

11. W. F. Megahan, N. F. Day, and T. M. Bliss. Landslide Occurrence in the Western and Central Northern Rocky Mountain Physiographic Provinces in Idaho. *In* Forest Soils and Land Use, Proc., Fifth North American Forest Soils Conference, Aug. 6-9, 1978, Colorado State University, Fort Collins, 1979.
12. R. Steele, R. D. Pfister, R. A. Ryker, and J. A. Kittams. Forest Habitat Types of Central Idaho. General Technical Report INT-114. Forest Service, U.S. Department of Agriculture, Ogden, Utah, 1981.
13. D. O. Nelson. Soil Survey of Middle Fork Payette River Area, Idaho, Parts of Valley and Boise Counties. Forest Service and Soil Conservation Service, U.S. Department of Agriculture; University of Idaho, Moscow, Idaho, 1976.
14. D. Hampton, W. F. Megahan, and J. L. Clayton. Soil and Rock Properties Research in the Idaho Batholith. Research Project Report. Howard University, Washington, D.C., 1974, 126 pp.
15. H. F. Haupt. A Simple Snowmelt Lysimeter. *Water Resources Research*, Vol. 5, No. 3, 1969, pp. 714-718.
16. J. K. Searcy and C. H. Hardison. Double-Mass Curves. Water-Supply Paper 1541-B. U.S. Geological Survey, Reston, Va., 1960, 66 pp.
17. M. D. Hoover and E. W. Shaw. More Water from the Mountains. *In* Yearbook of Agriculture, U.S. Department of Agriculture, 1962.
18. H. Gary. Snow Accumulation and Snowmelt as Influenced by a Small Clearing in a Lodgepole Pine Forest. *Water Resources Research*, Vol. 10, No. 2, 1974, pp. 348-353.
19. D. L. Golding and R. H. Swanson. Snow Accumulation and Melt in Small Forest Openings in Alberta. *Canadian Journal of Forest Research*, Vol. 8, 1978, pp. 380-388.
20. A. Hazen. Flood Flows, or Study of Frequencies and Magnitudes. Wiley, New York, 1930.

Publication of this paper sponsored by Committee on Engineering Geology.

Long-Term Groundwater Monitoring in Mountainous Terrain

RODNEY W. PRELLWITZ and RONALD E. BABBITT

ABSTRACT

Groundwater peak flows that trigger landslides in the northern Rocky Mountains occur in the winter and early spring when access is limited. The Forest Service, U.S. Department of Agriculture, is developing instrumentation for monitoring groundwater under these conditions. The system operates unattended under extreme weather conditions for 9 months, powered by rechargeable batteries; stores groundwater data on solid-state integrated-circuit storage modules that can be read directly into a host computer for data processing; is adaptable to precipitation monitoring; and is relatively inexpensive. Instrumentation and installation problems, as well as remedial measures, are discussed. Sample field data recovered since 1981 and practical applications of that data, including groundwater rise in response to precipitation modeling, landslide correction, and aquifer analysis, are discussed.

sponse to precipitation. In spite of this, little groundwater monitoring has been done and few response models have been developed for watershed analysis. Likewise, geotechnical engineers, who may go to great lengths to determine more exact values for the other variables in a stability analysis, will often assume a value for the critical phreatic surface that is not based on groundwater-monitoring data. One basic reason for insufficient monitoring to support predictions is that dependable, inexpensive, long-term monitoring instrumentation currently is not commercially available. This paper is a progress report on a feasibility study to develop this methodology.

PHYSIOGRAPHIC SETTING

Groundwater concentration and flow in forest watersheds in the northern Rockies is dictated largely by physiographic conditions. Precipitation at higher elevations is mostly in the form of snow that can yield equivalent annual rainfall of 50 to 100 in. or more, although the neighboring valleys may receive less than 20 in. The manner in which this snow melts in the spring is a key factor in the determination of the seasonally high groundwater level. At the upper reaches of the watersheds, organic matter and windblown material such as volcanic ash are abundant near the ground surface. As a result, most of the snowmelt enters the ground with little overland sur-

Groundwater in mountainous forest lands is the most dynamic variable to deal with in a slope stability analysis because it fluctuates constantly in re-

face flow. Near the ground surface, groundwater migrates downward in unsaturated flow to some less permeable drainage barrier where it is concentrated, forms a phreatic surface, and migrates along that barrier in saturated flow. Further concentration is controlled by the geomorphic shape of the landform.

Perched water tables that form under this mechanism are common in the loose surface material: in colluvial subsoils overlying residual soil or bedrock, in residual subsoil overlying less weathered bedrock, in glacial outwash subsoil overlying glacial till, in the weathered (by frost heave, vegetation, etc.) surface of most soils, and in numerous other geologic settings where a more permeable material overlies a less permeable one.

Groundwater migration along the drainage barrier is often not so simple as might be envisioned. The soil mantle has frequently made natural stabilizing adjustments as a response to groundwater movement. Through frost action, creep, rapid movement over short distances, and migration of the finer soil particles through piping, groundwater channels can develop that have hydraulic characteristics much different from those of the host soil material.

DEVELOPMENT OF METHODOLOGY

Need

Access is another important factor that limits the ability to monitor the seasonal groundwater fluctuations. These forest watersheds can be inaccessible (except by snowshoes, skis, snowmobile, or helicopter) from October through June. The seasonally high groundwater and resulting landslides occur during this snowmelt period. Groundwater measurements made during the summer are in no way indicative of the seasonal high to anticipate during the snowmelt period.

Progress Report

What is needed is a portable groundwater-monitoring instrument that can be installed in an observation well in October; will monitor (under extreme weather conditions) the groundwater in that well for an extended period without service, powered only by a rechargeable battery; allows the data to be easily retrieved in June; and is inexpensive. In response to these needs and as a part of an overall landslide evaluation project, the Forest Service, U.S. Department of Agriculture, is developing an instrumentation scheme. The feasibility study is near completion and sufficient data have been gathered to compile this progress report. To test the instrumentation under actual conditions and the feasibility of developing groundwater rise in response to precipitation models, groundwater has been monitored for 1 to 2 years in 11 observation wells on 6 small watersheds of various geologic and site conditions in the mountains of northern Idaho and western Montana. Three of these sites have active landslides and the groundwater data are being used to design landslide stabilization measures.

To link groundwater rise to precipitation for a given watershed, it is necessary to have precipitation data recovered at that site. For snow, it is important to know not only how much (equivalent rainfall) and when the snow falls but also when it melts and is available at the ground surface for groundwater recharge. Two precipitation-monitoring devices to provide these data are being tested (Figure 1):

1. A sacramento gauge (frustrum-of-cone shaped tank) on a stand above the highest snow accumulation to catch and monitor rain and snow as it falls and

2. A lysimeter (buried 55-gal oil drum with a catch basin at the ground surface) to catch and monitor snowmelt and rainfall when it is available at the ground surface for recharge.

Instrumentation for these devices is electronically similar to that used for groundwater monitoring.

Precipitation stations with each of these devices are being tested at three watersheds that are also being monitored for groundwater fluctuation. Monitoring has been conducted for one period (October 1982 through June 1983).

As should be expected in a new venture, not all the data collected to date are usable. Instrumentation and installation problems either have been or can be corrected. Sufficient progress has been made and sufficient useful data are available for this progress report.

INSTRUMENTATION

Features

Because of the advent of solid-state electronic technology, long-term groundwater-monitoring instrumentation with the following capabilities is now feasible:

1. The equipment will operate under extreme weather conditions without special temperature-controlled housing.

2. Groundwater (or precipitation) data can be recorded for a relatively long term without service (at least 9 months), with only rechargeable batteries for power.

3. In this long-term mode, the instruments sense the water level in one or two locations (one or two observation wells for groundwater and one or both precipitation gauges) every 30 min. At the end of the recording interval (12 hr for one station and 24 hr for two stations), minimum, maximum, and average of these 30-min readings are determined. These three sets of data are then stored (to document the fluctuations during the recording interval) on a solid-state data storage module (DSM), the 30-min readings are dumped, and the process is repeated for the next recording interval.

4. The instruments can be easily changed to shorter sensing and recording intervals for more intensive monitoring of peak conditions (when access permits). Optional short-term modes are summarized in Table 1.

5. Data from the DSM can be read directly into a computer (through a reader) for permanent storage on magnetic tape and for printing. Once on permanent file the data can be reduced, plotted, and so forth, through the computer with appropriate software.

6. The system is relatively inexpensive. Cost of instrumentation (1982 prices), not including drilling observation wells and installing precipitation gauges, was about \$1,300 for one station per recorder and \$1,500 for two stations per recorder.

Major Components

The major instrumentation components include a solid-state data-logging device, signal-conditioning circuitry, rechargeable battery, and pressure transducer water-level sensor (Figure 2). With the exception of the sensor (which is installed in the observation well or precipitation gauge), all components

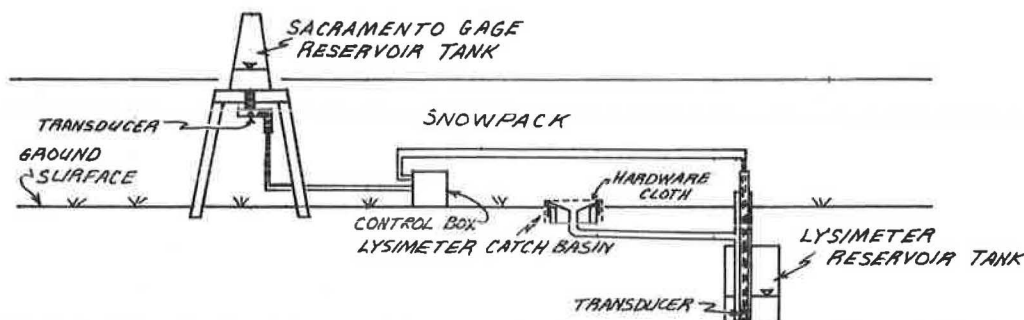


FIGURE 1 Precipitation station.

TABLE 1 Summary of Sensing and Recording Intervals

Recording Interval (hr)	Sensing Interval (min)	Maximum Period to Reach DSM Storage Capacity ^a			
		Single Channel		Double Channel	
		Days	Months	Days	Months
1	5	28.4		14.2	
3	10	85.3	2.8	42.7	1.4
6	15	170.6	5.7	85.3	2.8
12	30	341.2	11.4	170.6	5.7
24	30	682.3	22.7	341.2	11.4

Note: Data recorded were average, maximum, and minimum of readings at sensing intervals.

^aDSM capacity = 2,047 data registers.

are enclosed in a watertight electrical case that is 12 x 12 x 6 in. and 37 lb (Figure 3). Following is information on the main functions of each major component. Table 2 is a summary of some of the vital statistics and approximate costs; the manufacturers and brands listed were not necessarily the only ones available. Readers should make competitive comparisons before purchasing.

Data Logger

The data logger used is a Datapod voltage recorder manufactured by Omnidata International, Logan, Utah.

The manufacturer developed a special model (212S) of this two-channel voltage recorder for this project. This version has a program module that produces a "system on" command pulse 1 min before the sensor reading, which allows warm-up time for the signal-conditioning circuits and the sensor to stabilize. Five sensing and recording interval combinations have been programmed (three more are available for future programming) and are preset with internal switches to provide a wide range of sampling schemes. The maximum length of time before servicing (replacement of the DSM) is controlled by the storage capacity of the DSM and varies with the sampling scheme as summarized in Table 1. The recorder is equipped with a liquid crystal display and readback routine to allow the user to field check the instantaneous readings (against manual measurements) and the data previously stored on the DSM. This manufacturer markets a reader for transferring the data from the DSM to a variety of host computers for permanent storage and processing. Once the data have been transferred to permanent storage, the DSM can be erased by exposure to ultraviolet light and then reused.

Signal-Conditioning Circuitry

The signal-conditioning circuitry is triggered by the recorder command pulse to provide a stable excitation voltage for the sensor during the sampling and is shut down between samplings. This limits the

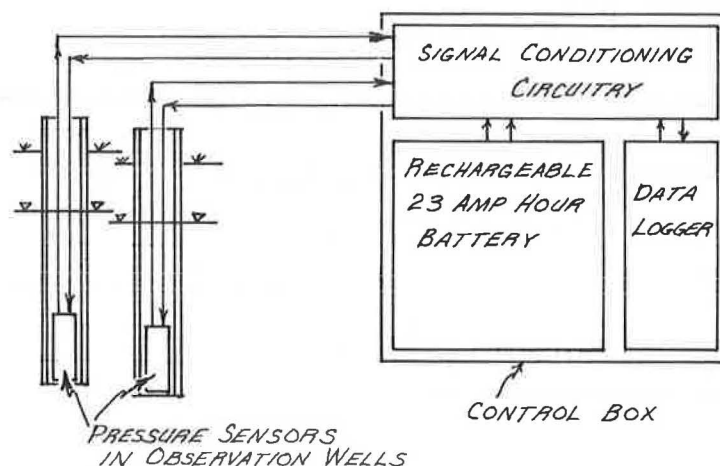


FIGURE 2 Major groundwater monitoring instrumentation components.

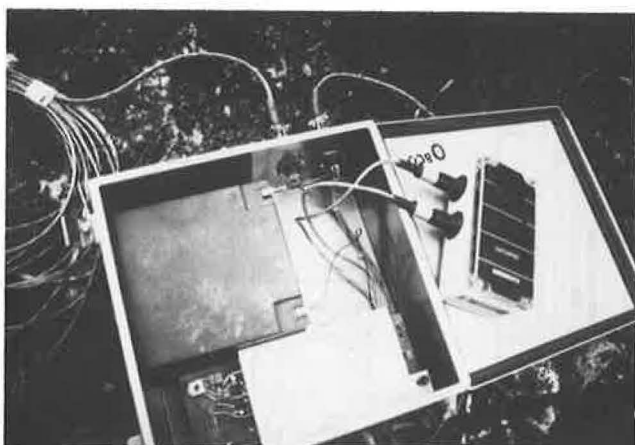


FIGURE 3 Watertight case with major components.

power drain to about 2 min per sampling interval (1 min before sampling and 1 min after). All critical components have low thermal coefficients to ensure accuracy over a wide temperature range. Reference and scale of the output voltage are adjustable to allow calibration of the sensor output to the recorder in either of the following optional modes:

1. Depth from the top of the observation well to the water level (as used in groundwater monitoring to be in the same format as manual water-level measurements) and
2. Height of water level above the sensor (as used in the precipitation gauges to monitor accumulated precipitation).

This circuitry was developed by the Forest Service and is not yet commercially available. Schematics, printed circuit diagram, materials list, and so on,

will be available in a technical report in the near future. Materials costs are summarized in Table 2. Using a printed circuit board, an electronics technician can assemble the unit in about a day and a half.

Sensor (Pressure Transducer)

A solid-state differential pressure transducer placed at the bottom of the observation well (or precipitation reservoir tank) senses the weight of the liquid above it. Silicon-diaphragm gauge-type transducers are being tested that have one port (the front of the diaphragm) open to the water and another port (the back of the diaphragm) vented to the surface to nullify the effects of variations in atmospheric pressure. These silicon-diaphragm transducers are available from several manufacturers and come in a variety of pressure ranges and accuracy ranges, with or without temperature-compensating thermistors, a variety of mechanical configurations, and a variety of price ranges. Unfortunately, none are made with a mechanical configuration designed for this purpose, that is, economical installation under water in a 1.5-in. I.D. observation well.

In Figure 4 and Table 2 three types of transducers and mechanical enclosures being tested in this project are summarized. Type A was used initially at all trial field applications and proved satisfactory in terms of cost, accuracy, and so on, for groundwater monitoring. However, extensive problems were encountered with the mechanical configuration in leakage and failure by saturation through the atmospheric vent port or by galvanic degradation. The transducer referred to as type B, although more expensive, has the best mechanical configuration because it is factory enclosed and the atmospheric port is vented to the surface through a second tube, greatly reducing the potential for saturation damage. At this time, the manufacturer is discontinuing this type as a stock item and in the future it will

TABLE 2 Summary of Instrumentation Components

Major Component	Manufacturer	Description	Approx. Cost (\$1982)
Data logger	Omnidata International, Logan, Utah	Datapod model 212S One or two channels Accuracy: 0.5 percent of full scale Power: eight internal AA alkaline batteries Operating life: 9-12 months	745
Signal-conditioning circuitry	Assembled by Forest Service	One or two channels Current consumption: standby, <0.15 mA; load, 5.5 mA Automatic zero amplifiers for temperature stability	250 ^a
Battery	Several	Sealed gelled electrolyte, 12-V, 23-A·hr Weight: 19 lb Size: 6.5 x 6.75 x 5.5 in.	90
Sensors (pressure transducer only)			
Type A	MicroSwitch, Freepport, Ill.	Model 135PC05G2 Range: pressure, 0-5 psi; height of water, 0-12 ft Accuracy: ±1.5 percent Not factory enclosed Not temperature compensated	40
Type B	Foxboro/I.C.T., San Jose, Calif.	Model 1700 Range: pressure, 0-10 psi; height of water, 0-23 ft Accuracy: ±0.5 percent Factory enclosed Not temperature compensated	160 (?)
Type C	Foxboro/I.C.T., San Jose, Calif.	Model 2170 Range: pressure, 0-15 psi; height of water, 0-35 ft Accuracy: ±0.25 percent Not factory enclosed Not temperature compensated	90

^aFor components.

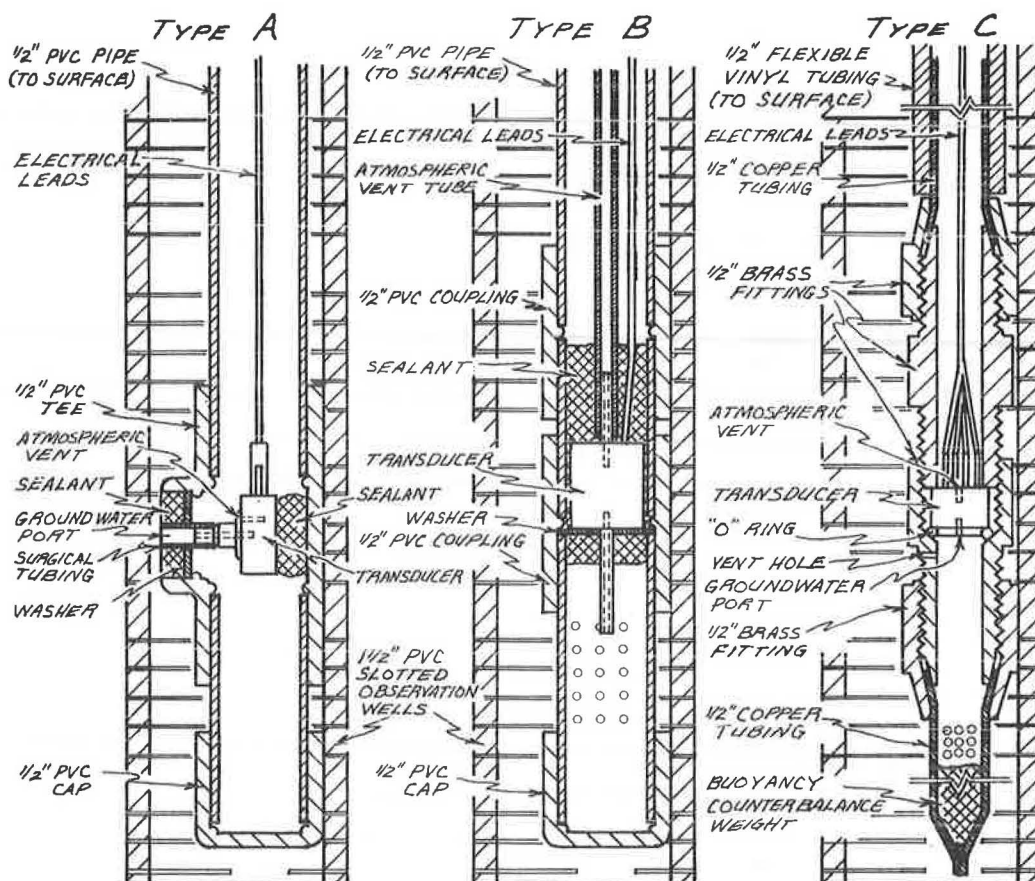


FIGURE 4 Mechanical configuration of three pressure sensors.

have to be custom made, further increasing the cost. Type C is performing well, is less likely to be saturated than type A, but is not as positively sealed and is more difficult to assemble than type B.

At this time, the unavailability of a dependable economical transducer in a positively sealed enclosure of the size and shape required for this purpose is the weakest link in the system.

FIELD INSTALLATIONS

Field installations to test the instrumentation under actual conditions have been made over the past two field seasons and new installations are continuing to be made in conjunction with current landslide stabilization projects being conducted by Forest Service geotechnical engineers. The following summarizes the field installation procedures.

Observation Wells

At sites inaccessible to truck-mounted or track-mounted rotary drilling equipment, a semiportable A-frame mast and motorized cathead were used with standard penetration test (SPT) equipment [140-lb hammer, AW rod, and 2-in. O.D. split-spoon sampler (ASTM D 1586)]. The drilling procedure was to perform successive standard penetration tests through the soil mantle and below the drainage barrier to a depth sufficient to verify that the barrier had been penetrated. Typical drill hole depths ranged from 5 to 30 ft in the variety of geologic materials sum-

marized previously. This method has the added advantages of providing continuous soil samples and SPT rates for compiling an accurate drill log and of not requiring drilling water so that groundwater is easier to detect. Production rates for a three-person crew (two drilling and one logging and processing samples) ranged from two to five observation wells per day.

The observation wells were cased with 1.5-in. I.D. polyvinylchloride (PVC) horizontal drain flush-joint casing slotted with 0.02-in. openings in the lower section and unslotted in the upper section. In most cases the hole diameter resulting from the penetration of the 2-in. sampler provided sufficient clearance and remained open long enough for easy installation of the PVC casing.

The annulus between the drill hole and PVC casing was small but required backfilling and sealing to prevent surface water infiltration along the casing. Backfilling was with clean, poorly graded sand to within 1 ft of the surface. Sealing at the surface was with bentonite pellets.

Sensors in Observation Wells

Type A and B transducers were mounted in conventional 0.5-in. I.D., thin-walled PVC plastic water pipe available at most hardware stores. This pipe is available in lengths that allow an uncoupled 20-ft rigid conduit from the top of the observation well to the transducer. The pipe serves two purposes:

- The type C transducer was mounted at the bottom of a clear 0.5-in. I.D. flexible vinyl tubing, which is more suitable for deeper holes because the length does not pose a limitation. The buoyancy of the submerged length of flexible tube must be compensated for by weight placed at the bottom of the sensor (see Figure 4).

The pressure transducer for the sacramento gauge should be of the temperature-compensating type because it is mounted above ground and subjected to extreme temperature fluctuations. A type A transducer (which is not temperature compensating) was used initially and the resulting data showed variations from temperature (i.e., daily fluctuations between minimum and maximum recordings over a period of the

A problem with the initial lysimeter installations rendered the first season's data useless. The catch basin was designed 1 x 1 ft square to ensure that the capacity of the 55-gal barrel would not be exceeded by a maximum equivalent rainfall of 100 in. The basins were installed about 1 in. above the ground to prevent surface runoff from entering (see Figure 1). In all installations for the first season the lysimeters contained a negligible quantity of water, even though the sacramento gauges had volumes indicating more than 30 in. of equivalent rainfall. One explanation is that ice over the hardware cloth covering the catch basin at the base of the snowpack might have prevented snowmelt from entering the basin. An alternate design now being tested involves

1. Burying the entire catchment area below the ground surface, backfilling with native topsoil, and revegetating to natural conditions; and
2. Using a much larger catchment area and resorting to a buried tipping-bucket type rain gauge if necessary to eliminate the problem of the 55-gal capacity.

The practical applications of long-term groundwater monitoring are numerous. The following discussion (based on interpretation of actual groundwater data recovered during the first two monitoring seasons) will be used to illustrate a few.



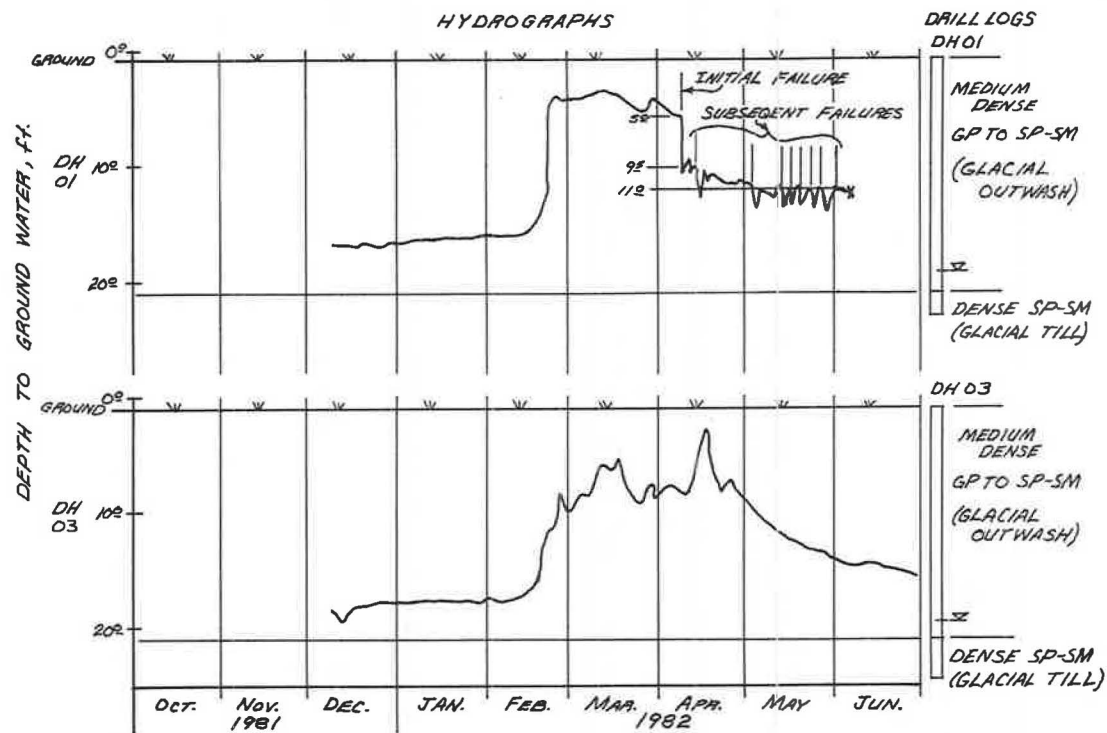


FIGURE 6 Groundwater plot for Cable Car landslide, Flathead National Forest, Montana.

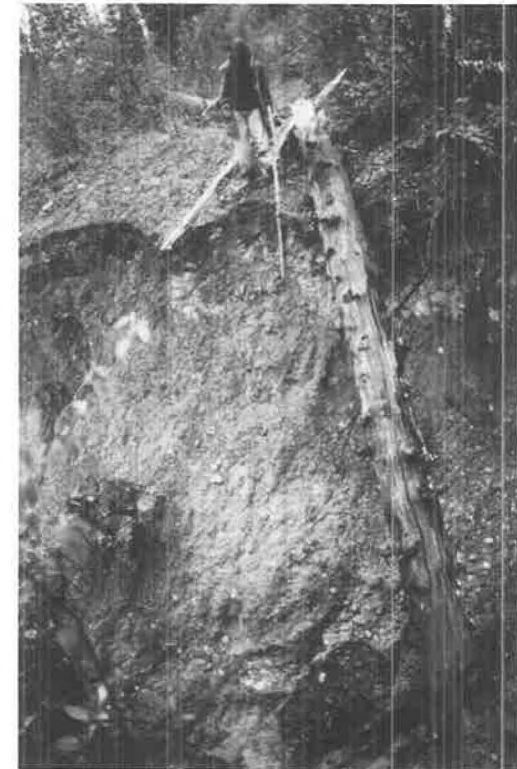


FIGURE 7 Scarp at drill hole 1 after 1982 failure of Cable Car landslide.

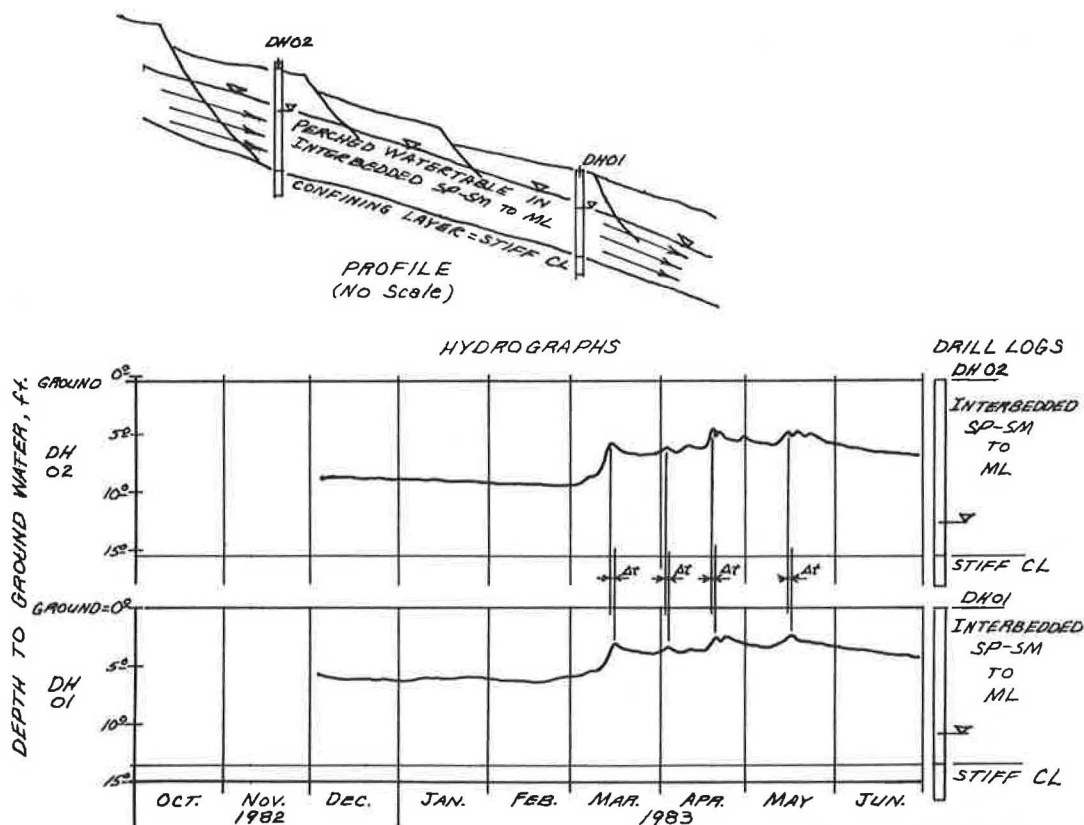


FIGURE 8 Groundwater plot for Doney-Willow landslide, Deerlodge National Forest, Montana.

Groundwater Rise in Response to Precipitation Modeling

Figure 5 is a composite plot of hydrographs of groundwater and sacramento gauge data recovered on two small watersheds in northern Idaho. All observation wells are in similar geologic material, as shown on the logs. One well (DH 24) is in a north-aspect watershed about 0.5 mile from the south-aspect watershed, where the other drill holes and precipitation station are located. The data from all three wells show a similar response to some of the precipitation as recorded in the sacramento gauge data. The response is primarily to late-season precipitation, which is usually in the form of rain on snow. Lysimeter data, when the monitoring technique is perfected, will help to explain this recharge phenomenon. Some preliminary inferences as to the location of the drainage barriers and relative differences in response due to aspect can also be made from comparison of the three groundwater hydrographs. Groundwater rise in response to precipitation modeling is the key element in analysis of probability of landslide occurrence.

Landslide Correction

Figure 6 shows a composite of hydrographs for groundwater data from two observation wells located above the scarp of an active landslide in western Montana. During the monitoring season, the scarp had advanced adjacent to and beyond the observation well in drill hole 1 (Figure 7). Comparison of the two hydrographs suggests a progressive mode of failure

at drill hole 1 with several groundwater peaks at subsequently lower levels apparently triggering additional landslide movement. The practical application of these data is in the selection of the critical undrained and drained phreatic surfaces to use in the stability analysis and stabilization drainage system design.

Aquifer Analysis

Figure 8 shows a composite of hydrographs for groundwater data from two observation wells about 100 ft apart in another active landslide in western Montana. The two wells are in the direction of groundwater flow and have similar response curves; the groundwater peaks arrive at the lower location about 24 hr after the upper location (closer time definition is possible by sampling at shorter intervals). Using a seepage velocity of 100 ft/day with the hydraulic gradient and estimated effective porosity of the soil, a coefficient of permeability in the range of 10^{-2} cm/sec was estimated.

The coarsest aquifer soil noted on the log was a fine SP (poorly graded sand). This field-determined value appears high when compared with laboratory-determined permeability for similar soils. Data such as these should be useful in evaluating the piping and channel-making phenomena discussed earlier and in the location and sizing of stabilization drainage systems.