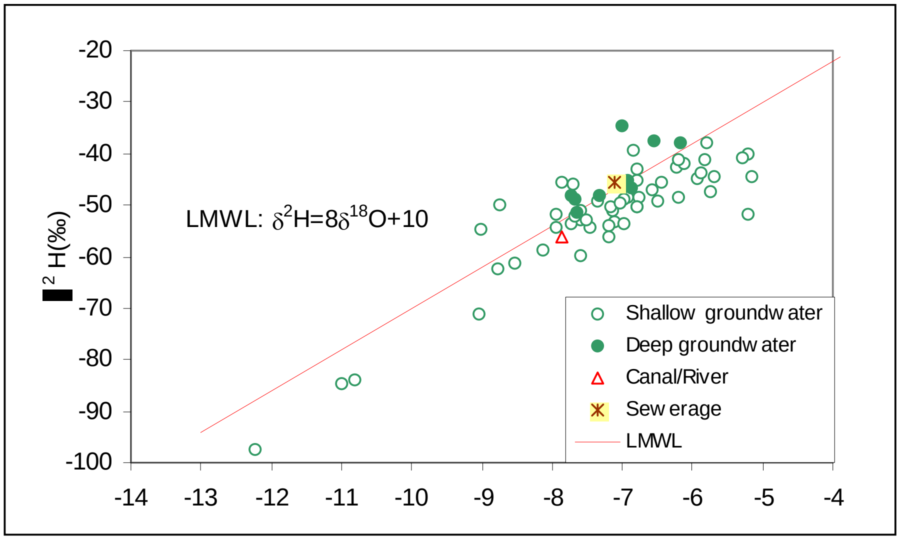

Figure – 18: Plot of δ^2H vs δ^{18}O (4th Sampling)

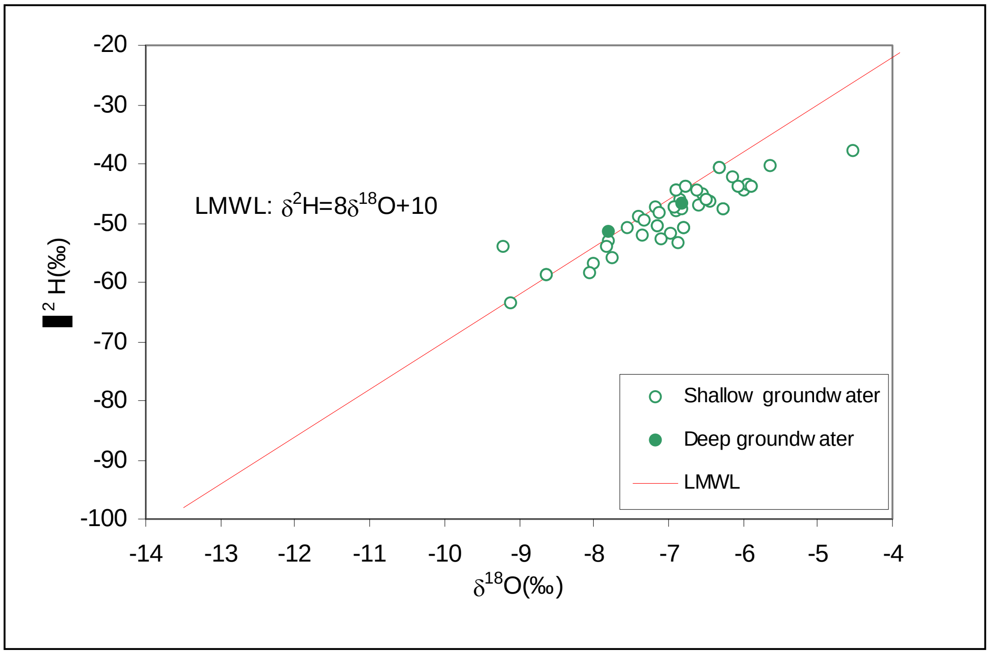

Figure – 19: Plot of δ^2H vs δ^{18}O (5th Sampling)

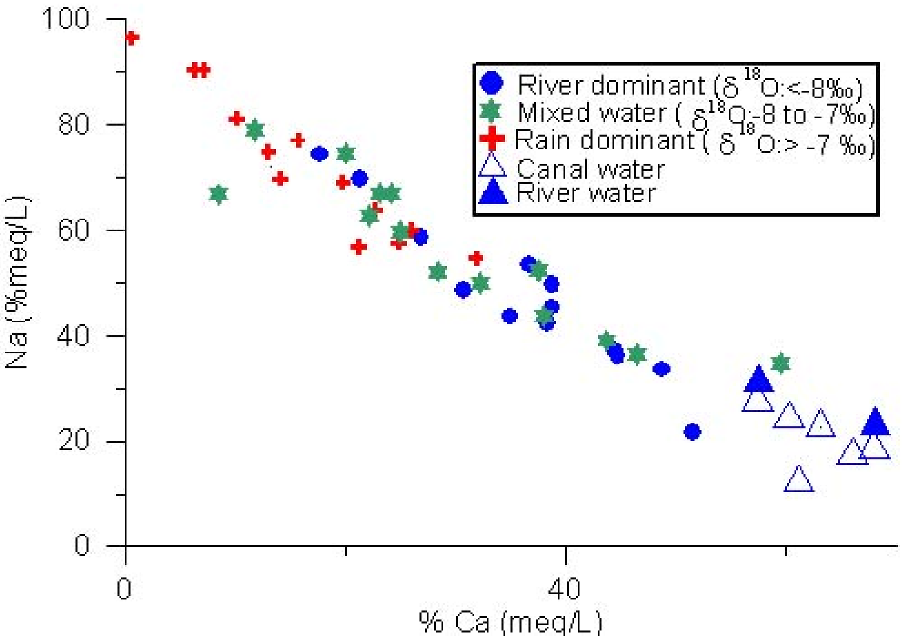

Figure – 20: Na-Ca relationship of deep groundwater

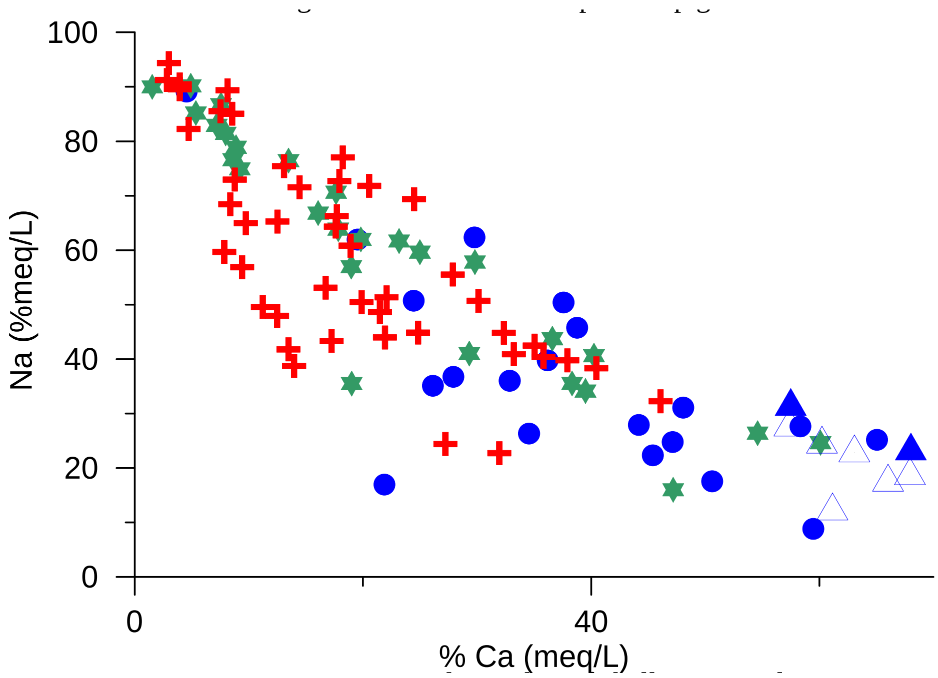

Figure – 21: Na-Ca Relationship of Shallow Groundwater

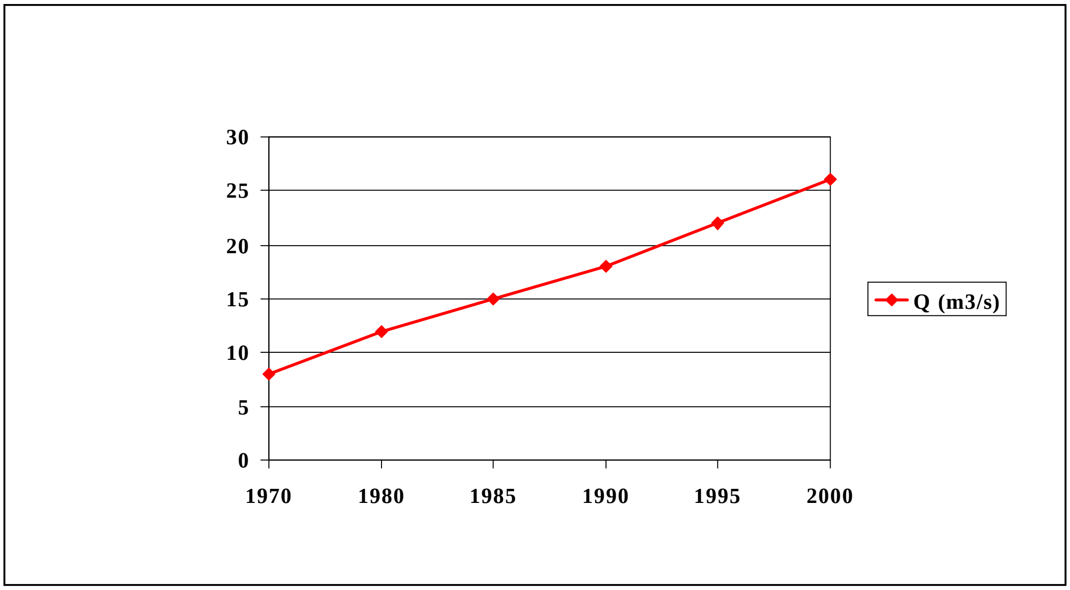

Figure - 22: Historical Abstraction of Groundwater from the Aquifer

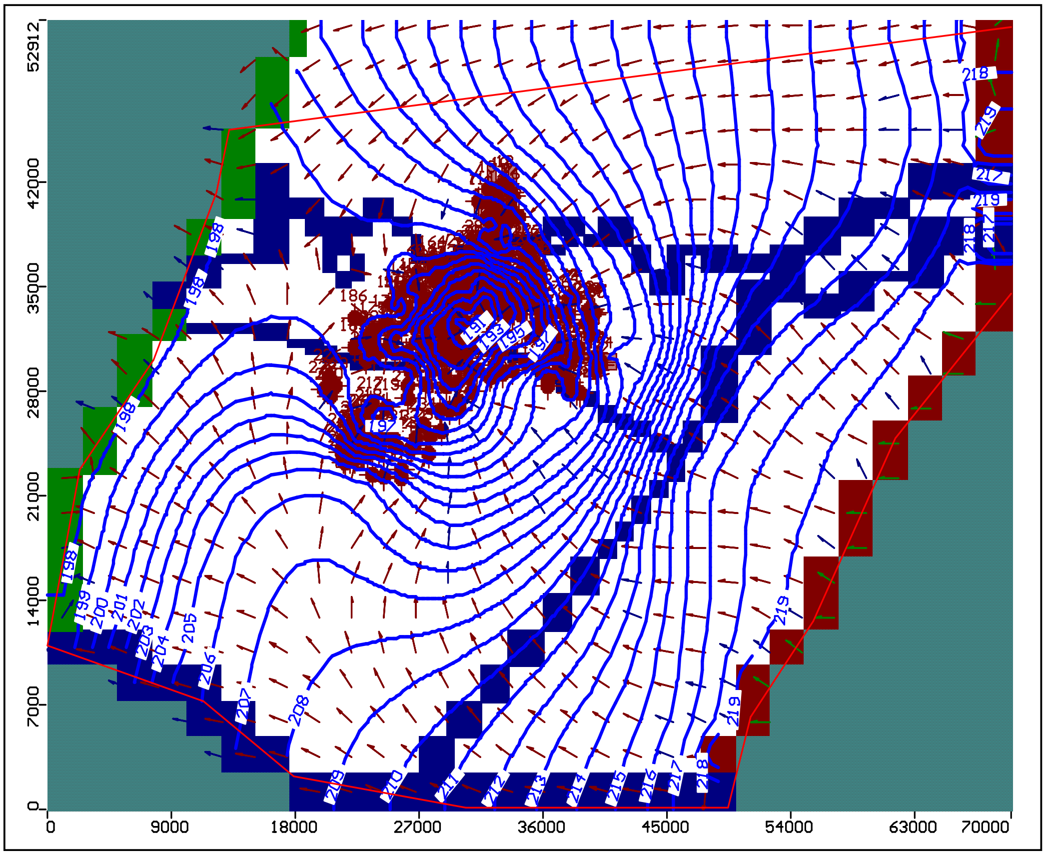

Figure - 23: Observed Contours of Water-Table (November 1989 by Visual Modflow)

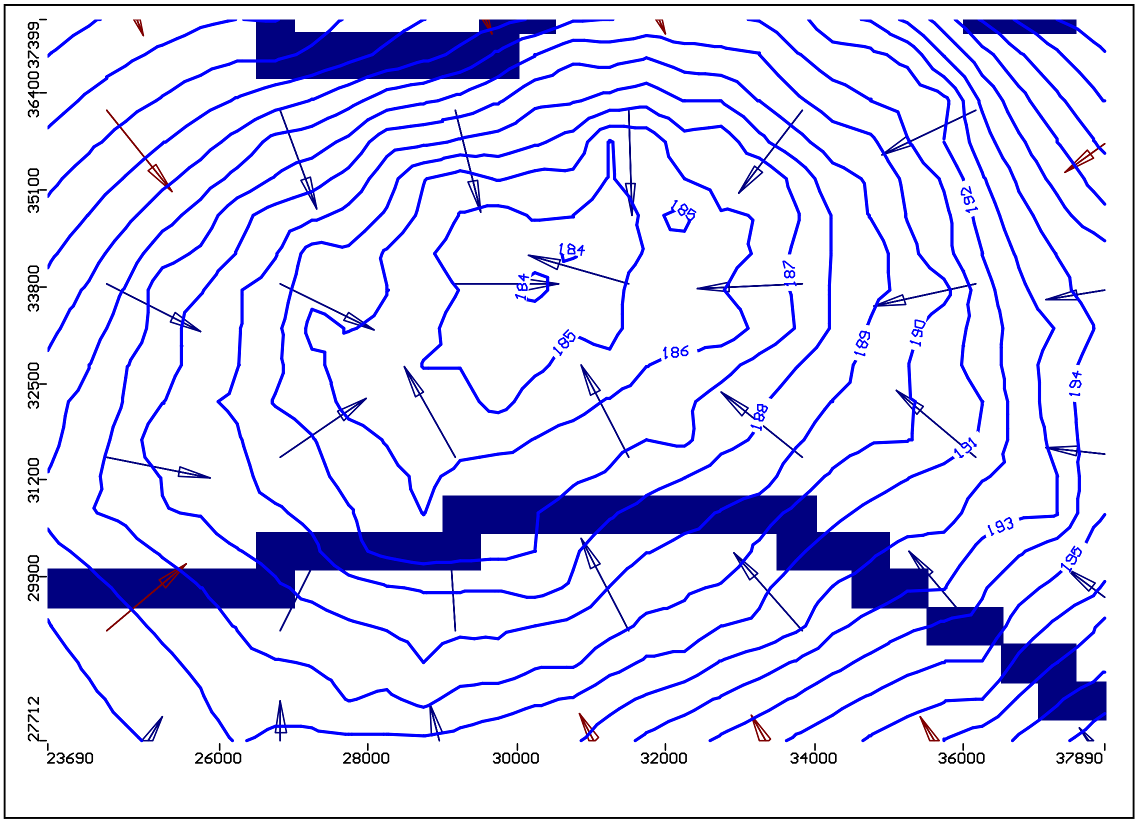

Figure - 24: Observed Water Table Contours in 1998 by Visual Modflow

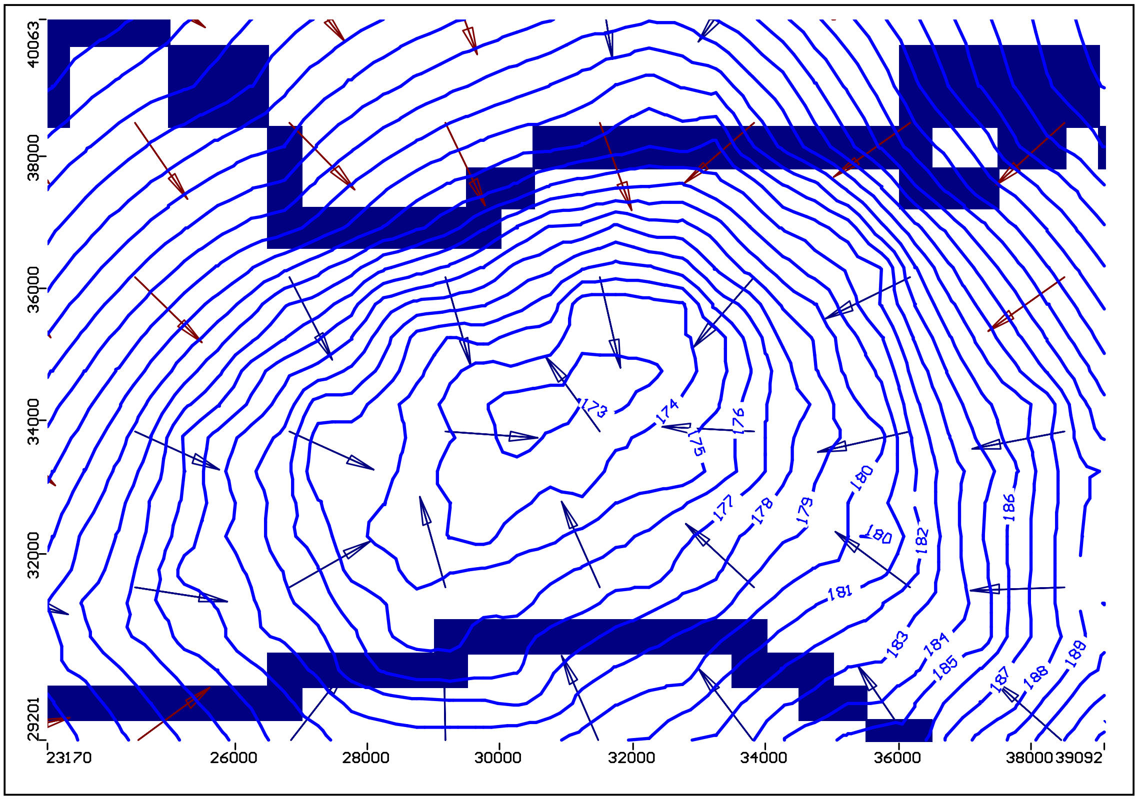

Figure - 25: Predicted Water-Table Contours in 2009 by Visual Modflow

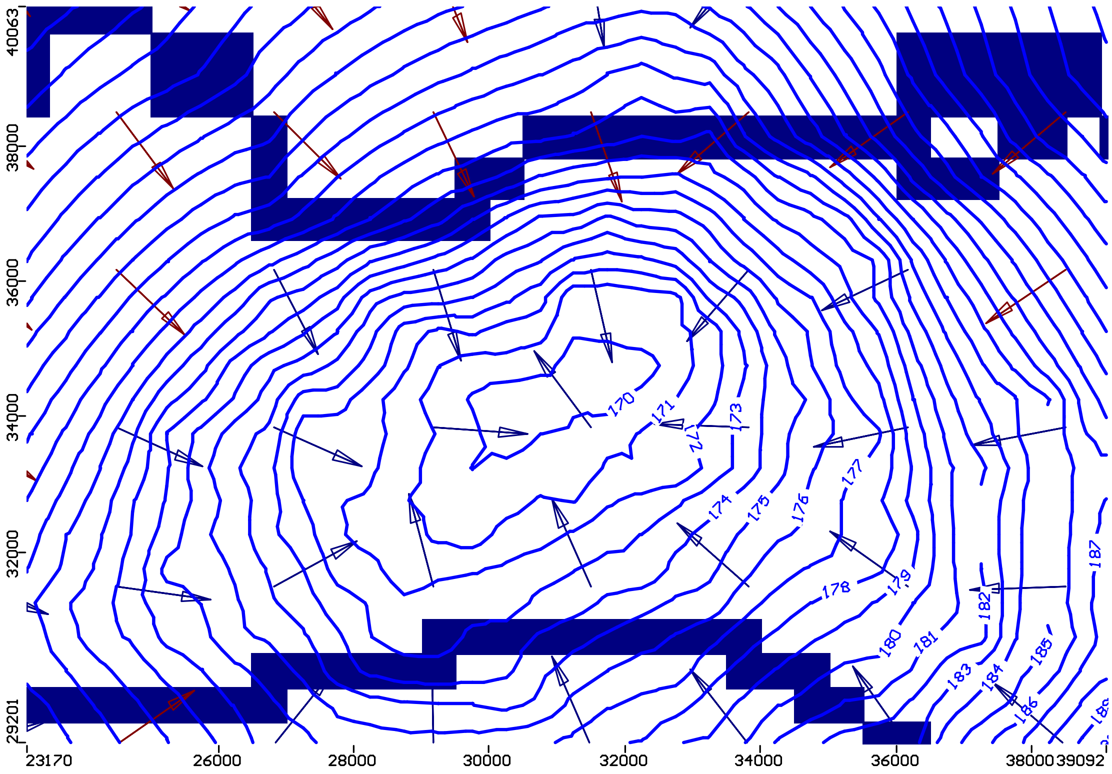

Fig. 26. Predicted Water-Table Contours in 2018 by Visual Modflow