

PROPOSAL FOR INSTRUMENTATION AND STUDY
OF THE GALLATIN SEISMIC-SENSITIVE WELL

by

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A professional paper submitted to the Graduate Faculty in partial
fulfillment of the requirements for the degree

of

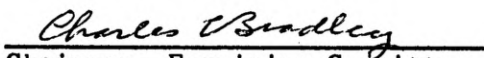
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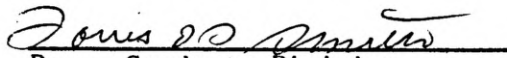
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AUTHOR'S NOTE

This paper is written with the intention that most of the contents may be used, without alteration, as a request for funds, to be submitted to the National Science Foundation. Therefore, certain liberties in standard form have been taken. Pages numbered with small-case letters following the normal digit are those that apply only to the academic use of the paper.

ACKNOWLEDGMENTS

I would like to thank Dr. C. C. Bradley, who originally introduced me to the Gallatin Well and has provided me with the results of his cursory studies as well as continued advice throughout the investigation.

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ABSTRACT

Water-level fluctuations in wells as a response to seismic activity have been a subject of occasional publication for over sixty years. Several attempts to correlate amplitude of fluctuation to the magnitude of the corresponding earthquakes have been made with varying degrees of success. Major drawbacks in the studies have been lack of adequate instrumentation and large distances to nearest seismograph stations.

A well in Gallatin County, Montana, has shown anomalous water-level fluctuations associated with distant earthquakes, passage of local freight trains, passage of barometric fronts, and unknown causes. The known responsiveness, plus location near two seismograph stations, as well as open-field accessibility, make the Gallatin Well outstanding in data potential.

Several possible water-level recording instrument systems for the Well were investigated. A modification of the Hydro-Sonic fluid-level monitor, manufactured by the Hydro Products Company, in San Diego, California, is proposed for use. With advanced instrumentation, further study of seismic-sensitive well activity will be possible to a degree of completeness yet unattained, thereby significantly contributing to the science of hydroseismology.

A grant of \$13,942 is requested for instrumentation and support of a three-year research program.

PROPOSAL FOR INSTRUMENTATION AND STUDY OF THE GALLATIN SEISMIC-SENSITIVE WELL

INTRODUCTION

Seismic-sensitive wells are water wells that exhibit anomalous water-level fluctuations as a result of natural or applied seismic disturbances. They may also respond to barometric pressure change, artificial loading of adjacent ground surface, and other phenomena.

To clarify the text, the following terms are defined:

Hydrograph--Any instrument used to maintain a graphic record of water level versus time. Reference is made to the resulting record as "hydrograph record" or merely "record."

Seismograph--An apparatus designed to record seismic waves in the earth's crust, generally mounted on or near the ground surface. The resulting records are designated "seismograph record" or "record" only.

Hydroseismograph--A hydrograph designed specifically to record water-surface fluctuations resulting from seismic disturbance. (Primarily a definition of intent or use rather than equipment.)

Hydroseismology--The study of the response of water bodies, primarily ground water, to seismic phenomena.

In order to avoid confusion, the terms hydrogram, seismogram, seismometer, phreatic seismograph, and seismohydrology are not utilized.

The more responsive wells penetrate confined aquifers, but many water-table wells are also seismic-sensitive.

A seismic-sensitive well, with no apparent confining layer, has been discovered in the Gallatin Valley of Montana. This well is herein referred to as the "Gallatin Well." A Stevens Type-F hydrograph (Figure 1) mounted on the Well has revealed anomalous rapid water-level fluctuations in response to distant earthquakes and to the passage of local freight trains.

A review of the literature discloses that the Gallatin Well is outstanding in data potential. It shows response to both natural and artificial loading, and its location near two prominent seismograph stations makes possible a correlation between seismic waves and the ground-water oscillations resulting from those seismic waves.

The condensed time scale of the present hydrograph records, however, does not permit observation in sufficient detail of water-table fluctuations for advanced study. Thus, the problem of finding or developing suitable instrumentation arises.

The following is a proposal which requests financial support for the instrumentation and further study of water-level fluctuations in the Gallatin Well.

STATEMENT OF THE PROBLEM

The objective of this investigation was to either find or develop suitable instrumentation for recording water-level fluctuations in the Gallatin Well.

It is hoped that this paper will not only lay the groundwork for continued research in hydroseismology at Montana State College, but will also lead to further applications of the proposed instrument system. The appendices provide future researchers with further details, some of which are tangential to the main purpose of this report. Appendix E-1 contains suggestions for use of this paper as a grant request to the National Science Foundation. This grant is to support a three-year study program of the behavior of the water surface in the Gallatin Well.

SEISMIC-SENSITIVE WELLS--PREVIOUS WORK

The seismicity of water wells seems to have been discovered accidentally as a result of normal hydrograph operations. Response to earthquake-generated seismic waves, passage of railroad trains, barometric pressure changes, tidal forces, and other phenomena has been reported.

Response to Seismic Waves

The earliest report of seismic activity in wells was made by King (Veatch, 1906) in 1892. Veatch (1906) stated that "Earthquakes may produce water-table fluctuations due to several causes; small fluctuations may result directly from the earth's tremors; a faulting without deformation may produce changes in pressure. . . ." He referred to no specific observations, however. Stearns (1928) and Piper (1932) reported that anomalous, rapid water fluctuations caused by earthquakes were recorded by hydrographs in California.

A few quantitative studies of hydroseismograph records have been published. Blanchard and Byerly (1935) reported that earthquake-generated S waves were not recorded but that strong P waves were recorded corresponding to an earthquake that displayed S waves four times as strong as P waves at the nearby Berkeley, California, seismograph. The P, or primary wave, is a longitudinal, body-traversing, seismic wave. The S, or secondary wave is a transverse, body-traversing, seismic wave of slightly slower velocity.

Blanchard and Byerly claimed that only waves creating dilatation of the aquifer [P and Rayleigh waves] will be recorded on a hydroseismograph.

Their operational theory is based on a change in volume of the aquifer from which they derive mathematical expressions using a confined water volume. For simplification they assumed the unreal condition of 100 per cent porosity with a water volume equivalent to actual porosity of the area involved. They also assumed a rectangular confinement. Thus, the flow time into and out of the well from the surrounding porous media was not considered in their formulae. Blanchard and Byerly noted, however, that a water-pressure recorder would be of greater interest to a seismologist than a hydrograph because of faster response.

Thomas (1940) reported that "stage recorders" (hydrographs) are most effective in wells for long-period seismic waves (i.e., waves of 20-second or more period), as wells are especially responsive to waves in this range. This is primarily a result of the time required for the water to flow to and from the well from surrounding porous earth. Shorter periods, he stated, of one to five seconds may better be recorded as resultant water-pressure change. This requires capping of the well, preferably at or below the static water level.

Since 1947, E. E. Rexin (1952, 1960) has maintained an expanded time-scale hydroseismograph on the especially responsive well in the basement of the Nunn-Bush Shoe Company in Milwaukee, Wisconsin. Rexin's records have been the basis for other interpretative reports and applied assumptions (Vorhis, 1955; Eaton and Takasaki, 1959; Rexin, Oliver and Prentiss, 1962). His is apparently the only regularly maintained hydroseismograph producing detailed records.

Vorhis (1955) was unable to find any correlation between the "maximum water-level flux" and true horizontal ground movement caused by earthquakes. He used Rexin's hydroseismograph records with seismograph records from Chicago, Illinois, and hydrograph and seismograph records from Honolulu, Hawaii. He believed that comparison to long-period vertical seismograph records would show a marked correlation. He found only poor correlation between the Gutenberg-Richter earthquake magnitudes, combined with epicentral distance, and water-table fluctuations. The earthquake magnitudes are values based on the maximum amplitude recorded on a standard seismograph.

Vorhis also mentioned that at that time (1955) the U. S. Geological Survey had data on file for several thousand earthquake-caused, water-level fluctuations, 161 of which were recorded for the quake in Assam on August 15, 1950. These data are continuously compiled and may be found in the annual publication "United States Earthquakes, 19__," which was first published in 1928 by the U. S. Coast and Geodetic Survey.

Eaton and Takasaki (1959), working in Hawaii using condensed time-scale hydrograph records, measured only the maximum double amplitude of earthquake response. They stated that the four major types of seismic waves (P, S, Love, and Rayleigh) may either produce a volume change in the material that carries them or generate waves that can. Rayleigh and Love waves are surface seismic waves. Rayleigh waves are analogous to water-surface waves, and Love waves are horizontally transverse. Eaton and Takasaki noted that evidence available at that time (1959) indicated

that the largest water-level fluctuations occurring in wells are induced by Rayleigh waves. Their main evidence was Rexin's (1952) previous records.

Eaton and Takasaki also discussed the theoretical aspects of dilatation and frequency, eliminating the P and S waves as possible producers of maximum fluctuations. They believed that if an earthquake produces large Love waves and small Rayleigh waves, the magnitude indicated by the well should be considerably smaller than that assigned by a conventional seismograph station. The conventional seismograph responds equally to either wave type.

Eaton and Takasaki also compared quake magnitudes assigned by the Pasadena, California, seismograph station with the amplitude of water-level fluctuations in a well in Hawaii. They also checked against the Oahu seismograph records for predominant wave type. The results confirmed their theory of the predominance of Rayleigh wave response in the Hawaiian well. They also concluded that their Hawaiian hydrograph (as a hydro-seismograph) was 70 times as responsive as a normal Woods-Anderson seismograph to Rayleigh waves of a 20-second or more period. The response for other types of disturbances varied down to one-third for a predominantly Love-wave earthquake.

Rexin and others (1962), utilizing the Rexin hydroseismograph in Milwaukee, tentatively identified P, PP, PPP, PS, PPS, S, SS, SSS, SKS, Love, and Rayleigh waves on their records. The Rayleigh waves of greater than 20-second period appeared to cause the largest amplitude of fluctuation. During the Assam quake of August 15, 1950, Rexin observed (but could not record) a double amplitude of 11.9 feet in the Milwaukee well!

The Hebgen, Montana, quake of August 18, 1959 produced 2.5 feet of fluctuation. Rexin and others (1962) also stated that Parker and Stringfield reported observing in Florida a double amplitude of $4\frac{1}{2}$ feet for a Dominican Republic quake. They estimated that value, however, from an interrupted record, assuming a direct correlation between earthquake magnitudes and water fluctuation. They used a value of 3.08 feet from a later quake for calculation. Parker and Stringfield also reported 16 quakes(?) not detected by seismograph stations.

Response to Passing Trains

The earliest report found of a well exhibiting a water-level response to the passage of a train was that of King in 1892 (Vorhis, 1906). He described a rapid rise and slow return of the level as the train passed. He noted that higher speeds of a train increased the amount of rise and that the water level fell only after the locomotive had passed a certain position.

C. E. Jacob (1939) reported similar train-induced water fluctuations in an artesian aquifer on Long Island. As the train applied a load to the surface, he observed a sharp rise in water level, then a gradual decline of the water level to the initial level. Upon release of the load there was a sharp drop nearly equal to the previous rise and again a slow, nearly equal, rate of return to initial level. He explained, assuming a near-perfect elastic aquifer material, that "ultimately all the increased proportion of the load is born by the solid material of the aquifer, the hydrostatic pressure having been restored to its initial level."

Upon release of the load, the aquifer rebounds, creating a pressure deficiency, and the water slowly returns. No earthquake response was described. Jacobs mentioned the need for friction-free, non float-driven instrumentation to eliminate inaccuracies in the records caused by float lag and friction.

Very complete records were obtained by Roberts and Romine (1947) from a well near a rail siding in Illinois. Through cooperation of the Illinois Central System, they recorded well response to trains at various speeds, starting, stopping, pausing for given intervals, and reversing over the sensitive surface area. They showed no drop of water level below initial level upon release of the loading. No earthquake response was described for this well.

Using condensed time-scale hydrographs, Parker and Stringfield (1950) showed train effects as asymmetrical pips on the records, indicating that there probably was a sharp drop below initial level after lifting of the load. They reported differing recovery response at separate wells and speculated that it was due to dissimilar elasticity of the aquifer involved. No attempts were made to relate train and earthquake reactions, though both appear on the same record.

Barometric Response

Veatch (1906) briefly reviewed previous accounts of wells reacting to barometric change by a change in water level sometimes accompanied by an inrushing or exhaust of air ("blowing wells"). He includes a short bibliography, the oldest reference being a U. S. Geological Survey paper of 1899 on a "blowing well."

Roberts and Romine (1947) described a well with a barometric efficiency of 50 per cent; i.e., for every unit of water change of a barometer reading, the well responds with one-half unit of water-level change. As the barometer "falls," the water level in the well rises. Parker and Stringfield (1950) also give an account of similar action.

Response to Tidal Forces

Response to ocean tides and possibly earth tides may be observed in ordinary wells and seismic-sensitive wells. An extensive bibliography concerning tidal effects and dating back to 1724 is given by Veatch (1906). Most of these accounts reported a delayed rise in water level in coastal area wells after high tide and a delayed lowering after low tide. Klönne (Robinson, 1939) reported in 1880 on tidal oscillations of water level in a coal mine in Dux, Germany. Young (Robinson, 1939) reported tidal effects in inland wells in South Africa. Robinson (1939) describes two wells, one in New Mexico and one in Iowa, that display water-table fluctuations synchronised with the tidal period. He applied corrections for barometric response to the hydrograph records. The Nunn-Bush Shoe Company well also displayed prominent water fluctuations reflecting tidal forces (Bradley, personal communication).

Other Responses

Rainstorms, adjacent river-level variations, irrigation systems, and nearby pumping wells may cause water-level changes in both ordinary and seismic-sensitive wells.

Parker and Stringfield (1950) also noted water-level rise due to the "atomizer effect," or pressure reduction, caused by high winds blowing past a well's open casing.

According to Veatch (1906), quite a few observers at dispersed locations have discovered regular 20-minute to 45-minute oscillations of unknown origin. While these authors do not mention it, the period strongly suggests that these fluctuations may reflect the fundamental body oscillations of the earth.

Summary

Most authors concluded that better instrumentation was needed for further interpretation of seismic-sensitive well activity. All authors who mention the type of equipment that was utilized used either a Stevens Type E or Type F hydrograph or a very similar float-driven apparatus. Some investigators believed that the wells were as good, if not better than, standard seismographs for detection and recording of long-period (20-second) Rayleigh waves and were of some value in recording other types. Rexin's instrument combined with the exceptional well in Milwaukee produces the only regularly maintained hydroseismograph records known. His hydroseismograph has some mechanical disadvantages, such as float lag and friction.

The actual mechanism by which the wells function is debated. Jacob (1939) has presented the most material concerning theoretical action of elastic aquifers. It is generally accepted that not all seismic-sensitive wells may operate by the same mechanism. Quantitative work

is hampered by difficulty in defining the involved volume of water, volume change in aquifer, and other underground parameters.

Most wells are lacking in one or more of the responsive phenomena or in having adjacent seismograph stations for comparison and analysis. There has been no attempt to relate, even empirically, known loading response to the behavior of a well under natural seismic activity. Correlation of well-water fluctuation to earthquake magnitudes and distances has only begun, and little is understood or reported in relation to earth tide or undefined anomalies appearing on the hydrograph records.

It appears that there is much that can and should be done in basic research on seismic-sensitive well behavior. This requires advanced instrumentation on a properly located well.

THE GALLATIN WELL

Description

The Gallatin seismic-sensitive well is located north of Belgrade, Montana, sec. 25, T. 1 N., R. 4 E., on the Quaternary stream gravels of the Gallatin Valley. It was drilled as an observation well for the U. S. Geological Survey as part of the geology and ground-water study conducted by O. M. Hackett and others. It is designated as Well A1-4-25dc in their report (Hackett and others, 1960). The Well is presently 101 feet deep and cased with 6-inch perforated steel casing. It is reported as a normal water-table well in spite of its seismicity.

Table 1 is a log of the Gallatin Well to present depth. Appendix A carries more complete data.

Table 1

Partial Log of the Gallatin Well

Layer Description	Thickness in Feet	Depth from Ground Level in Feet
(top)		
Gravel, sandy, silty, calcareous; contains cobbles composed of volcanic and metamor- phic rocks	50	50
Gravel; contains sand lenses	40	90
Gravel, sandy	120	210
(bottom)		
Principal water-bearing strata	45	10-55
Water surface average	--	10
Saturated zone	360	60-400

Modified from Page 189, Hackett and others (1960).

Hydrograph Records

A Stevens Type F hydrograph (Figure 1) is mounted on the Gallatin Well. The records produced since 1952 have been maintained under the direction of Dr. C. C. Bradley, of Montana State College. At the present time the horizontal time scale used is 0.3 inches per day. Past records

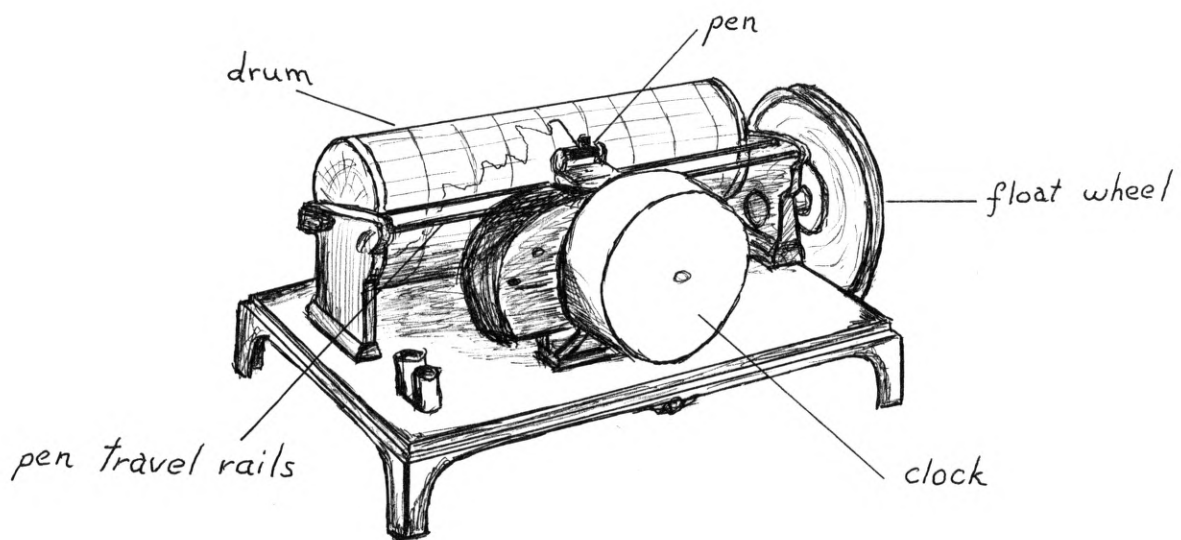


Figure 1. Stevens Type F Hydrograph

display anomalous, sharp, vertical traces, or pips, that indicate rapid water-level fluctuations. Correlation of the traces by Dr. Bradley reveals that many of the anomalous, rapid water-level movements have been caused by earthquakes and passage of local freight trains. Thus, the Gallatin Well is seismic-sensitive.

Earthquake Response

Seismic waves generated by earthquakes produce symmetrical pips on the hydrograph records. Individual oscillations are not differentiated

because of the condensed time scale. It is sometimes evident, however, that activity has continued or been repeated for many hours. Both the Bakersfield, California, quake of July 21, 1952 and the August 17, 1959 Hebgen, Montana, quake produced water-level oscillations in the Gallatin Well of over a foot. At one foot water-level change the hydrograph overlaps itself and true amplitude may not be read on the record. The Hebgen quake also caused the float wire to jump from the float wheel of the hydrograph, rendering it temporarily inoperative.

Plate I is a full-scale reproduction of the record resulting from the Siberian quake of November 4, 1952. Plate IV shows other small quakes.

Dr. Bradley (personal communication) has also found an approximate linear trend in the relationship of maximum water fluctuation in the Well and maximum amplitude on corresponding seismograph records (Figure 2). These records were from the old seismograph at Montana State College. It was replaced by a more sensitive type in 1959.

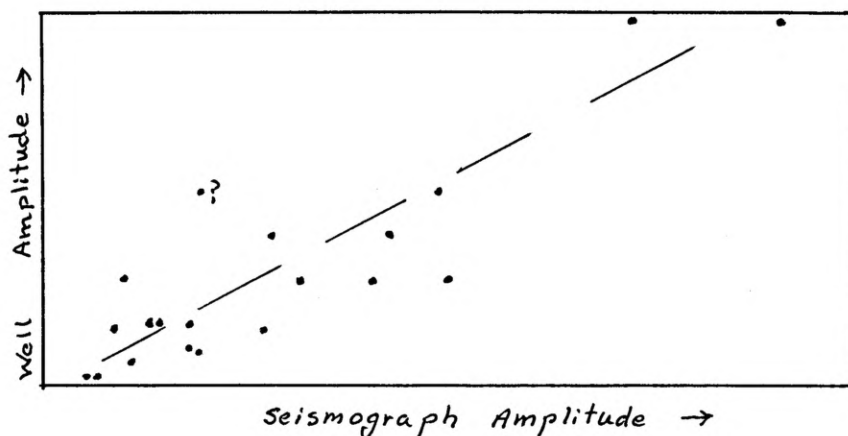


Figure 2. The relationship between the amplitude of the maximum water oscillation in the Gallatin Well caused by earthquakes and the corresponding maximum amplitude shown on the Montana State College seismograph records.

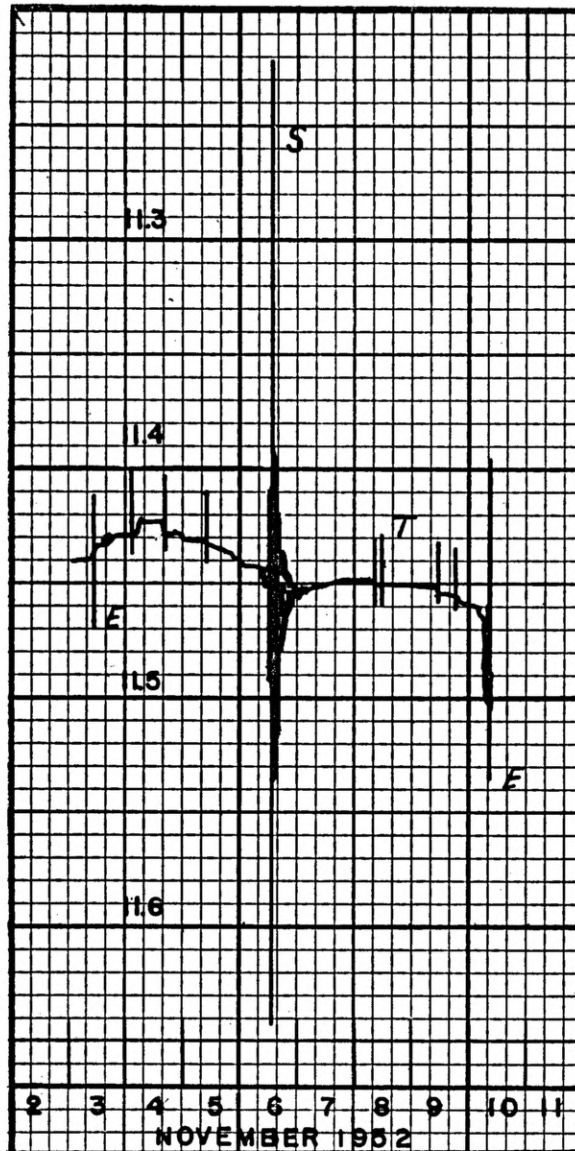


Plate I. Hydrograph record of a Siberian earthquake. A full-size reproduction of part of a monthly hydrograph record from the Gallatin Well. The large symmetrical pip, S, represents the Siberian quake of November 6, 1952. Note the continued or repeating oscillations for a period of 12 hours. Two other earthquake response traces, E, are also shown. Vertical scale is in feet; horizontal scale is in days.

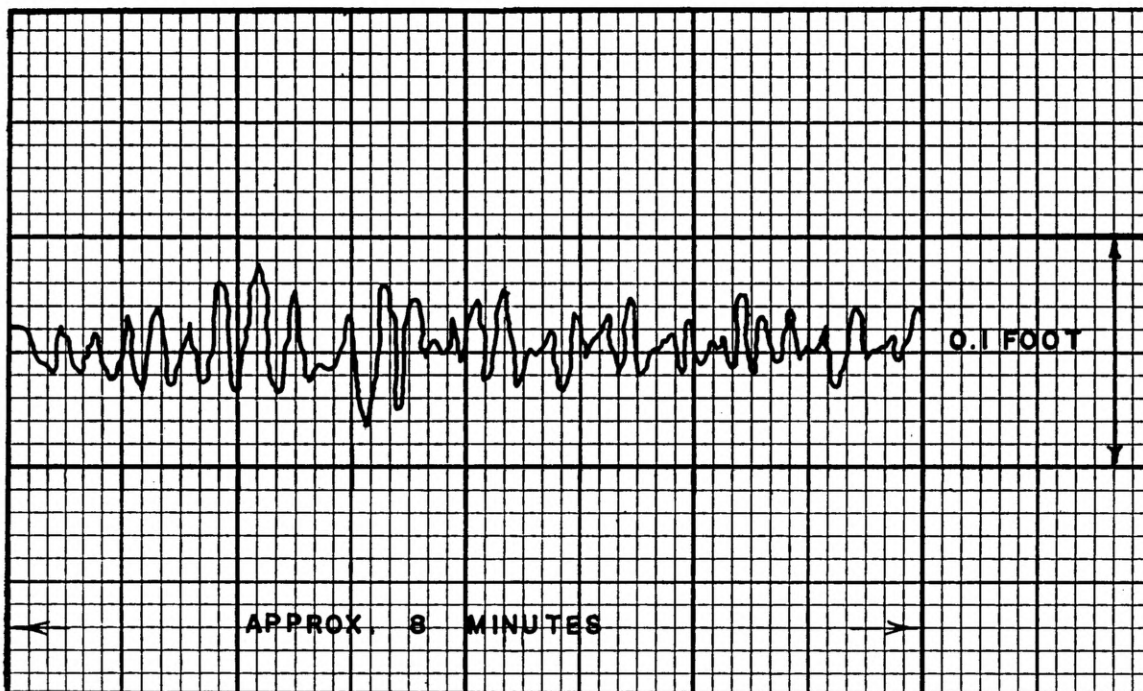
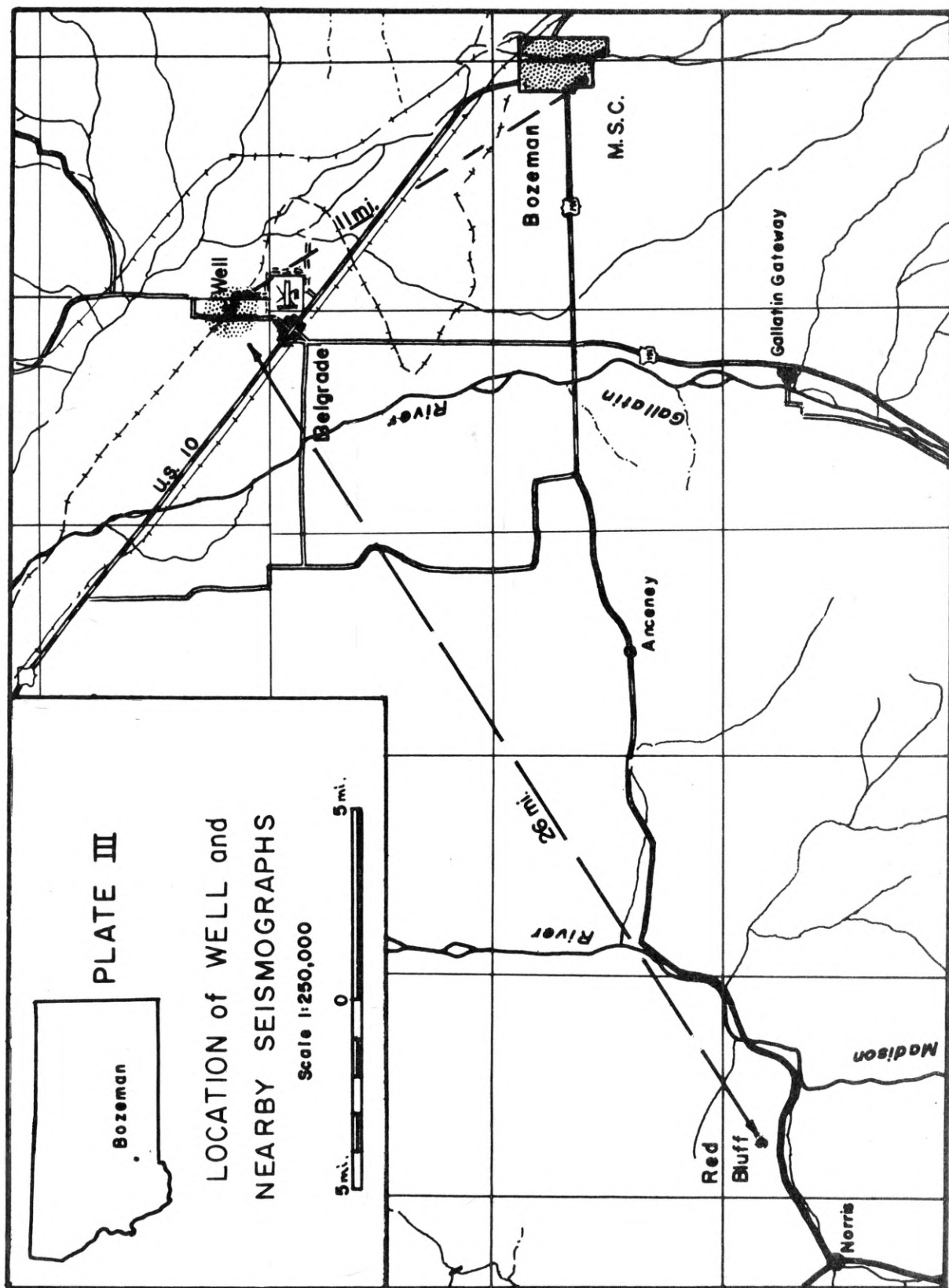


Plate II. Hydroseismograph record of a Chilean earthquake. A full-scale reproduction of the hydroseismograph record produced at the Gallatin Well, by manually advancing the recording pen. The response is to seismic waves from the Chilean quake of May 22, 1961. Note the approximate wave period of 20 seconds.

On May 22, 1961 Dr. Bradley had the luck to be present at the Gallatin Well when waves generated by an earthquake in Chili were passing. He manually advanced the hydrograph recording pen for a period of approximately eight minutes. The resulting detailed record is shown on Plate II. These Chilean quake-caused oscillations display a period of 15 to 20 seconds, which compared favorably with the records of the nearby Montana State College seismograph. This periodicity is also in the range of the previously mentioned earthquake response of other seismic-sensitive wells. With advanced instrumentation an attempt at correlation of earthquake magnitude, wave type, epicentral distance, and the well-water oscillations may be made. This would involve extensive use of available seismograph records.

Adjacent Seismographs

Two seismograph stations are in the vicinity of the Well. One is at Montana State College, only 11.2 miles southeast of the Well (Plate III). It is a three-component instrument mounted in Quaternary alluvial-fan gravels continuous and contiguous with the gravels penetrated by the Gallatin Well. The second station is currently under construction (summer, 1963) in the old Red Bluffs mine, 2.5 miles east of Norris, Montana, in the Lower Hot Springs mining district. It is 27 miles southwest of the Gallatin Well and 29 miles west of the Montana State College seismograph. This station is to be a member of the U. S. Coast and Geodetic Survey's 125-station, world-wide seismograph network. It will be mounted in Precambrian gneiss bedrock.



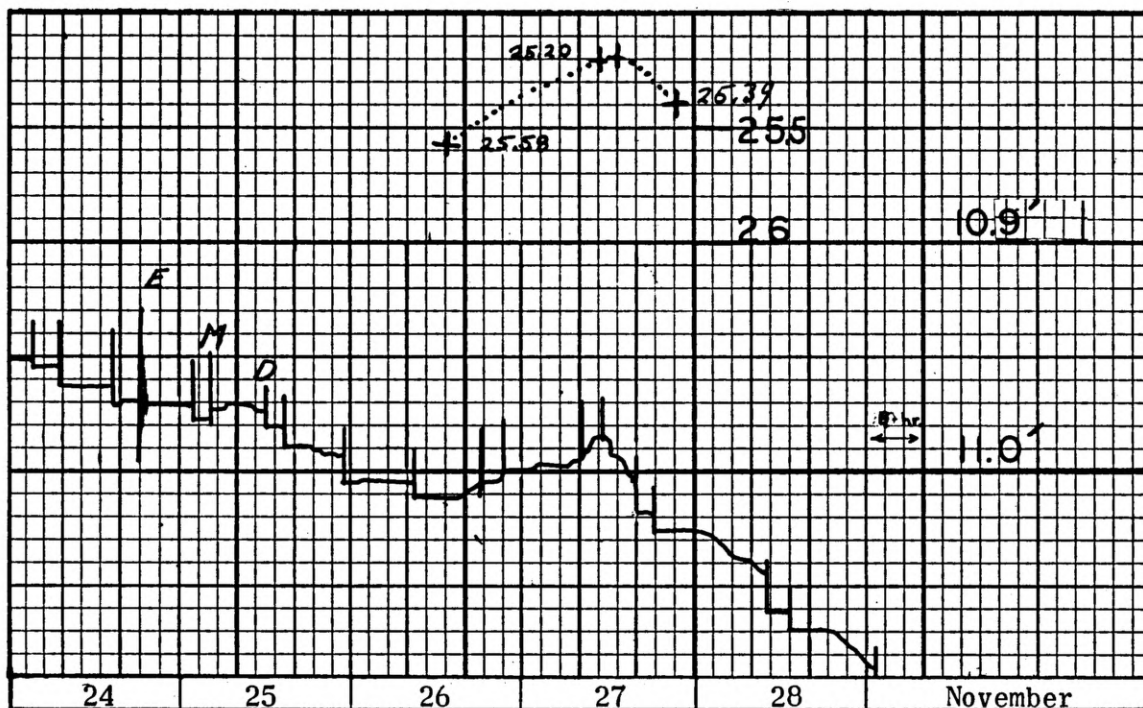


Plate IV. Hydrograph record showing several responses. A full-scale reproduction of a portion of a weekly hydrograph record from the Gallatin Well. An earthquake trace is shown as symmetrical pip, E. The asymmetrical pips represent passing trains with Mallet locomotives, M, and Diesel locomotives, D. The corresponding barometric pressure, in inches mercury, is indicated in the upper portion of the graph. This exhibits a barometric efficiency for the Well of approximately 15 per cent.

Train Response

Asymmetrical pips on the hydrograph records were caused by the passage of local freight trains on a track 150 feet from the Well (Plate V.). These pips indicate that the magnitude of the water-level oscillations generally corresponds to the weight of the locomotive. It was also indicated by response timing that the weight of the train is only effective in terms of well response over a limited surface area. This area extends about 40 feet measured in the direction of the track (Plate V.).

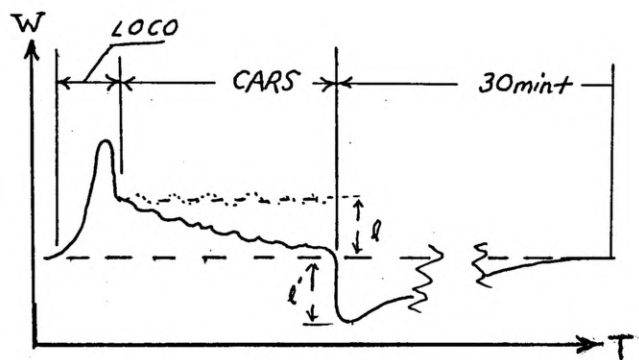


Figure 3. Schematic drawing of the Gallatin Well's response to passing trains. W is water level, T is time.

Figure 3 is a schematic drawing of the Well's response to trains as described by Dr. Bradley (personal communication). The diagram demonstrates that as the freight train passes over the sensitive area there is an immediate rise of water level in the well. After passage of the locomotive, there is a subsequent partial drop. Then, as the rest of the train passes by, the water surface oscillates slightly due to passage of

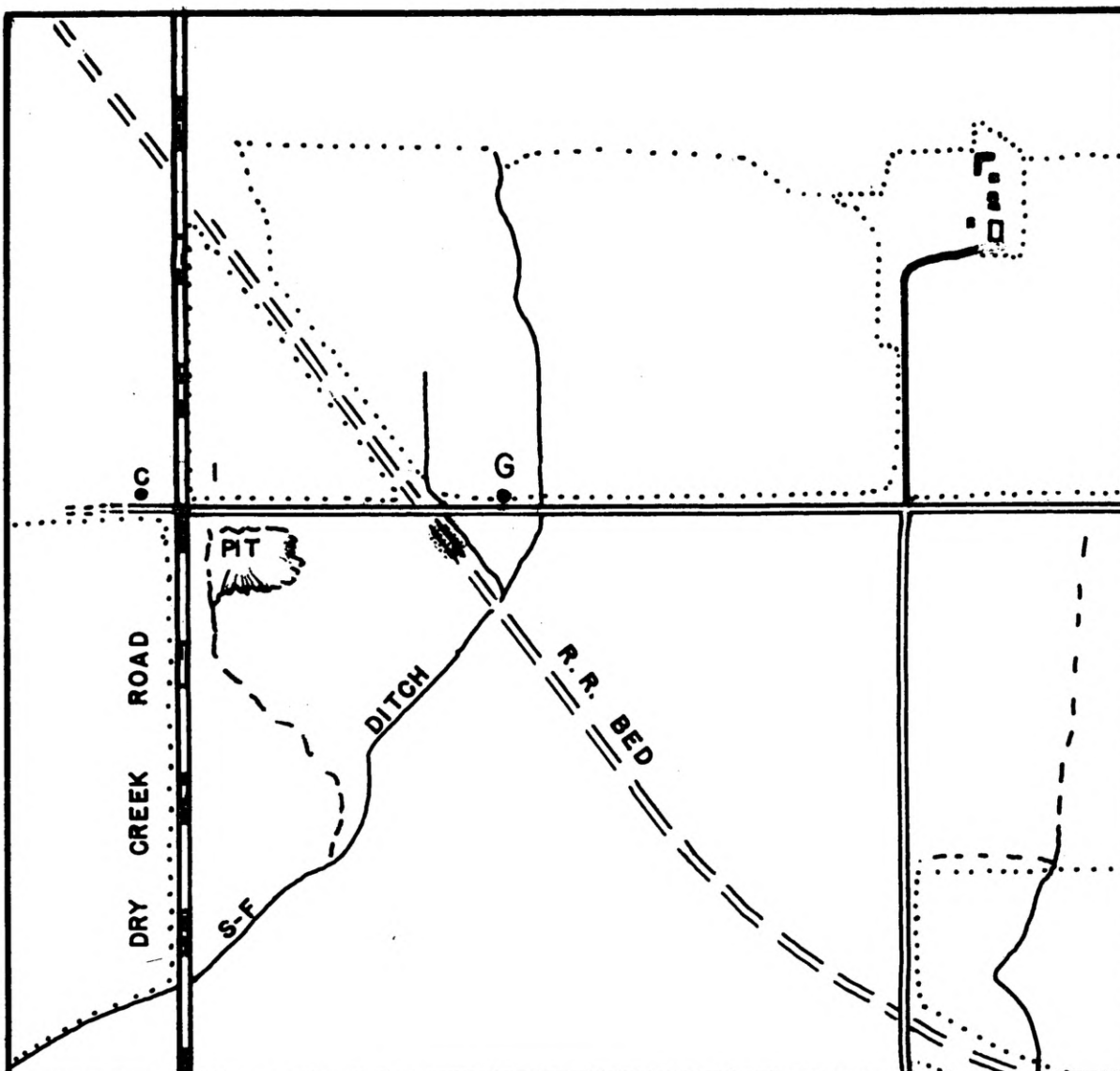
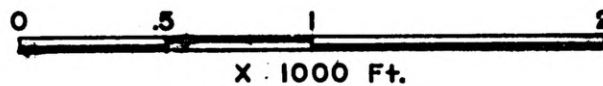


Plate V. GALLATIN WELL LOCATION

Legend

- | | |
|---|--|
| G | Gallatin Well |
| C | Cattle well |
|  | Approximate location of sensitive area |
| PIT | Gravel pit |
|  | Cultivated field boundary |
| I | Intersection 1.9 miles from Route 10 |



the various freight cars. During this time there is also a decline in water-level position. As the caboose leaves the area and surface loading is relieved, there is a rapid drop to a water level below the initial level. The recovery to the initial level requires from one-half hour to several hours. This indicates an expulsion of the water from the immediate field under the influence of loading conditions. Recovery takes place under natural gradients. These observations of the response of the Well to trains are very similar to those described by Jacobs (1939). The exception is that the final rate of recovery to initial level appears to be much slower in the Gallatin Well than in Jacobs' well.

The railroad tracks adjacent to the Gallatin Well were removed in 1956, so trains are no longer available for response study. However, it might be possible to utilize military tanks from the nearby National Guard motor pool and trucks from the Trident Cement Plant for load tests in future study. The cultivated field to the south of the Well offers opportunity for further artificial loading or shock tests to delineate the shape of the sensitive area.

The application of known loads on the ground surface will permit derivation of a load versus water-level-change relationship. From there it may be feasible to arrive at an approximation or empirical function of the unknown loads placed on the aquifer by the natural seismic waves generated by earthquakes.

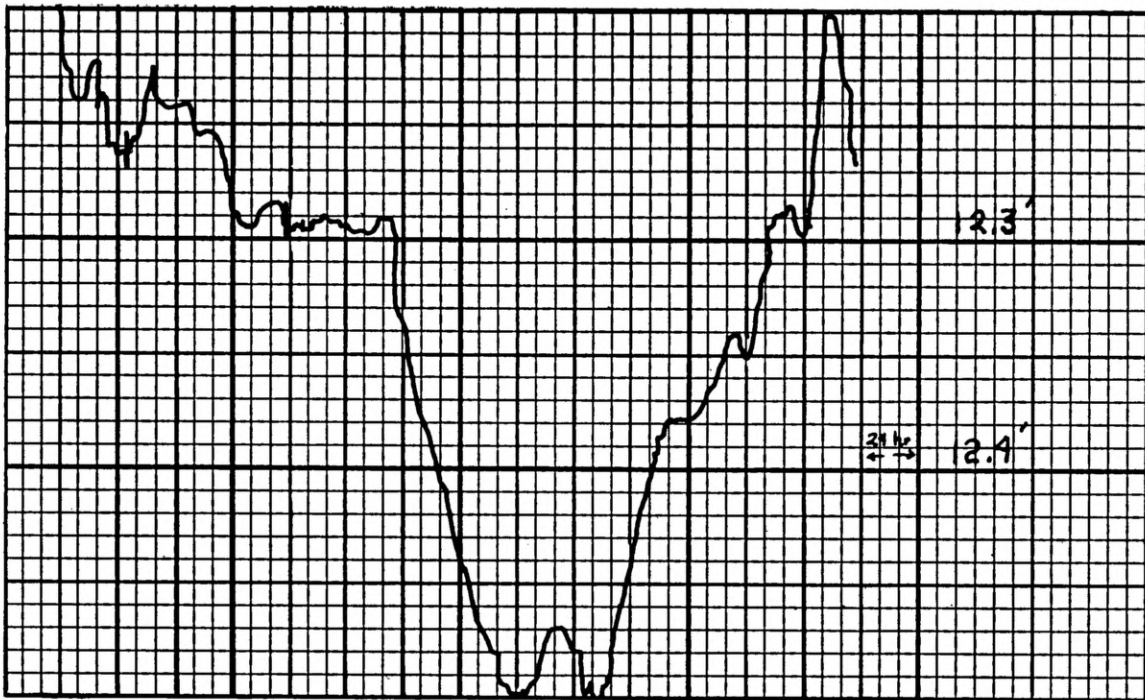


Plate VI. Hydrograph record showing diurnal trends. A full-scale reproduction of a portion of a monthly hydrograph from the Gallatin Well, showing recurrent depressions occurring at the midnight time-line.

Barometric Response

Plate IV. shows a rise in water level and a corresponding "fall" in barometric readings (taken two miles from the Well). This response agrees with that reported for other wells of this nature (Parker and Stringfield, 1955, also Roberts and Romine, 1947). The Well displays a barometric efficiency of about 15 per cent. More complete correlation and computation of barometric loading can be facilitated by a barograph installation at or near the Well.

Other Response

Many other anomalous water-level fluctuations in the Gallatin Well have unknown causes. Some are markedly diurnal. There is an unusual prevalence of small depressions on the record trace with a duration of approximately eight hours. These reach lowest level at midnight and are symmetrical about that time line (Plate VI.). Commonly associated with these lows are highs in water level centered nearly on 8 p.m. Many other similar troughs are themselves centered about the 8 p.m. time line. Tidal response may be partly involved but has not been proven.

It is hoped that with the application of advanced instrumentation and continued research the causative phenomena involved in the unknown anomalies may be discovered.

Summary

By the foregoing, it is shown that the Gallatin Well is especially favorable for study. It has proven to be responsive to several different phenomena. It is quite sensitive to distant earthquakes and is associated

with a small, response-producing, ground-surface area. It is readily accessible and is located near two prominent seismograph stations--one mounted in the same general gravel sheet, the other in Precambrian basement rock.

INSTRUMENTATION

Specifications

Through cursory study and suggestions from previous literature, specifications for an instrument to operate as a combination hydrograph and hydroseismograph on the Gallatin Well were outlined. They are as follows:

1. The instrument system should produce a condensed time-scale hydrograph record. The time units should be in the order of a few centimeters per day in order to facilitate observation of diurnal variations in water level.
2. An expanded time-scale hydrograph is also needed to automatically record rapid water-level fluctuations in the Well; i.e., those greater than a rise or fall of a few centimeters per minute or a period less than one cycle per minute. This should permit recording of most seismic waves. If it is discovered through correlation of hydrograph and hydroseismograph records that slower frequency waves are occurring and not being recorded in detail, then modifications in the instrument system may be made.
3. The hydroseismograph time scale should be in the order of a few centimeters per minute so that individual oscillations of 20-second period or less may be delineated.
4. The hydroseismograph should be arranged so that it only operates during an event of rapid fluctuations for a given time of say, 20 minutes, repeating as long or as often as the events occur.
5. An event marker should be incorporated in the hydrograph to record the time of operation of the hydroseismograph.
6. The instrument should be as accurate as possible. Previous records have indicated that anomalous fluctuations of less than 0.01 foot amplitude may exist.
7. The instrument should be able to operate unattended for a week or more.
8. The system should be as simple, compact, rugged, and economical as possible.

9. It should be portable or at least easily transferable so that it can be utilized at other locations.
10. It should, as should any instrument, interfere as little as possible with the quantity being measured. It is best, therefore, that little or no equipment be in contact with the water surface.
11. Battery-operated equipment (assuming electrical needs) is preferable to 110-volt power lines in order to develop an instrument package of general utility.

Though some specifications may have to be sacrificed to satisfy others, the ability of the instrument to automatically and accurately produce both a hydrograph record and a hydroseismograph record at the least cost is the ultimate qualification sought for the instrument.

Systems Investigated

Several basic instrument systems were investigated. First, attempts were made toward design modification of existing equipment. Then efforts were turned toward less mechanical systems. The principles involved in basic unit designs were conductance, capacitance, the Wheatstone Bridge, manometers, pressure transducers, modification of existing systems, light reflection, and sound reflection. Units involving all but the latter principle were rejected for hydroseismograph application. Some are suitable for general hydrograph operations, however. Appendix C includes brief descriptions of some of the "rejected" systems.

Proposed Instrumentation

General

The Hydro Products Company of San Diego, California, a division of Oceanographic Engineering Corporation, manufactures a non-immersed

fluid-level monitor. It is designated the Hydro-Sonic Model 770 and is a portable acoustic-pulse-transit-time monitoring device with an incorporated linear meter readout. A modification of the Hydro-Sonic fluid-level monitor is proposed as the nearest approach to ideal specifications. Operation is in the hyper-aural frequency range above 20 kcs. By monitoring the sound pulses sent out by the instrument and reflected back by the fluid surface, the monitor relates the sound travel time and the distance to that fluid surface. The standard Model 770 has a response time of 0.1 second. Ranges of 0 to 10 feet, 0 to 20 feet, and 0 to 40 feet may be selected by control switch. Accuracy is ± 1.0 per cent. There is also an offset range switch permitting compensation for relative height above the fluid surface, limited to 200 feet. The instrument has an output of 0 to 1.0 ma through terminals which may be connected to almost any time-base, strip-chart recorder.

Sensor

The Hydro-Sonic 770 consists of two components, the sensor and the monitor. The sensor is 3 inches square by 9 inches long and weighs approximately 2 pounds. It may be mounted by various means above the surface to be monitored. In Gallatin Well it would be suspended in the top of the well casing. The sensor has the main advantage of not interfering in any way with the water surface to be measured. Any corrosion, fouling, or deterioration of equipment due to water contact is also eliminated. Problems of float-lag and friction are also obviously absent. Freezing of the water surface or "ambient temperature change of the water

or the atmosphere have little effect on the action of the sensor." Thus, from the standpoint of the sensing device, the system is nearly ideal.

The sensor may be connected to the monitor by twin-lead wire any distance up to one mile. For more remote connections, a leased telephone company circuit may be utilized. Therefore, the sensor is the only equipment required to be located at the Well.

Monitor

The monitor may be powered by a 12-volt D.C. source permitting application at any accessible site. The entire electronic portion is solid state, utilizing transistors and diodes. Therefore, it is more dependable and uses less power than electronic-tube equipment. The monitor is housed in a single, dust-proof, steel case (Figure 4).

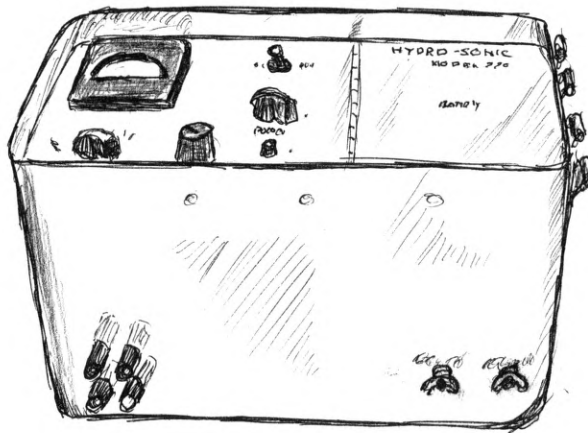


Figure 4. Hydro-Sonic fluid-level monitor with the lid removed.

The Hydro-Sonic (R) fluid-level monitor was originated by Donald P. Allen, general manager of the Hydro Products Company. He has agreed to

modify the circuitry to gain accuracy from the present 1/4 inch to 1/8 inch or better, possibly 1/16 inch. Response would range between 0.2 second and 0.1 second. This can be accomplished by a change in transistor frequency. The modification will necessarily reduce the full range of the instrument, but even a two-foot range would suffice for nearly a month's unattended operation.

Recorders

The recommended time-base, strip-chart recorder for use in conjunction with the Hydro-Sonic 770 is the recti/riter (R) portable, galvanometric recorder manufactured by Texas Instruments, Incorporated, of Houston, Texas. This is a rectilinear recorder; i.e., the galvanometer operates the recording pen through a linkage that converts the curvilinear motion of the galvanometer to rectilinear pen motion. The response time is 0.25 seconds. These recorders may also be powered by a 12-volt D.C. source. A selection of quick-change gears and an inch/hour-to-inch/minute switch permit rapid selection of ten chart speeds.

Two recti/riter recorders are proposed--both Models PRIM (Figure 5), a 0 to 1 ma, D.C. type using a 4½-inch-grid chart. One recorder will maintain the condensed time-scale continuous hydrograph record. The slowest time scale available as standard equipment is 3/4 inch per hour. It is recommended that a slower chart speed more in the order of a few inches a day be specially requested. This will facilitate observation of small, diurnal, water-level movements.

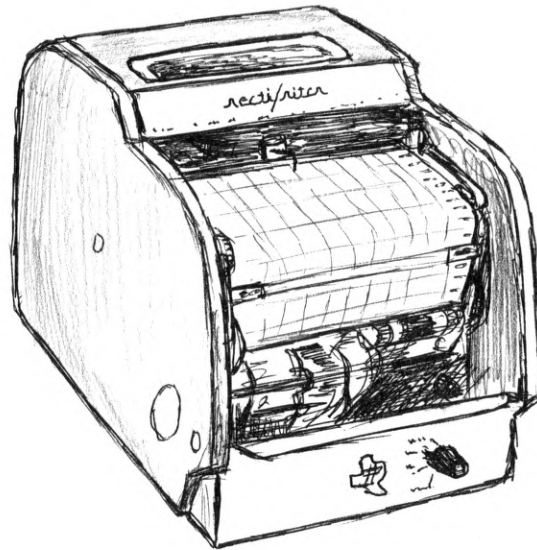


Figure 5. A recti/riter recorder Model PR1M.

The second recorder will be used to produce the hydroseismograph records. A magnetic integrator installed in the Hydro-Sonic 770 will detect threshold values of water-level change and engage the second recorder during any event of rapid water-level fluctuations. A scale-ranger will permit amplification on the record of water-level fluctuations to reveal greater detail. A Brailsford chronomatic switch will control time duration of the operation of the hydroseismograph. Should the event continue past the time limit, the magnetic integrator will cause the recorder to continue for another time interval. Thus, any and all rapid water-level fluctuations will be recorded.

An event marker installed on the condensed time-scale hydrograph will, by mark, record the time of operation of the hydroseismograph. The

recorders also provide for easy notation of dates, times, base-level adjustments, etc., on the charts while the machines are in operation. A zero adjustment is also provided.

Instrument Package

Complete specifications of the Hydro-Sonic 770 and the recti/riter recorders are given in Appendix B.

The only attendance required is for periodic setting of the base level at the monitor and removal of charts from the recorder. Chart rolls are 100 feet long so require infrequent removal, although information should be collected and observed as often as practical. An occasional calibration check by actually measuring water-level depth in the Well should be made.

The Hydro Products Company has agreed to provide the modifications, recorders, and a battery charger. Batteries will not be included. Upon modification of the units, the Company will assemble and test the system. It will be shipped so that only connection of the major components would be necessary. A price quotation for the system to be supplied by Hydro Products is \$1,990.

Two 100 ampere-hour, wet-cell, automobile batteries, Group 2 E, may be purchased at a local auto parts house for \$28 each. One may be stored on the trickle-charger while the other is in use.

Telemetry

Telemetering of the information is possible and proposed. In the proposed instrument package the sensor is the only equipment that must be

located at the Well. All other components can be placed in an appropriate office at Montana State College. This has several advantages. The equipment, though rugged, is protected from extreme temperatures and vandalism. Construction of a large, preferably bullet-resistant, instrument house will not be necessary. Frequent trips to the Well will also be unnecessary. Any malfunction of the equipment should be quickly noticed when readily accessible.

The cost of a telemetering circuit leased from the Mountain States Telephone Company includes a \$5 installation charge at each end of the line and a \$19.50 service charge per month. This gives a total of \$712 for the first three years of operation.

Barograph

It is proposed that a barograph also be included in the instrumentation system. The Number 353, "utility barograph" of Science Associates, Princeton, New Jersey, is recommended. It contains a multiple diaphragm unit, compensated for temperature, utilizes a $3\frac{1}{4}$ inch by $11\frac{1}{2}$ inch chart, and is graduated from 28.0 inches to 31.0 inches of mercury. Recording period of seven days is provided by a jeweled clock movement. The cost is \$120.

Installation

Funds are also requested to cover the cost of installation of the monitor and recorders in an office at Montana State College. A small shelter will be constructed at the Well to protect the top of the Well

casing and the sensor. Room in the shelter should be allowed for a barograph or other small equipment that might be temporarily installed at the Well.

Shipping costs, delivery, connection costs, including telemetering transformers, are also included in this category. Estimated total is \$500.

RESEARCH PROGRAM

Funds are also requested for a three-year research program utilizing the proposed instrument system. The objectives of this program are several fold:

1. To attempt correlation of wave type, epicentral distance, and magnitudes of earthquakes to the corresponding water fluctuations in the seismic-sensitive Gallatin Well.
2. To apply artificial loading to the ground surface adjacent to the Well in order to define the sensitive area and to establish a relationship between the known loading and the unknown loading caused by naturally occurring seismic waves.
3. To attempt discovery of unknown response-causing phenomena. Special emphasis will be placed on attempts to reveal response to tidal forces and the fundamental oscillations of the earth.
4. To define the mechanism by which the water oscillations take place.
5. To better define barometric response.
6. To study the response of the Well as a possible useful adjunct to the two nearby seismograph stations.
7. To study possible varieties of application of the proposed instrument. A search for other seismic-sensitive wells in the area may prove to be feasible.

The proposed research will require a large amount of time to be devoted to study of the hydrograph, hydroseismograph, and seismograph records. Earthquake data published by the U. S. Coast and Geodetic Survey should also be utilized. To properly carry out this program, a twelve-month graduate assistantship is proposed to provide a student who would be required to devote full-duty time to the Well research. The requested assistantship is \$2,500 per year for the three years.

Funds are also requested for support of artificial loading tests. The amount for the first year is \$200. For the following two years, \$100 per year is requested. Table 2 is a budget summary of the research grant requested. Discoveries will be published in appropriate journals, and oral presentations will be given at technical meetings.

It is believed that the instrumentation and research program as proposed will significantly advance the science of hydroseismology.

Table 2

<u>Budget</u>	<u>1st Year</u>	<u>2nd Year</u>	<u>3rd Year</u>
Hydrosonic Model 770 Fluid-Level Monitor	795		
Chronomatic Switch	35		
Two recti/riter Recorders @ \$495	990		
Integrator and Battery Charger	85		
One 12-Volt Normal Change Gear Drive	75		
One 12-Volt Finger Tip Speed Changer	150		
One Time Event Marker Pen	30		
Internal Lighting Kit	16		
Assembly, Modification and Testing	<u>N.C.</u>		
Subtotal	2176		
Discount	<u>-186</u>		
Amount to Hydro Products Company	1990		
Two Batteries @ \$28	56		
Shipping Costs, Installation, Shelter Construction	500		
Telemetering	244	234	234
Artificial Loading Tests	200	100	100
Assistantship (12 Months)	<u>2500</u>	<u>2500</u>	<u>2500</u>
	5490	2834	2834
Total for the Three-Year Program			\$11,154
Overhead @ 25% of Direct Costs			<u>+2,788</u>
TOTAL AMOUNT REQUESTED			\$13,942

There are no other sponsors involved in this project. The grant will be administered by the Montana State College Endowment and Research Foundation.

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APPENDIX A
Gallatin Well Data

APPENDIX A

Gallatin Well Data

Location: SW $\frac{1}{4}$, SE $\frac{1}{4}$, sec. 25, T. 1 N., R. 4 E., Montana. This is one mile north of Gallatin Field. (See Plates III and IV.)

U.S.G.S. Designation: Al-4-25dc.

History: Drilled in 1951 by a private contractor for the U. S. Geological Survey as part of the Gallatin Valley geology and ground water study directed by O. M. Hackett (Hackett and others, 1960).

Depth: Originally 400 feet but filled to present 101 foot depth.

Casing: 6-inch perforated steel originally from 10 feet to 329 feet.

Yield: 140 gallons per minute with a 7.1-foot drawdown.

Chemical Analysis: See Page, 162, Hackett and others (1960).

Log:

*Log of Well Al-4-25dc

Principal water bearing zone 10-55 feet.

Saturated from 60-400 feet.

Depth to water 10 feet.

	<u>Thickness</u>	<u>Depth</u>
Top		
Gravel, sandy, silty, calcareous; contains cobbles; composed of volcanic and metamorphic rocks	50 ft.	50 ft.
Gravel; contains sand lenses	40	90
Gravel, sandy	120	210
Sand, medium to coarse; contains pebbles	30	240
Gravel, sandy	35	275
Gravel, sandy silty	25	300
Gravel, sandy	78	378
Sand, medium, silty	6	384
Gravel, sandy	16	400
Bottom		

*P. 189, Table 33, Hackett and others (1960).

APPENDIX B
Instrument Specifications

APPENDIX B-1

Hydro-Sonic Fluid-Level Monitor

Construction

Case: Waterproof, dustproof, heavy duty, steel case, manufactured to Mil Specs, primed and finished with white epoxy paint.

A flat-folding handle is welded to the cover for ease of carrying.

Cover: Removable, with an integral neoprene gasket seal.

External Terminals:

Recorder Output	2 (combination binding post-banana jack)
Transducer Input	2 (combination binding post-banana jack)
External Battery Lugs	2 (insulated 1/4" brass lugs with wing nuts)

Controls:

- a. On-Off/internal-external battery control switch.
- b. Offset range.
- c. Range switch--0'-10', 0'-20', 0'-40', excluding offset.
- d. Battery Test Button--for indication of internal battery condition.

Technical Specifications

Sensing Range:	0' to 40' (longer or shorter ranges are available)
Response Time:	0.1 sec. max. 90% full scale.
Linearity:	$\pm 0.5\%$
Repeatability:	$\pm 0.5\%$
Accuracy:	$\pm 1.0\%$ or better (1/4" accuracy in 2 feet)
Power Requirements:	12 VDC, internal or external; low drain.
Recorder Output:	0 - 1 ma
Sensors:	Frequency: above 20 ks; multiple sensors may be switched by a HPC chrono-switch timer or selective stepping switch.

APPENDIX B-2

Specifications of the recti/riter Galvanometric Recorder

Manufacturer: Texas Instruments, Inc., Houston, Texas.

Distributor: Hydro Products Company, San Diego, California.

D.C. *power requirement	12 volts, 20 watt
Chart paper	Translucent rectilinear
Chart width	6 inches
Grid width	4½ inches
Chart length	100 ft.
Chart speeds	12, 6, 3, 1½, ¾ in/min or in/hr.
Input resistance	1500 ohms
Response time	0.25 sec.
Accuracy (d.c.)	± 1% of full scale
Weight	27 lb. net
Height, depth, width	4¼" x 15" x 8¼"
Controls: (1) in/hr - stand by - in/min - off	
(2) zero adjust	

Other features:

Automatic chart take-up; writing desk chart table; chart speed change gears; closed ink system; D'Asonval galvanometer movement using Alnico V magnets; rectilinear pen trace; Event marker pen*; Interior lighting*; Finger-tip speed changer*.

Price \$495

*Optional at extra cost

Model numbers of proposed units:

PRIM - D12 - L12 - R

PRIM - D12T - B12 - R

Total price \$1,261

(See brochure for detailed explanation.)

APPENDIX C

Other Systems Investigated

APPENDIX C-1

Modification of Stevens Type F

Inertia of the Stevens-F hydrograph may be reduced by extensive drilling and cutting of material from all moving parts.

For use as a hydroseismograph, a circuit of relays and microswitch was devised so that a high-speed pen would move across the drum, resetting itself at the end of the traverse. A satisfactory triggering mechanism to operate the system was not discovered.

A greater reduction of inertia may be accomplished by driving the pen with the float wheel and having the drum operated by the clock. This way a normal automobile windshield-wiper motor and switch may be utilized. The drum would then turn for one revolution each time it was triggered. This greatly simplifies the electrical components, as no complex reset system is required. Recording range is limited to pen travel, however.

Such an instrument was built (without the automatic timing components) and is better suited to attended use during artificial load tests than the unaltered Stevens Type-F hydrograph.

APPENDIX C-2

Conductivity

To eliminate mechanical problems, the properties of conductivity of the well water and resistance of metal wire may be utilized. Partially immersing two vertical parallel wires in the Well and applying a voltage across them will cause current to flow. This current will be inversely proportional to the length of the non-immersed wire. Tables of resistance for various types of wire are available in most physics handbooks.

The conductivity of the well water will be in the order of 100 to 500 micromhos (microsiemens, European). This will, however, vary with temperature, ions in solution, and pH, which may not remain constant but for a short time.

The wire, especially if copper, is subject to corrosion, which will also alter the conductivity of the system. This method is not applicable to any but very short-term hydrograph operations.

APPENDIX C-3

Capacitance

A capacitor, utilizing the water surface as one plate and a metal disc as the other, with air serving as the dielectric, may be utilized in detecting very small water-level changes. If the metal disc is stationary, any change in water-surface position will alter the capacitance by decreasing or increasing the value of d , the distance between the plates, in the general equation:

$$C = \frac{eA}{d} \quad (1)$$

C =capacitance, A =the area of the plates, e =the absolute dielectric constant, or permittivity which is $(1/36)\pi \times 10^{-9}$ for free space. Air values approximate free space values.

The general equation for the current i is:

$$i = C \, dv/dt \quad (2)$$

where v is the potential expressed in volts.

Combining (1) and (2) gives:

$$i = \frac{eA}{d} \, dv/dt \text{ or, } d = \frac{eA}{i} \, dv/dt \quad (3), (4)$$

If we were to use a 5,000 cps oscillator, which is available for \$100 (Sanborn Company, Waltham, Massachusetts), and utilize a plate the full size of the Well, 6 inches in diameter, then the distance between the plates required to pass a current of only 1 microampere may be calculated.

$$d = \frac{(4) (.763) (5 \times 10^{-9} \times 10^{-4} \times 10^3)}{36 \times 10}$$

$$d = 3.24 \text{ mm}$$

It can be seen from this result that either extremely high frequencies, which bring on other problems, or a much larger plate than is possible, must be utilized in order to gain a range greater than a small number of millimeters. This system is, therefore, not suited to well hydrograph applications.

APPENDIX C-4

Wheatstone Bridge

A modification of the Wheatstone Bridge is suited to float-driven hydrograph application. Figure c-1 shows the circuit involved.

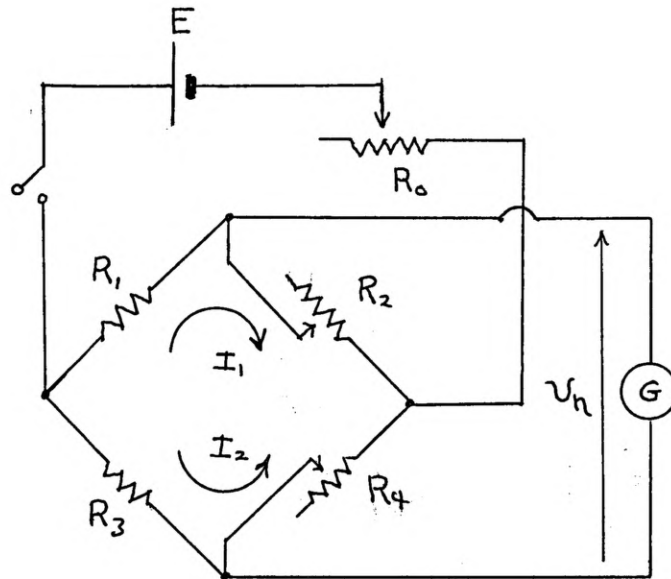


Figure c-1. Modified Wheatstone Bridge Circuit.

In this circuit, $R_1=R_3$ and $R_2=R_4$. The latter two are Helipots, many-turn potentiometers available in various maximum resistance values. They are usually either 10 or 25 turns stop to stop. R_2 and R_4 must be mechanically linked such that when R_2 is at maximum value R_0 is at minimum value (usually zero) and visa versa. At the mid position, or half full number of revolutions, the R_2 will = R_4 . Since $R_1=R_3$, this will be the null position; i.e., V_h will be zero and the galvanometer, G , will be at rest.

The galvanometer measures the potential difference V_n or $V_1 - V_2$.
By Ohm's Law, $V_1 = I_1 R_1$ and $V_2 = I_2 R_3$. (1), (2)

In this circuit, $R_1 = R_3$, so,

$$V_n = I_1 R_1 - I_2 R_3 \quad \text{or} \quad V_n = R_1 (I_1 - I_2) \quad (3)$$

It is also shown by Ohm's Law that: (4), (5)

$$I_1 = \frac{E}{R_1 + R_2} \quad \text{and} \quad I_2 = \frac{E}{R_3 + R_4} = \frac{E}{R_1 + R_4}$$

when $R_0 = 0$.

Let M equal the maximum value of the Helipots, R_2 and R_4 so that they may vary from 0 to M ohms. As stated previously, the Helipots are arranged oppositely. Thus,

$$R_2 = (M - R_4) \quad (6)$$

By combining equations (3), (4), (5), and (6), we get:

$$V_n = R_1 \left[\frac{E}{R_1 + M - R_4} - \frac{E}{R_1 + R_4} \right] \quad (7)$$

Equation (7) is the general equation for the instrument.

A float wheel will be directly or indirectly connected to the Helipot pair. A float and counter balance will be connected to the float wheel. Therefore, movement of the water level upon which the float rests will be directly proportional to the number of turns of the Helipots and thus directly proportional to the value R_4 in equation (7).

As a test for linearity of response, the following relationships are derived from (7). V_n will be at a maximum value when $R_4 = M$.

$$\frac{V_n}{R} = M \quad = \quad \frac{E M}{R_1 + M} \quad (8)$$

When $R_4 = 0$, then $R_2 = M$ (from 6).

$$\frac{V_n}{R_{R_4=0}} = \frac{-E M}{R + M} \quad (9)$$

At the mid-position, $R_4 = R_2 = \frac{1}{2} M$ and it follows that:

$$\frac{V_n}{R_{R_1=R_2}} = 0$$

Therefore, it can be seen that the mid-position is truly the null position and that the two stoppositions of the Heli pots give values V_n symmetrical about the null position. When $R_4 = 3/4 M$ the float is half way between the null position and position of maximum values of V_n . Again from (7) we derive:

$$V_n \Big|_{R_4 = \frac{3}{4} M} = \frac{\frac{1}{2} E M R_1}{\left(R_1 + \frac{1}{4} M\right) \left(R_1 + \frac{3}{4} M\right)} \quad (10)$$

For the system to have a linear relationship:

$$\left| V_n \Big|_{R_4 = \frac{3}{4} M} \right| = \frac{1}{2} \left| V_n \Big|_{R_4 = M} \right| \quad (11)$$

Figure c-2 is a graph of V_n versus R_1 for the two conditions of $R_4 = M$ and $R_4 = 3/4 M$. This shows the dependence of linearity upon the value of R_1 in terms of M .

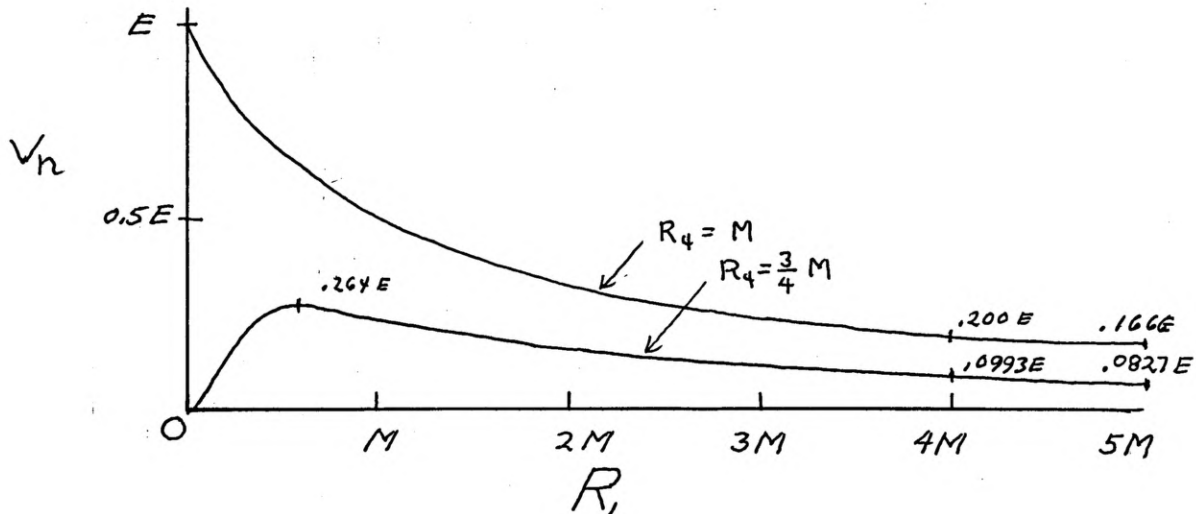


Figure c-2. V_n vs. R_1 for Two Conditions.

For values of $R_1 > 2.5M$, the relationship (11) is essentially satisfied. For values of $R_1 < 0.5M$, the instrument would indicate water-level change in a non-linear manner; the greater the departure from the null position, the larger the scale units would become. This system can be assembled for less than \$30 excluding the galvanometer. A 5-0-5 ma Rustrak (R) recorder is recommended for use as indicator.

By changing the float-wheel diameter or utilizing a gear connection to R_4 and R_2 , a wide selection of sensitivities is available. By limiting the applied voltage, E , with a potentiometer, R_0 , the range of scale of ammeter or galvanometer reading to M may be set. A mercury instrument cell for E is recommended as it will maintain a constant potential with rapid decrease at the end of its useful life. A carbon-zinc cell will show a gradual decrease in potential with use.

Though not applicable to hydroseismograph operation because of friction, float lag, and other drawbacks, the system is very applicable to normal condensed time-scale hydrograph uses.

APPENDIX C-5

Manometer

A manometer is a well-known device for measuring liquid level and gas pressures and has the advantage of no moving mechanical parts in the basic unit. It also requires only the side tube (Figure c-1) in contact with the measured fluid. If the cross-section of the side tube is greater than the u-tube or is coiled as a helix, the sensitivity may be increased.

The difficulty is to record manometer readings. When mercury is used as the indicator fluid, a small ferrite rod may be floated upon it. A two-coil electrical induction unit, a transformer, may be wound around the exterior of the u-tube. The ferrite rod may act as an armature, or core. As it moves in the region of the transformer, mutual inductance will vary. The ratio of the applied voltage of the primary coil to the recorded voltage of the secondary coil will vary according to the armature's position, which relates the measured liquid's position.

If the indicator fluid is of a lesser density, then greater movement and greater direct reading resolution of the indicator fluid may be obtained.

If the indicator fluid is opaque, the shading of a photocell (Appendix D-6) parallel to the u-tube may be used as an indicator. The photocell would respond to a light source parallel to, but on opposite side of, the u-tube.

The indicator fluid in a u-tube of uniform cross-section does not bear a linear relationship to the position of the measured fluid. Roy (1961) has presented equations for the construction of u-tubes of non-uniform cross-section which will correct that problem.

A greater problem concerning applications as a hydroseismograph is the bounce or "bobbing" phenomena, somewhat analogous to float lag. The indicator fluid column rests on an air column, which is essentially compressible, floating in the water body whose level is to be measured. For rapid movements of the water surface, the column will lag and rebound just as a wooden stick floating vertically on a free water surface will bob up and down out of phase with surface wave motion. This makes the manometer unsatisfactory for hydroseismograph application.

The following are some manometer calculations modified from Roy (1961), which are significant to utilization of a manometer as a standard hydrograph.

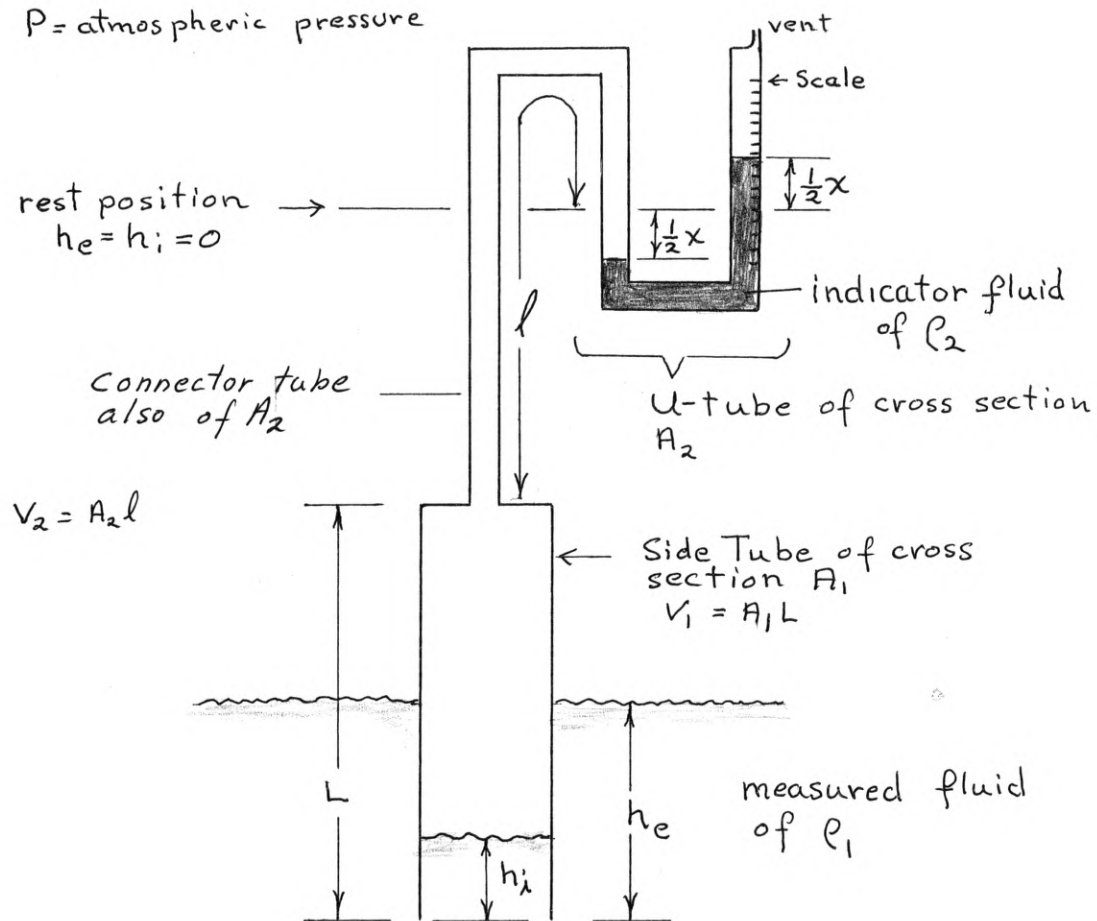


Figure c-3. Manometer Symbols.

$$x = (h_e - h_i) \frac{\rho_1}{\rho_2} \quad (\text{linear})$$

The relation of x to h_e expresses the relation of the indicator fluid to the height or level of the measured fluid, that which must be known to calibrate a manometer. For a u-tube of uniform cross-section:

$$h_e = x \left[\frac{A_1 \rho_2}{\rho_1} + \frac{A_2}{\rho_2} + V_1 + V_2 + \frac{P}{\rho_2 g} \left(A_1 \frac{\rho_2}{\rho_1} + \frac{A_2}{\rho_2} \right) \right]$$

$$\frac{A_1 P}{\rho_2 g}$$

After certain assumptions that $\chi \ll \frac{P}{\rho_2 g}$, then the approximation may be made that:

$$h_e \cong \chi \left[\rho_2 g A_1^{-1} P^{-1} (V_1 + V_2) + \frac{\rho_2}{\rho_1} + \frac{A_2}{2A_1} \right]$$

By applying a u-tube of non-uniform cross-section, the above relationship may be changed to a linear one.

If a manometer is made of uniform cross-section tube throughout and water is used as the indicator for a short study, then note that the relationship simplifies to:

$$h_e \cong \chi \left[\frac{g V}{A P} + \frac{3}{2} \right]$$

APPENDIX C-5a

The Photocell As an Indicator of Shadowing-Medium Displacement

Tests were conducted on a Type B-2-m selenium photocell placed 35 mm from a five-watt fluorescent lamp. A maximum current of $82 \mu\text{a}$ was obtained. By varying the exposed area of the photocell, it was found that the current output per unit area decreases with the decrease in total illuminated surface area. By permanently covering certain portions of the cell (black paper will do), a linear relationship between the displacement of an opaque shadowing medium and photocell output may be obtained. The shape of the covering may be determined by noting the output variation of an uncovered cell as it is gradually covered and then planning for the necessary compensation. The linear conversion cover for the B-2-m is shown in Figure c-4.

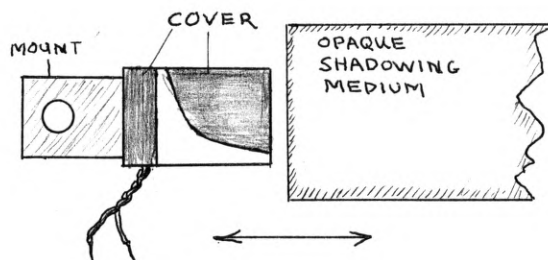


Figure c-4. Actual size sketch of linear conversion cover on a B-2-m photocell.

The fluorescent lamp was found to be a fairly reliable source of light. The output was steady though a 4 per cent gradual decrease in photocell output occurred during the usual, winter evening, utility service, voltage drop. The source could easily be monitored by another small photocell.

A B-17 selenium photocell manufactured by the International Rectifier Corporation would be best suited for manometer recorder application.

APPENDIX C-6

Pressure Transducers and an Application

There are several types of pressure transducers available that convert changes in pressure to changes in electrical energy. The most common is a type of differential transformer in which an iron or ferrite armature moves as a result of diaphragm movement. The armature position controls the mutual inductance of the transformer coils. The primary excitation source is usually of high frequency, 2500 cps to 5000 cps. Most pressure transducers are for rather high pressures. The Sanborn Company of Waltham, Massachusetts, manufactures several suitable for application in a well.

Linear displacement transducers, or probes, operate on the same principle, only one must apply his own bellows or other apparatus to relate the pressure changes to linear motion. Some probes have a full-scale reading as low as 0.001 inch. The Sanborn Company also manufactures a very small direct-current probe requiring no external excitation frequencies.

A sensitive pressure transducer could be applied to an open well in such a manner that the change in water-level position could be recorded. This could be done by submerging the transducer or connecting it to a submerged tube similar to the side tube in a manometer installation. In order to use a very sensitive transducer to record the small seismic-induced water fluctuation, it would be desirable to have the transducer mounted in such a way that it would follow the larger, slower, diurnal fluctuations at a given distance below the water surface.

The Leupold Stevens Company, of Portland, Oregon, manufactures a delayed response, motor-driven-float hydrograph designated the Stevens Surface Detector. The float moves as slow as 12 feet per hour. The manufacturer has stated that the speed of the float could be reduced. A pressure transducer could be installed in the float. The surface detector with a Stevens A-35 recorder connected could act as a condensed time-scale hydrograph. The transducer, coupled with proper oscillators, amplifiers, and recorder, could act as a hydroseismograph. The float movement would not respond to the rapid fluctuations that would be recorded by the transducer. The float then serves as a mobile base position for the hydroseismograph components. The total cost of the system is estimated to be \$3,500. The system is complex and requires equipment that penetrates the water surface. It also requires extensive equipment at the Well. The system approaches the answer to the instrumentation problem but is not recommended.

APPENDIX C-7

A Hydraulic Filter

The following is from Snodgrass, Frank E., 1958. (See, also, Van Dorn, 1956.)

A hydraulic filter may be constructed so that the included pressure transducer responds only to a desired range of wave frequencies.

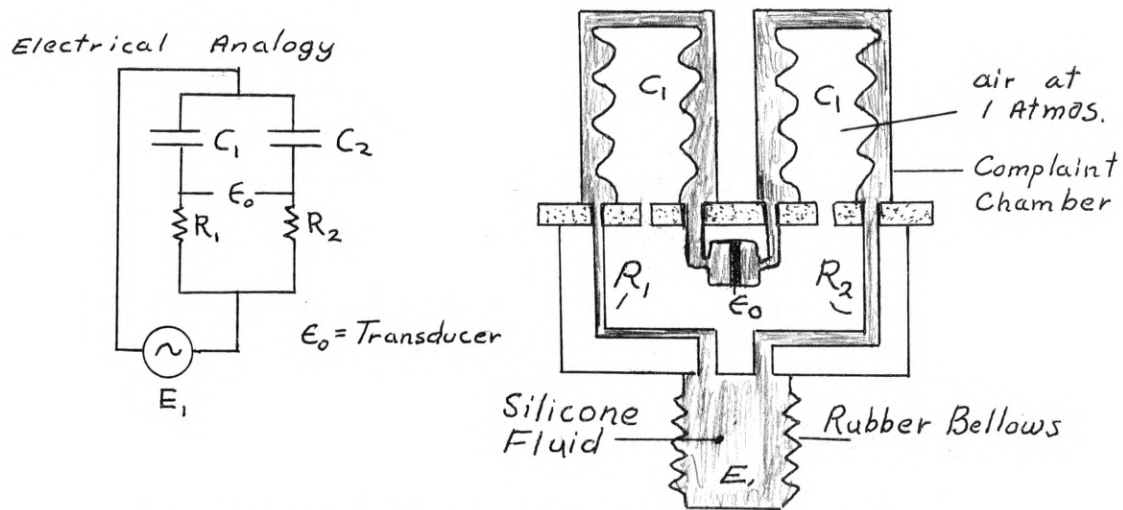


Figure c-5. Schematic drawing of a hydraulic frequency filter.

The capillary tubes (R_1, R_2) restrict high-frequency response through flow resistance. Low frequencies are unrecorded, as pressure is altered equally on both sides of the transducer. (Capillary size difference will not be effective.)

Frequencies small enough to cause flow in the capillary tubes yet high enough to be affected by the dissimilar tube diameters will cause a pressure difference at the transducer and will therefore be recorded.

APPENDIX C-8

Optic System

I have been informed that an optical system utilizing the reflective properties of water surface is available. Reflected light as a function of the square of the distance is read-out electronically. The instrument is believed to have been originated by Dr. McGregor, of the Scripps Oceanographic Institute. The accuracy of the system is very high. The cost of the basic system would be \$6,000. It would require location of the instrument package at the Well. It does, though, have the advantage of requiring no equipment in contact with the water surface. The expense and need to locate at the Well are two of the reasons for not proposing this system.

APPENDIX D
Seismic Terminology

APPENDIX D

Seismic Terminology

Waves

The majority of the following information is from Richter (1958) and Jacobs and others (1960).

There are four basic types of seismic waves generated by earthquakes: the P, or primary; the S, or secondary; the Rayleigh, and the Love. The latter two are sometimes grouped and designated L, or long waves.

The P wave is a longitudinal body wave. The particles of the material through which the wave travels are displaced in the direction of propagation as in a sound wave. It will cause compression and dilatation of the carrier medium.

$$\text{The velocity of a P wave, } v_p = \left(\frac{\lambda + 2\mu}{\rho} \right)^{1/2}$$

μ --the modulus of rigidity of the material
(zero for a liquid)

λ --the wave length

ρ --the density of the carrier medium

The S wave is a transverse body wave analogous to light-wave theory. It is a shear type of wave.

$$\text{The velocity of the S wave, } v_s = \left(\frac{\mu}{\rho} \right)^{1/2}$$

Note that the S wave cannot be transmitted through a liquid. An interesting relationship is:

$$v_p^2 - \frac{4}{3} v_s^2 = \frac{1}{\rho} \left(\lambda + \frac{2}{3} \mu \right) = \frac{k}{\rho}$$

where K is the bulk modulus or incompressibility of the carrier medium. (page 18, Jacobs and others, 1960). By using this relationship, the variation of physical properties of the earth may be determined from arrival times of the two types of waves.

The Rayleigh wave is a surface wave in which the particle motion is partly vertical and partly in the direction of propagation of the wave. The carrier medium particle has a retrograde elliptical orbit. The

Rayleigh wave is very similar to a water-surface wave, but it is mainly controlled by elasticity rather than gravity. This wave will cause dilatation of the material through which it passes.

The Love wave is a surface wave in which displacement is entirely horizontal and at right angles to the direction of propagation. It is possible only in a material which has a horizontal discontinuity; i.e., one layer resting upon the other, with the velocity of the S wave less in the upper layer than in the lower.

A P wave generated by the reflection of a P wave is termed a PP wave. One generated by an S wave would be an SP wave, and so on. The symbol c is used to indicate an upward reflection at the boundary of the core of the earth. The symbol K denotes refraction through the outer core, and I is used to indicate the passage of a P wave through the inner core of the earth. Many types of waves are possible through multiple refraction and reflection. Waves designated PP, ScS, SKS, PKIP, PPP, etc., will be found in the literature and may be understood by the above symbol system.

Magnitudes

The magnitude of an earthquake is defined as the logarithm of the maximum single amplitude, in microns, of the waves as recorded on a certain standard Woods-Anderson seismograph, located 100 km from the epicenter of the given quake. The assumption is made that the manner of decreasing amplitude is independent of quake "size." This holds true for normal shallow earthquakes occurring at depths of less than 25 km.

A modification of the above system is based on certain amplitudes of the P and S waves and is known as the Gutenberg-Richter magnitude. It is more generally applied for it also holds true for deep earthquakes.

Intensity

The Mercalli and Modified Mercalli earthquake intensity scales are based on the observed damage and the human reaction to the earthquake. These scales, though essentially non-quantitative, are closely related to earth surface acceleration, which is the major cause of damage and human reaction. This acceleration is in turn a quantitative measurement of the earthquake intensity.

APPENDIX E

Notes and Suggestions

APPENDIX E-1

Suggestions for Use of This Paper As a Grant Request

As mentioned in the Author's Note, it is hoped that this paper will be used with little or no alteration as a request to the National Science Foundation for a research grant. The pages not included in the Arabic numbering system, such as the Index, Vita, and Acknowledgments, plus those that are numbered with the small-case letters following the normal digit, pertain to the academic use of this paper only. With these removed, the paper should be in proper request form. The title page which is to be used with the grant request is included as a last item in this paper. It is realized that some changes may be made by the person submitting the request, but those pages that are unaltered may be printed from the duplimats of this paper. The duplimats will be on file in the Montana State College Department of Earth Sciences.

It is recommended that the request be sent in at the earliest date feasible. It will take some time for the Hydro Products Company to modify and test the equipment. During this time a program may be set up and a graduate assistant sought. If the instrument is ready for use before the program is ready or the student assigned, records may be accumulated with very little effort.

A copy of the grant request should be sent to Don Allen, of the Hydro Products Company. Refer to the correspondence between Mr. Allen and myself for further comments concerning this.

APPENDIX E-2

Notes and Suggestions to Future Researchers of the Gallatin Well

1. Previous Work. The reference to King (1892) is not in the Montana State College Library though listed in the card catalog. I have sent a request to the Weather Bureau for a copy. It is believed to contain interesting historical information concerning seismic-sensitive wells.

2. Blowing Well. Paul Jordon, of the Engineering Research Laboratory here at Montana State College, has reported a blowing well. It is on his property north of Spring Hill. His description of the intensity and duration of the air exhaust would lead me to believe that, if the cause is barometric, the well is extremely efficient. It would be worth investigating.

3. Artificial Loading. The weight of a Diesel locomotive is about 400,000 pounds and has a length of about 45 feet. The Mallet locomotives weighed around 600,000 pounds, and their tenders often weighed as much as 400,000 pounds loaded.

The Trident Cement Company operates trucks on Route 10 that gross 73,000 pounds. The drivers could possibly be persuaded to make some short detours past the Well.

The National Guard motor pool is located on the road leading into the Gallatin Field airport from the south. Members of the Guard have expressed interest concerning proposed use of a military tank in loading tests for the Well. The tank weighs about 24,000 pounds and must be taken out on occasional runs.

4. Other Wells. Note the stock well that is located 128 feet west of Dry Creek Road, almost due west of the Gallatin Well. Volume pumped is easy to calculate. It is quite a distance from the Gallatin Well, but correlation of time of operation of the stock well and any events occurring in the Gallatin Well should at least be checked.

The well at Shed's Bridge is also seismic-sensitive though to a much lesser degree than the Gallatin Well. See attached photostats of the Siberian Quake record.

5. A notebook is available in the Montana State College Department of Earth Sciences. It contains reprints of literature not available in the Montana State College Library, letters, estimates of cost, bulletins and price sheets for equipment, and other miscellaneous material that was accumulated during the investigation.

6. This proposed instrument system could easily be made into a mobile unit. The monitor and a recorder can be mounted in a single, small case. Shock mounts are available for the recorder from Texas Instruments. The sensor may be connected by a long line of light twin-lead. A wire may be fixed so that the instrument may be plugged into the cigarette lighter of the vehicle to be used.

7. Recent correlation with the siesmograph at M.S.C. has indicated that the Gallatin Well may respond to microseisms of approximately 18 second period.

8. The researcher should place his name on the U. S. Coast and Geodetic Survey mailing list for earthquake report cards.

9. The barograph could be placed at Gallatin Field. This permits protected location near the Well. The F. A. A. employees might maintain the records for they presently have only the barometer.

APPENDIX E-3

Apropos Addresses

The following are addresses of persons with whom contact might be desired during continued well research.

Allen, D. P., General Manager of Hydro Products Company, 4930 Maples Place, San Diego 10, California. He is the originator of the Hydro-Sonic 770 and has offered more help than any other outside contact.

Koopman, Francis, Hydrology Lab, USGS, Building 25, Denver Federal Center, Denver, Colorado. See references.

Leupold, Norbert, Assistant Manager of Leupold & Stevens Instruments, Inc. See letters in the accessory notebook.

Ropes, Leverett H., Department of Oceanography, Oregon State University, Corvallis, Oregon. Will be glad to answer any questions that might come up concerning this report.

Schneider, Robert, Acting Chief, Research Section, Ground Water Branch, U. S. Department of the Interior, Geological Survey, Washington 25, D. C.

Swensen, Frank, USGS, Building 25, Denver Federal Center, Denver, Colorado. Was with Billings USGS when Well was drilled.

Ziegler, Victor E., Operations Engineer, N. D. State Water Conservation Commission, 1301 State Capitol, Bismark, N. D. Utilizes low-priced, transistorized, water-level device in wells.

APPENDIX F

Title Page for Grant Request

RESEARCH PROPOSAL

Submitted to

Director

NATIONAL SCIENCE FOUNDATION
Math-Physics Division
Earth Sciences

Title: INSTRUMENTATION AND STUDY OF THE
GALLATIN SEISMIC-SENSITIVE WELL

Principal Investigator: Dean Charles C. Bradley

Institution: Montana State College, Bozeman,
Montana; Grant to be administered
by the Endowment and Research
Foundation

Desired Starting Date: June 1, 1964

Period of Support Requested: June 1, 1964 to June 1, 1967
(3 years)

Total Request: \$13,942

Endorsement of Proposal:

Charles C. Bradley, Dean, Letters
and Science Division, and Princi-
pal Investigator

Leon H. Johnson, Acting President
of Montana State College and
Executive Director, Endowment
and Research Foundation

Nicholas H. Helburn, Professor
and Head, Dept. of Earth Sciences