DATA ACQUISITION
FOR
LOW-TEMPERATURE GEOTHERMAL
WELL TESTS AND LONG-TERM MONITORING

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Prepared For:

U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls, ID 83401

Contract No. DE-FG07-90ID 13040

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March 1992

DISCLAIMER STATEMENT

This material was prepared with the support of the U.S. Department of Energy (DOE Grant No. DE-FG07-90ID 13040). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the view of DOE."

ABSTRACT

Groundwater monitoring is an essential part of the development of a low-temperature geothermal field for production and injection wells. State water resource and environmental departments are requiring both geothermal well testing and long-term monitoring as a part of the permitting process for geothermal developments. This report covers water-level measurement methods, instruments used for well testing, geochemical sampling, examples of data acquisition and regulatory mandates on groundwater monitoring.

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1. INTRODUCTION

The acquisition and interpretation of water-level and geochemical data are essential parts of any groundwater monitoring system. When expressed in values of hydraulic head, water-level measurements are used to determine hydraulic head distributions, which in turn are used to assess groundwater flow directions within an aquifer. When referenced to changes in time, water-level measurements can reveal changes in groundwater flow regimes brought about by production or injection of geothermal fluids. When measured as part of a well or aquifer pumping test, water levels provide information needed to evaluate the hydraulic properties of groundwater systems.

State water resource and/or environmental quality agencies may require well testing and long-term monitoring of geothermal production and injection wells. Potential impacts on underground sources of drinking water and water-level declines of geothermal reservoirs are concerns that require groundwater sampling and monitoring.

2. WATER-LEVEL AND HYDRAULIC HEAD RELATIONSHIPS

An aquifer is defined as a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Todd, 1980). Aquifers are generally classified based on where a water-level lies with respect to the top of geologic unit. Figure 1 shows an example of a fault charged geothermal hydrogeologic media forming both confined and unconfined aquifers. The confined aquifer is a relatively permeable unit, bounded on its upper surface by a relatively lower permeability layer. Hydraulic head in the confined aquifer is described by a potentiometric surface, which is higher in elevation than the physical top of the aquifer.

The upper layer in Figure 1 contains an unconfined aquifer which has the water table as its upper boundary. The water table is the surface corresponding to the top of the unconfined aquifer where total hydraulic head is zero relative to atmospheric pressure or the hydrostatic pressure is equal to the atmospheric pressure. Hydraulic head varies greatly in three dimensions over small areas, and the design and placement of water-level monitoring equipment is critical for a proper understanding of the groundwater system.

3. DESIGNING A GROUNDWATER MONITORING SYSTEM

The design of a groundwater monitoring system usually considers requirements for both water-level monitoring and groundwater sampling. Design of a water-level monitoring system should begin with thorough review of existing data. This review should be directed towards a conceptual model of the site geologic and hydrologic conditions. Existing wells in the area should be identified as to their use and availability for monitoring as observation wells. If well logs are available--location, recent use, well depth, lithologies, casing schedules, water levels, pumping rates, temperature profiles and dates drilled should be recorded.

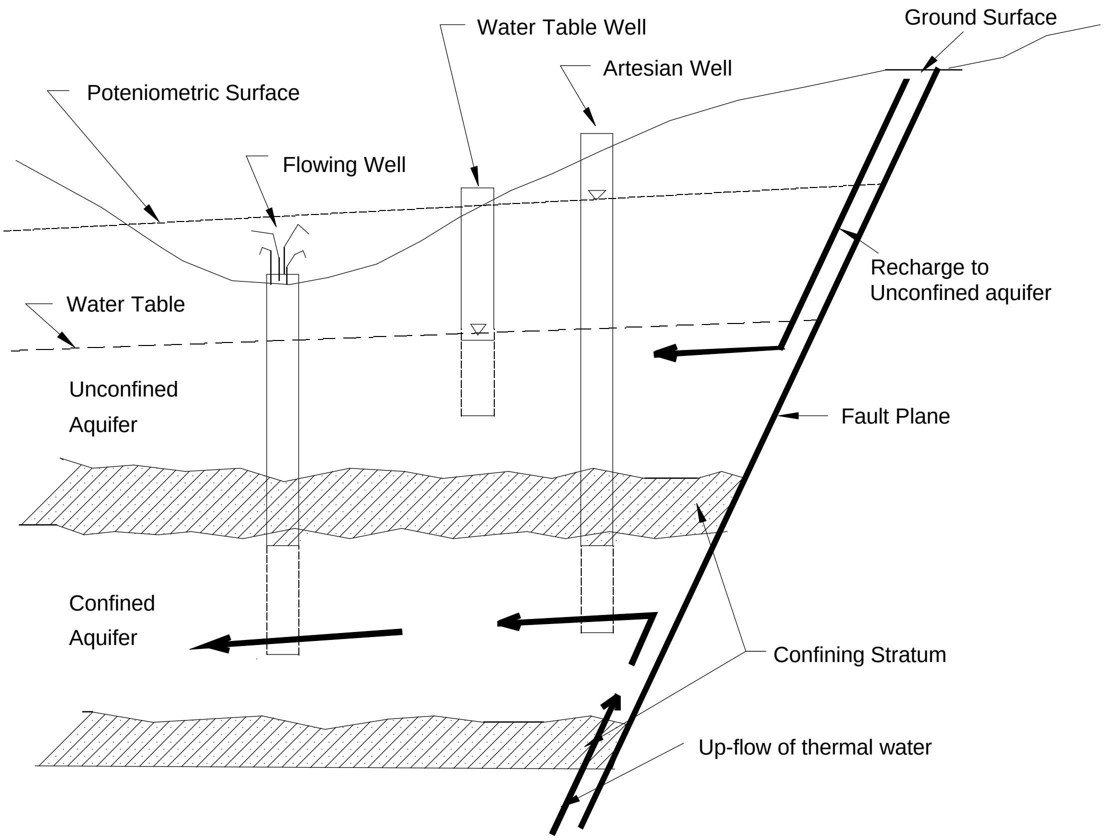


Figure 1. Fault Charged Confined and Unconfined Aquifers.

The available data should be reviewed to identify:

1. Flow rates for production and injection wells
2. The depth of permeable saturated zones beneath a site
3. Depth to water table or potentiometric surface
4. Probable groundwater flow directions (hydraulic gradient)
5. Features that might cause groundwater levels to fluctuate, such as pumping, river levels, seasons (dry vs. wet), etc.
6. Probable frequency of fluctuations
7. Geochemical data, and
8. Existing wells that may be incorporated into the water-level monitoring and water sampling program.

The minimum number of wells required to estimate a groundwater flow direction is three (Todd, 1981). However, the use of three wells is only appropriate from relatively small sites. On large sites an initial grid of six to nine wells is usually sufficient to provide estimates of groundwater flow directions and water-level changes due to production and injection.

4. MEASUREMENT REQUIREMENTS

Measurements required for well tests and long-term monitoring could include flow rates, water-level or wellbore pressure, temperature and barometric pressure. In addition, wells should be accurately located horizontally and vertically depending on the site and available base map. The precision of the horizontal distances are generally not as important as the precision of the elevation survey and water-level measurements. Water-level measurements should have a minimum resolution range of 0.1 to 0.2 ft (0.04 to 0.009 psi) or 0.5% of drawdown, whichever is smaller. This should include any temperature sensitivity in the pressure transducer and/or recording device. If the potentiometric slope is very gradual, more precise elevation control and water-level measurements may be required.

Accuracy and resolution are used to express the precision of instruments used for groundwater monitoring. Accuracy is a measure of how closely a measured parameter compares to the correct value, as determined by the Bureau of Standards. The accuracy of an instrument is a function of its calibration, hysteresis, drift, repeatability and resolution. The resolution of an instrument is a function of the sensitivity of the transducer to the parameter being measured, and the smallest quantity that can be observed and measured when using the instrument.

In the case of well tests, flow rates are usually measured with an orifice plate or turbine meter. Production or injection flow rate could be controlled by a variable speed drive at the pump or by valve adjustment. Flow rate measurements should be continuous if changing or hourly if constant with an accuracy of ±5%. For well tests, precise (±5 second) synchronization of all clocks is mandatory.

The frequency of measurements of the active well and observation wells for a well test will vary, with shorter intervals during the start and initial recovery period of the test. For a test, the recommended monitoring schedule is given in Table 1.

For long-term monitoring, environmental regulations generally require that water-levels be monitored and reported on a quarterly basis. A quarterly monitoring schedule may be appropriate for sites where water-levels fluctuate in response to seasonal conditions. However, water-levels at many sites respond not only to seasonal factors but also to factors of shorter duration or frequency. These factors may include fluctuations caused by daily well pumping, injection of fluids, changes in river stages, rain fall, atmospheric pressure changes and earth tides, among others. In these cases daily or more frequent (for example 6-hr intervals) measurements are desirable.

Table 1. Typical Monitoring Schedule for Well Tests

Period	Interval	Duration
Background	30 minutes	24 hours
Drawdown	30 seconds	first 1-10 minutes
	60 seconds	next 30 minutes
	2 minutes	next 60 minutes
	10 minutes	next 4 hours
	30 minutes	remainder
Recovery	Repeat the same sequence used for the drawdown.	

With computer technology, our ability to collect and analyze data for groundwater monitoring at a reasonable cost is increasing. Data loggers (microprocessors) connected to transducers allow the collection and analysis of water-level data over extended periods of time. The period in which long-term monitoring should be conducted depends on the duration and frequency of the fluctuations. For example, on sites affected by production and/or injection of geothermal fluids, monitoring on a continuous basis may be desirable.

5. INSTRUMENTATION

One of the most common measurements in groundwater investigations is the determination of the depth to groundwater. In existing wells such data are needed to define groundwater flow directions, changes in water levels over time due to production and injection of geothermal fluids, and effects of pumping and/or injection tests.

Water level data acquisition techniques can be manual measurements or continuous measurements using instruments that provide a record. These methods are summarized in Table 2.

5.1 Wetted-Tape Method

A simple and accurate method for obtaining water depth is lowering a steel tape into a well. By adding chalk to the end of the tape, the length of submersion becomes apparent, thus giving the distance from the top of the well to the water surface. Coefficients of stretch and temperature expansion of the steel tape become a concern when water-level measurements are made in wells of higher temperatures or at depths greater than 1,000 ft. For most groundwater investigations, corrections for these errors are not necessary.

Table 2. Summary of Water-Level Instruments.

Measurement Method	Resolution (ft)	Major Interference
Wetted-tape Manual	0.01	Casing wall water
Electrical Manual	0.02 to 0.1	Cable wear; hydrocarbons on surface
Air-line Manual	0.25	Air-line leaks and gage inaccuracies
Capillary tube Manual or Continuous	0.1 to 0.25	Temp. changes; tube leaks
Float Method Continuous	0.01 to 0.5	Float or cable drag; float size & lag
Pressure Transducer Continuous	0.02 to 0.05	Temp. changes; electronic drift

A disadvantage of using the wetted-tape method is that if the appropriate depth to water is unknown, too short or too long a length of chalked tape may be lowered into the well, thereby necessitating a number of attempts. Also, water on the sides of the casing may wet the tape above the actual water level and result in errors in measurements.

5.2 Electrical Methods

Currently, the most favored technique for manual water level measurements is the use of an electrical probe. This type of instrument operates on the principle that a circuit is completed when two electrodes come in contact with the water surface in the well. These instruments employ a two wire conductor which is marked every 5 ft, at 10 ft, 50 ft and 100 ft levels with coded colors. When the electrodes come into contact with the water surface, the borehole fluid conducts the current, and a meter, light, or buzzer is activated at the ground surface. Figure 2 shows an example of an electrical, well water-level depth probe.

Errors in water level measurements using electrical probes results from changes in the cable length as a function of use, depth, and temperature. After repeated use the markings tend to become loose and slide or become illegible from wear.

A common disadvantage in most electrical probe instruments is that if substantial amounts of non-electrical conducting constituents are floating upon the water surface, contact cannot be reliably made.

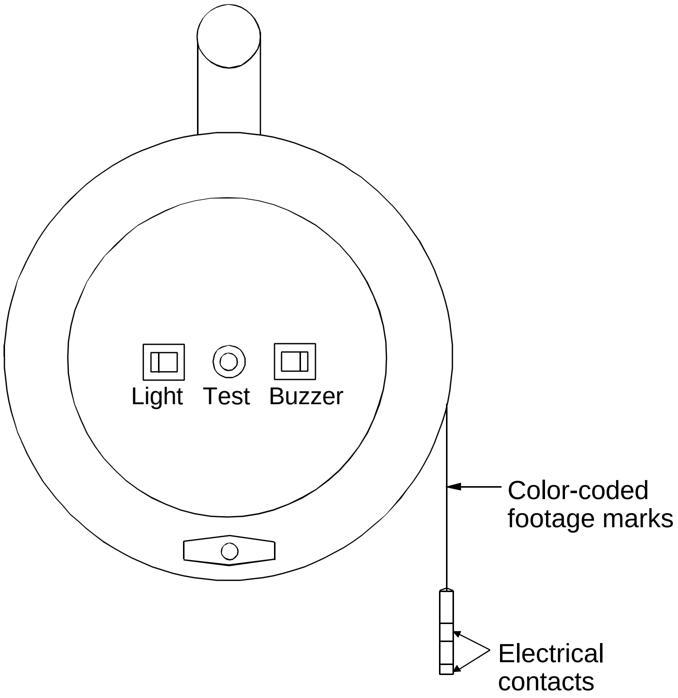


Figure 2. Electrical Water-Level Probe.

5.3 Air-Line Methods

The air-line method, although less precise than other manual water-level measurement methods, continues to be the preferred technique in wells that are pumped. To make an air-line measurement of water level in a well, a small, straight tube of accurately known length is installed in the well. This tube, usually of 0.25 in. or less in diameter, can be made of copper or steel or plastic. The air-line and all connections must be air tight and installed to several feet below the expected lowest water level. A pressure gage is attached to this line, as well as a fitting for an air source. In wells where multiple water level measurements are made, a small air compressor or bottled gas is useful.

A water level measurement is made when air is pumped into the small tube and the pressure is monitored. Air pressure will continue to increase until all the water is expelled from the tube. Air pressure, which is determined when the pressure stabilizes, is used to calculate the height of water above the bottom of the tube. If the pressure gage is calibrated in psi, a conversion to feet is made by multiplying the psi reading by 2.31 for cold water. The conversion of pressure (psi) to depth of water (ft) is dependent on the specific weight of water which is a function of the temperature. The equation is:

$$p = \gamma x h$$

where: p = pressure, psi
γ = specific weight of liquid, lb/ft^3
h = depth of liquid, ft

For example, the specific weight of water at 50°F is 62.410 lb/ft^3 and at 200°F, 60.107 lb/ft^3. The conversion factors are:

at 50°F: 144/62.410 = 2.307 ft/psi

or

at 200°F: 144/60.107 = 2.396 ft/psi

These values would apply to a wellbore with an isothermal profile. If the wellbore has an linear temperature gradient, then the density gradients above the measuring point may have to be integrated to obtain very accurate depths from pressure data.

The actual water level below the surface is determined by subtracting the calculated distance from the air-line's length. The dependability of measurements by the air-line method varies with the accuracy of the pressure gage. If the gage has gradations as small as 0.1 psi, the maximum possible resolution would be 0.23 ft for cold water (50°F) or 0.24 ft for hot water (200°F).

5.4 Capillary Tube

The capillary tube method is similar to the air-line; however, it does not require the expulsion of water from the end of the tube for each measurement. The capillary tube system consists of a 0.125 in. outside diameter and 0.085 in. inside diameter, 316 stainless steel (soft annealed) capillary tubing attached to a connector at the wellhead which has fittings for a pressure gage, transducer and an access (valve stem) for introducing nitrogen gas. At the bottom of the tube a pressure chamber (pressure bomb) is attached, which is 10 ft long and made of 0.75 to 1.25 in. pipe. A 1/4 in. diameter, 6 in. long pipe is attached to the lower end of the pressure chamber. The entire system must be air tight and charged with nitrogen gas. The nitrogen gas and water interface in the large chamber minimizes interface changes. The pressure chamber at the lower end of the capillary tube can be installed several feet below the lowest expected water level to measure water level changes or at the bottom of the well to measure reservoir pressure. Figure 3 illustrates the capillary tube method.

A water level measurement is made by reading the gage pressure or a pressure transducer, calculating the water level above the end of the pressure chamber and subtracting from the total length of the capillary tube. The precision of the capillary tube is primarily dependent on the accuracy of the pressure gage or transducer. Any temperature changes in time along the tube create additional pressure signals which distorts the downhole signal. Corrections for these effects must be used to obtain the desired, accurate pressure measurements (Miller, 1978).

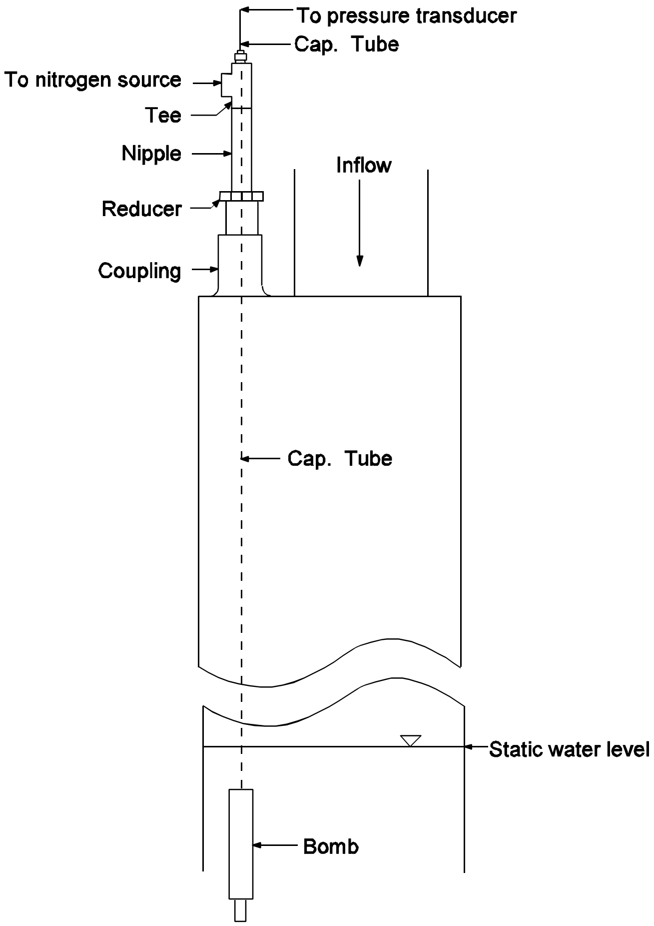


Figure 3. Capillary Tube Method.

5.5 Float Method

The float method can utilize two types of instruments. The first is clock-driven chart recorder and the second is digital data logger. A float is attached to a length of steel wire and suspended over a pulley into the well. At the opposite end of the steel wire, a counterweight is attached. The pulley operates a chart recorder; a drum covered with chart paper and containing a time-driven marking pen or a shaft encoder for the digital instrument.

The chart recorder produces a continuous analog record of water level change, usually as a graph. Depending upon the gage scale and time-scale gearing, a single chart may record many months of water level fluctuations. The resolution of a chart recorder varies from 0.01 to 0.20 ft depending on a gage scale ratio of 1:1 to 1:20, corresponding to a water level change for 1 revolution of the drum of 1.00 to 20.0 ft.

The shaft encoder water level instrument is a digital instrument, which is mounted on a shaft, connected to a pulley (with a calibrated circumference of for example, 500 mm or 1.0 ft) that transfers the motion of water float and float wire to shaft rotation, measured as 1 bit per mm. The rotation of the shaft encoder is stored in a 16 bit (0 to 65,536 mm) processor (up/down counter). Therefore the resolution of the shaft encoder water level instrument is 0.003 ft (1.0 mm), which does not take into account float lag, float line shift, etc. This counter may be read by the data logger via a high speed bi-direction serial data bus. A digital record is stored in the data logger and can be unloaded by a lap-top computer. Frequency of measurements can be programmed into the data logger and the record gives date, time, and water level in desired units. Figure 4 illustrates a shaft encoder water level instrument.

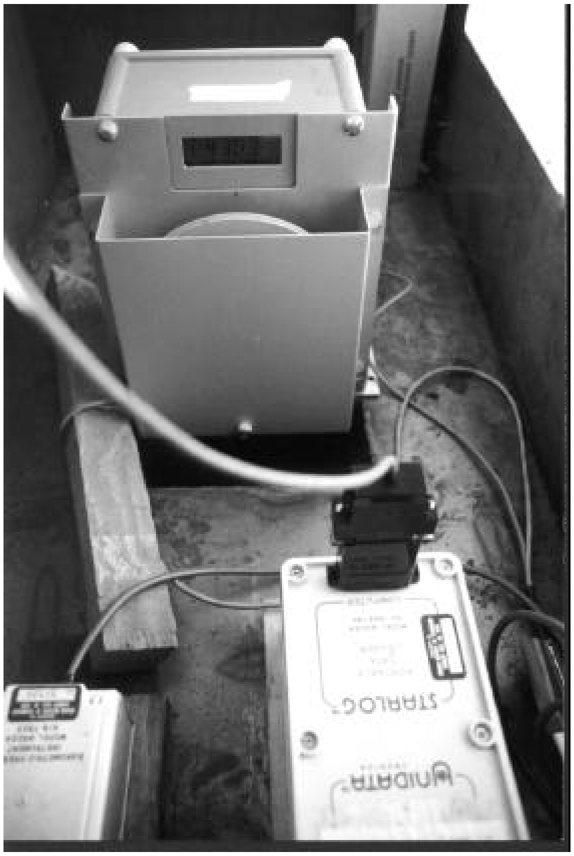


Figure 4. Shaft Encoder Water Level Instrument.

Float operated devices are subject to several sources of error which include float lag, line shift, submergence of counterweight, and temperature. Float line lag is the result of a certain amount of force which is required to move the shaft mechanism of the pulley and bend the float line over the pulley. This force must be supplied by the pressure of the water on the float. This error (caused by friction in the measuring apparatus) is not cumulative and is usually not very large.

Float line shift results with every change in level, a portion of the float line passes from one side of the pulley to the other. This change of line weight (from one side of the pulley to the other) changes the depth of floatation of the float and hence, causes an error in the registered level. The error is inversely proportional to the square of the float diameter; therefore, the larger the float, the smaller the error.

When the counterweight (and any portion of the float line) becomes submerged, the pull on the float is reduced and its depth of floatation is reduced. In this case, the level will measure slightly lower than it actually is.

Changes in temperature will cause the float line to expand and contract. The amount of expansion (contraction) is usually small. For example, 0.4 mm stainless steel wire has a coefficient of thermal expansion of 9×10^{-7} per °C; therefore, the error expected from a 10°C change in ambient temperature in 10 m of float wire will be 0.09 mm. However, well temperatures tend to remain relatively constant.

5.6 Pressure Transducer

Pressure transducers can accurately monitor changes in pressure over a wide range. The transducer is lowered by means of a cable to a level below the water level which will remain submerged during changes in the water level. The transducer measures the depth of water as pressure (psi) which can be converted to depth of submergence. Subtracting this depth from the distance the transducer was lowered into the well results in the water level measurement. If the pressure transducer range is carefully matched with the well pressure, measurements to ±0.02 ft can be obtained. A digital record of date, time and water level is stored in a data logger which can be unloaded with a lap-top computer.

Two types of pressure transducers that have been used to monitor low-temperature geothermal wells are the strain gauge bridge type (<180°F) and the digiquartz (<225°F) pressure transducer. The digiquartz transducer operates on the principle of a quartz crystal resonator whose frequency of oscillation varies with pressure induced stress. Frequency outputs allow ease of interfacing with counters, computers or other digital data acquisition systems. The transducers also provide a quartz crystal temperature signal for full thermal compensation over a wide temperature range. The resolution of the digiquartz pressure transducer is <0.1% of full scale.

The Lawrence Berkeley Laboratory Reservoir Engineering group designed a housing for the shock-mounted digiquartz pressure transducer and temperature transducer (INEL, 1982). The pressure transducer is connected to a pressure port with a stainless steel capillary tubing filled with Dow Corning f.s. 1265 fluid. The combination pressure/temperature housing is constructed from 316 stainless steel and has an outside diameter of 2.75 in. and a length of 9.5 in. The combination pressure/temperature chambers are lowered into the well on armored four-conductor cable. The temperature sensing element is a YSI 44011 100,000 ohm at 77°F thermistor, isolated from the well fluid by 1/8 in. outside diameter stainless steel tubing with a 0.010 in. wall thickness. The digiquartz transducer has an overall accuracy of 0.1% full scale. The thermistor has a resolution of ±0.2°C (including thermistor interchangeability) and a response time of approximately 1 second in liquids.

The resistance of the thermistor, which is temperature dependent, is read at the surface and converted to temperature. Figure 5 is a schematic of the LBL downhole pressure and temperature instrument.

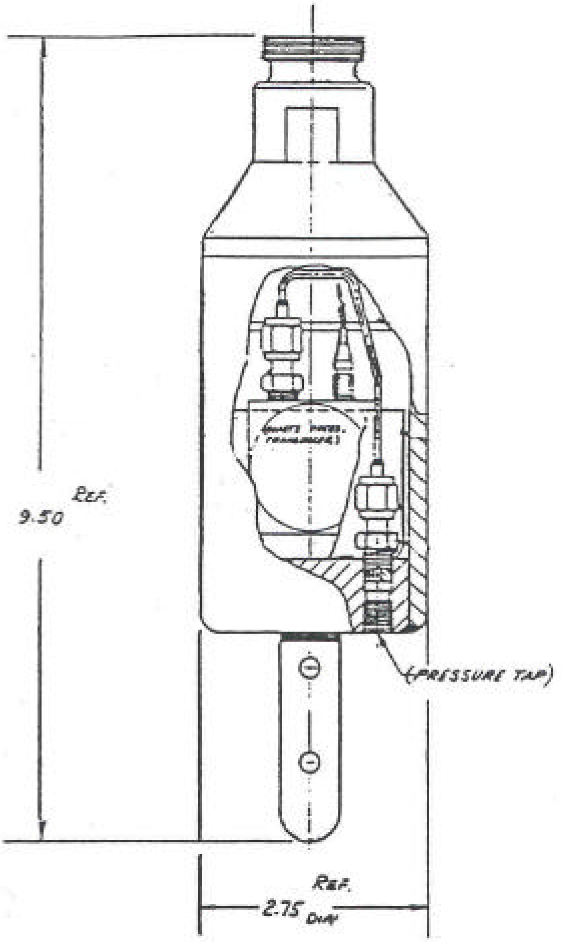


Figure 5. LBL Downhole Pressure and Temperature Instrument.

The basic sensing element of a strain gauge pressure transducer is made by diffusing a fully active four arm strain gauge bridge into the surface of single crystal silicon diaphragm whose active diameter and thickness can be varied according to pressure range and application. In cases where the pressure media are not compatible with the silicon diaphragm, stainless steel or other materials are used as isolating diaphragms such that the sensor is totally immersed in oil with negligible degradation in performance. These instruments require a reference pressure such as atmospheric pressure; therefore, the connecting cable to the surface includes a vent tube in addition to four conductors. They are available in a series of operating pressure ranges, such as 1, 5, 10, 15, 20, 30, 50, 100, 150, 200, 500, and 900 psi gauge. The pressure range is selected according to the amount of variation in water level.

The resolution is dependent on the bit accuracy of the data logger and the pressure range. For example, a 5 psig transducer operating in conjunction with an 8 bit data logger has a resolution of 0.05 ft. However, the accuracy of the transducer is ±1.5% for the temperature range -5 to 175°F for a 5 psi range and above. The accuracy is the sum of the data logger and pressure transducer, which is ±1.5% + ±0.4% = ±1.9%.

5.7 Barometric Pressure Instrument

Changes in atmospheric pressure produce measurable fluctuations in wells penetrating confined aquifers. The relationship is inverse; that is, increases in atmospheric pressure produce decreases in water-levels, and conversely. When atmospheric changes are expressed in terms of a column of water, the ratio of water-level change to pressure change expresses the barometric efficiency of an aquifer.

$$B = (\gamma \Delta h) / (144 \Delta p_a)$$

where: B = barometric efficiency
γ = specific weight of water, lb/ft^3
Δh = change in level, ft
Δp_a = change in atmospheric pressure, lb/in^2

Most observations yield barometric efficiency values in the range of 20 to 70 percent. For example, a well which showed a 50 percent barometric efficiency would have a water level rise of 0.05 ft for each decrease of 0.10 ft in barometric pressure measured in feet of water. Such values should be added to or subtracted from the measured water-levels to eliminate the influence of atmospheric pressure changes.

Two types of instruments are available for continuous recordings: a chart recording aneroid barometer or a digital barometric pressure instrument designed to interface with a data logger. The advantage of the digital instrument is that the time record of the barometric pressure measurement is simultaneous with the water level measurement. The digital barometric pressure instrument is designed to provide a voltage signal that is analogous to the atmospheric pressure surrounding the instrument. The instrument uses a vacuum with which it compares the atmospheric pressure to determine absolute pressure. These instruments are temperature compensated for a range of outdoor temperatures.

For the digital barometric instrument, the resolution is 0.01 in. Hg (0.04 kPa) and the accuracy is ±1.0% of full scale.

5.8 Temperature Sensors

Three generally accepted electrical temperature measurement devices are thermocouples, resistance temperature devices (RTD's), and thermistors. Thermocouples consist of two wires composed of dissimilar metals, joined at both ends and when one end is heated, there is a continuous current in the thermoelectric circuit. If this circuit is broken at the center, the net open circuit voltage (the Seebeck voltage) is a function of the junction temperature and the composition of the two metals. Thermocouples must use a reference junction to measure the desired temperature at the junction of the two dissimilar wires. The reference junction can be an ice bath, a reference circuit or a reference junction voltage equal to a 0°C junction. Thermocouples can be used over a wide range of temperatures, they are more rugged than thermistors and are the most versatile temperature transducers available.

The resistivity of metals show a marked temperature dependence. The most common RTD's are made of either platinum, nickel or nickel alloys. Unlike the thermocouple, the RTD is not self powered. A current must be passed through the device to provide a voltage that can be measured, this current causes Joule heating within the RTD, changing its temperature. This self-heating appears as measurement error. To reduce self-heating errors, the minimum ohm measurement current is used that will still give the required resolution.

Thermistors are generally composed of semi-conductor materials and exhibit the greatest sensitivity of the three major temperature sensors. Most thermistors have a negative temperature coefficient (TC); that is, their resistance decreases with increasing temperature. The negative TC can be as large as several percent per degree Celsius, allowing the thermistor circuit to detect minute changes in temperature which could not be observed with an RTD or thermocouple circuit. The use of thermistors is generally limited to a few hundred degrees Celsius and manufacturers warn that extended exposures even well below maximum operating limits will cause the thermistor to drift out of its specified tolerance.

A comparison of the three electrical temperature measurement devices is given in Table 3.

Table 3. Temperature Sensors

	Thermocouple	RTD	Thermistor
Service range	-270 to 2000°C	-260 to 900°C	-100 to 400°C
Sensitivity	Good: +0.5%/°C	Very low: 1%/°C	High: -5%/°C
Accuracy	0.1%	0.01%	1%
Linearity	Poor: 10 - 25%	Excellent: 1%	Poor: 10 - 20% Linearized: 2%

5.9 Flow Measurements

The most commonly used device for measuring discharge flow during a pumping test is probably the free discharge pipe orifice (U.S. Department of Interior, 1981). When used in conjunction with a pipeline, the orifice may be placed at the end of the pipeline. A free discharge orifice is simply a flat piece of metal with a specific-sized hole bored in it. Major advantages of orifices are that they have no moving parts and their cost does not increase significantly with pipe size. Figure 6 illustrates pipe orifice arrangement and details.

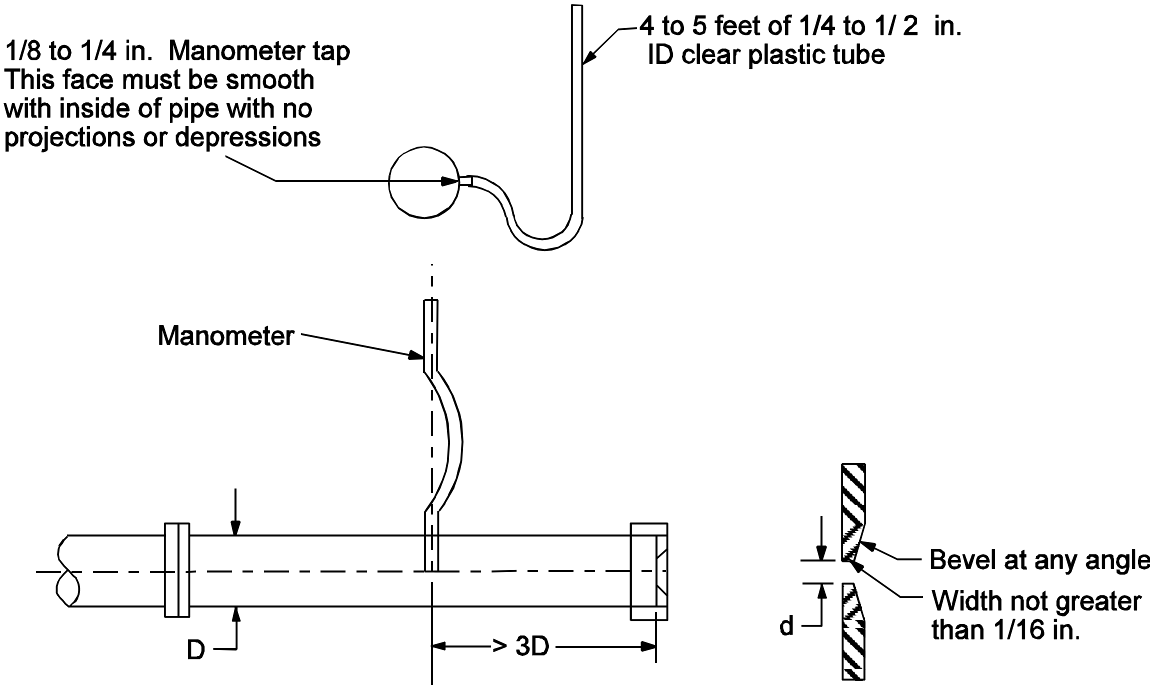


Figure 6. Pipe Orifice Details.

Generally orifice tables are used to measure a range of discharges which can be measured with various orifice and pipe combinations. Appendix A shows a range of discharges for various orifice and pipe sizes. The discharge flow can also be determined by using an equation and discharge coefficient curve (Figure 7).

The equation used to calculate flow rate for a free discharge pipe orifice is:

$$Q = CA\sqrt{(2gH)}$$

where:
Q = ft^3/sec of orifice discharge
Q x 449 = gallons per min. (gpm)
C = discharge coefficient taken from Figure 7
A = area of orifice opening, ft^2
g = 32.17 ft/sec^2
H = feet of manometer head

The d/D ratio in C should be between 0.4 and 0.85, where d is the diameter of the orifice and D is the inside diameter of the pipe.

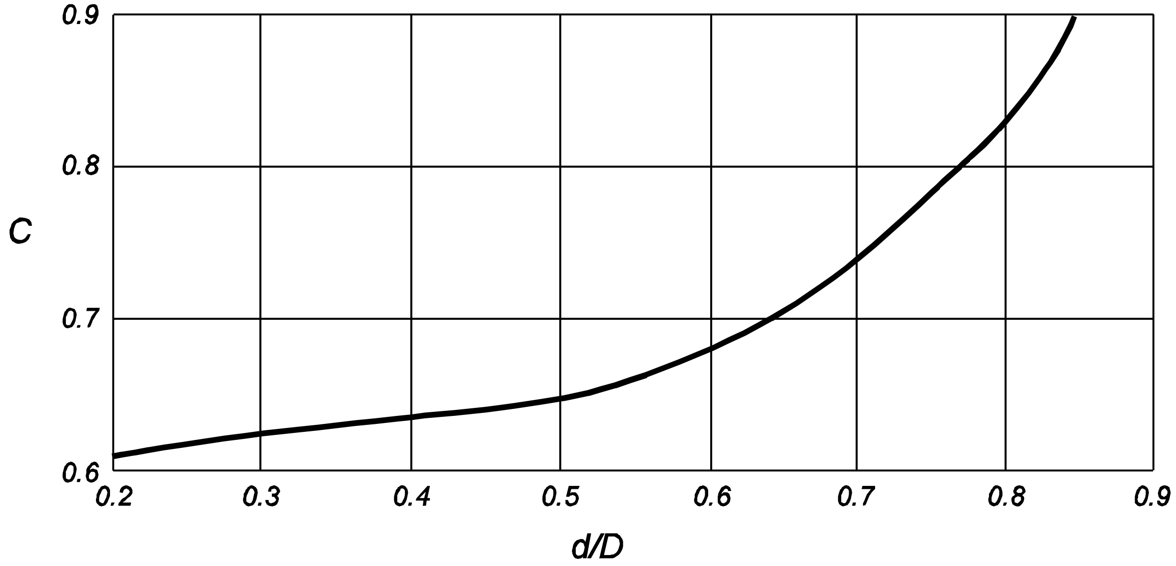


Figure 7. Pipe orifice discharge coefficient.

6. DATA ACQUISITION HARDWARE

The data acquisition system can be a centralized computer-based system consisting of pressure sensors, line drivers, signal line from each well, and a recording station, such as one designed by Lawrence Berkeley Laboratory (Benson, 1986) or a remote system.

An approach used by the Geo-Heat Center is a remote data acquisition system consisting of shaft encoder water level instrument or pressure transducer, temperature probe and data logger for each well. One well is equipped with a barometric pressure instrument used to serve the entire network. The operation of the remote system which can be used for either well tests or long-term monitoring will be considered in the following discussion. A partial list of suppliers of complete groundwater monitoring systems is given in Appendix B.

6.1 Data Loggers.

When using digital instruments (such as shaft encoder water level, pressure transducer, barometric pressure and temperature probes) a device is necessary for automatic data collection at remote locations. The data logger is a microprocessor based device designed to offer very low power consumption from internal batteries to operate the connected instruments and data logger. The recorded data is stored in low power CMOS RAM memory which is available in a variety of sizes (i.e., 8K bytes to 64K bytes). An internal crystal clock provides accurate time referencing of all recorded data and also controls the adjustable cycle time (sampling rate). The only external connections to the data logger are the input signal connector for instrument signals to be recorded and the computer connector for the transfer of recorded data to the unloading device (computer).

Data loggers may have a variety of input signals. For example, one model has:

8 Analog voltage inputs (8 bit resolution)
4 Pulse counting inputs (4 and 8 bit resolution)
2 Digital (ON/OFF) inputs
1 Digital (ON/OFF) output
1 Serial input/output bi-directional high speed data bus

Instruments are assigned channels in a data logging system. Each different type of instrument is assigned a particular type of channel, depending on the type of signal. The type of signal being transmitted from an instrument needs to be known so it can be connected to a channel which can carry its signal.

The data logger is fully programmable, allowing its use in a wide variety of applications, such as water level, temperature and barometric pressure for a single well. The data logger program can be user defined and is installed into the data logger from a computer via the computer connector, such as RS-232 communication. Baud rates may be fixed or programmable up to 9600 baud. The data logger battery life is 12 to 18 months which is influenced by logger cycle time and program run time and data storage capacity.

Data logger resolution is dependent on the microprocessor. They are available as 8, 12, and 16 bit processors. For example, an 8 bit data logger used for recording pressure readings from a strain gage pressure transducer (5 psi range) would have the following resolution:

$$(5 \text{ psi})\,(2.307 \text{ ft/psi})/2^8 =$$
$$(11.54 \text{ ft})/256 \qquad = 0.05 \text{ ft}$$

If a 12 bit data logger were used, then the resolution would be:

$$(11.54 \text{ ft})/2^{12} \qquad = 0.003 \text{ ft}$$

6.2 Computer

A lap-top computer with 512 kilobytes of random access memory (RAM) serves as the method for unloading and transferring field data from the data logger to a compatible IBM-PC in the office. An RS-232 cable is used to communicate between the computer and data logger. The operating system and hardware come "factory ready" for interfacing the computer with a variety of instruments. To generate a data logging scheme and to display data logged requires a field (portable lap-top) computer with the minimum configuration below:

- One diskette drive (two preferred)
- 512 K memory
- RS-232 communications port
- MS DOS version 2.1 (or later) operating system

A compatible IBM-PC/XT/AT computer in the office can be used to manipulate the data to produce hydrographs from spreadsheets or use software to analyze hydrologic properties of the aquifer. Data in ASCII or LOTUS 123 format is transferred from the field computer to the office computer via a diskette.

6.3 Software

A software package is used to control the data logging scheme. A commercial software package may be available from an equipment vendor or you may write your own software. The commercial program is usually menu-driven and in most instances provides you with a list of options from which you select one relevant to your particular project. Each choice you make determines which menu will appear next, so that you are guided step-by-step through any process. Help messages are also provided.

Menus are especially helpful in setting up a data logging project. It is here that you define what kind of information and when it will be logged. You will also specify how you wish to retrieve the data.

Once data has been stored in the logger, you will use the software package to unload the data. Logged data is unloaded onto your computer, then made available in a format you choose.

Different formats are usually provided to enable you to use the data in several different ways. For example, using software, you can read the data, look at a plot of the data, print it, or, you can unload data in a file format (LOTUS, ASCII, etc.) compatible with popular spreadsheet programs so that sophisticated reports and graphs can be produced.

7. GROUNDWATER SAMPLING AND GEOCHEMICAL MONITORING

7.1 Objective

Objectives of groundwater geochemical monitoring programs could include meeting regulatory requirements, ambient groundwater quality monitoring, geothermal fluid disposal monitoring, reservoir evaluation and corrosion control for equipment used in plant construction. The ultimate objective of all monitoring programs is to obtain a sample of water that is as representative of the actual groundwater quality for analysis of chemical and isotopic constituents.

A monitoring program to determine the impact of injecting geothermal fluids involves first taking background samples from the injection well, production well and observation wells before the injection of any fluids. Then a frequency of sampling injected fluids and observation wells could, for example, follow a schedule of monthly for the first quarter and quarterly for the next year or more. Regulatory agencies in each state will usually specify the sampling frequency. Appendix C provides a listing of state regulatory agencies.

7.2 Regulatory Objectives

Regulatory concerns regarding disposal of geothermal fluids by means of injection primarily focus on protection of drinking water aquifers.

Existing federal regulations which have established lists of parameters for analysis of groundwater samples that apply to the disposal of geothermal fluids include: the Safe Drinking Water Act (SDWA) and the Clean Water Act (CWA). In general, the CWA considers surface water quality and discharges into the surface water. The SDWA protects underground sources of drinking water (USDW) by compliance with the Underground Injection Control program, which includes geothermal injection wells. These federal regulations specify maximum contaminant levels (MCLs) for drinking water supplies and apply to all public water systems. At the recommended maximum contaminant levels, no adverse health effects are known to exist. The primary standards for various inorganic parameters are presented in Table 4 (Nielsen, 1991).

Table 4. National Primary Drinking Water Standards.

Parameter	MCL[a] (mg/L)	Proposed MCL
Arsenic (As)	0.05	
Barium (Ba)	1.0	2.0 (30 Jan 91)
Cadmium (Cd)	0.005	
Chromium (Cr)	0.10	
Lead (Pb)	0.05	0.005 (10 Aug 88)
Mercury (Hg)	0.002	
Selenium (Se)	0.05	
Nitrate (as N)	10.0	
Fluoride (F)	4.0	

a. MCL - Maximum Contamination Level

The secondary contaminant levels established by the SDWA are set for both aesthetic and health reasons. Contaminants covered by these regulations are those which may adversely affect the aesthetic qualities of drinking water such as taste, odor, color and appearance which thereby may deter the public acceptance of drinking water provided by public water systems. These secondary levels represent reasonable goals for drinking water quality, but are not federally enforceable. The secondary contaminant levels are present in Table 5 (Nielsen, 1991).

Table 5. National Secondary Drinking Water Regulations

Constituent	Recommended Level[a] (mg/L)
Chloride (Cl)	250
Copper (Cu)	1.0
Iron (Fe)	0.3
Manganese (Mn)	0.05
Sulfate (SO_4)	250
Zinc (Zn)	5.0
Foaming agents	0.5
Total Dissolved Solids	500
Color	15 color units
Corrosivity	Noncorrosive
Odor	3 threshold odor number
pH	6.5 - 8.5

a. Recommended levels for these constituents are mainly to provide acceptable aesthetic and taste characteristics.

7.3 Documentation

The sampling effort should be thoroughly documented to cover accountability, controllability and traceability. Proper documentation is necessary for data interpretation and for data to hold up under legal scrutiny. While many aspects of a monitoring program can only be documented once (e.g., well drilling techniques and construction details), sampling procedures can and should be documented for every sampling trip and every well.

The field book should contain sufficient information so that someone else can later reconstruct the sampling event solely from data contained in the log book. The importance of good documentation cannot be overemphasized because the lack of it can render expensive data suspect or useless. Appendix D contains an example of a sampling data sheet.

7.4 Factors Affecting Groundwater Samples

At least five different factors affect the accuracy of analytical determinations in the geothermal fluids. These sources of variations include (Kindle, 1991):

1. Flow composition shift with time from the well.

2. Differences in sampling methods.

3. Sample stabilization processes.

4. Different analytical methods.

5. Differences between laboratories using the same methods.

The information needs for a particular study and the desired accuracy should be established first; then, the appropriate sampling techniques can be selected. Sample treatment (stabilization) and field analysis techniques appropriate for minimizing errors (that may result from changes in water samples between time of collection and time of analysis) should be used. Analyses of the samples are generally done by a certified laboratory; however, data quality checks should be used when results are returned from the laboratory, to ensure that the results are consistent. Charge balance (anion-to-cation ratio) and mass balance (total dissolved solids-to-analyzed constituents ratio) should be calculated. These procedures are given in Kindle (1991).

Some constituents in the geothermal fluids are unstable and change with time. Depending on the purpose and nature of the study, changes in samples, upon collection and storage, may or may not be a problem. Preservation of a sample is often a problem; constituents may precipitate out, undergo chemical change, or evolve as a gas. Most sample constituents can be stabilized in the field for analysis in the laboratory.

8. EXAMPLES OF DATA ACQUISITION

8.1 Example 1 - Monitoring Production and Injection of Geothermal Fluids of the Klamath Falls Resource.

The Klamath Falls geothermal resource, located in south-central Oregon, is situated in a horst and graben structure of the Basin and Range Province. The subsurface lithology consists of alternating layers of basalt flows, lake sediments, volcanic ash, and tuff. The stratigraphy is complex, with considerable faulting, fracturing and thermal alteration.

A shallow geothermal anomaly (<2,000 ft depth) is described hydrologically as a highly permeable, fractured network interspersed with distinct rock units either way producing 140 to 230°F fluids. Over 500 wells penetrate the formation, producing geothermal energy for heating homes, apartment buildings, schools, businesses, and swimming pools.

In 1982, the city built a geothermal district heating system to service downtown government buildings (Figure 8). The two production wells were located in an area of many private wells used for heating homes with downhole heat exchangers (DHE). Concern was expressed by private well owners that producing geothermal fluids from these two wells would adversely interfere with the operation and performance of the wells with DHEs. In order to assess the impact of interference, the potential, and nature of the Klamath Falls resource, a geothermal aquifer test was conducted.

During the summer of 1983, investigators from Lawrence Berkeley Laboratories (LBL), Stanford University and Oregon Institute of Technology (OIT) were co-investigators with the U.S. Geological Survey (USGS), in an intensive study of the Klamath geothermal aquifer (Sammel, 1984). This project included a pumping and injection test by LBL, tracer studies by Stanford and OIT, and sampling for chemical and isotopic analysis by the USGS.

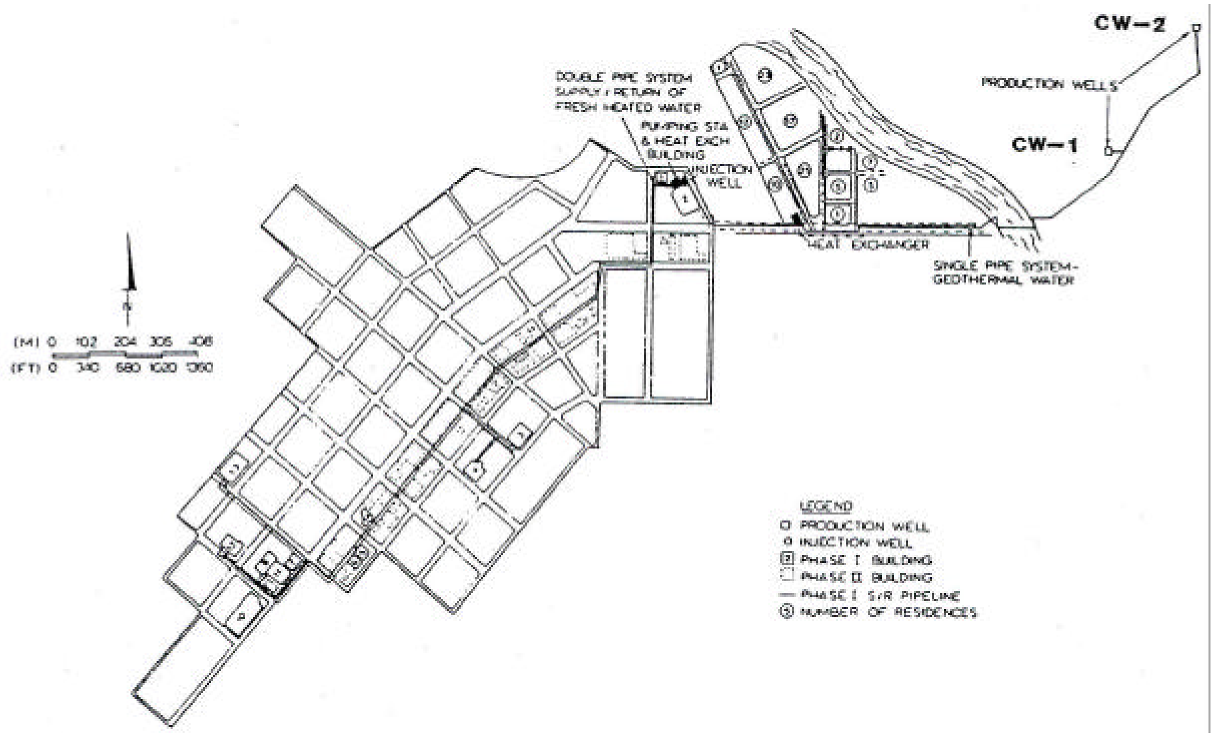


Figure 8. Klamath Falls Geothermal District Heating System.

During the pumping and injection test conducted 29 June to 1 September 1983, 52 wells were regularly monitored. Nine wells were fitted with digiquartz pressure transducers supplied by LBL. These wells were all connected by temporary wiring to a central data logger and multiplexer where all pressures and temperatures were simultaneously recorded. Eight wells were fitted with float type continuous chart recorders. An additional 33 wells were monitored by hand with electric water-level sensors. Specific wells were regularly depth and temperature profiled, barometric pressure changes were monitored and one well was fitted with a downhole seismograph. One well outside the hot well area was monitored with continuous recorders. Water samples for chemical analysis were taken from the pumped well periodically throughout the duration of the test.

The location of wells are identified in Figure 9, an example hydrograph of the Head well interference data showing response to pumping and injection are shown in Figure 10, and the results of the test are summarized in Table 6.

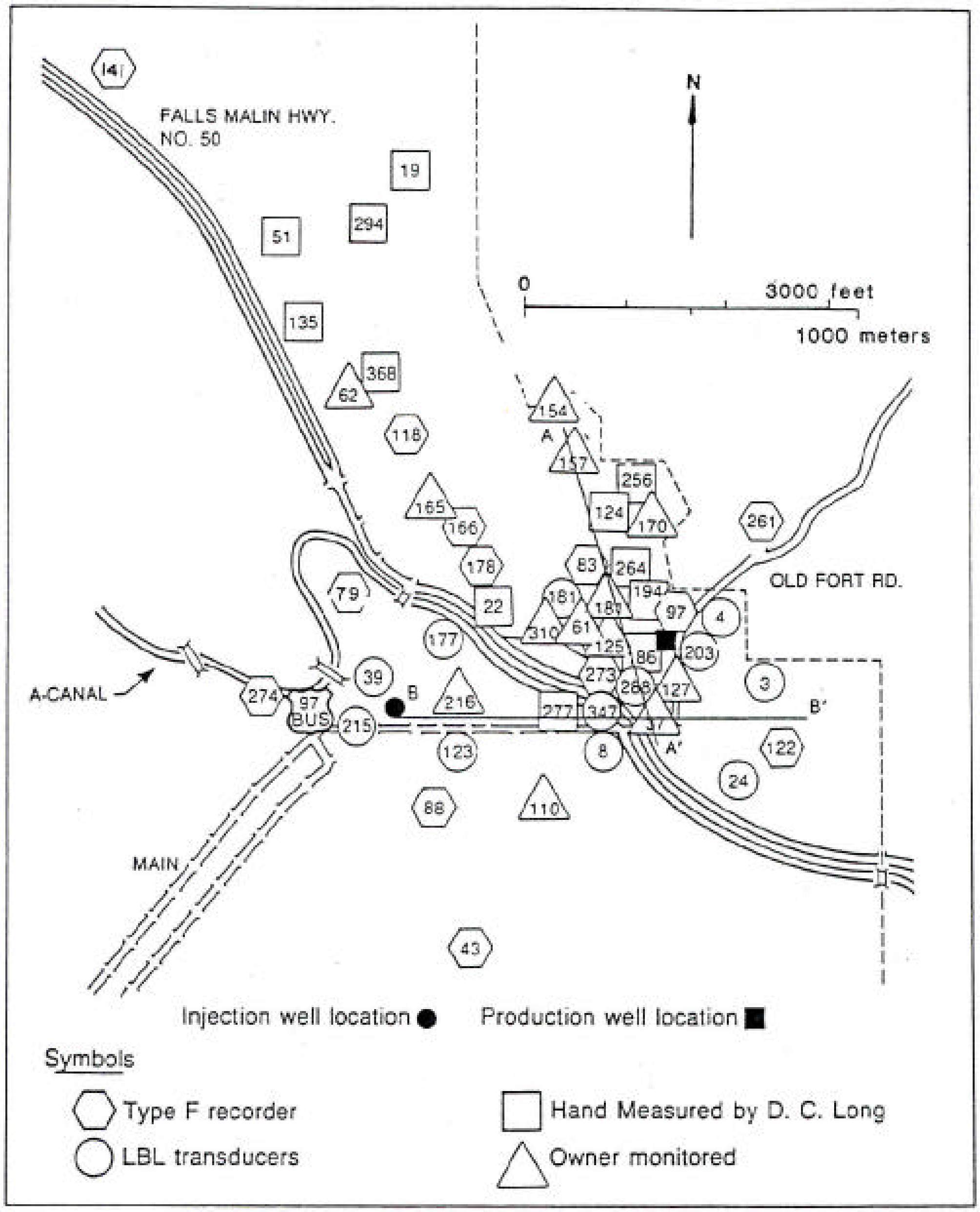


Figure 9. Location of Wells for the Klamath Falls Aquifer Test.

An enormous quantity of hydrologic data were obtained from the Klamath Falls geothermal aquifer test. Under well controlled conditions, the response of the aquifer and individual wells to both pumping and injection were measured. The test was of sufficient duration and the data of adequate quality that conventional and non-conventional analysis techniques could be applied.

The overall hydrologic characteristics of the geothermal aquifer were determined and are summarized in Table 6. Most of the data are remarkably consistent which allows the prediction of the aquifer response to pumping and injection with a relatively simple mathematical model (Sammel, 1984).

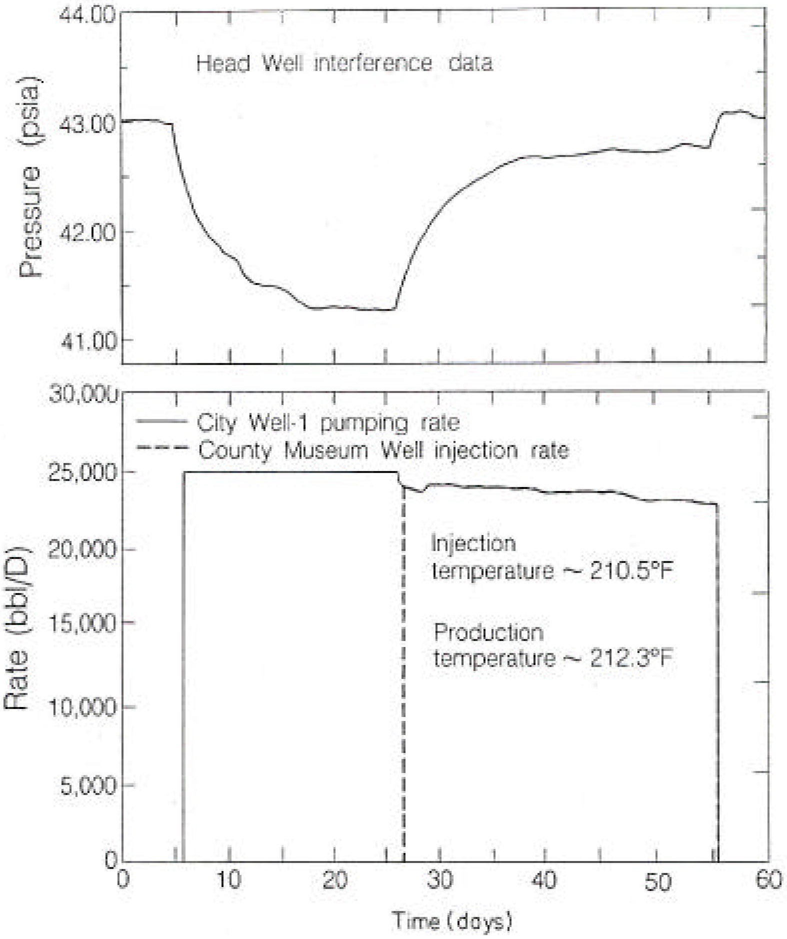


Figure 10. Head Well Interference Data and Pumping/Injection Record for Klamath Falls Aquifer Test.

Table 6. Summary of Test Description, Instrumentation and Analysis of the Klamath Falls Aquifer Test (Benson, 1986).

Well	Test Description			Instrumentation	Analysis	
Classification	Fluid Flow	ΔP (psi)	Distance to Prod./Inj. Wells(s) (ft)	(P) Pressure (T) Temperature (Q) Flowrate	T (md*ft/cp)*	S (ft/psi)**
CW-1 (Production)	720 gpm (7 weeks)		0/2,750	(Q) Doppler Flow Meter		
County Museum (Injection)	700 gpm (4 weeks)		2,750/0	(Q) Doppler Flow Meter		
Page (Observation)		0.8	2,200/850	(P)***	1.5×10^{6}	5.7×10^{-3}
Assembly (Observation)		1.5	1,285/3,460	(P)***	1.7×10^{6}	5.1×10^{-3}
Head (Observation)		1.7	1,050/2,100	(P)***	1.3×10^{6}	4.6×10^{-3}
Parks (Observation)		1.7	710/3,460	(P)***	1.7×10^{6}	n.a.
Carroll (Observation)		1.7	540/3,200	(P)***	1.4×10^{6}	2.3×10^{-3}
Rogers (Observation)		1.9	410/2,650	(P)***	1.4×10^{6}	n.a.
Steamer (Observation)		2.0	122/2,850	(P)***	1.3×10^{6}	3.2×10^{-3}
Spires & Mest (Observation)		2.5	2,100/750	(P)***	1.3×10^{6}	6.0×10^{-3}
Medo Bell (Observation)		2.5+	2,740/630	(P)***	1.1×10^{6}	1.0×10^{-3}

* Conversion from md.ft/cp to m^3/Pa.s = 3.05×10^{-13}

** Conversion from ft/psi to m/Pa = 4.42×10^{-6}

*** Paroscientific Digiquartz Transducer encapsulated in a downhole instrument package. Depth . 50 ft below the static water level.

8.2 Example 2 - Monitoring Injection of Geothermal Fluids at OIT.

The Oregon Institute of Technology (OIT) campus has used geothermal energy for heating since 1964, and cooling since 1980. Three hot water wells drilled during the original campus construction range in depth from 1,300 to 1,800 ft. These wells supply all the heating needs of the 11 building (675,000 ft^2) campus, Figure 11. The combined capacity of the geothermal well pumps is about 800 gpm of 192°F water.

Since its original construction, the OIT system has employed surface disposal. Geothermal waste water has historically been collected, either through storm drains or more recently via a dedicated collection system, and delivered to a drainage ditch on the west side of the campus. In 1985, a city ordinance was established that prohibits surface disposal of geothermal fluids by July of 1990. In 1987, OIT contracted the drilling of an injection well, which was completed to a depth of 1,650 ft.

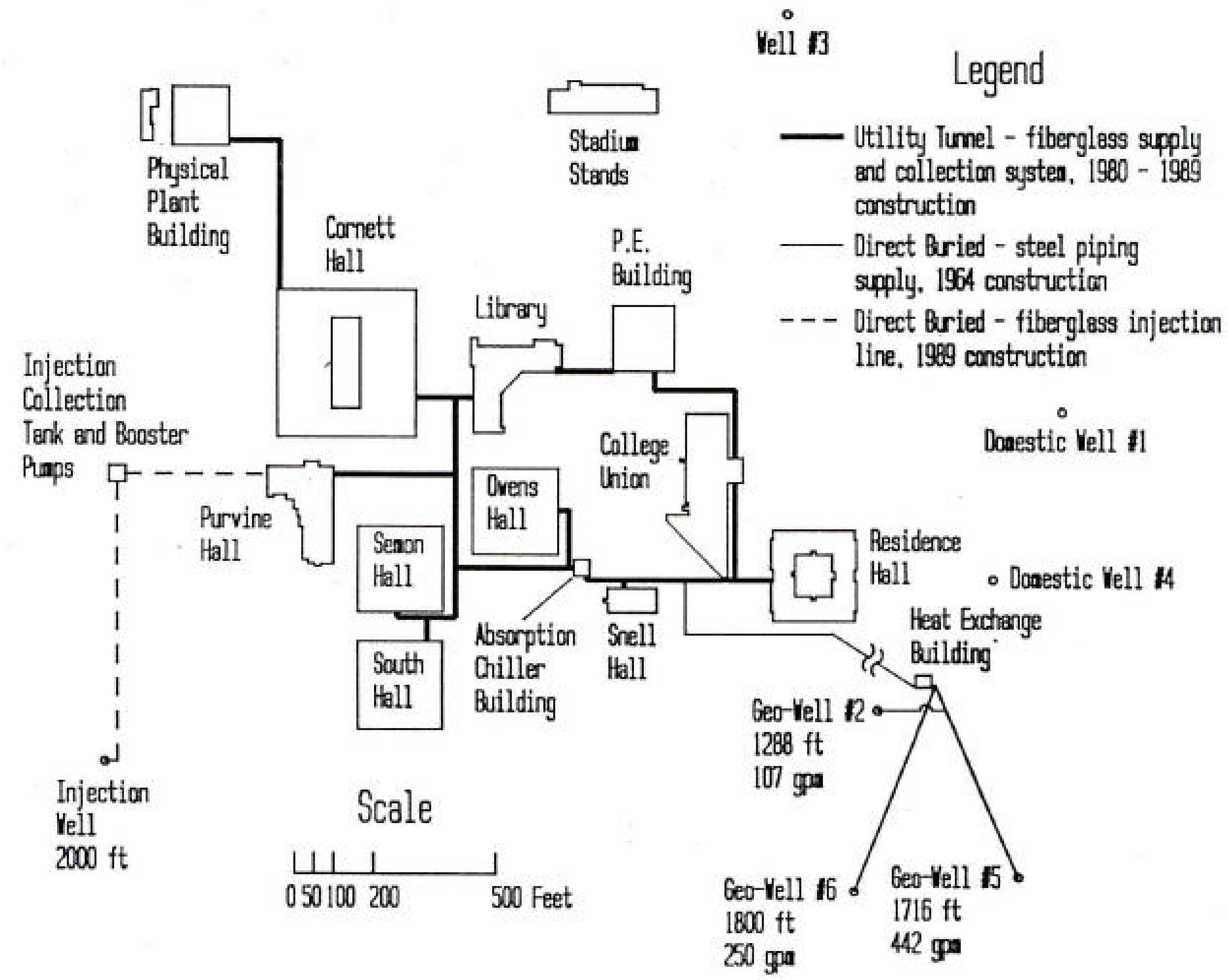
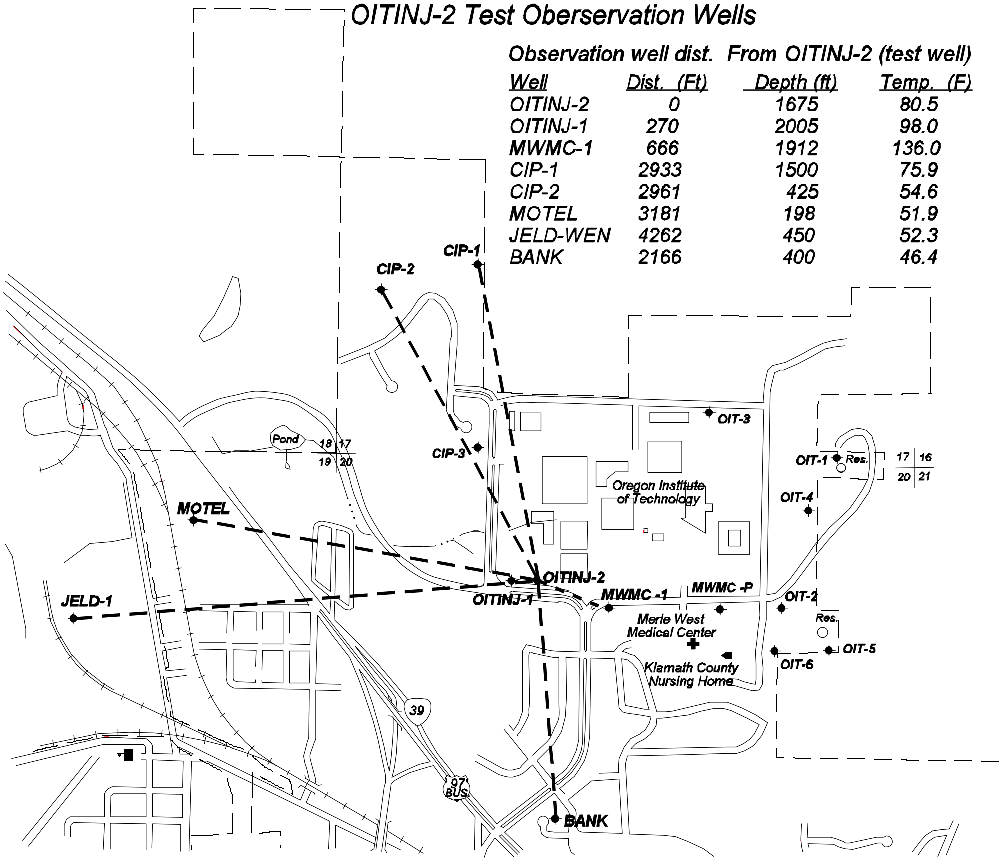


Figure 11. OIT Geothermal Distribution System.



Observation well dist. From OITINJ-2 (test well)

Well	Dist. (Ft)	Depth (ft)	Temp. (F)
OITINJ-2	0	1675	80.5
OITINJ-1	270	2005	98.0
MWMC-1	666	1912	136.0
CIP-1	2933	1500	75.9
CIP-2	2961	425	54.6
MOTEL	3181	198	51.9
JELD-WEN	4262	450	52.3
BANK	2166	400	46.4

Figure 12. Location of Observation Wells.

A monitoring grid of 6 observation wells were established to collect background and injection well test data, Figure 12. The data included interval measurements of reservoir water level (pressure), bottom hole temperature, barometric pressure and chemical constituents from pumped wells in the area. The purpose of the monitoring was:

1. To establish a comparison of reservoir equilibrium pressure before and after development of the injection well.

2. To determine potential interference and cooling on a production zone due to injection of geothermal fluid from the campus.

3. To determine potential environmental impact of injected fluid on a potable groundwater aquifer.

Shaft encoder water level instruments connected to data loggers were used to monitor 4 observation wells. Thermistor temperature probes were connected to the same data loggers and placed at the bottom of the well. Pressure transducers with data loggers were used to monitor two wells with submersible pumps (unused) installed.

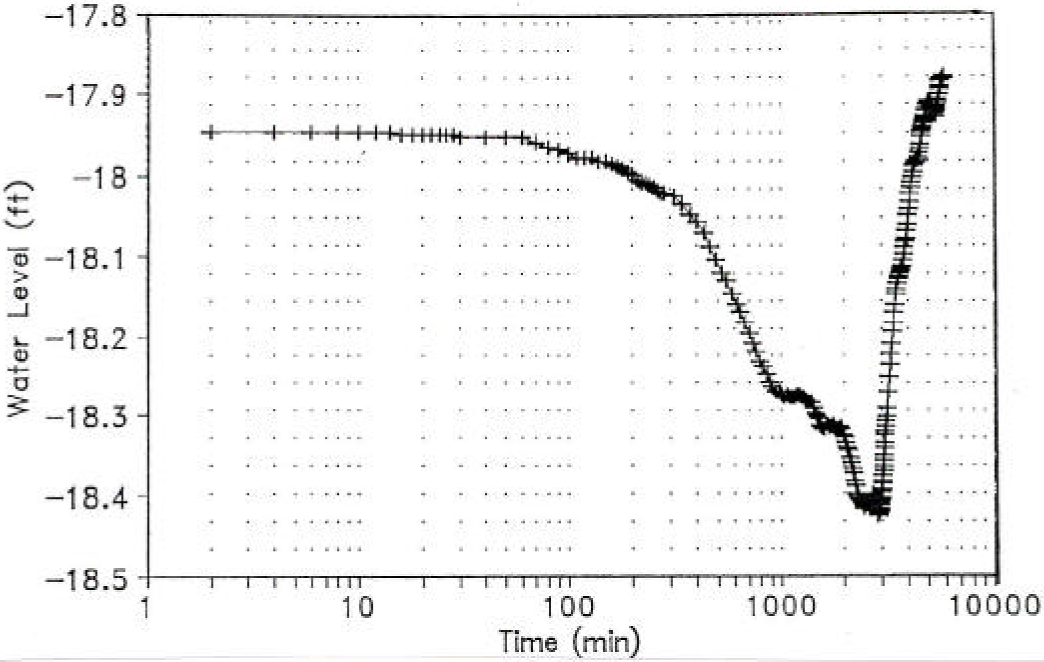


Figure 13. Hydrograph of Observation Well JELD-WEN for the OIT Injection Well Test Showing Drawdown and Recovery Data From 0900, 12/20 to 1030, 12/24/91.

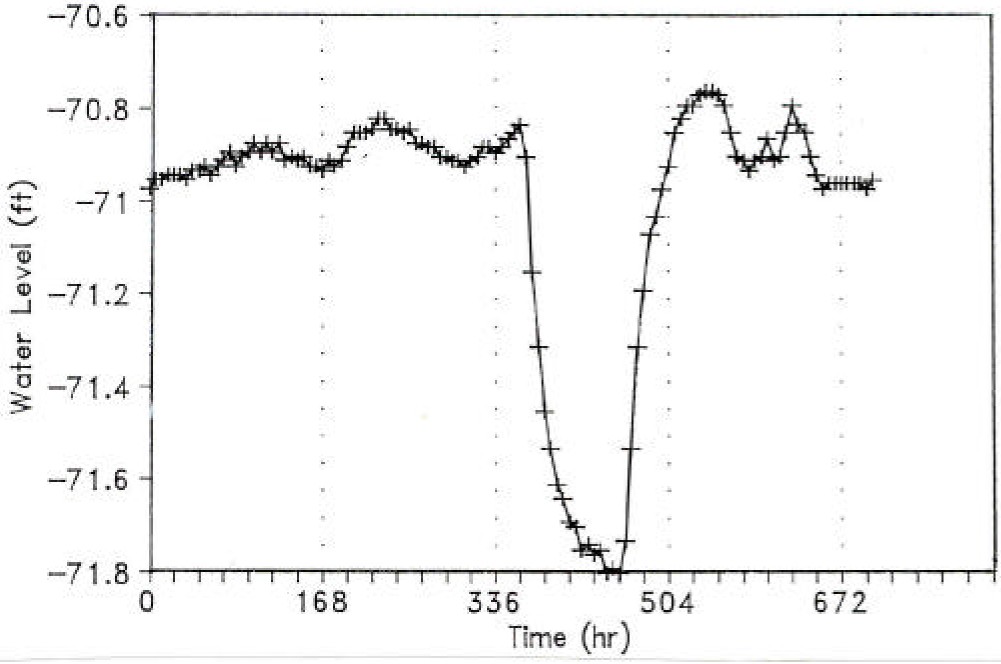


Figure 14. Hydrograph of Observation Well MOTEL for Long-Term Monitoring. Interference is due to pumping nearby second well. Data from 2/6 to 3/12/91.

Data loggers were programmed to record readings at 6-hour intervals for long-term monitoring. For well tests, the monitoring schedule in Section 4.0 was used. Data loggers were unloaded to a portable PC, which then can be used to plot graphs and perform hydrologic analysis.

To illustrate methods data can be displayed to enhance hydrologic interpretation of the results; examples of hydrographs, time series comparisons for chemical constituents and water-level contouring are given for the OIT observation wells. Table 7 shows a portion of a data run on the CIP-2 well and Figures 13 and 14 show hydrographs for well test and long-term monitoring. Figure 15 shows the effect of barometric pressure on water level. Note the inverse relationship between pressure and water level.

Table 7. Observation CIP-2 Data Printout.

Date	Time	Temp (°F)	Bar. Press. (in. Hg)	Water-Level (ft)	Time (hr)
02-06-91	12:00	54.7	26.01	212.64	0
02-06-91	18:00	54.7	25.91	212.62	6
02-07-91	00:00	54.7	26.04	212.63	12
02-07-91	06:00	54.7	26.08	212.62	18
02-07-91	12:00	54.7	26.05	212.62	24
02-07-91	18:00	54.7	25.90	212.62	30
02-08-91	00:00	54.7	26.02	212.62	36
02-08-91	06:00	54.7	26.04	212.60	42
02-08-91	12:00	54.7	26.02	212.60	48
02-08-91	18:00	54.7	25.59	212.59	54
*	*	*	*	*	*
*	*	*	*	*	*
*	*	*	*	*	*
03-07-91	18:00	54.7	25.89	212.53	702
03-08-91	00:00	54.7	26.03	212.51	708
03-08-91	06:00	54.7	26.09	212.50	714
03-08-91	12:00	54.7	25.95	212.49	720

A constant discharge well test was conducted from December 20 to 22, 1991 on OIT Injection Well No. 2. Five observation wells produced water level changes during the well test which were related to pumping OIT Injection Well No. 2 at a rate of 900 gpm. The aquifer parameters were computed by WEN, Inc. by matching to the Theis equation. Late-time data were given preference in the matches because of double porosity effects on the drawdown/time response and because the smaller the drawdown, the greater the potential for it to be in error. The values of transmissivity and storage coefficient estimated from the well test are listed in Table 8, in order of increasing distance from OIT Injection Well No. 2. The transmissivity does seem to increase towards the west (see Table 8 and Figure 12). The results of the constant discharge test show that the pressure effects of pumping extends at least half a mile north, east, and south. Consequently, because of the area of the aquifer involved, it should have little difficulty in transporting at least 1000 gpm of the fluid away from OIT Injection Well No. 2 (Nork, 1992).

Table 8. Summary of Well Test on OIT Injection Well No. 2

Well	Fluid Flow	Drawdown	Dist. to Prod./Inj. Wells (ft)	Instrumentation[a]	T (gpd/ft)	S
OIT Inj. #2 (Production)	900 gpm (3 days)	10.3	0	Q	0.77×10^5	--
MWMC Inj. #1		3.4	666	E	1.8×10^5	5.4×10^{-4}
Bank		0.95	2166	P	1.0×10^5	1.5×10^{-2}
CIP-2		0.39	2961	F	1.8×10^5	9.4×10^{-3}
Motel		1.49	3181	F	2.8×10^5	3.4×10^{-4}
Jeld-Wen		0.45	4262	F	6.5×10^5	1.1×10^{-3}

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a. P - Pressure Transducer   F - Float Water Level
E - Electric Probe Water Level   Q - Flowrate, Pipe Orifice

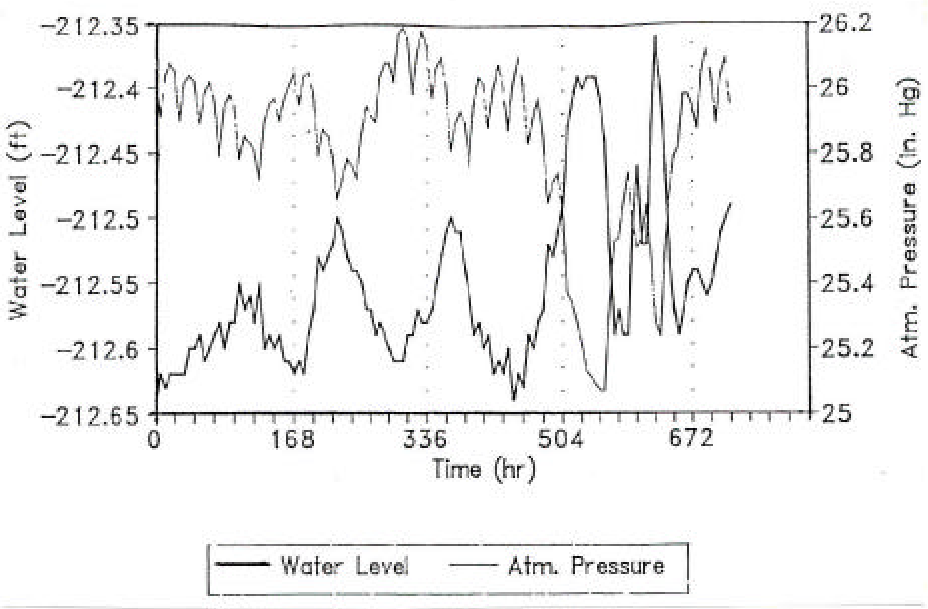

Figure 15. Barometric Pressure and Water-Level for CIP-2 Observation Well.

Fluid quality information was required by the Oregon Department of Environmental Quality (DEQ) concerning the geothermal production fluid, the geothermal injection fluid, and the groundwater in the receiving zone of the geothermal injection well. Table 9 shows the chemical analysis for 6 wells. Wells 3 through 6 were analyzed for major geothermal constituents to determine if there would be an intrusion of injected geo-fluids into the potable groundwater aquifer. These parameters are monitored on a quarterly basis for the first year of operation of the injection well.

Table 9. Chemical Analysis.

Well[a]	1	2	3	4	5	6
Temperature, °F	98	192	78	89	54	57
pH	6.90	8.45	7.65	7.50	6.60	7.15
Specific Conductance	340	993	270	320	190	230
Total Dissolved Solids	-	-	175	228	164	183
Total Coliform, MPN/100 ml	<2.2	<2.2				
Chloride, mg/L	41.0	46.4	3.0	7.8	7.8	5.2
Sulfate, mg/L	7.6	389	25.1	43.6	4.7	13.1
Sodium, mg/L	39.0	186	25.4	34.0	17.5	20.9
Silica, mg/L	38.9	85.2	29.5	30.4	53.1	48.8
Bicarbonate, mg/L	104	25.6				
Fluoride, mg/L	7.9	1.3				
Magnesium, ug/L	734	<50				
Potassium, mg/L	1.5	3.0				
Arsenic, ug/L	14	47				
Boron, ug/L	70	916				
Calcium, mg/L	30.5	22.7				
Iron, ug/L	454	<40				
Manganese, ug/L	212	1				

---

a. Wells: (1) OIT Injection Well, (2) OIT Geo-Well No.5,
(3) OIT Domestic Well No. 1, (4) Balme Heat Pump Well,
(5) Wocus Irrigation Well, and (6) Motel Domestic Well

Water quality at a single point can change with time. These changes can be illustrated by a series presentations that take changes in water quality with time into consideration. Figure 16 shows a comparison of four wells with time for total dissolved solids (TDS) and chloride (Cl).

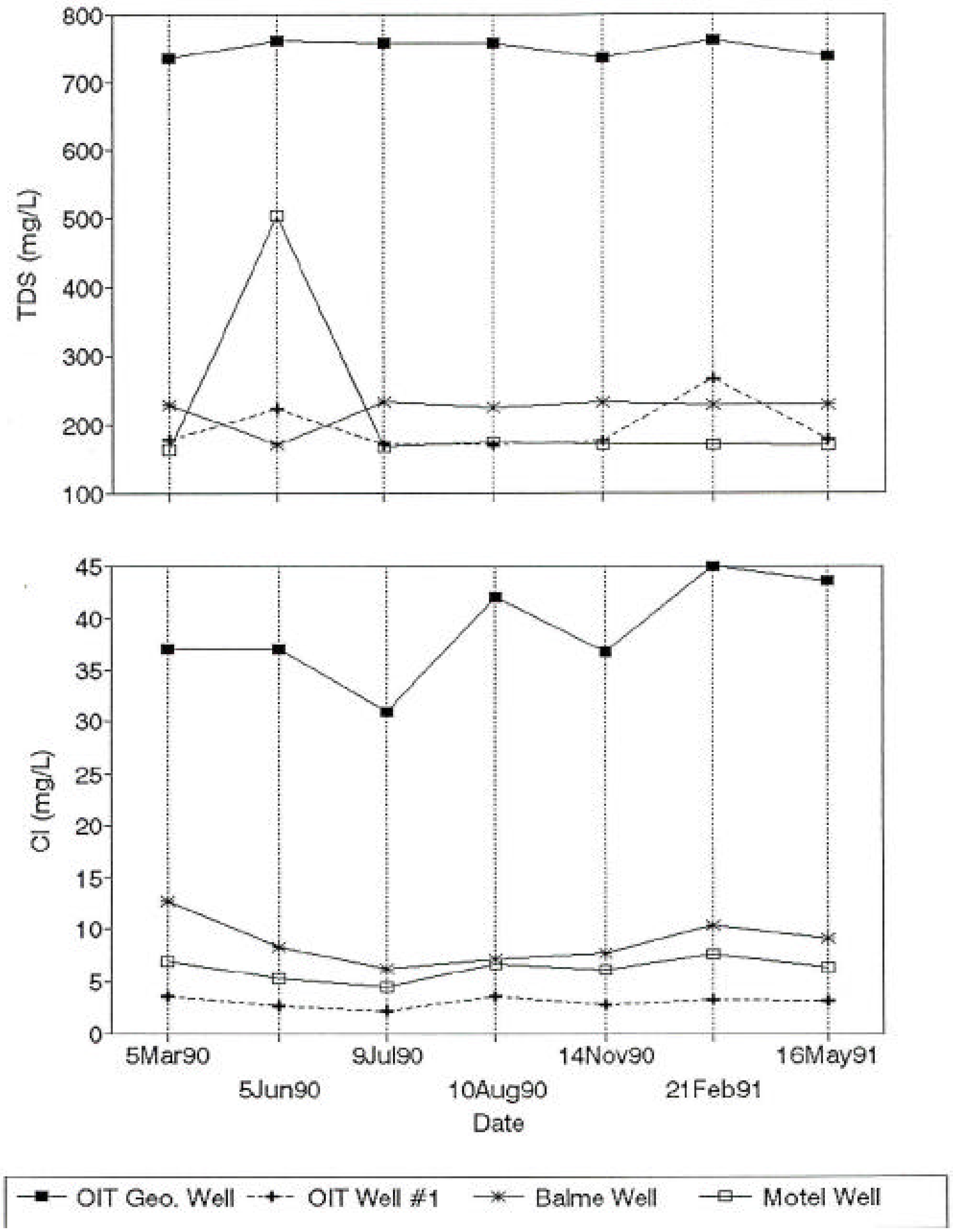

Figure 16. Time Comparison of Total Dissolved Solids (TDS) and Chloride (Cl) for Four Wells.

9. REGULATORY MANDATES ON GROUNDWATER MONITORING

The rules developed by the U.S. Environmental Protection Agency (EPA), administered EPA and federally approved state programs, pertaining to disposal of geothermal fluid include the Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA). The CWA applies to control of the pollution of surface water. The discharge regulations were established under the National Pollutant Discharge Elimination System (NPDES) and surface discharge of geothermal fluids requires an NPDES permit. While the CWA has provided mechanisms for the classification, monitoring, and cleanup of surface water, it has virtually no provisions for groundwater pollution control. Under the SDWA, groundwater sampling may be done for compliance with one of four programs: the Underground Injection Control (UIC) program, the Sole Source Aquifer program, the National Primary Drinking Water Regulations, and indirectly, the Wellhead Protection program.

Geothermal injection wells fall under the UIC program. UIC regulations are administered either by the USEPA or by federally approved state UIC programs. The UIC regulations define and establish five classes of injection wells (Kaufman, 1990).

1. Class I wells inject hazardous and non-hazardous waste and non-hazardous waste beneath the lowermost formation containing, within one-quarter mile of the wellbore and underground source of drinking water (USDW).

2. Class II wells are used in conjunction with oil and gas production, primarily to inject the salt water co-produced with crude oil and gas.

3. Class III wells are used in conjunction with solution mining of minerals.

4. Class IV wells inject hazardous radioactive wastes into or above a formation which is within one-quarter mile of an USDW (Class IV wells are banned nationally).

5. Class V wells include any wells that do not fall under classes I-IV and typically inject non-hazardous fluids into or above USDW.

If a well does not fit into one of the first four classes and meets the definition of an injection well, it is considered a Class V well. Class V wells are divided into two general types depending on construction. "Low-tech" wells: 1) have no casing designs or have simple casing designs and wellhead equipment and 2) inject into shallow formations by gravity flow or low volume pumps. In contrast, "high-tech" wells typically: 1) have multiple casing strings, 2) have sophisticated well equipment to control and measure pressure and volume of injected fluid, and 3) inject high volumes into deep formations.

Generally, Class V injection is into or above an underground source of drinking water (USDW). An USDW is defined as an aquifer or its portion which supplies any public water system or contains a sufficient quantity of groundwater to supply a public water system and currently supplies drinking water for human consumption and contains fewer than 10,000 mg/L total dissolved solids and is not an exempted aquifer (Kaufman, 1990).

There are 11 specific types of Class V wells, including geothermal injection wells, which are identified as electric power reinjection wells (5A5), direct heat reinjection wells (5A6) or heat pump/air conditioning return flow wells (5A7). Electric power and direct heat geothermal wells are classified as "high-tech" wells and heat pump wells as "low-tech."

Each state has specific requirements for data acquisition to monitor low-temperature geothermal development. Appendix C lists western state agencies with these responsibilities.

10. CONCLUSIONS

Acquisition of data to monitor water-level and geochemistry of aquifers for development of low-temperature geothermal resources is important from a resource management point of view as well as a requirement by many regulatory agencies.

Computer based data acquisition systems for well testing and long-term monitoring have advantages that could include:

1. Facilitating processing large volumes of data typically obtained during well tests and long-term monitoring;

2. Improving data quality by using a single-time reference for all measurements;

3. Enhancing data quality by allowing high-speed and high resolution water-level and pressure measurements;

4. Facilitating the display of data into hydrographs, water-level contours, etc., to reveal changes in groundwater flow regimes due to geothermal fluid production and injection, and

5. Facilitating the analysis of data for reservoir characteristics from well testing such as storativity, transmissivity, etc.

The injection of low-temperature geothermal effluents helps maintain aquifer pressure, prevents waste of water, and protects long-term resource values. However, state regulatory agencies may require a groundwater chemical constituents monitoring program with the objective to protect underground sources of drinking water.

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Appendix A

Orifice Tables

For measurement of water in gallons per minute through pipe orifices with free discharge. The following tables have been complied by the Engineering Department of Layne and Bowler, Inc., from original calibrations by Purdue University (U.S. Department of Interior, 1981).

Head in inches	3" Orifice		4" Orifice		5" Orifice		6" Orifice		7" Orifice	8" Orifice	9" Orifice	10" Orifice
	4 in. pipe	6 in. pipe	6 in. pipe	8 in. pipe	6 in. pipe	8 in. pipe	8 in. pipe	10 in. pipe	10 in. pipe	10 in. pipe	12 in. pipe	12 in. pipe
5.	100	76	145	140	280	220	380	320			825	1100
5.5	104	79	153	145	293	230	394	333			860	1150
6.	108	82	160	150	305	240	408	345			895	1200
6.5	111	86	167	155	316	250	421	358			930	1250
7.	115	88	172	160	328	260	433	370			965	1300
7.5	119	91	179	165	339	270	446	383			1000	1350
8.	122	94	185	170	350	280	458	395	600	935	1032	1400
8.5	125	96	190	175	361	289	471	408	617	963	1065	1440
9.	128	99	195	180	372	298	483	420	633	992	1093	1480
9.5	130	102	200	185	383	307	495	433	650	1016	1120	1520
10.	133	104	205	190	393	316	508	445	666	1040	1148	1560
10.5	137	107	210	195	402	324	521	458	682	1060	1172	1600
11.	140	109	215	200	412	330	533	470	698	1080	1200	1635
11.5	143	111	220	204	421	338	545	480	713	1100	1225	1670
12.	146	114	225	208	430	346	556	490	728	1120	1250	1705
12.5	149	116	230	212	439	354	567	500	743	1139	1277	1740
13.	151	118	234	216	448	362	578	510	757	1158	1303	1775
13.5	154	121	239	219	457	369	589	520	771	1176	1328	1810
14.	157	123	243	224	465	376	599	530	785	1194	1352	1845
14.5	159	126	247	227	473	383	609	540	799	1212	1376	1875
15.	162	128	250	231	480	390	618	550	812	1230	1400	1905
15.5	164	130	254	234	488	396	627	559	825	1248	1421	1940
16.	167	132	257	238	495	402	636	568	838	1266	1441	1970
16.5	170	134	261	241	503	408	645	577	851	1284	1460	2000
17.	172	136	264	245	510	414	654	586	863	1302	1480	2030
17.5	175	138	268	249	517	420	663	595	875	1319	1500	2060
18.	178	140	271	252	524	426	672	604	887	1336	1520	2089
18.5	180	142	275	256	530	432	681	612	899	1353	1540	2118
19.	183	144	278	259	536	438	690	620	910	1370	1560	2146
19.5	185	146	282	263	542	444	699	628	922	1387	1580	2175
20.	187	148	285	266	548	449	708	636	933	1404	1600	2204
20.5	190	150	289	270	554	455	717	643	945	1421	1620	2232

Head in inches	3" Orifice		4" Orifice		5" Orifice		6" Orifice		7" Orifice	8" Orifice	9" Orifice	10" Orifice
	4 in. pipe	6 in. pipe	6 in. pipe	8 in. pipe	6 in. pipe	8 in. pipe	8 in. pipe	10 in. pipe	10 in. pipe	10 in. pipe	12 in. pipe	12 in. pipe
21.	192	152	292	273	560	460	726	650	956	1438	1640	2260
21.5	195	154	295	275	566	465	735	657	968	1455	1659	2288
22.	197	156	299	279	572	470	744	664	979	1471	1677	2316
22.5	199	158	302	282	578	475	752	671	990	1486	1695	2343
23.	201	160	305	285	584	479	760	678	1001	1500	1714	2360
23.5	203	162	307	288	590	484	768	685	1012	1515	1732	2382
24.	205	164	310	291	596	488	776	692	1022	1529	1750	2409
24.5	207	165	314	294	602	492	784	699	1033	1543	1767	2435
25.	210	167	317	297	608	496	791	706	1043	1557	1783	2461
25.5	212	169	320	300	614	500	798	713	1059	1571	1799	2487
26.	214	171	323	303	620	504	805	720	1065	1585	1815	2513
26.5	216	173	326	305	626	508	812	727	1074	1599	1830	2539
27.	219	174	329	308	632	512	818	734	1084	1613	1845	2565
27.5	221	176	332	311	638	516	825	741	1094	1627	1860	2590
28.	222	177	335	314	644	520	831	747	1104	1641	1875	2610
28.5	224	179	337	317	650	524	838	754	1114	1655	1890	2630
29.	226	180	340	320	656	528	844	760	1124	1669	1905	2650
29.5	228	182	343	323	662	532	851	767	1134	1683	1920	2670
30.	230	183	346	325	668	536	857	773	1143	1697	1935	2690
30.5	232	185	348	328	674	540	863	780	1153	1711	1950	2713
31.	235	186	351	330	680	544	869	786	1162	1725	1965	2736
31.5	236	188	354	333	686	548	876	793	1172	1739	1980	2759
32.	239	189	357	335	692	552	882	799	1181	1753	2005	2782
32.5	240	191	360	338	697	556	889	806	1191	1767	2020	2805
33.	242	192	363	340	703	560	895	812	1200	1791	2040	2828
33.5	244	194	366	342	709	564	901	818	1209	1795	2050	2850
34.	246	195	369	345	715	568	907	824	1218	1809	2060	2873
34.5	248	196	372	347	720	572	913	830	1227	1823	2075	2896
35.	250	197	375	349	726	576	919	836	1235	1837	2090	2919
35.5	252	198	377	351	732	580	925	842	1243	1851	2100	2964
36.	254	200	380	354	737	584	931	847	1251	1865	2112	2964
36.5	256	291	383	356	743	588	937	852	1259	1879	2124	2980
37.	257	293	385	358	748	592	943	857	1266	1893	2136	3002
37.5	259	204	388	360	754	596	949	863	1274		2148	3024
38.	260	205	390	363	759	600	955	867	1281		2160	3046
38.5	262	206	393	365	767	604	961	872	1289		2173	3068
39.	263	208	396	367	770	608	967	877	1295		2185	3088
39.5	265	209	398	369	776	612	974	882	1304		2197	3110
40.	266	210	401	371	781	616	979	887	1311		2210	3130
40.5	267	211	403	373	786	620	985	891	1319		2225	3146

Head in inches	3" Orifice		4" Orifice		5" Orifice		6" Orifice		7" Orifice	8" Orifice	9" Orifice	10" Orifice
	4 in. pipe	6 in. pipe	6 in. pipe	8 in. pipe	6 in. pipe	8 in. pipe	8 in. pipe	10 in. pipe	10 in. pipe	10 in. pipe	12 in. pipe	12 in. pipe
41.	269	212	406	375	790	624	990	896	1326		2233	3160
41.5	271	213	408	378	795	628	996	901	1334		2245	3179
42.	272	214	411	380	800	631	1001	906	1341		2257	3199
42.5	274	216	413	382	805	635	1007	910	1349		2273	3219
43.	275	217	415	384	810	638	1012	915	1356		2285	3230
43.5	277	218	481	386	815	642	1018	920	1364		2297	3250
44.	278	219	420	388	820	645	1023	925	1371		2309	3263
44.5	280	220	422	390	824	649	1029	929	1379		2326	3280
45.	281	222	425	392	828	652	1034	934	1387		2338	3298
45.5	283	223	427	394	832	656	1040	939	1394		2350	3316
46.	284	224	429	396	837	659	1045	944	1401		2363	3334
46.5	285	225	432	399	842	663	1051	948	1409		2375	3351
47.	287	227	434	401	847	666	1056	953	1416		2387	3368
47.5	289	228	437	403	851	669	1062	958	1424		2399	3389
48.	290	229	440	405	855	672	1067	963	1431		2411	3405
48.5	292	230	442	407	859	676	1073	967	1439		2423	3426
49.	293	231	444	409	863	679	1078	972	1446		2434	3443
49.5	294	232	446	411	868	683	1084	977	1454		2444	3460
50.	296	234	448	413	872	686	1089	982	1461		2454	3477
50.5	298	235	450	415	876	690	1095	986	1469		2464	3494
51.	300	236	435	417	880	693	1100	991	1476		2474	3511
51.5	301	237	455	419	884	697	1105	996	1484		2486	3527
52.	302	238	457	421	888	700	1110	1000	1491		2498	3544
52.5	303	239	459	423	892	704	1115	1005	1499		2510	3560
53.	304	240	461	425	896	707	1120	1009	1506		2522	3575
53.5	305	241	463	427	900	711	1125	1014	1513		2534	3591
54.	307	243	465	429	904	714	1130	1018	1520		2545	3602
54.5	309	244	467	431	908	718	1135	1023	1527		2555	3618
55.	310	246	469	433	912	721	1140	1027	1534		2565	3634
55.5	311	247	471	435	915	725	1145	1032	1541		2575	3650
56.	313	248	472	437	919	727	1150	1036	1548		2586	3667
56.5	314	249	474	439	923	730	1155	1040	1554		2597	3684
57.	315	250	476	441	927	733	1160	1044	1560		2608	3702
57.5	316	251	478	443	930	736	1165	1046	1567		2619	3719
58.	317	252	480	445	934	739	1170	1052	1574		2630	3736
58.5	319	253	432	447	938	742	1175	1056	1580		2641	3752
59.	320	254	485	449	942	745	1180	1060	1586		2653	3768
59.5	321	256	487	451	945	748	1185	1064	1592		2665	3784
60.	323	257	489	453	948	751	1190	1068	1598		2676	3800
60.5	324	258	491	455	951	754	1195	1072				

Head in inches	3" Orifice		4" Orifice		5" Orifice		6" Orifice		7" Orifice	8" Orifice	9" Orifice	10" Orifice
	4 in. pipe	6 in. pipe	6 in. pipe	8 in. pipe	6 in. pipe	8 in. pipe	8 in. pipe	10 in. pipe	10 in. pipe	10 in. pipe	12 in. pipe	12 in. pipe
61.	325	259	492	457	955	757	1200	1076				
61.5	326	261	494	459	958	760	1205	1080				
62.	328	262	496	461	961	763	1209	1084				
62.5	329	263	498	463	964	766	1214	1088				
63.	330	264	500	465	968	769	1218	1092				
63.5	331	265	502	467	971	772	1223	1096				
64.	333	266	504	469	974	775	1227	1099				
64.5	334	267	507	471	977	778	1232	1103				
65.	335	268	509	472	981	781	1236	1106				
65.5	336	269	511	474	984	784	1241	1110				
66.	338	271	513	475	988	787	1245	1113				
66.5	339	272	515	477	991	790	1250	1117				
67.	340	273	517	479	995	793	1254	1120				
67.5	341	274	518	481	998	796	1259	1124				
68.	343	275	520	483	1002	799	1263	1127				
68.5	344	276	521	485	1005	802	1268	1131				
69.	346	277	523	487	1009	805	1272	1134				
69.5	347	278	524	489	1012	808	1276	1137				
70.	349	280	525	491	1016	811	1280	1140				

Appendix B

Partial List of Suppliers of Complete Groundwater Monitoring Systems

In-Situ Inc.
210 South Third Street
P.O. Box I
Laramie, WY 82070
(307) 742-8213

Leupold & Stevens, Inc.
P.O. Box 688
Beaverton, OR 97075-0688
(503) 646-9171

Terra Systems Incorporated
22118 20th Avenue SE, Suite G142
Bothell, WA 98021
(206) 488-0400

Unidata
Lake Oswego Business Park
17408 S.W. Boones Ferry Road
Lake Oswego, OR 97035
(503) 697-3570

Appendix C

Agencies Responsible for Groundwater Regulations

Alaska: Division of Land & Water Management
South Central Area
P.O. Box 107005
Anchorage, AK 99518

Arizona: Department of Water Resources
99 E. Virginia
Phoenix, AZ 85004

California: Division of Oil & Gas
1416 9th Street, Room 1310
Sacramento, CA 95814

Colorado: Department of Natural Resources
Division of Water Resources
818 Centennial Building
1313 Sherman Street
Denver, CO 80203

Hawaii: Department of Land & Natural Resources
P.O. Box 373
Honolulu, HI 96809

Idaho: Idaho Department of Water Resources
Statehouse
Boise, ID 83720

Montana: Department of Natural Resources & Conservation
Water Resource Division
Cogswell Building - 32 S. Ewing
Capital Station
Helena, MT 59620

Nevada: Department of Conservation and Natural Resources
Division of Environmental Protection
201 S. Falls Street
Carson City, NV 89710

New Mexico:
Office of the State Engineer
Batoan Memorial Building, Suite 101
Santa Fe, NM 87503

North Dakota:
Industrial Commission
Office of State Geologist
University Station
Grand Forks, ND 58202-8156

South Dakota:
Department of Water & Natural Resources
Division of Water Rights and/or Division
of Environmental Quality
523 E. Capital Avenue
Pierre, SD 57501

Oregon:
Department of Water Resources
3850 Portland Road NE
Salem, OR 97310

Department of Environmental Quality
811 S.W. 6th Street
Portland, OR 97204

Texas:
Texas Water Commission
Steven Austin Building
1700 N. Congress
Austin, TX 78711

Utah:
Utah Division of Water Rights
1636 W. North Temple
Salt Lake City, UT 84116

Washington:
Department of Natural Resources
Department of Ecology
Rowe Six, Building 1
Olympia, WA 98504

Wyoming:
State Engineer's Office
4th Floor West
Herschler Building
Cheyenne, WY 82002

Appendix D

Geothermal Fluid Sampling Data Sheet

Date: ____/____/____ Location: ______________________________

Person(s) Sampling: ______________________________

Geothermal Flow: Sample Point: ______________________________

Access (Probe or ?): ______________ Well or Process: ______________

Temp: _______ (F or C), Pressure _______ (psi), Flow Rate: _______ ( ), Air Temp ______

Start Time: ______________

Sample Temp.: _________; pH______ at ______ (Temp) at _______ (Time)

Conductivity: _____________ at ________ (Temp) at ______ (Time)

Raw-unfiltered (R), Unacidified (U) Samples

	ID Code	Sample Temp	Time	Comments
RU				

Gas Analysis by Field Test Kit

	ID Code	Sample Temp	Time	Comments
O_2				
H_2S				

Filtered (F) Samples, Some Acidified (A)

	ID Code	Sample Temp	Time	Comments
FA				
FU				
SiO_2				
FAH_g				
CO_2				

Filter: Time Off ___________________. Total Volume Through ______________

Sample: Conductivity _____________ at ____________(Temp) at ______(Time)

Shut Down: Pressure _______ (psi), Temp ______(C or F), Flow Rate _______

Time Completed: _________________ Recorded by: ______________________________

Remarks/Other Measurements: