

SECTION 1

Investigation and Evaluation of Surface and Subsurface Drainage

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Groundwater Instrumentation for Mining Projects

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Groundwater measurements enter into many phases of the mining industry. Recently, Westbay Instruments has developed new equipment for groundwater monitoring and sampling. This paper presents a brief summary of some of these developments, particularly as they affect the quality of technical data collected and the cost and scheduling of groundwater instrumentation programs.

TYPES OF GROUNDWATER MEASUREMENTS

There are only a few types of groundwater measurements that are commonly required in mining operations. These are the elevation of the groundwater table, water pressure and water quality. Some groundwater parameters are derived from these measurements, particularly permeability and related aquifer characteristics. The collection of groundwater data sounds as though it should be a rather straightforward procedure. One would expect that the best quality and the most cost effective methods would now be well established. However, recent developments promise significant improvements in the quality and cost of groundwater measurements.

The groundwater table should be quite simple to determine. Yet in practice it can be difficult to establish the groundwater table even if it remains stationary with time.

Many devices are available to measure groundwater pressures (1, 2, 3, 4). Groundwater pressures need to be recorded at several locations in order to establish the three-dimensional character of the groundwater flow system. However, in practice, it can be difficult to install and verify the readings from just one water pressure recording device (5). It is even more difficult as more measurement devices are installed in a single hole.

The determination of the permeability of soil and rock to groundwater is relatively straightforward in theory. It can be found by pumping from wells and making time-drawdown measurements in surrounding observation holes (6, 7, 8) or by making slug or response tests in the observation wells themselves (9, 10, 11). The test results permit permeability and other aquifer characteristics to be calculated. These calculated values can be quite dependent upon the duration of the tests, and the number and the quality of the observation points.

Obtaining samples from drill holes for water quality determinations would appear to be quite simple. It is not. Water sampling requires careful attention to drilling procedures, the removal of drilling induced waters prior to sampling, the isolation or sealing of the casing between sampling points, and the use of pressurized containers to maintain the sample in its natural state. When any of these procedures are omitted or unduly relaxed, the sampling results are suspect.

There is an increasing need for multiple purpose groundwater instruments that can be used to measure water levels and water pressures and also allow good quality water samples to be obtained. Adjacent to mining operations there can be a need to measure deformation as well as water pressure distribution in the same drill hole. There are also economic and technical reasons for high-density, multiple purpose instruments to be placed in a single drill hole.

DIFFERENT ROLES FOR GROUNDWATER INSTRUMENTATION IN MINING

The many different roles of groundwater measurements in the mineral industry have not always been fully recognized. Groundwater instrumentation can enter into mineral exploration, mine design, environmental impact assessment, mine production, in-situ and waste dump leaching, and tailings monitoring.

Mineral Exploration

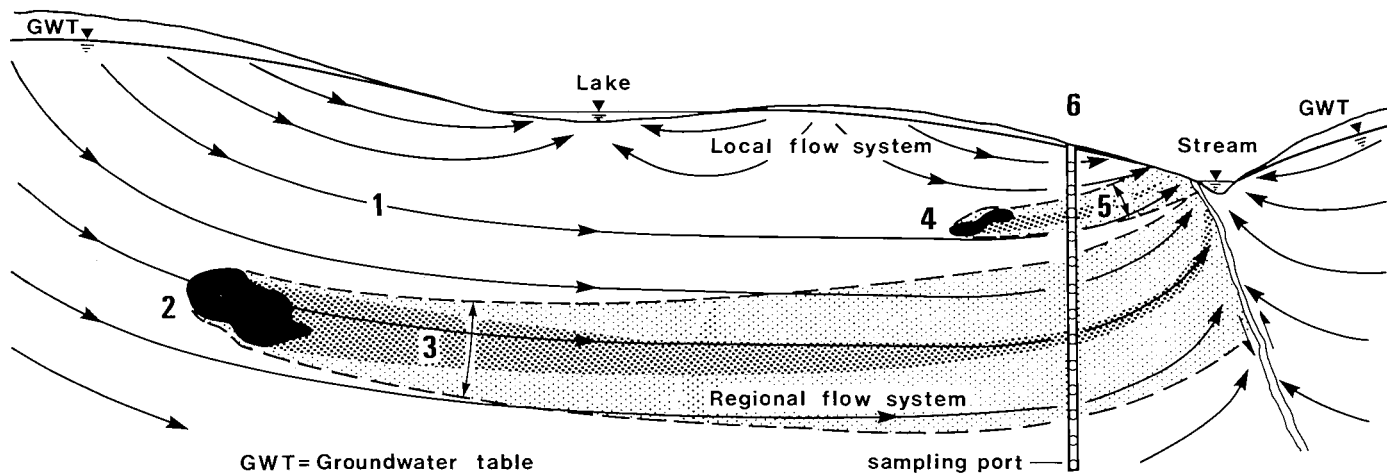
Groundwater geochemistry when combined with a knowledge of hydrogeologic flow systems holds promise of being a powerful tool for mineral exploration. The requirements are only that: 1) an orebody has a perceptible effect on the surrounding groundwater, 2) a representative sample of the groundwater can be taken, and 3) a chemical analysis of the water sample can detect the trace of the orebody. Trace elements can be measured to parts per million and parts per billion making it possible to recognize minor anomalies caused by flow past orebodies. As groundwater flows through the rocks in a region, a large volume of the surrounding bedrock will be sampled. By intercepting the groundwater and carefully analyzing it for its dissolved and gaseous constituents, anomalies can be recognized. With hydrogeochemical sampling of drill holes, an anomaly can be tested so as to determine a vector pointing to its source. Herein lies the greatest potential power in the use of groundwater measurements as an exploration tool.

The possible effect on an orebody by a typical groundwater flow system is illustrated in Figure 1.

To determine this numerous pressure measurement points and sampling points must be placed in small-diameter drill holes. It is important that the measuring or sampling points be properly sealed from each other and that the sampling areas be decontaminated (of the fluids introduced by drilling) prior to sampling.

Mine Design and Environmental Assessment

For the design phase of the mine development, basic data on the properties of the materials and fluids present must be gathered and their probable impact on the mining operation



LEGEND

- 1 Groundwater flow lines showing flow paths penetrating and "sampling" the entire region (flow is driven by differences in fluid potential).
- 2 Location of hypothetical source of anomaly (orebody).
- 3 Zone of groundwater affected by orebody (2).
- 4 Location of another hypothetical orebody.
- 5 Zone of groundwater affected by orebody (4).
- 6 Exploratory drill hole with sampling and pressure measuring ports.

Figure 1. Groundwater measurements in mineral exploration.

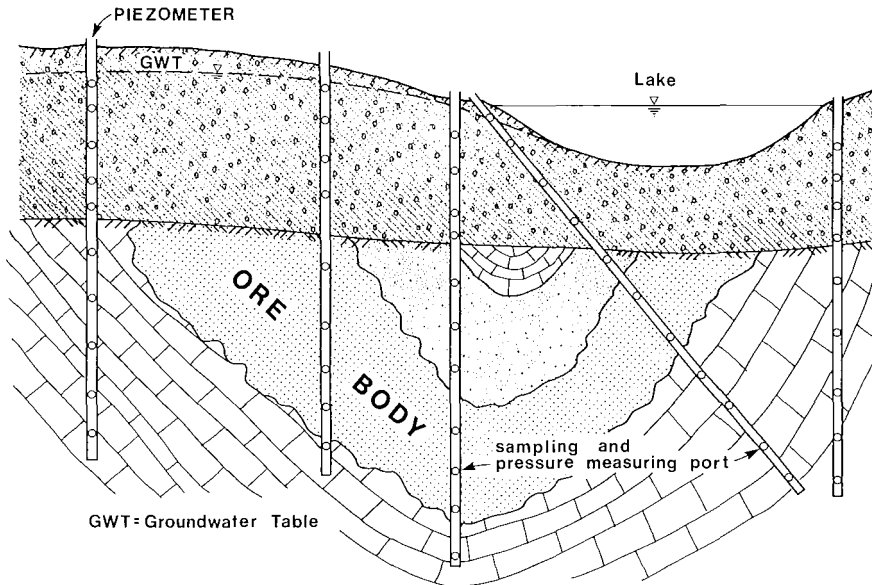
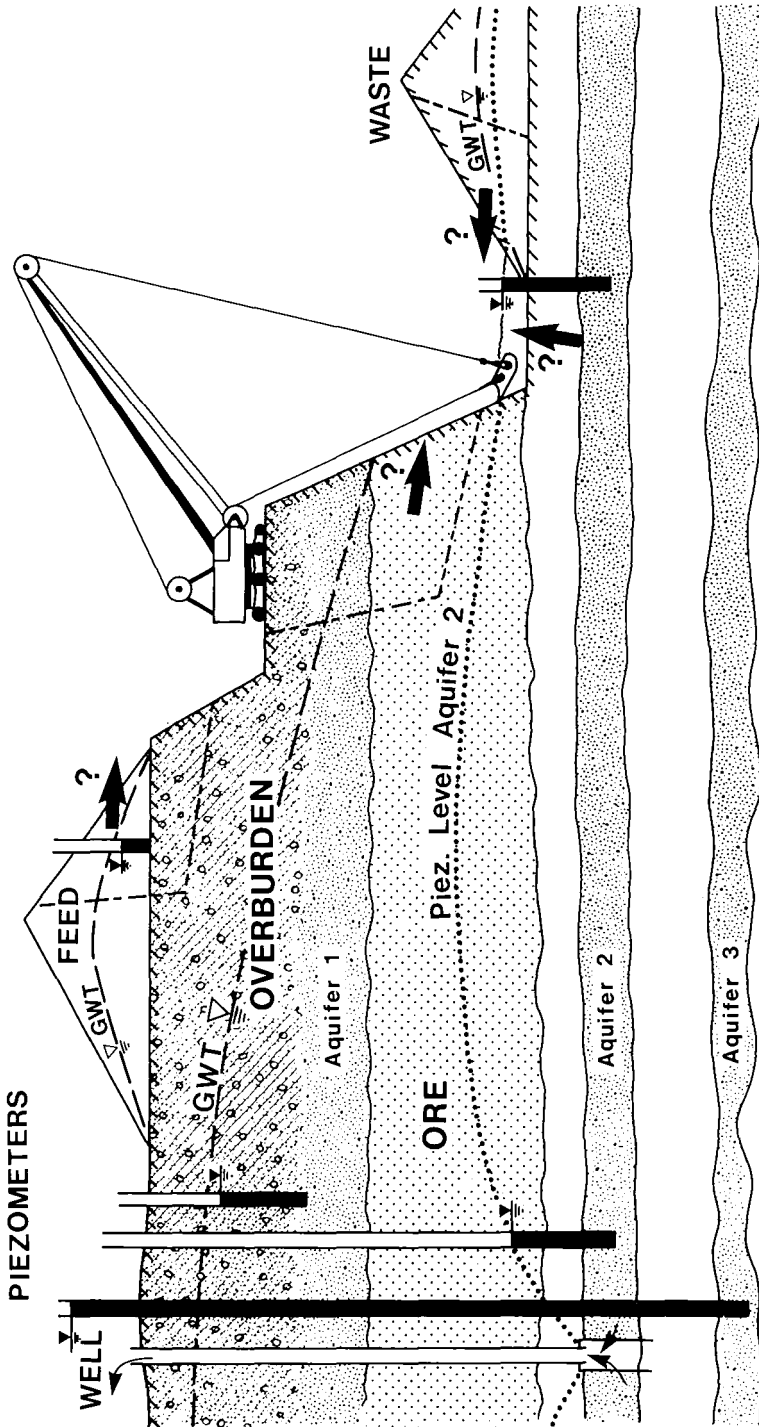


Figure 2. Groundwater measurements in mine design and environmental assessment.

and the local and regional environment assessed. Water levels, water pressures, permeabilities and water quality must be determined. In some cases the dewatering problems can be the most significant aspect of the mine design since dewatering costs can affect economic feasibility.

For an environmental assessment, water quality sampling and pressure measurements are required to estimate local and regional groundwater flow systems and the character of the waters that they contain. In some mineralized areas the mineral content of the natural groundwater discharges is greatly in excess of that permitted by environmental authorities. It is important to establish such natural conditions in advance of mining.

Figure 2 illustrates one situation that could face a mine designer. In this case saturated and highly permeable sediments overlie the potential mine. Small differences in the permeability which can lead to large differences in the water pressure distribution can become apparent when the groundwater system is stressed such as during dewatering. It is therefore important to place an adequate number of pressure measuring points, often more than might be thought necessary, so that the effects of dewatering can be observed.



GWT=Groundwater Table

Figure 3. Groundwater measurements in mine production.

Mine Production, Tailings and Waste Dump Monitoring

In some mines groundwater monitoring is required only as a precautionary measure. However, in other cases dewatering and depressurization are required for the safe and economic operation of the mine. Two mines in the latter category are the Lee Creek Phosphate Mine of Texasgulf Inc. in North Carolina and the Syncrude Oil Sand Mine in northern Alberta.

Figure 3 illustrates the variety of problems that can occur in production when two or three aquifers are present. In such cases groundwater conditions can have a controlling effect on production. Allowance must be made for their control and measurement prior to production and their monitoring during production. It may be necessary to take measurements near the actual production area. In order not to interfere with production, it becomes important to place as many monitoring points as possible in a single drill hole and combine monitoring operations that currently require separate drill holes. For example, if both deformation and pressure measurements can be made in the same drill hole, there can be appreciable savings in time and money.

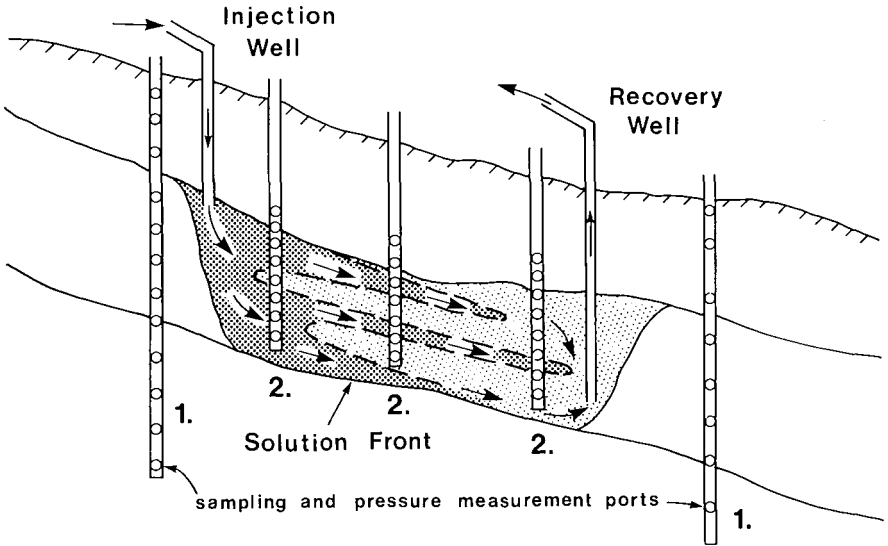
In-Situ and Waste Dump Leaching

Where mineral production is obtained from subsurface or surface leaching operations it is important to be able to monitor and thereby follow the production process within the leaching area.

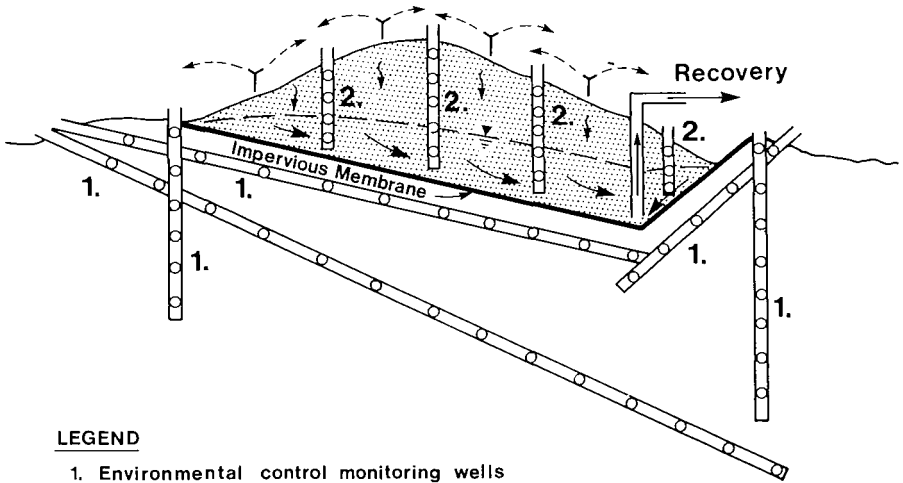
Most leaching operations involve fluids that are undesirable in the natural environment, and close control of the region surrounding the production area is likely to be a requirement. This environmental monitoring also can be helpful in recognizing and thereby limiting undue losses of the valuable leachate.

Figure 4 illustrates two types of leaching operations where detailed groundwater monitoring of the surrounding groundwater environment can be undertaken. In certain situations it may also be useful to monitor the leaching operation. The sampling aspect of groundwater monitoring is particularly important. Detailed water pressure measurements may also be necessary to understand and predict the flow directions in the saturated zones in the production area and in the groundwater in the surrounding rock.

a) Underground Leaching and Solution Mining



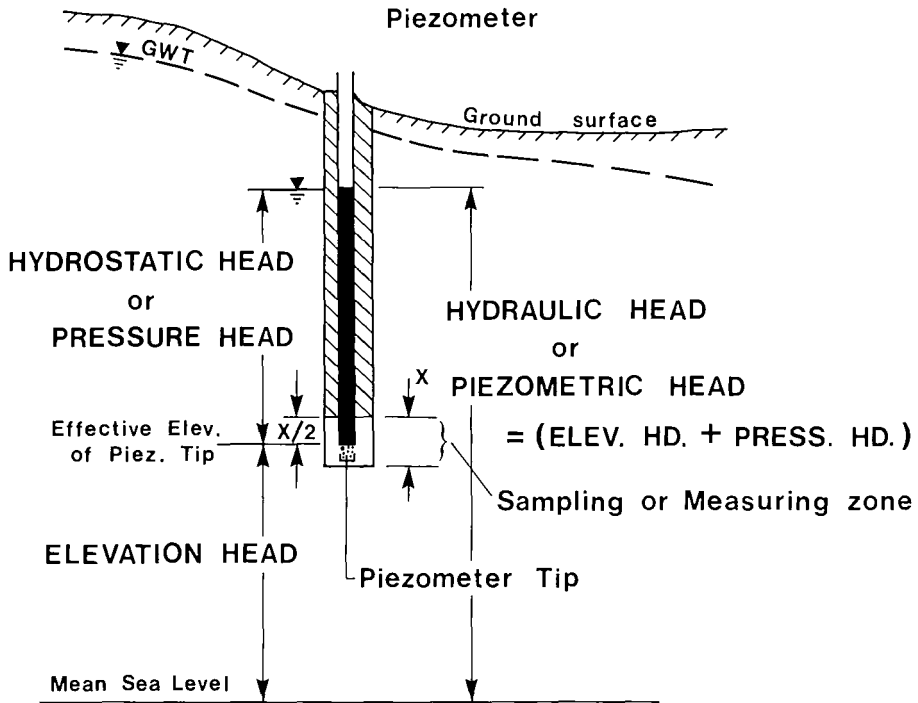
b) Surface Leaching



LEGEND

- 1. Environmental control monitoring wells
- 2. Process control monitoring wells

Figure 4. Groundwater measurements in leaching operations.



GWT = Groundwater Table

Figure 5. Definition of terms.

DEFINITION OF TERMS

Figure 5 provides a graphic illustration of a number of the terms used in this paper. Piezometers are water pressure measuring devices which are commonly placed in drill holes. True piezometers are sealed along their length except for an open section at their tip in a measurement or sampling zone. The effective elevation of the piezometer is the center of the open sampling or measurement zone. In soils and fine-grained friable rocks, the tips commonly consist of a filter and the space surrounding the tip and the walls of the drill hole is filled with a selected graded sand. In stable rocks the filters and sand are unlikely to be needed.

Piezometers placed in drill holes are commonly constructed with impervious casing or tubing so that the water cannot flow into or be influenced by water in another zone encountered in a different portion of the same drill hole. Water

pressure measurements made in open, unlined and unsealed drill holes should be designated as "open hole" measurements. Such drill holes usually provide unsatisfactory pressure measurements and water quality samples.

Figure 5 shows that the piezometer records the mean hydrostatic pressure or pressure head that is present at the tip or sampling zone of the piezometer. The total hydraulic head or piezometric head is calculated from the recorded pressure head and a knowledge of the effective elevation of the piezometer tip. When referring to an individual piezometer it is usually convenient to work with pressure heads. However, in comparing the measurements from different piezometers it is usually necessary to work with piezometric heads related to a common reference plane (sea level) to determine flow directions and related factors.

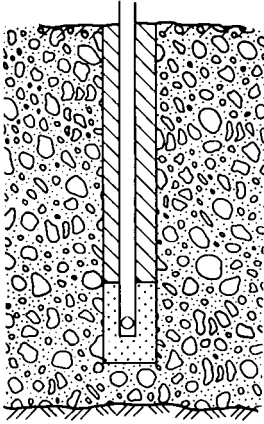
On Figure 5 the elevation of the piezometric head measured in the piezometer is not equal to the elevation of the surrounding groundwater table (GWT). In nature they are equal only when there is no flow (a hydrostatic condition) or when the flow is entirely horizontal. Because hydrostatic conditions are seldom achieved in nature and because the flow usually has a small vertical component, the level to which water will rise in a well constructed piezometer will seldom be equal to the level of the groundwater table. For this reason a reading from a single piezometer is seldom sufficient to define the distribution of water pressures in an aquifer.

In this paper the term "port" is used to describe a point in a piezometer where a groundwater sample may be taken and where groundwater pressures may be measured.

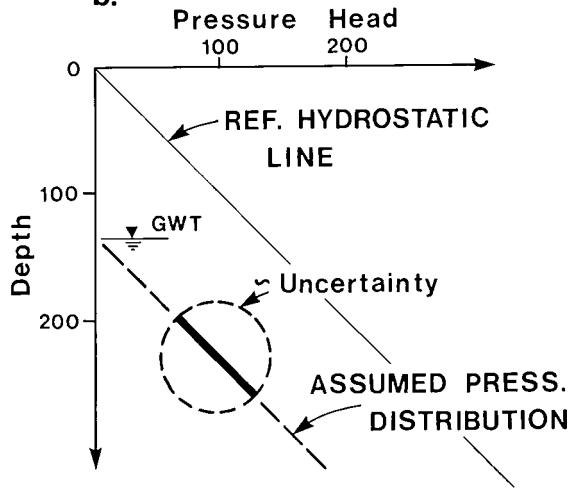
ESTIMATION OF PIEZOMETER REQUIREMENTS

Figures 6 and 7 show how diagrams of depth versus pressure head can be used to estimate the number of piezometer ports required to establish the pressure distribution and flow conditions in two different situations: a single aquifer (shown in Figure 6) and two aquifers (shown in Figure 7). The single aquifer in Figure 6 is shown underlain by a single aquitard--a unit that restricts the flow of water, whereas the two aquifers in Figure 7 are shown sandwiched between three aquitards. These situations are relatively common in mining operations and it is not unusual to encounter three or more aquifers in a single mine.

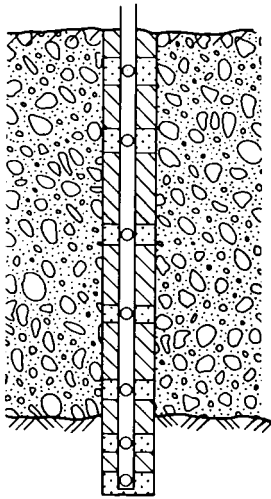
a. Single Piezometer



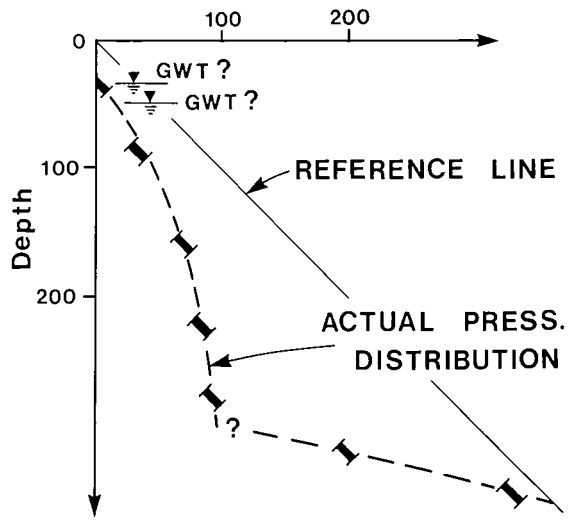
b.



c. Multiple Piezometer



d.



GWT = Groundwater Table

Figure 6. Piezometer requirements, single aquifer.

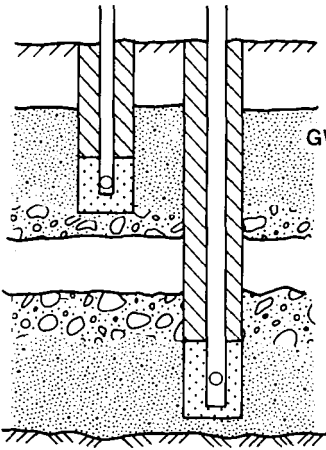
The geology and general groundwater situation is shown on the lefthand side of each of the figures and the corresponding depth versus pressure head diagram is shown on the righthand side. On each figure a comparison can be made between the groundwater data obtained with a single piezometer in each aquifer and with multiple piezometers.

The depth versus pressure head diagrams are a convenient method of plotting and interpreting the piezometer measurements in a single drill hole. If possible, both depth and pressure should be plotted in the same units and to the same scale. On these plots it is helpful to show a reference "hydrostatic line" which indicates the slope of a hydrostatic pressure distribution. This line would represent the pressure distribution in an open body of water. When the plot of pressure head versus depth is inclined more steeply than the hydrostatic line, a downward flow condition is indicated. When the pressure distribution is flatter than the hydrostatic line, an upward flow condition is indicated.

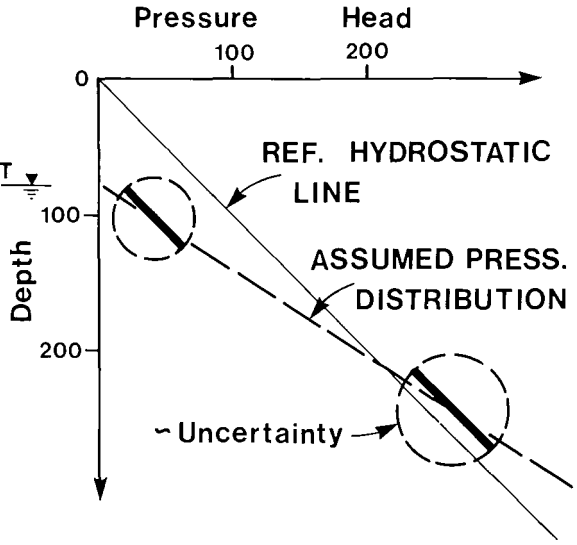
The heavy bar on Figure 6b shows the water pressure data obtained from a single piezometer in Figure 6a. The midpoint of the bar is the pressure recorded in the piezometer at a depth which is assumed to be the midpoint of the measurement zone. The heavy bar is inclined parallel to the reference hydrostatic line over the length of the measurement zone shown on Figure 6a. Without further water pressure data one would have to assume that the pressure distribution in the remainder of the aquifer is hydrostatic. Hence, the groundwater table would be estimated to be at a depth of about 135 units as shown on Figure 6b. Increasing the length of the measurement zone can introduce appreciable uncertainty in the depth-pressure relationship. An initial estimate of this uncertainty can be given by a circle with a diameter equal to the length of the bar shown in Figure 6b. The actual measurements can greatly exceed the uncertainty circle, but a circle can provide a reasonable first estimate of the possible errors present.

The identical aquifer is shown in Figure 6c, but with more piezometer ports installed. The corresponding distribution of pressure head with depth is shown on Figure 6d. At first glance it may be difficult to believe that the measurements on Figures 6b and 6d could be made in the same aquifer. For example, the real groundwater table in Figure 6d would appear to be 100 units above that obtained in Figure 6b. Furthermore, in Figure 6d the pressure distribution in the aquifer is steeper than the reference

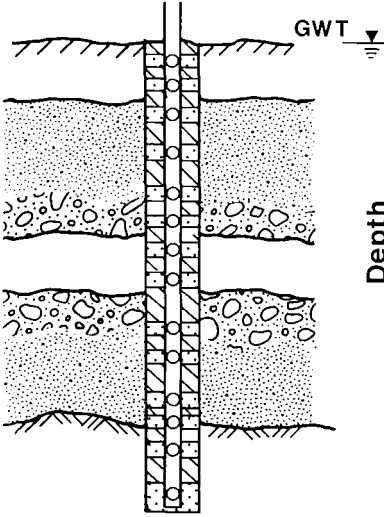
a. Single Piezometers



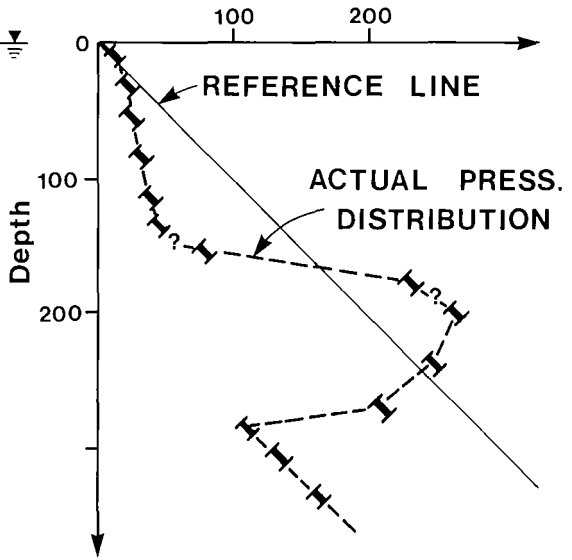
b.



c. Multiple Piezometers



d.



GWT= Groundwater Table

Figure 7. Piezometer requirements, two aquifers.

hydrostatic line. Figure 6d shows that the pressure distribution in the bedrock below the aquifer is flatter than the reference line. Thus, the groundwater is flowing downwards in the aquifer and upwards in the bedrock toward the bedrock contact. The question marks indicate that there is uncertainty about the water pressure at the bedrock contact and about the precise position of the groundwater table. Even more piezometers would be required to remove these uncertainties. It is apparent from this example that measurements from a single piezometer can be highly misleading, even when the geology is very simple.

A similar but more complex hydrogeologic condition is shown on Figure 7. The positions of the two single piezometers, one in each aquifer, are shown on Figure 7a. The corresponding results of the measurements from these piezometers are shown on Figure 7b. As before, the measurements are shown by the heavy bars. The length of each bar is determined by the depth interval in the measurement zones. The slope of each bar is made equal to the slope of the reference hydrostatic line. The equivalent uncertainty circles are shown together with an interpreted groundwater table.

The identical aquifers are shown in Figure 7c, but with more piezometer ports installed. The corresponding distribution of pressure head versus depth is shown on Figure 7d. As in Figure 6, the results obtained with more piezometers show little resemblance to those given in Figure 7b. The pressure distribution in Figure 7d indicates that the upper aquifer is draining downwards and that a second drain occurs at the top of the bedrock contact. The results also indicate that the top of the lower aquifer is a high pressure region where flowing artesian conditions are present and water is being fed both upward through the aquitard between the aquifers and downward toward the bedrock contact. The pressure distribution is hydrostatic in the bedrock. Also, the groundwater table is near the ground surface rather than 80 units below the surface as indicated in Figure 7b.

Figure 8 shows the pressure distribution versus depth for a drill hole made in mountainous terrain in central British Columbia. The pressure distribution given in Figure 8 was collected with the Westbay Profiler, an instrument which measures bottomhole pressures and allows permeability values to be obtained during intervals in the drilling operation. The Profiler is used inside HQ and

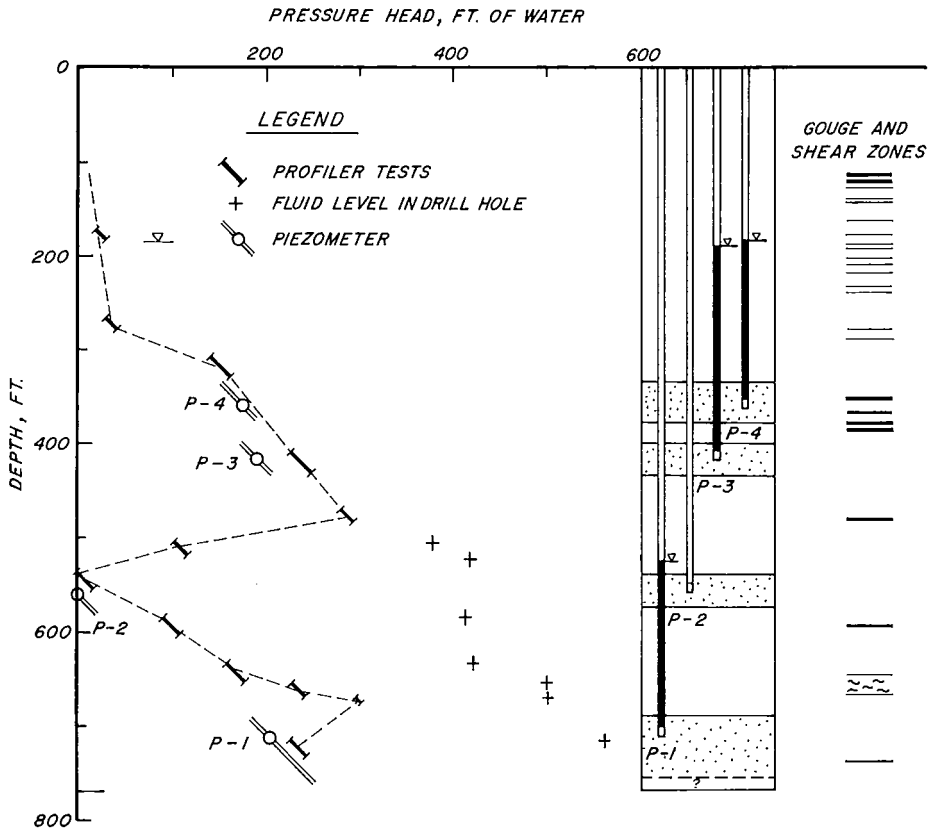


Figure 8. Field record, pressure head versus depth using Westbay's Profiler.

NQ-size wireline rods and has been operated to depths of 300 meters. Figure 8 also shows the results obtained from the few piezometers installed in this drill hole. Profiler measurements were made to establish the best locations for the permanent piezometers. It can be seen that without knowledge of the pressure distribution obtained from the numerous Profiler water pressure measurements, it would be easy to interpret incorrectly the results from a few piezometers.

It is necessary to have at least two data points in each aquifer when the pressure distribution is represented by a straight line. Another data point is required to confirm the straight-line pressure interpretation and a further

data point is required if the monitoring system is to have the minimum amount of built-in redundancy. Thus, two data points per aquifer are the absolute minimum to investigate the pressure distribution and four data points per aquifer are the minimum needed to recognize non-linear pressure distributions and have a single redundant data point. For an evaluation of an aquifer there should be at least one data point in the adjacent unit. Hence, for one aquifer the absolute minimum number of piezometer data points is three. The minimum number does not permit unusual situations to be checked and significant exceptions could easily go unrecognized. For an adequate monitoring system five data points are required, four in the aquifer and one in the layer below. The adequate number has some redundancy and enables one to detect unusual situations.

Assuming that the pressure distribution in the aquitards separating the aquifers will not be particularly significant, a minimum of one and preferably two data points in each aquitard would be required. Thus, for the two aquifers shown in Figure 7 the minimum number of data points would be seven (two in each aquifer and one in each of the overlying, intervening and underlying aquitards), whereas adequate coverage would require fourteen data points (four in each aquifer and two in each aquitard). If the settlement of compressible layers is of concern, then additional piezometers would be required in any compressible aquitards.

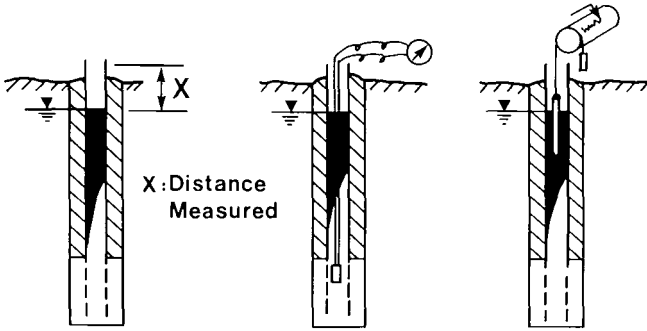
TYPES OF PIEZOMETER INSTALLATIONS

The available types of piezometer will generally fall within one of the categories shown on Figure 9. These categories are: a) open piezometers, b) closed piezometers, and c) valved (or combined open/closed) piezometers. This classification has been adapted from those suggested by Schmidt and Dunnicliff (3), Cording et al (2) and Dunnicliff (12). The main modification is the addition of the valved category which was not available at the time these earlier classifications were made.

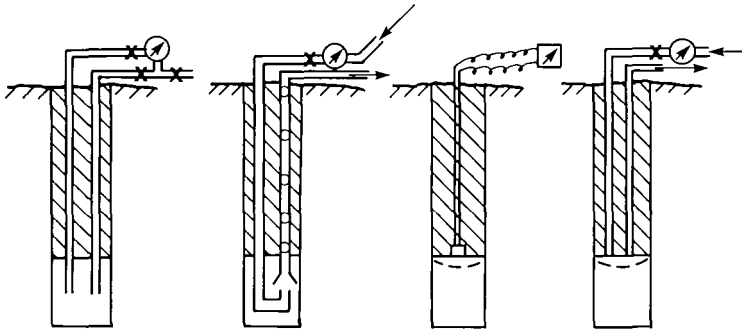
Open Piezometers

The open piezometers shown in Figure 9a are those in which the air-water interface is contained within the piezometer casing or tubing and the position of the interface is recorded for a particular measurement zone. The open piezometers shown are essentially the same and only differ

a. OPEN PIEZOMETERS

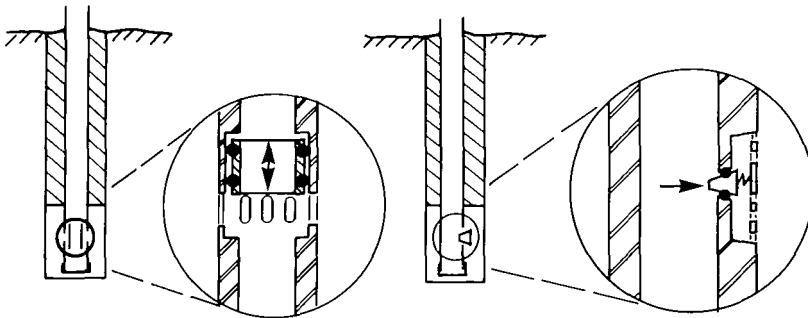


b. 'CLOSED' PIEZOMETERS



i. Formation Fluid Types ii. Diaphragm Types

c. VALVED PIEZOMETERS



i. Sliding Valve Type ii. One-way Check Valve Type

Figure 9. Types of piezometers.

in the method used to record the elevation of the interface.

These methods can include tape measurements, sonic measurements, floats attached to rotating drum recorders and almost any of the systems used to measure water pressure in the other types of piezometers (for example, pneumatic or strain-gauge pressure transducers, etc.). The principal advantages of the open piezometers are their simplicity, the ease with which they can be checked by response testing, and the relative ease with which water samples can be obtained. Open piezometers can be constructed so as to permit the "development" of the formation surrounding the tip following installation. This development is often required to remove the effects of natural and added drilling muds and to decontaminate (i.e., remove traces of the drilling fluids) prior to water quality sampling. The principal disadvantages of the open system piezometers are their slow response times in low permeability soil and rock formations and the technical difficulties that can result when one attempts to place several in the same drill hole. Another disadvantage can be that the open piezometers cannot be used to measure negative pore-water pressures. Open piezometers generally cannot handle flowing artesian conditions effectively, particularly in freezing weather.

Closed Piezometers

Closed piezometers are of two main types: those that use the actual pore fluid of the soil or rock to make the measurements and those that sense the fluid pressure through diaphragms. These are referred to on Figure 9 as "formation fluid types" and "diaphragm types," respectively.

The formation fluid type of piezometer is similar in several respects to the open piezometer. Tubes are introduced into the piezometer casing or drill hole which is then sealed and the tubes are led away to a recording station. Here the water pressure is recorded or air is introduced and allowed to bubble out of the end of the tube and the pressures are recorded. Response tests are generally quite difficult to make for calibration of the performance of the piezometers. Water samples sometimes can be obtained from the formation fluid type of piezometer. The response time for this type of piezometer is usually much faster than for open piezometers. An added advantage is that the lines can often be led out horizontally thereby reducing any interference with mining operations. The main disadvantage is that long lines from the tip are

susceptible to damage. Damaged or leaking lines can be difficult to detect and repair and can result in incorrect data being recorded.

The diaphragm type of closed piezometer has many variations, but generally the sensing mechanism uses the displacement of a diaphragm to indirectly indicate the water pressure. In certain diaphragm piezometers the diaphragm acts as a butterfly valve. In some the movement or displacement of the diaphragm is sensed. In others the stress in the flexing diaphragm is interpreted by strain measurements. Movement of the diaphragm or the stresses introduced by the movement can be sensed pneumatically, hydraulically or by electrical and electronic means.

The principal advantages of diaphragm piezometers are: 1) their shorter response time in comparison with open piezometers, 2) their ease in adapting to automatic recording devices, 3) the ability of some types to avoid the presence of water either at the top of the piezometer casing or in the measurement lines (important in freezing weather), and 4) their ability to have their measurement lines led away horizontally from the piezometer tip if required. The principal disadvantage is that one is usually unable to check the calibration of these instruments once installed. (In some cases calibration can be achieved with extra lines). Other disadvantages include: the inability to collect water samples, the susceptibility of the electrical systems in the subsurface environment to short circuiting, and the susceptibility of the pneumatic and hydraulic systems to leakage resulting in erroneous results. Furthermore, to attain levels of accuracy comparable with those obtained in open piezometers, relatively expensive electronic apparatus is required. Most electrical systems are susceptible to transient electrical currents as the leads can act as long antennae. Lightning has also damaged permanent electrical/electronic systems. The pneumatic systems become rather slow below depths of 80 meters and readings are often unacceptably slow below 200 meters.

Valved Piezometers

Valved piezometers are a relatively new development of Westbay Instruments Ltd. whereby a valve which can be opened and closed is placed on the side of the piezometer casing. In the two types shown in Figure 9, the valve can be a sliding valve which can remain open or closed or it can be a one-way check valve which remains closed due to external

water pressures until it is opened from the inside as shown by the arrow.

The sliding valve type of piezometer can be operated as an open piezometer or as a closed piezometer. In the latter case an inflatable packer would be installed on either side of the valve to seal off a portion of the inside of the piezometer casing.

The valved piezometer with a one-way check valve requires a special probe which can find the valve at the correct depth and orientation, seal the valve from the water inside the piezometer casing, open the valve, and finally sense the exterior water pressure or take a water sample. The probe can contain an electronic, pneumatic or hydraulic pressure transducer which can be read at the surface.

The valved piezometers tend to combine the best attributes of the open piezometers and the closed piezometers and eliminate some of the disadvantages of each. For example, they can be as responsive as all but a few of the closed piezometers yet can readily undergo response testing to check the calibration of the transducers, the operation of the valve, and its connection to the formation outside. Also, when using electrical transducers for pressure measurements no electrical or pneumatic lines are left in the casing between readings unless continuous measurements are required. In the latter case the transducers can still be removed for calibration or repair. This allows one to take advantage of the accuracy and convenience of electrical pressure transducers without leaving such devices in the drill hole with the attendant problems discussed by Casagrande (1). Valved piezometers may readily be used to measure pressures below atmospheric pressure.

A significant advantage of valved piezometers is that large numbers of them can be placed in a single drill hole. With other types of piezometers there are both practical and economic limits to the number that can be placed in a drill hole. For the other piezometers the practical limits are generally reached for all but the most skilled field technicians at about three piezometers per drill hole. The need for multiple piezometer installations becomes apparent when groundwater instrumentation considerations are examined in detail.

GROUNDWATER INSTRUMENTATION CONSIDERATIONS

Cost of Drill Holes

The cost of drill holes is usually a significant factor in groundwater instrumentation budgets. Drill hole costs can run from a few dollars to over \$100 per foot with good quality cored drill holes generally running from \$20 per foot and up. Costs are influenced by many variables including the size and depth of the drill hole, accessibility, the total footage drilled, etc. Drilling costs typically amount to from 40 to 90 percent of a groundwater instrumentation budget. Thus, reducing the number of drill holes per installed piezometer can appreciably lower the groundwater instrumentation costs.

Scheduling

On many jobs the number of drill holes that can be used for instrumentation is not limited by cost so much as by scheduling. In all phases of mining--exploration, environmental assessment, design, production and monitoring--the drilling operation is commonly on the critical path or can easily interfere with critical path operations. Thus, the fewer the drill holes, the fewer the scheduling problems.

Surface Protection

If the groundwater instrumentation is to survive and permit monitoring over a period of time, it is generally necessary to protect the top of the drill hole. In freezing weather this could mean the construction of an insulated shack. Near mine operations reinforced structures may be required or the area may have to be isolated from operations. Sometimes protection consists of burying the piezometer casing. All of these methods can be costly in terms of labor and capital costs or in terms of reduced operational efficiency. There is an obvious advantage in reducing the number of field protection facilities.

Potential Damage to Formations to be Monitored or Sampled

Unless each drill hole is carefully drilled and sealed after the piezometer casing is installed, it is quite easy to adversely influence the groundwater measurements or samples with the very program that is supposed to obtain

these data. The potential for damage can be high in environmental monitoring of hazardous underground fluids. Leakage from one formation to another through the drill hole or casing can be a principal means of spreading a contaminated fluid. Groundwater quality monitoring systems can adversely affect the problem they are supposed to be helping to solve. The potential for formation damage increases directly with the number of holes drilled. Thus, from the viewpoint of formation damage, the more piezometers placed in one drill hole, and therefore the fewer the drill holes, the better.

Three-Dimensional Sampling Requirements

Groundwater sampling and pressure measurements occur in a three-dimensional framework. This requires a spacial distribution of sampling and measurement points. Thus, one must usually consider portraying the groundwater data on plans showing their areal distribution as well as on several hydrogeologic sections made more or less at right angles to each other. To do this, the groundwater data must be available at a considerable number of locations and at numerous depths. Deep groundwater sampling may require that pressurized samples are taken to ensure that no gases have escaped from the sample between the sampling point and the laboratory. The mathematics of the situation can quickly show that great economy in drill holes and data monitoring points can be obtained if numerous measurements can be made in single drill holes. A large number of sampling points can be particularly important in environmental monitoring situations where the actual location of a leakage path is not known in advance of sampling and analyses.

Redundancy Requirements

As previously noted, no good groundwater instrumentation system would be complete without a consideration of redundancy requirements. Installations which achieve over 90 percent functional operation of the completed groundwater monitoring systems are quite rare, particularly when the depths of the drill holes extend below several hundred feet. After the system has been installed, various environmental factors operate to reduce the efficiency of the system and attrition occurs. Human error can also result in losses to the groundwater monitoring system. A fully redundant system might have two data points installed for each one required. The amount of redundancy required is dependent upon the needs of the project, but should commonly range from 10 to 20 percent of the installed system.

Verification Requirements

A good quality groundwater instrumentation system should have a method for verifying the accuracy of the measurements. For pressure and permeability measurements this means that response testing of the entire measurement system must be possible. This would include testing of the transducer, leads, and readout as well as testing of the degree of connection of the interior of the piezometer tip to the water in the geologic formations outside. In water quality sampling 'verification' means that one can demonstrate that the drilling fluids have been removed and that repeated samples can be taken to check the results of anomalous laboratory analyses.

Redundant data from adjacent piezometer ports can help to verify results. Hence, verification can also mean having sufficient piezometer ports so that it can be shown that an adequate number of measurements have been made. Again, it is apparent that multiple measurements in the same location can help solve the verification requirement but only if each measurement itself can be independently checked.

Documentation of the Geology and Hydrology

The groundwater measurements, in most cases, must be closely tied to the geologic conditions encountered in the drill holes. This usually means that the geology of the instrumentation drill holes must be well documented by drill core, geophysical wireline logging or both. This type of documentation can be almost a necessity to enable the seals along the piezometer casing to be placed in the most advantageous locations. When deciding upon the location of piezometer ports and seals, it is particularly helpful if the distribution of the piezometric pressures and the distribution of permeability in the drill hole is known as soon as the drilling is completed and before the permanent piezometer casing is placed in the drill hole. This can be done by single or double-packer injection tests made at intervals during or following drilling and presented as in Figure 8.

When one accepts the necessity for documentation of the geology and hydrology of the instrumentation drill holes, it becomes apparent that a significant advantage can result

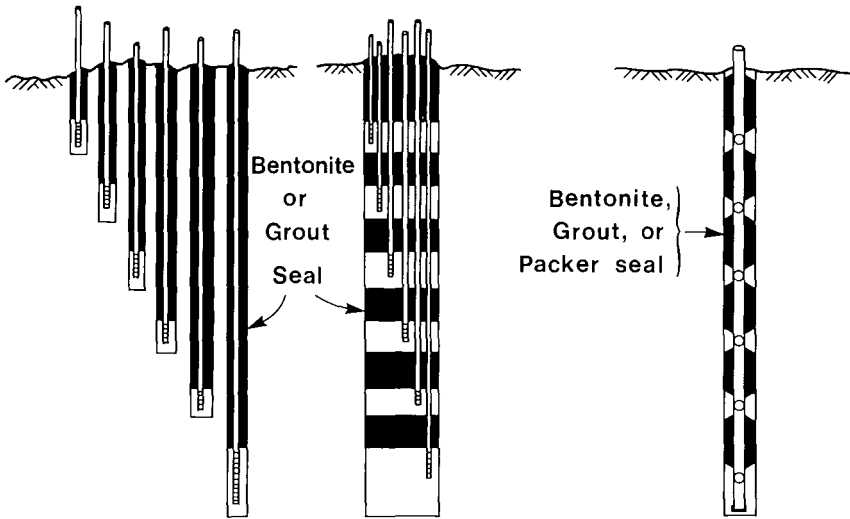
from increasing the number of piezometers in a single drill hole and thereby reducing the number of the more costly cored and logged drill holes.

Sealing Requirements

Groundwater measurements and sampling can suffer greatly if the seals are not properly made above each piezometer tip and/or between each piezometer port. Seals can be difficult to place in caving hole conditions and where flows can develop between different parts of a drill hole. Seals are made by using bentonite, settable grouts, or solid or inflatable packers. Inflatable packers can be expanded with air, water, or grout mixtures. When flowing conditions are encountered, inflatable packers are usually the minimum treatment required. In the typical drill hole the water pressure distribution is seldom hydrostatic; thus, there is almost always the possibility of flows occurring within the drill hole which are unknown to the surface crew. Hence, inflatable packers can provide appreciable assurance that the piezometer tips or ports are properly sealed.

Where water sampling is undertaken, it can be important that chemically active sealing materials such as bentonite and cement grout do not contact the sampling waters since they could have a significant and irreversible effect on the quality of the sampled waters. Unlike the other items noted in this section of the paper, sealing can become more difficult when the number of piezometers or piezometer ports installed in a single drill hole is increased because this also increases the number of seals required. With all but the valved piezometers, the complexity of each seal increases directly with the number of piezometers placed in a single drill hole.

In conclusion, it is apparent that with all these groundwater instrumentation considerations, except sealing, there is a significant advantage in placing an increased number of piezometers in single drill holes (i.e., multiple piezometer installations). In the matter of sealing the problem is made appreciably more difficult for multiple installations of all types of piezometers discussed except for the valved piezometers. Therefore, it is worthwhile examining multiple piezometer installations in more detail.



a. Nest of single standpipe piezometers

b. Single drillhole with conventional multiple piezometer completion

c. Single drillhole with multiple valved piezometer (Westbay's MP System)

Figure 10. Comparison of multiple piezometer installations.

MULTIPLE PIEZOMETER INSTALLATIONS

The technical need for multiple piezometer installations has been discussed but practical considerations, costs, and scheduling have not received sufficient attention.

Practical Considerations

Figure 10 shows a comparison of three types of multiple piezometers: a) a nest of several standpipe piezometers placed in individual drill holes, b) conventional multiple piezometers installed in one drill hole, and c) a single drill hole with multiple piezometers of the valved type (the new Westbay MP System).

A visual comparison of the relative complexity of the three systems suggests some of the advantages of the valved

type of piezometers for multiple completions. The nest of single position standpipe piezometers can be installed but it is usually time-consuming and costly, even if the successive drill holes did not influence the measurements made in those piezometers placed first. The installation of the conventional multiple piezometer shown in Figure 10b would be a technical challenge even to an experienced field crew. In such types of installations the chances of losing the drill hole and some of the piezometers increases directly with the number of completions attempted. Also, as the number of piezometers increases, it becomes more difficult to place an adequate seal between the maze of tubes, casings or wires within the drill hole. The sealing problems tend to increase geometrically with the number of piezometers attempted. Figures 10a and 10b also illustrate the severe problems that can result when one is confronted with a multitude of similar appearing pipes or wires at the ground surface. If the individual casings or leads are not permanently and correctly labelled, then the best of measurements cannot overcome the error introduced by reading the wrong piezometer tip.

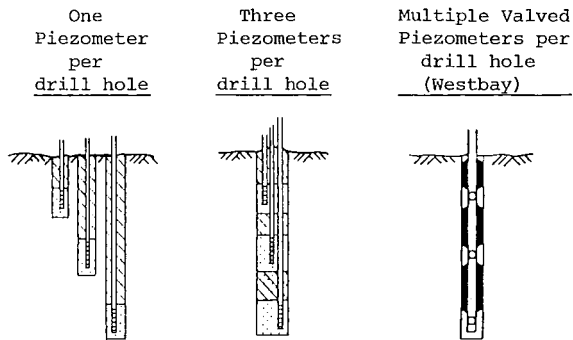
With the valved multiple piezometer installations, such as illustrated in Figure 10c, there is almost no practical limit to the number of piezometer ports that can be installed in a single drill hole. This is achieved because no wires or tubes are required to join each port to the surface. Currently, piezometer ports can be installed as close as 1 foot apart, although it is most convenient to install them at spacings of 5 feet. The plastic casing has been installed to depths of 1000 feet and should be suitable in drill holes extending 2000 to 4000 feet in good quality rock. With valved piezometers 20 piezometer ports can be placed in a 100-foot drill hole or 200 piezometer ports can be placed in a 1000-foot drill hole. Drill holes may be vertical, inclined or horizontal.

Cost and Scheduling Considerations

It is worth reviewing briefly the cost and scheduling considerations which should be taken into account in comparing alternative groundwater instrumentation systems. Estimates of costs and schedules are summarized on Table 1. This table compares the three types of multiple piezometer installations shown on Figure 10.

For each of the three types of multiple piezometer installation reviewed, three different numbers of piezometer

Table 1. Comparative summary of costs and scheduling for multiple piezometer installations.



	<u>One Piezometer per drill hole</u>	<u>Three Piezometers per drill hole</u>	<u>Multiple Valved Piezometers per drill hole (Westbay)</u>
	<u>Units</u>	<u>Units</u>	<u>Units</u>
<u>3 Piezometer Installation</u>			
Drill hole costs	2	1	1*
Installation labor	3	1.5-2.0	1
Installation equipment	0.3	0.2	1
Material costs	0.5	0.3	1
Overhead costs	3	2	1
Drill hole protection costs	3	1	1
Schedule Time	3	2	1
<u>10 Piezometer Installation</u>			
Drill hole costs	5.5	3.3	1
Installation labor	8	5	1.1
Installation equipment	0.8	0.5	1.1
Material costs	2	1	1.5
Overhead costs	8	5	1.1
Drill hole protection costs	10	3.3	1
Schedule Time	8	5	1.1
<u>20 Piezometer Installation</u>			
Drill hole costs	10.5	7	1
Installation labor	15	10	1.2
Installation equipment	3	1	1.2
Material costs	4	2	3
Overhead costs	15	10	1.2
Drill hole protection costs	20	7	1
Schedule Time	15	10	1.2

* Includes no allowance for using smaller diameter drill holes.

nests are considered: a) a three piezometer installation, b) a ten piezometer installation, and c) a twenty piezometer installation.

The costs included are for the drill hole, installation labor, installation equipment, materials, overhead and drill hole protection. The schedule time required for each installation is also indicated.

Drill hole costs include all on-site drilling operations as a function of total footage of the drill hole. Installation labor costs are considered to be directly related to the schedule time. Installation equipment costs attempt to account for the cost of rented installation equipment such as grout or water pumps and piezometer readout and sampling equipment. These costs can vary considerably with project requirements. Material costs are the costs of materials placed in the drill hole--usually casing, couplings, piezometer tips, filter sand and sealing materials. Overhead costs are assumed to be directly related to schedule time. Drill hole protection costs will vary directly with the number of drill holes. These latter costs can vary from fifty dollars per drill hole to several thousand dollars or more for winter protection or for reinforced structures in a critical operation area. The schedule time is the total elapsed time from start to finish of the field installation and assumes an increase in efficiency for placing larger numbers of piezometers in single drill holes and a decrease in efficiency for a larger number of conventional piezometers in a single drill hole. On Table I the costs and times are given in terms of units rather than actual dollars or days.

The principal reason for preparing Table I is to show that the material costs tend to be a smaller fraction of the total costs than is commonly assumed. This is true for a small number of piezometers per drill hole, and material costs become an even smaller fraction of total costs as the number of piezometers per drill hole increases.

Perhaps the most significant item on Table I is the comparison of schedule times. Installation of a single piezometer in three separate drill holes is estimated to take three times as long as the installation of three piezometers in one drill hole. Thus, if the valved piezometer installation took one day, then installation of a nest of piezometers would take three days. However, in a real project these figures can be one month and three months,

respectively. When large numbers of piezometers are installed, the schedule times can differ by factors of six to ten, or one month versus six to ten months for the cases noted. Thus, the total cost of the installation and the scheduling favor the valved type of multiple piezometer installation.

CONCLUSIONS

The scope of groundwater instrumentation in mining projects is currently expanding rapidly for both mineral exploration and the assessment of water quality for environmental monitoring.

A review of moderately simple single and multiple aquifer situations suggests that the least number of piezometers required for minimum coverage of water pressure distributions is $2n + 1m$. For adequate coverage the number is $4n + 2m$, where n is the number of aquifers present of appreciable thickness and m is the number of aquitards (confining beds) present below the groundwater table. Thus, when two aquifers and three confining beds are present, fourteen piezometers would be considered adequate coverage. Such geologic field conditions are not unusual but few current piezometer installations have this density. Where water quality monitoring is undertaken, much higher densities may be required for adequate coverage. Where settlement or consolidation of soft sediments is of interest, then additional piezometers should be placed in the compressible aquitard layers.

There are numerous reasons, both technical and practical, for favoring multiple piezometer installations. These include costs, scheduling, surface protection, formation damage, three-dimensional sampling, redundancy, verification, and documentation requirements. All of these favor multiple installations. Only sealing requirements are potentially more difficult with multiple installations. However, the sealing of multiple installations of valved piezometers is essentially no more difficult than sealing a single piezometer tip.

Different types of single position piezometers have been examined. These include open, closed and combined open/closed or valved types of piezometers. Each has its advantages and disadvantages. However, in multiple installations in the same drill hole, the valved type of piezometer

is clearly superior, particularly as the number of piezometers per drill hole increases. In the past the cost and scheduling requirements for conventional groundwater systems strongly discouraged the use of dense multiple piezometer installations even when they were required for technical purposes. However, there are no particularly large increases in costs or the scheduling time required for the valved type of multiple piezometer. It is now possible to install groundwater monitoring systems with the piezometer density that is technically required.

Valved piezometers also permit the installation of a high density of water quality sampling points and can be combined in such a way that each sampling point can be decontaminated prior to sampling by using sliding valves called "Pumping Ports." Valved piezometers have undergone field trials for the past year and have been installed in small-diameter drill holes to depths of 1000 feet with as many as twelve piezometer ports. Much deeper depths and much higher sampling densities are possible.

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