Subsurface Characterization of Aquifers

SUDHIR KUMAR
National Institute of Hydrology, Roorkee

INTRODUCTION

Approximately 78% of the total freshwater on Earth is located and stored in the subsurface. Nevertheless, despite the abundance of groundwater resources, un-controlled and unregulated extraction of the resource can contribute to changes in the aquifer systems. In coastal areas for instance, overexploitation has disturbed the naturally established equilibrium between seawater and freshwater resulting in uncontrolled saltwater encroachment into coastal aquifers. As a large portion of the world's population (e.g. about 70%) dwells in coastal zones, it is therefore important to develop optimal exploitation of groundwater and to control saltwater intrusion. For proper and optimal exploitation of the costal aquifers, it is necessary to understand the hydrogeological conditions and characterize the coastal aquifers.

SUBSURFACE INVESTIGATIONS

For subsurface characterization of an area, geological, geophysical, and water quality investigations are required to be conducted. Various stages involved in the investigations are depicted schematically in Table 1.

Table 1. Stages in subsurface characterization.

Stage	Description	Investigations
I	Office Study	• Topographic maps • Aerial photographs and Satellite images • Regional geological and hydrogeological maps and reports • Bore hole logs, fence diagrams etc.
II	Reconnaissance Survey	• Geological mapping (including Geomorphological, structural, lithological, stratigraphical and hydrological investigations) • Primary water level and quality monitoring
III	Detailed Investigations	• Exploratory drilling and well logging • Geophysical exploration • Drilling of observation and production wells • Estimation of aquifer parameters by pumping test • Tracer and isotopic investigations • Water level & quality monitoring • Water quality assessment

Stage-I (Office Study)

In the first stage, a search should be made for existing data available in published or unpublished reports of the Central or State departments of geology, water resources, soil surveys, published papers by researchers from academic institutions and other agencies. Valuable hydrogeological data are often inaccessible as parts of carefully guarded documentation of oil companies and mines. Additional useful information may also be available from local contractors and municipal bodies.

In the absence of any required information, depending on the nature of problem, investigations are required to be carried out.

Stage –II (Reconnaissance Survey)

Surface Geological Investigation: Reconnaissance surveys consist of rather extensive studies of the hydrogeology of the region under investigations, using geological maps, aerial photographs, remote sensing data, and ground observations to detect sufficiently permeable strata that by virtue of their relative elevations or depressions, geologic history, and hydrology could be water bearing. Much can be learned from the examination of available maps, reports, and data. There are published geological maps by Geological Survey of India on 1:50,000 scale for most of the parts of India and soil maps by National Bureau of Soil Survey and Land Use Planning. Published geologic maps and reports provide the initial indication of the rock formation, together with their stratigraphic and structural interrelationships. Soil maps together with topographic maps provide an introduction to the distribution of potential recharge areas. In view of the importance of unconsolidated sands and gravels as potential aquifers, special attention must be paid to geomorphic landforms and to the distribution of alluvial deposits. Where sand and gravel deposits are sparse, or where these deposits are shallow and unsaturated, more detailed attention must be paid to the lithology, stratigraphy, and structure of the bed rock formations.

Seeps and springs are among the hydrologic surface features that may aid in evaluating the subsurface conditions in the area. Hillside seeps above outcrop of less permeable strata indicate groundwater in overlying formations. A few large springs may indicate thick transmissive aquifers, whereas frequent, small springs tend to indicate thin aquifer of low transmissivity. In arid areas, presence of trees or other deep rooted vegetation in an otherwise barren landscape may indicate shallow groundwater, for example below ephemeral streams, floodplains, or oases. If the groundwater table in arid areas is close to the surface, evaporation can cause salt accumulation on the surface of the soil. These salt flats, with or without salt tolerant vegetation, should not be confused with playas which are ephemeral lakes formed by surface runoff in low areas with soil of low permeability. Biological indicators of groundwater may even include ants, which are reported to be able tunnel down as much as 30 m to reach groundwater and are used to detect groundwater in the deserts.

Stage-III (Detailed Investigations)

Subsurface Geological investigations: Surface manifestations of a hydrogeological environment may not always be sufficient to locate potential aquifers. It is unlikely that subsurface stratigraphic relationships will be fully revealed without direct subsurface investigations. Once again, the initial steps usually involve scanning the available records. Many State and Central government departments drill wells for water supply and other purposes and maintain the geological logs of all borewells drilled by them and other agencies. These data, while varying widely in quality, can often provide considerable information on past successes and failures in a given region.

In most exploration programs, it is necessary to carry out test drilling to better delineate subsurface conditions. Test holes provide the opportunity for geological geophysical logging and for the coring or sampling of geological materials. Test holes can also be used to obtain water samples for chemical analysis and to indicate the evolution of the water table at a site. Test drilling programs, together with published geological maps and available well log records, can be interpreted in terms of the local and regional lithology, stratigraphy and structure. Their logs are used to prepare stratigraphic cross sections, geological fence diagrams. Isopach maps of overburden thickness or formation thickness, and lithofacies maps. Hydrogeological interpretations might include water table contours and isopachs of saturated thickness of unconfined aquifers. The results of chemical analysis of groundwater samples, when graphically displayed, can provide important evidence on the natural geochemical environment as well as a direct measure of water quality.

HYDROGEOLOGIC WELL LOGGING

Hydrogeologic well logging is the continuous inspection or measurement and recording of details of drill cuttings, drilling mud, discharge, water levels and other information during the course of drilling. In order to delineate depthwise lithologic and ground-water conditions, drilling-time logs and geologic (lithological) and hydrologic logs (discharge) are prepared. These logs form the basis for interpretation of geophysical logs, and for design and construction of wells.

Drilling Time Log: A drilling time log consists of a record of depthwise variations in the rate of drilling (Fig. 1). The rate of drilling is recorded in m/hr or ft/hr or min/m or min/ft. As the resistance to the penetration of the drill bit is largely a measure of the aggregate mineral composition and consolidation of the rock, the drilling rate is a useful index to differentiate formations when drill cuttings are similar. The drilling time log is especially useful with hydraulic rotary drilling where samples are contaminated with mud and caving material, while it is less useful in pneumatic and percussion drilling where the rate of drilling is comparatively slow and representative formation cuttings can be obtained. While interpreting the drilling time log, factors like type of bit, bit condition, superincumbent weight on bit, bore diameter, rotation speed, drilling method, mud viscosity, etc. should be considered.

Weathered granitic and gneissic rocks can be distinguished from alluvial material by their distinctive penetration rates. Very often, a good correspondence is observed between the drilling-time and resistivity logs. The range of drill time for some formations is given in Table 1.

Geologic and Hydrologic Logging: The geologic log gives a depthwise record of the nature, texture and mineral composition of the rocks drilled through (lithological log), interpreted on the basis of drill-cutting samples coming out of the borehole, drilling rate, drilling action, fluid losses, changes in mud consistency, etc. An accurate geologic log is fundamental to all other log interpretations and for proper well construction. Geologic logs are used for correlation of strata, to indicate the thickness and extent of aquifers and confining layers, and the configuration of the bed-rock topography. The drill-cutting samples obtained during the course of the drilling are utilised for laboratory determinations of their hydrologic properties.

Interpretations can be misleading if one is to rely solely on the description of the sample without considering other aspects. What is important is to identify the lithology of the rock as it occurs *in situ,* and not as what the sludge appears to be on the surface. A clear distinction should be made in the log description between what is observed and inferred. Geologic logging of holes drilled by the cable-tool and DTH methods of drilling is comparatively simple. Logging of holes drilled by the rotary method requires that the following aspects be considered:

1. Representative samples should be collected from different parts of the sample catcher. Samples obtained from a close proximity of the borehole contain disproportionately large percentages of coarser fractions.
2. Fines are lost in circulation if the drilling mud is too thick. After drilling through thick clays, the mud becomes too thick to allow a representative sample to settle. Hence it should be properly conditioned. The mud may have to be thickened while drilling through permeable water-bearing formations so that coarser cuttings are brought out of the hole.

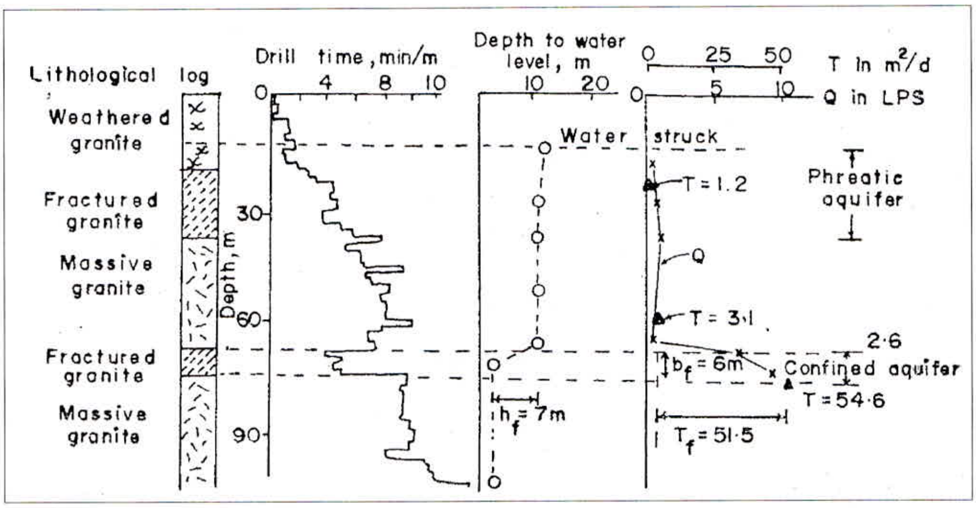

Fig.1 Hydrogeologic logs of a well drilled in granitic rock.

Table 1: Drilling Penetration Rates (Feet / Hour)

Drilling Method	Geologic Formations						
	1	2	3	4	5	6	7
Rotary Drilling (Air)	40 and up	30 - 50	20 - 40	10 - 30	7 - 15	5 - 10	3 – 5
1 Rotary Bits	20 and up	10 - 20	8 - 15	6 - 10	3 - 6	2.5 - 5	1 - 3
2 Diamond Bits		7 - 15	6 - 12	5.5 - 9	4 - 7	3 - 5	1.5 - 4
3 PDC Bits	40 and up	20 - 50	10 - 30	5 - 25			
Downhole Motor Drilling		20 - 30	16 - 20	8 - 15	5 - 10	2.5 - 5	1 - 3
Conventional		5- 10	5- 10	3- 8	3- 5	3- S	1- 3
Wireline		20 - 30	18 - 28	15 - 25	15 - 22	15 - 20	10 - 15

Note:

(1) Drilling Penetration Rates may vary widely depending upon RPM, wt. on bit, type of bit, geology, etc.

(2) Geological Materials: ***Class 1***: Soft shale, clay, sand, salt; ***Class 2***: Clay, red beds, sandstone, soft limestone, sandy shale, unconsolidated shales; ***Class 3:*** Sandy shales, sand, unconsolidated shales; ***Class 4***: Shale, lime sand, shaley lime; ***Class 5***: Dolomites, hard shale, hard limestone, hard sandy limestone; ***Class 6:*** Quartz, chert, dolomite; ***Class 7***: Granite, tacomite, basalt etc.

3. Samples should be washed in muslin bags to remove the drilling mud. Drilling mud, especially when thick, may impart a clayey feel to the sample.

4. To ensure collection of a representative sample from a depth interval, the borehole should be thoroughly washed, by circulating drilling mud, before the bit is allowed to penetrate the depth interval to be sampled. Further drilling should be resumed only after the cuttings are cleaned from the sample catcher. Samples are usually collected at 3 m intervals or whenever there is a change in the formation. Samples are liable to be contaminated due to caving of materials from the overlying loose formations if the mud is thinned too much and the mud cake is not effectively thick.

5. In some formations the drilling sound and action are characteristic and distinctive. The drilling is hard and crunchy while penetrating through *kankar* pans and boulders, while it is even and smooth in sands. These peculiarities in drilling action provide supplemental information on the nature of the formation.
6. The time lag for the transport of cuttings from the depth penetrated to the surface (lag time) should be considered while correlating the samples with the proper depth. The vertical velocity of mud depends on the annular space between the bit and the hole and the rate of circulation. In a 15 cm hole with 7.5 cm drill pipe, the velocity may range from 15 m/min for a circulation rate of 200 LPM to 60 m/min. for 800 LPM. The lag time may be determined by observing the time taken for the drill cuttings to surface when drilling is resumed after a period of washing by mud circulation. It may also be determined by typing a brick to the bit when a new bit is attached and observing the time it takes for crushed material to reach the surface.

In conjunction with the record of lag time, the drilling log facilitates the preparation of an accurate geologic log. Other useful supplemental information that may be recorded during drilling includes the temperature and EC of the drilling mud and the depths at which caving, mud loss and thinning occur.

In the case of boreholes drilled by DTH and percussion rigs, the following additional information may be collected:

1. Depth at which ground water was struck and at which the level stood is to be recorded in order to interpret potentiometric heads, thickness of aquifers, and related information. This information is essential if fracture permeability of hard rocks is to be determined. The position of static water levels can be monitored if a series of water-level readings are taken during rest periods.
2. Discharge must be recorded during drilling at various depths.
3. At various depths, slug or bailer tests may be carried out during idle periods to obtain K and T values of different zones.
4. Water samples are to be collected at various depths of drilling for quality determinations.

GEOPHYSICAL INVESTIGATIONS

The basic objective of geophysical investigations is to study the subsurface formations and structural configuration of earth by measuring physical properties on or near the earth surface. The success of a particular geophysical method largely depends upon the presence of significant and detectable contrast in the physical properties of different lithological units.

Geophysical methods of prospecting available for ground water and mineral exploration may be classified into two groups, i.e, (i) Surface methods (including Gravity and Magnetic methods, Seismic methods, Electrical and Electromagnetic methods and Radioactive methods), and (ii) Well logging methods .

Surface Geophysical Methods

Gravity Method: Gravity method, based on the measurement of density contrast between anomalous body/material and the surrounding rocks, may be used for exploration of minerals, ground water, oil and gas. Gravity surveys help in locating ground water by mapping key beds, bearing stratigraphic or structural relation to the water bearing bed. Not commonly used in ground water targeting.

Magnetic Method: Magnetic method, based on the measurement of susceptibility contrast between the anomalous body and the surrounding rock, is used for exploration of magnetic minerals and associated minerals. The magnetic method may be used for locating structures where the basement rock is magnetic. In ground water, the method is mainly employed in detection of dolerite dykes and other intrusive bodies which act as flow barriers.

Seismic Methods: These methods are based on the measurement of seismic wave velocity contrast obtained from available time-distance curves. Seismic Refraction method may be used for locating aquifers having a velocity contrast. Shallow salt domes as possible places for occurrence of oil and gas may be detected by Refraction technique. The Reflection seismic is generally not used for shallow mineral and ground water exploration.

Electrical and Electromagnetic Methods: Electrical and electromagnetic methods, based on the measurement of the electrical resistivity or conductivity of the subsurface minerals and formations, are most useful for exploring ground water. This type of investigations include Resistivity methods, Electromagnetic methods, Induced polarization method and Very low frequency (VLF).

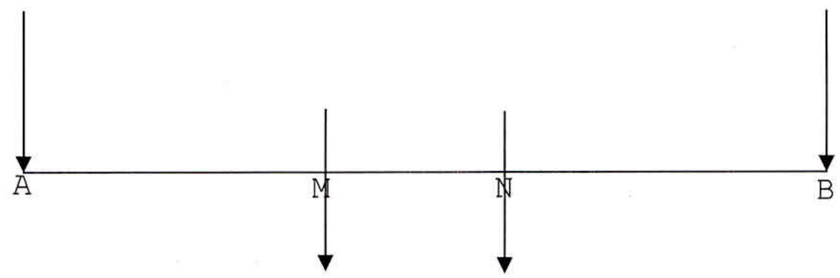

Fig. 2 Layout of Symmetrical electrode array used for resistivity measurement in field survey. A & B represent the current electrodes and M and N represent the potential measuring electrodes.

One of the most widely used methods of geoelectric prospecting is the resistivity method [Fig.2]. Resistivity studies may be broadly classified into resistivity sounding and profiling depending on field procedure. Resistivity sounding, where positions of the electrodes are changed with respect to a fixed central point (known as the sounding point), is particularly useful for locating horizontal discontinuities whereas, in profiling, useful for vertical discontinuity, all the electrodes are shifted simultaneously along a predetermined line. The well known electrode configurations, which may be, used either for sounding or profiling are Schlumberger, Wenner and dipole arrangements.

Time Domain Electromagnetic (TDEM): Technique is used for a sounding in which Transmitter loop of metallic wire with specific length is laid on the ground and a time varying (AC) current is injected. The transmitter current is abruptly reduced to zero which induces a short duration pulse in the ground and causes a loop of current to flow in the immediate vicinity of the transmitter loop. However, because of ground resistivity, the amplitude of the current starts to decay immediately. This decaying current induced a voltage impulse which causes more current to flow but at a large distance from transmitter loop, and also at a greater depth. This deeper current flow also decays due to finite resistivity of ground, further inducing deeper current flow and so on. The amplitude of the current flow is measured as a function of time by measuring its decaying magnetic field using a small receiver coil. This process forms the basis of sounding in the time domain [Fig.3]. This method is most useful in shallow groundwater exploration when the surface rock is highly resistive.

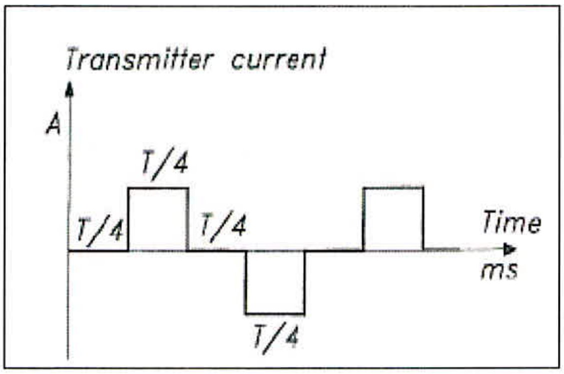

Fig. 3 Transmitter current wave form

Induced Polarization (IP) method based on over-voltage effect makes measurement of the decay voltage (in time domain or frequency domain) produced due to polarization of the electrode interfaces at the subsurface after the current flow has stopped. The IP values are typically high in clay rich sandy horizon whereas in the sands with no clay, these are low. This helps to distinguish between sands with and without clay content.

Very low frequency (VLF) method makes use of the available fields due to electromagnetic waves transmitted from powerful radio broadcasting stations as the source. The depth of investigation is limited and only the shallow conductors and water-saturated zones may be detected.

Radioactive Methods: Radioactive methods of prospecting are based on the measurement of the spontaneously disintegrated alpha, beta and gamma rays by various radioactive materials and detect sources of such disintegration by means of G-M counter or Scintillation counter. Depending on whether measurements are done at the surface or from air, these are called - Ground radioactive methods and Airborne radioactive methods. These methods are not used in groundwater exploration.

Subsurface Well logging Methods

Any characteristic information regarding the formation met within a well and recorded in terms of depth is known as a "well log". Such logs help in evaluating porosity, permeability and water saturation of the formation and are useful in the development stage of groundwater. Various logs used in subsurface geophysical exploration technique may be enlisted as follows:

(i) Self Potential (SP) log
(ii) Resistivity log, conventional, (Short normal, Long Normal & Lateral), and Micrologs
(iii) Radiation logs: (a) natural gamma, (b) neutron, (c) gamma-gamma-density
(iv) Sonic log
(v) Calliper log
(vi) Temperature log

SP log gives a record of the naturally occurring potential with depth and is utilized for distinguishing "porous and permeable" beds (sand) against shales. A +ve SP with respect to an average self potential (pertaining to shale base line) indicates presence of a fresh water zone.

Conventional resistivity logs comprising mainly of point resistivity, short normal, long normal logs are used (together with SP log) to calculate true resistivity of the formation. Various combinations of Point resistivity, short normal, long normal, lateral logs are used in field depending on the nature of information required. Micrologs with focusing arrangements help to find formation resistivity when saline mud is used for drilling. Gamma-ray log measures the natural radioactivity of the formations and is used to identify shales against sand, particularly when SP log fails. Neutron log records the response due to neutron-capture gamma rays, which depends on the hydrogen content of the formation. Gamma-gamma ray or density log measures the intensity of scattered gamma rays, which is dependent on the density of the formation. Sonic log records the time required for a sound wave to travel through unit length of the formation from which the sonic velocity is noted and porosity calculated. Calliper logs measure the effective diameter of the borehole. Temperature log records variation in temperature with depth.

Choice of Geophysical Methods

Soft Rock Areas: The application of geophysical methods in soft rock areas for ground water is well established. The cheapest and the best methods are vertical electrical resistivity soundings with resistivity profiling, if necessary. Normally, Schlumberger resistivity sounding is carried out after the probable water saturated zones are roughly located through remote sensing data. A step-wise detailing in soft rock areas will be as follows:

(1) Schlumberger vertical electrical sounding and seismic refraction studies at prospective sites.

(2) Recommendation of the borehole points.

(3) Electrical logging of the borehole after drilling for detailing of the water well.

(4) Planned utilization of available ground water after water quality analysis, for a sustained yield throughout the year and over the years.

Hard Rock Areas: Fractured rock hydrogeology had been of marginal interest for ground water so far. Of late, the hydrogeologists have discovered that the favourite sand and gravel aquifer is not commonly available in hard rock terrains. The step-wise plan given for the soft rock areas have been found suitable for hard rock areas as well. Several conventional geophysical methods like gravity magnetic and seismic methods may be used in hard rock area surveys following remote sensing for delineating the overall targets. Detailing may be done using the geophysical methods. As mentioned earlier, the conventional electrical resistivity sounding and profiling are often used under favourable circumstances.

A combination of electrical, electromagnetic and seismic refraction methods will be used for detailed ground water exploration in areas where faults and fractured zones have been located by means of remote sensing. The procedures will be as follows:

(1) Resistivity profiling/sounding

(2) Very low frequency (VLF) method.

VLF is the cheapest electromagnetic method for ground water survey. Thus, a combination of resistivity and VLF profiles will be sufficient to delineate fractured saturated zones in hard rock areas and will form the foundation for drinking water supply in the near future. Cavities filled with water in limestone countries can be easily detected by seismic refraction method.

SUBSURFACE CHARACTERIZATION

With the increasing demand for fresh water resources, the task of hydrogeologists and water managers is becoming more complex and challenging. Understanding the local subsurface and regional hydrogeological framework is the key to addressing these issues. Many processes and careful analyses are needed to progress from aquifer characterization and model building to simulation, calibration and updating. Efficiencies are produced with a seamless workflow in which each step can be verified and quality controlled.

The lack of a regional framework and detailed aquifer characterization is known to exist in many aquifer investigations. The selection of site investigations is based in many cases on factors such as land availability, water quality, the availability of existing water distribution infrastructure and wells, etc. To develop a suitable three dimensional (3D) hydrogeological model of an aquifer system, sufficient subsurface information must be available. In the past, little effort has been made to integrate local information into a regional hydrogeological analysis.

To develop a 3D hydrogeological model of an aquifer system, subsurface information must be available. The integration of geophysical borehole data and other data sources (e.g. geologists' log, core analysis, surface geophysical analyses, hydrodynamic test analyses) can lead to a comprehensive understanding of the subsurface aquifers. Applying the constantly evolving technology of geophysical logging in newly drilled wells can contribute greatly to the subsurface information necessary for a detailed aquifer characterisation. Geophysical logging systems are designed to give an accurate and precise measurement of formation properties. Formation parameters commonly measured include porosity, moisture content, salinity, bulk geochemistry, hydraulic conductivity, orientation of bedding and fractures, identification of specific radionuclides. Interpretation of the geophysical logs allows the identification of a vertical hydrostratigraphical profile of an aquifer. The extent of hydrogeological units can be determined by correlation of the identified tops and bases at each well and a 3D hydrogeological model can then be constructed. In ideal conditions, the subsurface charactisation of the area should be the integration of the following disciplines:

- geophysical interpretation,
- surface imaging and mapping,
- log interpretation and well correlation,
- complex fault and fracture identification,
- hydrodynamic analysis,
- uncertainty analysis,
- surface and subsurface interaction,
- flow and mass transport.

Advanced tools for aquifer characterisation allow the development and exploration of realistic solution scenarios, reducing uncertainty and risk. Examining data in detail allows a greater comprehension of the complex relationships between faults and horizons and improves field understanding. Inconsistencies that may be difficult to identify in two dimensions (2D) are immediately apparent in 3D. By discounting conceptual models that do not fit the available data, uncertainty in the interpretation is reduced, resulting in a more robust model. The process is then concluded by the development of a 3D hydrogeological model that represents the conceptual model used to generate a 3D hydrogeological grid (gridding process).

Preserving small features from well logs is also important for a hydrogeological grid. These grids are constructed with varying grid element sizes, and are designed to preserve the heterogeneity of the aquifer typically by subdividing it on a fine scale vertically whilst keeping the XY Y representation of the grid cells as small as possible. A hydrogeological grid often has several hundred thousand elements.

ROCKWORKS software (for generating subsurface aquifer geometry)

As mentioned earlier, subsurface characterisation is important for proper model conceptualization. There are various methods for development of aquifer geometry, but the most common and most reliable method is by the interpretation of borehole data.

The lithological data is collected by various people and at different times. There is always difference inconsistency in recording of data collected from various sources. Computer analysis can be carried out if the data is in standardised form. From the raw data, the standard key words generated to best represent the lithological description. For this RockWorks software developed by Rockware Inc. was used. The software is capable of visualization, interpolation, analyzing, & presenting surface and sub-surface data.

Map Visualisation

- Borehole location maps (variable symbols, multiple labels)
- Component maps (pie-chart, bargraph, spider, starburst)
- Bubble maps (size- & color-coded)
- Lease maps
- Land grid maps

Log Diagrams

- 2D logs, log maps, and log profiles & cross-sections
- 3D logs and multi-log displays
- Flexible log designer – turn on/off and rearrange columns
- Clip logs to specific elevation range

Visualize – Interpolated Data

<u>Maps and Surfaces</u>

- Line contours
- Color-filled contours
- 3D surfaces (solid, mesh, points)

<u>Solid Models</u>

- Isosurfaces
- All-voxels
- Point clouds
- Cutouts
- Nested isosurfaces
- Iso-mesh

<u>Cross Sections</u>

- Multi-panel cross sections
- Single-panel profiles
- Append logs
- Include line contours on quantitative sections

<u>Fence Diagrams</u>

- Regularly-spaced and/or hand drawn panels
- Append 3D logs, surfaces, solids

Stratigraphy Models & Diagrams

- Surface model-based dozens of gridding tools and erode models
- Structural surfaces
- Isopachs
- 3D stratigraphic models
- Straight cross sections
- Interpolated cross sections & profiles
- Fence diagrams
- Plan maps
- Surface maps

Lithology Models & Diagrams

- Solid model-based
  - Constrain within surfaces
  - Warp/tilt modeling
- 3D voxel models
- Interpolated cross sections & profiles
- Fence diagrams
- Plan maps
- Surface maps

Fracture Models and diagrams

- Solid model-based
- 3D voxel models
- Interpolated cross sections& profiles
- Fence diagrams
- Surface maps