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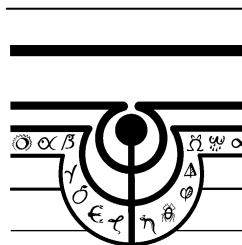
Estimation of Aquifer Parameters in Basaltic Terrain and the Application of Wireless Sensor Networks; Chikaldhara Region, Amravati District, Maharashtra, India

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Estimation of Aquifer Parameters in Basaltic Terrain and the Application of Wireless Sensor Networks; Chikaldhara Region, Amravati District, Maharashtra, India

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ABSTRACT:

The estimation of aquifer parameters, like transmissivity (T) and storativity (S), is vital for evaluating and managing groundwater resources. Hydrograph analysis and pumping tests are among the different methods available to estimate aquifer parameters, but pumping tests are the most commonly used. The study and data presented in this paper was conducted in the Chikaldhara Region (Amravati District) in the state of Maharashtra, in India. Large diameter wells, which are abundant in this area, are a cost-effective means to conducting pumping tests. The tests were performed at 20 locations using the local farmers' well pumps. This region has a predominantly basaltic terrain. The data collected was interpreted using both analytical and numerical methods. In comparison to the field observations, results from the two analytical methods produced a percentage of error of up to 35% in the calculated and residual drawdowns. In contrast, the numerical method used produced less than a 4.5% error compared to the field observations. Hence, the study and results presented here show the numerical method to be more accurate than the analytical curve matching methods for estimating aquifer parameters.

Results from the numerical method showed the 'T' value to vary from 16.21 to 41.98 m²/day in basalts and from 16.54.6 to 108.02 m²/day in laterites. The 'S' value produced from the numerical method varied from 0.6 x 10⁻⁶ to 9.8 x 10⁻³ in basalts and 0.10 x 10⁻⁵ to 7.8 x 10⁻² in laterites. In the second half of the paper, the strategy of using sensors and wireless sensor networks is presented. Their use could greatly benefit the effort to provide more accurate and timely data for the development of aquifer models, used by officials, managers, and conservationists.

1.0 INTRODUCTION

Systemic mapping of hydrogeological conditions in basaltic rock is of prime

importance in understanding its water bearing characteristics – especially since many factors like weathering, structural set-up, and the nature of the rock type – affect its water bearing characteristics. To understand the physical state of groundwater within a geological framework, shallow and unconfined aquifers are mapped and the relationship between the lithology and aquifer characteristics is studied. Determining groundwater potentiality, movement, storage and other parameters in an area is only possible only when the characteristics of the rock formation are known (Krusemam and de Ridder 1970, Karanth 1987, Walton 1989).

1.1 Pumping Tests and Methods of Analysis

A pumping test is the best available method to evaluate aquifer parameters. This test involves extracting water from a well at a controlled rate and observing the water level changes in the pumped well and/or in one or more observation wells, with respect to time (Theis 1935, Singhal and Gupta 1999). During the past few decades, researchers have proposed several different methods to analyze the pumping test data and estimate the aquifer parameters (Theis 1935, Cooper-Jacob 1946, Chow 1952, Hantush and Jacob 1955, Hantush 1960, 1966, Javandel and Witherspoon 1983, Thiem 1906, Pradeep Raj 2001). Among the main techniques are analytical/conventional methods and numerical methods.

Analytical/conventional methods involve one of the following: 1) curve matching, 2) finding inflection points, or for special cases, 3) fitting straight lines to the pumping test data. In curve matching techniques, field results are generally plotted and matched against the results of analytical solutions. There are also several alternative techniques for estimating aquifer parameters from the pumping phase (like log-log plots and log-arithmetic plots), as well as techniques for estimating aquifer parameters from the recovery phase. Comparatively, the numerical method uses a single model to obtain a “best fit” between the field and modeled results for both the pumping and recovery phases (using different parameters). A trial and error technique is employed to obtain a best fit (Rushton 2003). The entire computation procedure and hydrological equations is typically written into a computer program(s). Each of the methods described above are based on basic assumptions relating to the basic type of well, such as well diameter, dug well, and bore well. Therefore, it is important to choose the right method of interpretation based on the field conditions (Krusemam & de Ridder 1970).

2.0 CURRENT STUDY, METHODS, AND RESULTS

In the study presented here, pumping tests were conducted on large diameter wells in basaltic terrain within the Chikaldhara region of Maharashtra. An attempt was made to interpret the pumping data by using two conventional methods: the Papadopulos and Cooper method (1967) and the Mishra and Chachadi method (1985), and one numerical method, as proposed by Singh and Gupta (1991). The results of the analysis obtained by these methods are discussed in this paper.

2.1 Climate and Evaporation Rate

The climate of the area studied is classified as semi-arid, according to Thornthwaite's scheme of classification (1948). The temperature of the area is considerably hot. The difference between the maximum and minimum temperature is moderate. The mean annual rainfall is 850 mm.

The evaporation rate in the area ranges from 3.2 to 7.6 mm per day. Evaporation is highest during the months of May, June, and July. The mean wind velocity ranges between 7 km and 16 km per hour. The wind velocity is highest during June and July.

2.2 Geological and Hydrogeological Setting

Basalts are the main litho types found in the study area. The basalts exposed on the surface area along the southern flank of the Deccan traps belong to the upper cretaceous age. These basalts are devoid of primary openings but possess secondary openings in the form of fractures and joints. These features aid in the infiltration of surface water. Pores and fractures in laterites and fractures and joints in basalts act as reservoirs of groundwater. In the area studied, groundwater occurs in phreatic, unconfined conditions in the weathered basalts that outcrop at the surface. Groundwater is also present in the basalts under semi-confined to confined conditions. The groundwater in the study is extracted by either dug wells or bore wells. In areas where the water table is shallow (depths of 2.0 to 15.0 m), dug wells are more popular due to their lower cost and simplicity in construction and operation. The bore wells are drilled in basalts where the water level is deeper, with depths varying from 35.0 to 45.0 m. The dug wells are replenished by shallow aquifers while the bore wells are replenished from deep aquifers.

2.3 Methodology

In the present study, three methods are adapted to estimate the aquifer parameters in a basaltic terrain. Out of the three methods, two are conventional/analytical curve matching techniques: the Papadopulos & Cooper Method (1967) and the Mishra & Chachadi Method (1985). The other technique is a numerical method, as proposed by Singh & Gupta (1991). As the conventional/analytical curve methods are well known, only the numerical method is discussed in detail in this paper.

2.4 The Numerical Method (Singh & Gupta, 1991)

In the study presented here, the aquifer parameters were estimated using the numerical approach and methods proposed by Singh & Gupta (1991). This method considers both the pumping and recovery phases to interpret the data from the pumping tests. This method assumes that the following conditions are valid: 1) the water level in the well is static prior to the pumping test, 2) the pumping well fully penetrates the aquifer, 3) the flow towards the well is radially symmetrical (implying isotropy and homogeneity of the aquifer), and 4) the drawdown is significantly smaller compared to the total saturated thickness. Hence, transmissivity could be regarded as invariable during the pumping test, making the system linear and allowing the principles of super-position to be used. The method also permits the pumping durations to be separated into a number of equal time steps for analysis.

The aquifer response is then calculated for each time step through the computation of the abstraction with the impulse response function. The extraction rate during each time step is assumed to be constant (even though it could have different rates during various time steps). The drawdown for each time step is calculated considering “guess values” of aquifer parameters. The computed drawdown is then compared with the observed drawdown. The aquifer parameters are progressively modified in an iterative manner until a satisfactory match is achieved between the observed and the calculated drawdown/recovery time. The best-fit drawdown/recovery time curve gives the representative aquifer parameters.

The entire computational procedure for this method was written into an interactive, user friendly, computer program. The software application takes into account the combined effects of one or more field conditions, like variable abstraction rate, seepage face, and the effect of nearby hydrogeological boundaries. The software is used to compute the response of

an aquifer for a given set of parameters – instead of using a large number of type curves.

2.5 Data Acquisition and Interpretation

For this study, 20 pumping tests were conducted to characterize the aquifer parameters of dug wells in the Chikaldhara region: a region with basaltic terrain. Eight of the tests were conducted in laterites and 12 tests were conducted in basalts. The pumping phase of the tests had a short duration of 60 to 210 minutes; the recovery phase of the tests had a longer duration of 90 to 300 minutes. Details of the pumping tests are given in Table 1. The discharge rates varied from 12.74 to 307.13 m³/day and the drawdown rates varied from 0.33 to 3.19 m. Except at well location #11, 70-100% of the recovery from drawdown was observed at each location. The data was analyzed and interpreted by the three methods mentioned in Section 2.3 – Methodology. The results are presented in Table 2.

3.0 REGIONAL GEOLOGICAL SETTINGS AND STRATIGRAPHY

The following subsections present the geological settings and stratigraphy of the study area. The values obtained during the pumping tests are also discussed.

3.1 Water Level

In this region, the general behavior of groundwater is studied using water level data. In winter, the water level is typically 12.02 meters, with a minimum of 6.54 meters in the extreme west and central parts of the area. The water level during the southwest monsoon is between 10.9 meters to 4.52 meter, with respect to the ground level. Comparatively, in summer, the water level is a maximum of 20.52 meters, with a minimum of 5.39 meters. The water level during the northeast monsoon is between 10.29 meters and 4.16 meters. Thus, the groundwater level varies greatly and does not follow any rhythmic pattern. The water level fluctuations in this area are calculated at a maximum of 3.52 meters and a minimum of 1.44 meters.

3.2 Groundwater Flow

Using static ground water level data within a basin from the past 20 years (1972-1992), an annual average water level map was constructed (with respect to the above mean sea level). The flow system of these basins has revealed an east-to-west movement, with a well

defined relief, recharge area at the topographic high and an adjacent discharge area. Further, the topographic elevation and groundwater level gradient gradually decreases from west to east – further confirming the flow pattern. It was also observed that the central and eastern part of the area has more favorable permeability (low gradient of water level) than the other areas. Similarly, the areas of west, west–central, and northwest and southwest corners have lower recharge levels (high gradient of water level) than discharge levels.

Substantial contributions in the field of groundwater hydraulics has been made by several scientists; however, despite the routine use of aquifer testing methods to determine aquifer properties, their applications to fractured rocks are debatable. Additionally, the effects weathering processes also exert significant influence on aquifer heterogeneity at shallower depths. Nonetheless, a pumping test is one of the most useful means of determining hydraulic characteristics of the aquifer, as well as, determining yield and draw down.

3.3 Storage Coefficient

In unconfined aquifers, the storage coefficient (also called specific yield) is high in the northeast and southwest parts of the area and very low in the central part of the basin. The values range from 0.02 to above 0.22. Further, it could be seen that there is a progressive decrease of specific yield in the eastern to central parts and again an increase towards the west.

3.4 Transmissivity

Results show that the value of transmissivity varies from 25 m²/day to more than 100m²/day. This follows the general pattern of increasing value from east to west; that is, the value increases from the upper part of the basin to the lower. This also shows a gradual increase of the hydraulic gradient. The transmissivity of 100m²/day and above coincide with areas where the fault zone occurs.

3.5 Specific Capacity

A decline in specific capacity may indicate declining S or T values due to declining water levels or piezometric surfaces. It can also be used to determine the distribution of transmissivity in the aquifer. The spatial distribution of specific capacity reveals that the increase in values coincides with the storage co-efficient or transmissivity value. Values of

specific capacity range from -6 to above 1pm/mdd/m². Specific capacity in pink granites is found in ranges from -3 to 1pm/mdd/m². Higher specific capacity values were also found to coincide with areas where extension fracture systems occur.

3.6 Optimum Yield

The optimum yield indicates that only the western half of the study area delivers substantial yields of water, whereas the southern and northern areas show uniformity in their yield of water. The optimum yield ranges from 25m³/d to more than 100m³/d. The high yield areas are close to extension fractures and where lineament intensities are high.

3.7 Recovery Rate

The spatial distribution of the recovery rates for the area increases from east to west. The values of recovery rates range from 50 to 200m³/day. The areas which yield the highest recovery rates are also close to the areas with higher optimum yields.

3.8 Recuperation Rate

The recuperation rates indicate the period in hours or day required to restore the water from adjacent areas. The computed result shows the recuperation rates to range from 25 hours to more than 75 hours towards the northern areas.

3.9 Saturated Aquifer Thickness

Saturated aquifer thickness represents the width of an aquifer saturated with water. Within the study area, the spatial distribution of saturated thickness indicates uniformity in thickness of an aquifer saturated with water. The values found in the study area range from less than 3 meters and up to 6 meters.

4.0 ASSESSMENTS

4.1 Aquifer Parameter Assessment

To evaluate the relationship between well yield, specific capacity, saturated aquifer thickness, well depth, recovery rate, and transmissivity – linear correlation analyses were conducted. The resulting regression line fit indicates a steep negative relationship between

depth and well yield. The lines of regression are almost non-informative; which indicates a near zero change in well yields irrespective of depth. A similar relationship is also exemplified between depth and specific capacity.

In the case of saturated aquifer thickness versus optimum yield, representative line fits are significantly positive for weathered basalts and significantly negative for compact and massive basalts. That is, with increases in the saturated aquifer thickness, the optimum yield also increases steeply in weathered basalts ($Y_1 = x + (-36.949)$); however, in areas of massive basalts, the increase is significantly less steep.

The rate for transmissivity vs. recovery shows a very significant positive trend in weathered basalts; whereas massive and compact basalts show a negative relationship between transmission and saturated aquifer thickness. As well, transmissivity and optimum yields show a similar trend of regression.

4.2 Hydrogeophysical Assessment

For the purpose of hydrogeophysical assessments, the resistivity data was measured at 50 locations using an Anvic microprocessor-based resistivity meter. In basaltic terrains, groundwater occurs in fractures, fissures, crushed zones, and joints. The objective of geophysical exploration is to locate such features. However, geophysical properties of water bearing zones depend on many factors. For that reason, the geophysical techniques used for groundwater prospecting in hard rock areas must be selected with these different aspects and factors in mind.

Interpretations have been made using the Schlumberger inverse slope method. From the results, resistivity was classified into four types: 10, 20, 30 and 40 meters iso-apparent resistivity. Iso-lines were drawn in order to assess the spatial distribution of these iso-apparent resistivity values used in demarcating favorable ground water locations. The results show that iso apparent resistivity is < 50 ohm meters in most of the basin area, with increasing resistivity towards the central part of the region.

Medium level iso apparent resistivity (20 ohm meters or less) is the most pervasive type in the area, followed by high resistivity as the second most pervasive type in the area. However, low resistivity (< 50 ohm meters) and high resistivity (> 100 ohm meters) are also seen in small pockets. High resistivity is more wide spread: mostly in the east and central

east. The most favorable groundwater potential zones are in the Midwest. Most of the eastern part of the basin is less favorable as potential groundwater zones, with more favorable areas in between. The west is more favorable than the east for integrated ground water development.

5.0 STUDY FINDINGS

The hydrogeology of the region investigated for this study is characterized by a steep gradient of water levels, which indicates a low permeability – and therefore – a lower rate of recharge capacity. In the central and western parts of the study area, more favorable permeability conditions were found than in other areas.

The water level fluctuations in the Chandrabhaga river basin follow familiar seasonal rhythmic patterns. Seasonal variations in the water levels reflect the general climatic balance between rainfall and evaporation. The optimum yield in the area ranges from 25 m³/d to 100 m³/d. The highest yield areas are in close proximity to extension fractures and to lineaments. The saturated aquifer thickness is between 3 and 6 meters. The recuperation rate ranges from 25 – 75 hours. The average transmissivity rate in massive basalt regions is 38.65m²/day; whereas the transmissivity rate in highly altered and fractured basalts is approximately 76.99m²/day. The average optimum yield is 35m³/d in weathered basalts – with a very low yield of approximately 19.95m³/d in massive basalt areas. The average recuperation rate of all rock types is about 25 hours. Resistivity showed different spatial patterns: the western parts of the basins were found to be more favorable than the eastern parts for integrated groundwater development.

5.1 Results and Discussion of Study

The transmissivity (T) value was obtained using the Papadopulos & Cooper method and is presented in Table 2. The T results varied from 16.21m²/day to 40.84m²/day in basalts; whereas, in laterites, it varied from 16.88m²/day to 41.44.22m²/day.

Storativity (S) values varied from 1.4 x 10⁻⁵ to 6.8 x 10⁻³ in basalts and 9.9 x 10⁻⁵ to 72.0 x 10⁻³ in laterites. Similarly T values obtained using the Mishra & Chachadi method varied from 17.67 to 38.86m²/day in basalts and from 6.64 to 99.20m²/day in laterites. S values resulting from the Mishra & Chachadi method varied from 6 x 10⁻⁵ to 9.9 x 10⁻³ in

basalts and from 10.0×10^{-5} to 78.0×10^{-3} in laterites.

In general, the results of the Papadopoulos & Cooper method, as compared to the Mishra & Chachadi method, resemble each other (except for S values at some locations). The results of numerical methods showed that the T value varied from to $43.25\text{m}^2/\text{day}$ in basalts and 8.6 to $112.0\text{m}^2/\text{day}$ in laterites. The S value varied from 0.05×10^{-5} to 2.0×10^{-3} and 0.10×10^{-5} to 30.0×10^{-3} in basalts and laterites respectively. The results of the numerical and theoretical methods are compared with each other in terms of ratios – and presented in Table 3. This table shows that the T values obtained using theoretical methods are underestimated by 6-15% in basalts and 3-42% in laterites, as compared to the values obtained using the numerical method. S values obtained by theoretical methods were overestimated by 45% in basalts and 52% in laterites, as compared to the values obtained using numerical methods.

The percentage of error for the methods was calculated by comparing the total drawdown and residual drawdown obtained for the three methods (cited in Table 4) to the field observed measurements. Table 4 shows that the percentage of error resulting from the theoretical methods was 21% for the total drawdown and 30% for the residual drawdown for basalts. Comparatively, the percentage of error resulting from the numerical method for basalts was less than 1% for the total drawdown and less than 3% in the residual drawdown. In laterites, the percentage of error was 29% for total drawdown and 35% for residual drawdown using the theoretical methods; however, using the numerical method, the percentage of error was less than 1.0% for total drawdown and less than 4.5% for residual drawdown.

As stated above, the percentage of error resulting from the numerical method as proposed by Singh & Gupta (1991) is less than 5% for both basalts and laterites. In conclusion, the numerical approach was found to be a more accurate method in comparison to the theoretical curve matching methods in determining the aquifer parameters by pumping tests.

6.0 SENSOR-RELATED AQUIFER MONITORING

Groundwater is fresh surface water that has soaked into the rocks/land mass underground. The importance of this water source for human consumption and agricultural use increases as groundwater becomes scarce. For this reason, the monitoring of this

precious resource is critical for effective conservation and management. However, changes in both the quantity and quality of groundwater are often very slow processes that are difficult to detect. Minute transformations that occur underground are hard to detect but can have a substantial impact on the availability and quality of the water. More elaborate monitoring techniques and data interpretations are required than conventional snapshot surveys can provide. The following sections describe wireless sensor networks and how they can be applied to the task of continuous monitoring, automated transmission, and analysis of collected data in the effort to conserve and manage groundwater.

The goal of sensor-related aquifer monitoring is to provide more accurate and timely data to help develop models of aquifers and water availability. The goal is that these models will enable policy makers to make more informed decisions on groundwater issues; like controlling the impact of groundwater abstraction and contamination, increasing rainwater collection, and increasing the storage capacity of aquifers. To accomplish this, sensor-related monitoring and wireless network technology systems need to be developed and deployed, in concert with a good understanding of the hydrological details of the aquifer, groundwater levels, and flow.

In the monitoring of groundwater -- wells serve as the portholes into aquifers. Through wells, groundwater pressure, levels, quality, and health of an aquifer can be measured. For monitoring purposes, there are two basic types of wells: abstraction wells from which water is pumped and observation wells which are dedicated monitoring stations. Abstraction wells provide valuable information on the aquifer's characteristics of draw and recharge; however, as they are operational wells, the data collected from them is typically more difficult to interpret as the groundwater levels are affected by the drawdown-recovery cycle and the pumped sample quality reflects a mixture of the groundwater from a wide range of aquifer depths and residence times. Observation wells are dedicated monitoring stations that are sited and designed to detect potential changes in groundwater flow and quality and monitor static water levels. These wells do not use pumps, but rather, instruments are used to monitor the water. Wireless sensors capable of continuous or scheduled measurement, and with accurate time stamping and automated transmission of data to a central site for data correlation and analysis, could also be equipped in the wells. A network of sensors could be deployed on both types of wells to monitor and evaluate groundwater resources, behavior,

and trends resulting from land-use changes, climatic variations, and continual processes, like recharging.

Traditional ground water monitoring can be expensive and time consuming and is not typically done on a frequent or continual basis. These methods also use assumptions on parameters; for example, recharge rates are considered constant. Alternatively, the use of remote wireless sensors would provide more accurate sampling -- greatly improving the accuracy of the model and results. Another benefit of sensor-based monitoring is that measurements can be performed at any time: on a pre-defined sampling schedule or run continuously for long periods of time. Sensor-based monitoring also enables data to be accurately time-stamped and pre-processed locally (to reduce the volume of data) and then remotely and automatically transmitted to a central location using any available wireless communication medium, such as cellular, satellite, or a hybrid of WiFi and landline internet connectivity. Data from numerous wells could be logged and correlated in a central database to enable a near real-time analysis of an entire region to verify predicted aquifer responses, and if necessary, take timely action to reduce abstraction.

7.0 ARCHITECTURE of WIRELESS SENSOR NETWORKS

The following section describes a high level overview of the components and architecture of a remote wireless sensor network system.

7.1 Component/Network Overview

Equipping wells will require sensor devices that are embedded with wireless radio devices. These devices are comprised of radio frequency (RF) electronics, including a transmitting and receiving device, an embedded microprocessor, and on-board memory. Integrated together, a sensor and radio device is referred to as a “sensor node.” The radio device controls the operation and data sampling of the sensor and converts the measured sensor data (typically an electrical signal) into engineering units, like pressure or temperature. Once converted, the data can then be processed or sent on to the next level – a gateway node. A wireless gateway node will have more memory, a powerful microprocessor, and wide-area network communications capabilities, like cellular or satellite communications (depending on the resources in the area) that enable it to transmit data wirelessly at longer distances.

Multiple sensor/radio device nodes will be able to transmit data to a single gateway node, which can then transmit the data to the next link in the communications path or directly to a central database. A significant benefit of this architecture is that it supports remote monitoring and automated transfer of data (see Fig I).

The actual sensors themselves could be a heterogeneous mix of analog or digital devices. They will be integrated with radio devices that are capable of ad hoc mesh networking – which will enable the radio(s) to automatically and dynamically configure into a communications network in the field. The controlling element of the network will be the gateway node (also called a base station). The gateway node has the ability to control each individual sensor within its network. It will receive data from the sensors as well as send commands to the sensors. Additionally, the gateway node is able to communicate with other gateway nodes and/or with a central command unit. It can transmit the data up to the central unit and receive commands or instructions back from the central unit.

7.2 Goal of Sensor Network Monitoring

The goal is to design a flexible **wireless, ad-hoc, sensor network architecture** that is **tuned for monitoring minute changes in aquifer parameters** and that is capable of **remote surveillance and automated data transmission**. This requires that the architecture: 1) support various types of hydrological sensors in a heterogeneous sensor network, 2) use “smart” sensor nodes that can pre-process the enormous amount of data they collect, 3) facilitate collaborative communication and routing between sensor nodes and gateway nodes within a loosely dispersed and irregular network grid, and 4) wirelessly transmit the data to a central unit, in real-time or near real-time. To achieve flexibility, the concept of layers will be used to define the network level and sensor level. To achieve smart decision making and processing capabilities, the nodes will include artificial intelligence (AI) based software agents. To achieve network auto-configuration, collaboration, and real-time data transmission; ad-hoc mesh networking techniques will be employed.

7.3 Network Communications Layer – Self Organized Networks

The architecture of the communications layer will be based on ad-hoc, mesh networking technology. A network consists of many nodes, each with multiple links

connecting to other nodes. Information moves “hop by hop” along a route from the point of production to the point of use. In a wired network like the Internet, each router connects to a specific set of other routers, forming a routing graph. In Wireless Sensor Networks (WSN), each node has a radio that provides a set of communication links to nearby nodes. By exchanging information, nodes can discover their neighbors and perform a distributed algorithm to determine how to route data according to the application's needs. This technology provides each sensor node with the capability to store and forward data. It also provides multiple paths from a source node to a destination node. Thus, if connectivity from a primary path to a destination is lost, the network can automatically select an optional path to complete the connectivity between the source and destination node. Although physical placement primarily determines connectivity, variables such as obstructions, interference, environmental factors, and antenna orientation make determining prior connectivity difficult. Using an ad-hoc network strategy eliminates the need to perform an extensive wireless design of the area prior to deployment – in ad hoc networks, the sensor nodes can be distributed in the area of interest and then self-configure. That is, the network discovers and adapts to whatever connectivity is present

7.4 Sensor Node Layer (Sensor Device + Radio Device=Sensor Node)

Sensor Devices: Sensors are devices which can respond in a predictable fashion to changes in physical phenomenon, such as temperature or pressure. Many materials change their electrical characteristics when subjected to varying environmental conditions. Sensors are manufactured so these changes are predictable over a certain range. For example, a thermostat is a variable resistor that changes smoothly with temperature. More sophisticated structures have been developed to detect other phenomena. These structures consume a few milliwatts and only need to be turned on a fraction of the time. The new category of microelectromechanical systems (MEMS) can sense a wide variety of physical phenomena cheaply and efficiently. In MEMS devices, gravitational forces or pressure can deflect their cantilevered masses to effect powerful internal forces that cause changes in material properties or delicate alignments. These changes can then be amplified and digitized. For example, one of the first major commercial MEMS sensors, the accelerometer, was used to trigger automotive airbag release. Whereas high-precision piezoelectric accelerometers cost

hundreds of dollars, MEMS-based devices provided sufficient precision for a few dollars. A wide variety of MEMS devices can sense various forces, chemical concentrations, and environmental factors.

For aquifer monitoring, a pressure sensor will be used to accurately monitor water pressure and water levels. An alternate option would be to use an ultrasound depth sensor to sense the height of the water column in inspection wells. Along with sensors to monitor water depth, other sensor could also be added to perform chemical analysis. Although the variation in the chemical composition of the aquifer does not change frequently, the ability to conduct onboard chemical analyses would greatly benefit water quality analysis and safety.

Radio Devices: As briefly described earlier, a radio transmitter/receiver device will be integrated with each sensor (or group of sensors). In a wireless sensor network, the radio device consists of a microprocessor, on-board data storage, an analog-to-digital converter (ADC), data transceiver, controller, and an energy source. Data acquisition, which is performed by the radio device, is the process of collecting the sensor readings. This task can be programmed to occur on-demand or on scheduled intervals. The system should also support different types of sensor calibration methods; such as linear, polynomial, and binary.

Both of the aquifer sensors mentioned above are analog; hence, the data will need to be converted from analog to digital by the analog to digital convertor (ADC) on the radio device. In analog devices, the sensor typically records a change in voltage. The radio device collects that sensor measurement and the ADC converts the voltage into a binary number that a microcontroller can store or process. If the application requires further data processing, algorithms can be implemented in the microprocessor to perform calculations like data averaging based on a sliding window and standard deviations.

The embedded software on the radio device will be developed to operate under the TinyOS operating system (TOS), an open operating system designed specifically for miniaturized radio devices and wireless sensor networks by the University of California, Berkeley (see Fig II). A similar strategy and software was developed in previous projects. That embedded software can be modified to incorporate real-time data communications and on-board data processing – tailored to the needs of aquifer monitoring.

Power Requirements: As semiconductor circuits become smaller, they consume less power for a given clock frequency. In simple microcontrollers, miniaturization increases

efficiency rather than adding functionality; thus, they can operate near one milliwatt while running at about 10 MHz. Additionally, most circuits can be powered off so the standby power consumes only about one microwatt. If the device is active only 1% of the time, then its average power consumption is just a few microwatts.

The power for these devices can be obtained in many ways (in addition to or instead of batteries). Solar cells generate about 10 milliwatts per square centimeter outdoors and 10 to 100 micro-watts per square centimeter indoors. Mechanical sources of energy, such as vibration of mechanical devices, can generate about 100 microwatts. A typical cubic-centimeter battery stores about 1,000 milliamp-hours, so centimeter-scaled devices could run almost indefinitely in many environments. However, disadvantage of these low-power microprocessors is that they also have limited storage, typically less than 10 Kbytes of RAM for data and less than 100 Kbytes of ROM for program storage (or about 10,000 times less storage than a PC). This limited amount of memory consumes most of the chip area and much of the power budget. For this reason, designers typically incorporate larger amounts of flash storage (megabyte) on a separate chip.

7.5 Communications/Transmission

For some time now, manufacturers have added sensors to many appliances, vehicles, and gadgets; however, the breakthrough comes when the sensor readings can be wirelessly and effortlessly communicated to other devices. Radio components are now manufactured using conventional CMOS technology, which enables their use in wireless devices like pagers, walkie-talkies, cell phones, and wireless local area networks for mobile laptops. Unfortunately the amount of energy required to communicate wirelessly increases rapidly with distance. Obstructions, such as people or walls and interference, further attenuate the signal. Wireless local area networks and cell phones consume hundreds of milliwatts and rely on a powerful infrastructure. Conversely, wireless sensor network radios consume about 20 milliwatts but their range is typically measured in tens of meters. For small devices to cover long distances, the network must route the information hop by hop through nodes, much as routers move information across the Internet. Even so, communication is the most energy-consuming operations: each bit costs as much energy as about 1,000 instructions. For this reason, it is best to pre-process data on-board the radio node, before transmitting the data.

To optimize and conserve power consumption, the planned system will implement on-board processing and use a combination of micro radios and single wide area (cellular or satellite) radio.

8.0 CONCLUSION

The estimation of aquifer parameters is vital for evaluating and managing groundwater resources. Using data collected from aquifer pumping tests performed at 20 locations in the Chikaldhara Region, this study found the numerical approach of analysis to be a more accurate method, in comparison to the theoretical curve matching methods, in determining the aquifer parameters by pumping tests. In an effort to provide more accurate and timely data, the strategy of deploying sensors and wireless sensor networks for aquifer monitoring was also presented here. Benefits that could be realized from this approach include a more robust set of data that can be collected continuously or on a pre-defined schedule. The data would also be time-stamped to enable easy correlation of data between wells and automatically transmitted to a central site on a timely basis. The ultimate goal of the analysis, modeling, and data collection strategies presented here is to provide better information on the state of the aquifers and groundwater so that policy makers can be empowered to make informed decisions on critical issues of conservation and management of this precious resource.

Table 1: Pumping Test Results obtained in the Chilkaldhara Region

Well no	Depth of well (meters)	Diameter of well (meters)	Water Level (meters)	Q (m ³ /d)	DD recorded (in min)	Max. DD observed	REC recorded (in min)	% of REC observed
1	24.72	2.04	4.40	26.09	140	1.41	160	78.72
2	32.19	1.37	6.13	20.07	180	0.54	270	63.37
3	21.72	1.07	7.64	13.77	150	0.53	180	96.23
4	19.14	1.28	4.57	21.00	210	0.55	250	100.24
5	25.85	1.98	5.88	307.13	60	3.19	120	54.23
6	16.76	1.12	6.25	21.85	182	0.39	180	97.44
7	12.19	1.26	7.03	26.71	154	1.46	240	70.55
8	15.24	1.73	8.95	42.39	186	0.33	92	102.00
9	22.25	1.14	14.07	12.74	160	0.60	240	80.00
10	18.29	1.60	15.15	22.69	170	0.58	300	98.28
11	20.76	2.59	6.38	91.76	150	0.49	300	100.78
12	19.64	1.52	6.25	24.83	120	0.45	248	86.00
13	15.85	1.98	4.88	307.13	80	3.19	140	54.23
14	16.76	1.82	6.89	21.85	190	0.39	190	97.44
15	12.19	1.76	5.82	26.71	130	1.48	220	70.55
16	16.24	1.78	6.98	42.39	164	0.33	98	100.21
17	20.65	1.44	12.05	12.74	182	0.66	240	80.00
18	18.23	1.86	14.12	22.69	186	0.52	321	98.28
19	19.76	2.24	6.86	91.76	148	0.59	306	100.56
20	18.84	1.82	6.85	24.83	134	0.44	242	98.00

Well no. & location: 1.; 2.; 3.; 4., 5. 6.; 7. ; 8. 9., ..; 10.; 11. 12.;

Q = discharge rate (in m³/day), DD = Drawdown (in m), REC = Recovery

Transmissivity values are in sq. meters/day. Storativity values are dimensionless.

Table 2: Comparison of Pumping Test Results obtained by Different Methods

Well	Lithology	Transmissivity value obtained by:			Storativity value obtained by:		
No.		PAC	MAC	NUM	PAC	MAC	NUM
1	Basalt	16.82	17.84	18.52	0.000084	0.000071	0.000042
2	Basalt	18.34	18.82	20.74	0.00078	0.00099	0.00034
3	Basalt	17.96	17.62	19.25	0.00064	0.0098	0.00032
4	Basalt	40.84	41.44	41.98	0.00026	0.00043	0.00014
5	Basalt	16.21	16.88	19.72	0.000072	0.000068	0.000018
6	Basalt	19.42	18.84	21.25	0.00068	0.00099	0.00028
7	Basalt	17.96	17.67	19.35	0.0063	0.0095	0.0035
8	Basalt	36.75	37.86	38.25	0.000044	0.000063	0.000024
9	Basalt	23.81	22.62	24.78	0.0000072	0.0000081	0.0000024
10	Basalt	29.34	28.94	31.71	0.00065	0.00092	0.00023
11	Basalt	24.94	25.68	26.65	0.00083	0.0064	0.00012
12	Basalt	38.64	38.86	40.02	0.00006	0.00007	0.00003
Minimum		16.21	16.88	18.52	0.00008	0.00006	0.00004
Maximum		40.84	41.44	41.98	0.0083	0.0058	0.0018
13	Laterite	26.04	22.44	24.06	0.000034	0.00066	0.000024
14	Laterite	34.82	36.80	40.64	0.00048	0.00064	0.00012
15	Laterite	16.54	16.64	18.60	0.000062	0.000098	0.000024
16	Laterite	98.24	99.28	108.02	0.00086	0.00098	0.00032
17	Laterite	19.22	17.24	18.28	0.0046	0.0059	0.0016
18	Laterite	20.46	18.44	22.54	0.00064	0.00086	0.0033
19	Laterite	62.54	64.46	68.52	0.0078	0.0086	0.0042
20	Laterite	42.03	41.16	44.45	0.00042	0.00062	0.00016
Minimum		16.54	16.64	18.28	0.000094	0.000068	0.000046
Maximum		98.24	99.28	108.02	0.0078	0.0059	0.042

PAC = Results obtained from the curve matching method of Papadopulos and Cooper (1967)

MAC = Results obtained from the curve matching method of Mishra and Chachadi (1985)

NUM = Results obtained from the numerical method as proposed by Singh and Gupta (1991)

Table 3: Comparison of Results: Numerical Method vs. Theoretical Methods (in-terms of ratio)

Well No.	Lithology	Transmissivity		Storativity	
		NUM / MAC	NUM/ PAC	NUM/ MAC	NUM/ PAC
1	Basalt	1.04	1.10	0.59	0.50
2	Basalt	1.10	1.13	0.34	0.05
3	Basalt	1.09	1.07	0.33	0.50
4	Basalt	1.01	1.03	0.32	0.54
5	Basalt	1.17	1.22	0.26	0.25
6	Basalt	1.13	1.13	0.28	0.41
7	Basalt	1.09	1.09	0.37	0.55
8	Basalt	1.01	1.04	0.38	0.54
9	Basalt	1.09	1.04	0.29	0.33
10	Basalt	1.09	1.08	0.25	0.35
11	Basalt	1.04	1.07	0.02	0.14
12	Basalt	1.03	1.04	0.43	0.50
Minimum		1.01	1.03	0.66	0.50
Maximum		1.17	1.22	0.31	0.21
5	Laterite	1.07	0.92	0.36	0.70
	Laterite	1.10	1.17	0.19	0.25
7	Laterite	1.12	1.12	0.24	0.39
8	Laterite	1.09	1.10	0.33	0.37
9	Laterite	1.06	0.95	0.27	0.35
10	Laterite	1.22	1.10	0.38	0.52
11	Laterite	1.06	1.09	0.49	0.54
12	Laterite	1.08	1.06	0.25	0.38
Minimum		1.06	0.92	0.68	0.48
Maximum		1.22	1.17	0.03	0.05

Transmissivity values are in sq. meters/day. Storativity values are dimensionless.

PAC = Results obtained from curve the matching method of Papadopulos and Cooper (1967)

MAC= Results obtained from curve the matching method of Mishra and Chachadi (1985)

NUM = Results obtained from the numerical method proposed by Singh and Gupta (1991)

Table 4: Percentage of Error in Results from the Numerical and Theoretical Methods

Well No.	Lithology	PAC		MAC		NUM	
		DD	R-DD	DD	R-DD	DD	R-DD
1	Basalt	16.95	11.97	0.64	0.07	1.13	1.37
2	Basalt	4.76	3.96	7.35	6.89	0.00	2.14
3	Basalt	8.26	19.27	21.34	30.78	0.00	2.12
4	Basalt	1.18	10.00	5.56	16.00	0.00	2.95
5	Basalt	16.95	11.97	0.64	0.07	1.13	1.37
6	Basalt	4.76	3.96	7.35	6.89	0.00	2.14
7	Basalt	8.26	19.27	21.34	30.78	0.00	2.12
8	Basalt	1.18	10.00	5.56	16.00	0.00	2.95
9	Basalt	16.95	11.97	0.64	0.07	1.13	1.37
10	Basalt	4.76	3.96	7.35	6.89	0.00	2.14
11	Basalt	8.26	19.27	21.34	30.78	0.00	2.12
12	Basalt	1.18	10.00	5.56	16.00	0.00	2.95
Minimum		1.18	3.96	0.64	0.07	0.00	1.37
Maximum		16.95	19.27	21.34	30.78	1.13	2.95
13	Laterite	8.18	7.40	5.08	6.88	0.22	0.98
14	Laterite	26.59	34.84	5.49	14.08	0.00	2.07
15	Laterite	4.32	13.38	4.11	12.77	0.75	2.17
16	Laterite	17.52	33.19	5.12	14.84	0.21	4.43
17	Laterite	4.48	5.67	13.03	17.17	0.12	0.10
18	Laterite	0.14	14.44	7.66	21.77	0.10	3.63
19	Laterite	9.57	20.85	5.33	17.98	0.06	3.10
20	Laterite	28.73	29.95	17.11	17.12	0.04	0.49
Minimum		0.14	5.67	4.11	6.88	0.00	0.10
Maximum		28.73	34.84	17.11	21.77	0.75	4.43

Transmissivity values are in sq. meters/day. Storativity values are dimensionless.

PAC = Results obtained from curve the matching method of Papadopulos and Cooper (1967)

MAC= Results obtained from curve the matching method of Mishra and Chachadi (1985)

NUM = Results obtained from the numerical method proposed by Singh and Gupta (1991)

DD & R-DD = Total drawdown and Residual drawdown respectively

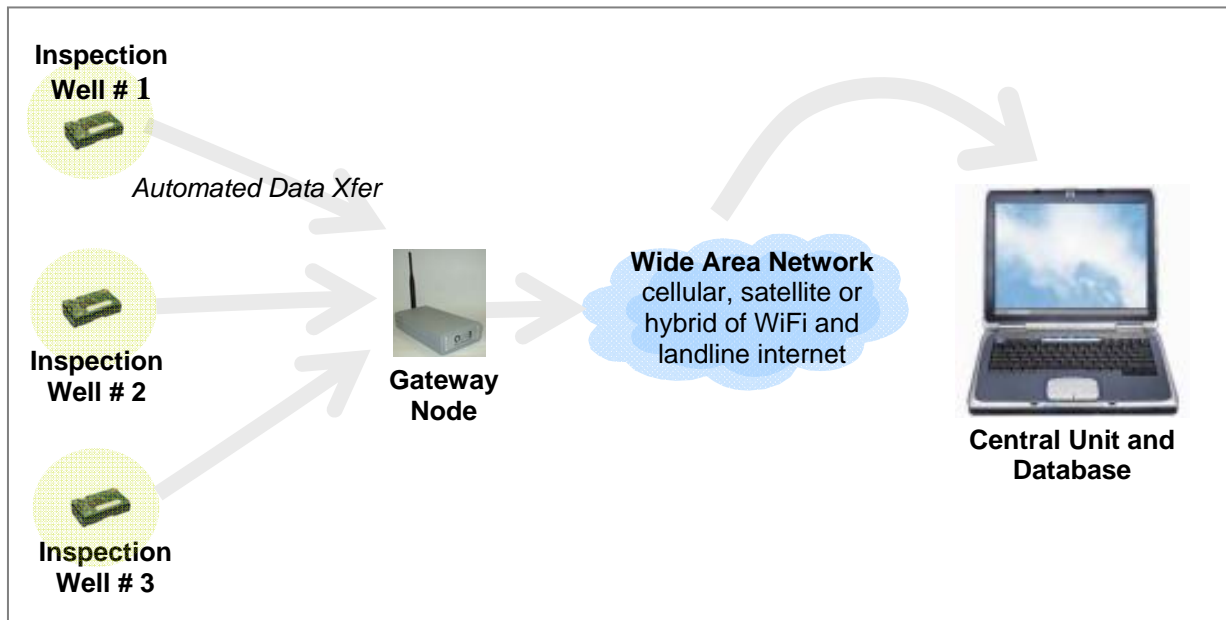


Fig I: Illustration of a Wireless Sensor Network

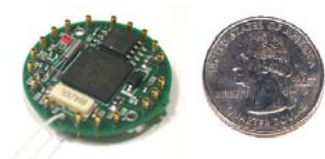


Fig II: RF radio chip with Amtel ATmega128L micro-processor, running TinyOS

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