This is to certify that the

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A Bubbler System for Water Table Monitoring

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Kurt Goebel

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George E. Merva
Major professor

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A BUBBLER SYSTEM FOR WATERTABLE MONITORING

By

Kurt Michael Goebel

A THESIS

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ABSTRACT

A BUBBLER SYSTEM FOR WATERTABLE MONITORING

By

Kurt Michael Goebel

The bubbler system is an electronic data acquisition system to monitor and record the position of the watertable for drainage and subsurface irrigation research. It uses a small diameter observation well to minimize the time lag between the actual watertable and the water level in the observation well. Nitrogen gas bubbles slowly through smaller diameter spaghetti tubing which is in the observation well. A pressure transducer connected to the spaghetti tubing senses the pressure required to force a bubble out of the bubbler tube, thereby sensing the water level surrounding the tube. A pressure transducer converts the pressure into a voltage. A datalogger changes the voltage from the pressure transducer to a digital output. The data acquisition equipment is located in one central location from which the spaghetti tubing fans out to the observation wells. Data is stored in the datalogger and transferred to floppy diskette for further analysis.

Approved: George E. Merva
Major Professor

Approved: Donald M. Edwards
Department Chairman

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Mention of specific manufactured products in this thesis is made in the interest of clarity, and in no way implies endorsement of these products by the author or Michigan State University.

I. Introduction

Research in the area of soil and water has not kept pace with the electronic technology available for data collection. An example is something as simple as monitoring a water level. A record of water level versus time is very important for many parameters used in soil and water research. Some examples of these are the position of a water table for subsurface irrigation research, rate of change of position for the calculation of hydraulic conductivity, actual depth in a flume to calculate flow, or stage of a river.

Both non-recording and recording methods have been used to measure water levels. Non-recording methods use a calibrated tape, rod, or tube inserted into an observation well until the water surface is reached. The manual, non-recording method of water level data collection is adequate only if frequent readings are not necessary or if simultaneous readings are not required at multiple sites.

Many techniques have been devised to monitor and record water level. A popular and widely used chart recorder is the Steven's meter which utilizes a float-type system consisting of a beaded cable that passes over a pulley. The cable is equipped with a float on one end and a counterweight on the other. The float follows the rise or fall of the water surface and the stage or level may be read from the tape, or from a recorder connected to the pulley producing graphic records of water surface elevation with time. The float-type chart recorder is probably the most common method used to produce a water level-time relationships. To analyze float-type data, values have to be read from the chart either manually or through the use of a digitizer and entered into a computer, a time consuming task.

The increased use of the personal computer allows more data to be analyzed to better describe an event or management practice. To take more data, reliable instrumentation to record water level readings at each site, and methods for easy or automatic transfer of the data to computer for analysis must be used.

To facilitate computer analysis, techniques to get the information to a computer have been developed. Several attempts at converting a float-type meter to give an electrical output have been tried. One method used a potentiometer connected to the float drive shaft to give a linear DC voltage output dependent on the vertical position of the float. Another method used a water level sensing probe. The sensor activates microswitches that control the electric motor to move the sensor up or down to determine the water surface. A potentiometer gives as output a linear DC voltage dependent on the vertical position of the sensor. An inherent problem with a motorized probe device is that it is expensive, requires frequent maintenance, and the electric potential on the probe causes direct current flow through the groundwater resulting in electrolysis.

Another method measured water level using platinum electrodes connected in parallel and placed at given intervals along a probe inserted into an observation well. The presence of water at a given electrode level provides a pathway for signal to flow to a common electrode running the length of the probe. The data is stored on a strip-chart recorder. This has the limitation of not being easily modified to give analog output as well as the above mentioned problem with electrolysis. To avoid electrolysis and rapid deterioration of the probe contacts, the above system was modified to use an AC input signal to energize the probe. The AC signal was converted to DC prior to being recorded.

The system proposed in this work uses a small water table observation well, approximately 3/4" I.D., to minimize the time required for the water level in the observation well to reach the actual water table level following a change in the actual water table level. Into the observation well a smaller diameter bubbler tube (1/8" I.D.) connected by flexible tubing to a tank of compressed nitrogen gas is inserted. Nitrogen gas is used to retard the growth of algae. The nitrogen gas is allowed to bubble slowly through the tubing into the observation well. A pressure transducer connected to the supply line senses the pressure required to force a bubble out of the bubbler tube, hence, sensing the water level surrounding the bubbler tube. The bubbling rate is controlled by an in-line needle valve. The pressure transducer converts the pressure required to force a bubble out of the supply line into a voltage. A datalogger, which converts a voltage into a digital output, is connected to the pressure transducer and a reading is taken at some time interval depending on the circumstances.

II. Literature Review

A. Non-recording methods of water level monitoring

The non-recording method of monitoring a water level uses a calibrated tape, rod, or tube lowered until the water surface is reached. Many methods have been devised to make water level monitoring easier and more accurate.

Reeve (1965), as stated by MacVicar (1978), describes two typical methods for locating water level in an observation or stilling well. The first requires the user to blow through a graduated tube and lower it until a bubbling sound occurs. The second utilizes a brass bell connected to a graduated tape which is lowered until the bell is heard hitting the water surface. The United States Bureau of Reclamation's, Water Measurement Manual (1974) describes two general types of non-recording gages that are in use for river stage measurements: staff gages and chain or wire gages. A staff gage can be vertical or inclined and the stage readings are taken directly from the gage. The chain or wire gage is usually mounted at some fixed elevation above the water and the weight or float lowered until the water surface is reached. The water level is then read from the chain or wire index on a horizontal scale.

This type of gage measures from a fixed point and is affected by settling and/or frost heave of the structure that supports it, temperature changes, changes in the chain length due to wear, and wind which may not allow the weight or float to hang vertically. The wire weight gage is similar to the chain gage but wire or small cable is wound on a reel. The reel is graduated to tenths and hundredths of a foot.

To get a field measurement of the hydraulic conductivity of a soil below the watertable using the auger hole method, the change of water level in an auger hole must be monitored. Van Beers (1958) used a simple apparatus to follow the water rise in an auger hole. It consisted of a vertical standard which was pressed into the ground a preset distance and to which a ruler was attached. A light weight steel tape, equipped with a pointer to show position on the ruler, was connected to a float. After the water in the auger hole was bailed out, readings were taken at a time interval of 5 seconds to several minutes dependent on the soil's hydraulic conductivity.

To make an instrument easier to read and use, devices have been developed to use electrical output to locate a water level. An example is an electrical point gage, the distance to the water surface is measured using a plumb bob connected to a graduated tape. The bob is lowered until it reaches the water surface, contact of the bob with the water surface completes an electric circuit causing current to flow through the circuit. Wilm and Collet (1941) designed a compact and simple instrument using a flashlight case as the main body. A milliammeter used to detect contact with the water surface, was mounted in place of the lens and bulb. The device was supported by a plug-in socket mounted at some reference point with a ground wire going from the socket to the water. Three standard 1-1/2 volt flashlight batteries were connected in series with a 5000 ohm resistor and the milliammeter. The negative side of the circuit was connected to the ground wire, while the positive side was connected to a steel measuring tape graduated in feet, tenths, and hundredths. The bob was lowered until the needle on the milliammeter deflected, signaling that the water surface had been reached. The depth was read from the steel measuring tape. Russel (1945) developed a similar probe consisting of a graduated copper probe rod, and a sensing circuit consisting of a 45 volt battery, a 500-ohm resistor, and a small milliammeter. A wire was connected to a small brass machine screw embedded in a rubber insulator and inserted into the bottom end of the copper tube, the other end of the wire was soldered to the sensing circuit. The probe was inserted into the observation well until the milliammeter showed current flow, implying the water level had been reached. The distance to the water level was recorded from the scale on the copper tubing. Lissey (1967) used a variation of a Fisher M-Scope electrical tape modified by replacing the original wire with two conductor shielded phono-pickup wire, color-coded footage tags were attached to the wire to facilitate measurement. The probe used two splicing sleeves to separate the upper and lower electrodes and a fishing line leader with attached weights. The electrodes were 1/2 inch apart and the outside diameter of the probe was 1/8 inch at the electrodes. The upper electrode was connected to the outer metallic shielding while the lower electrode was connected to both insulated conductors. The probe was lowered until the meter on the M-Scope reel deflected. The distance to the water surface was determined using the color-coded footage tags.

Van Everdingen (1966) used pressure transducers to determine the piezometric pressures in confined aquifers in South Saskatchewan, Canada. The pressure transducers were variable-reluctance type with a range of 0 to 100 pounds per square inch absolute (p.s.i.a.). The pressure transducers were installed in the bottom of the piezometers in specially constructed waterproof housings. Measurements of the water levels in the piezometers were taken monthly using a battery powered read-out instrument. The meter was adjusted so that it read 0 for atmospheric pressure and 85 for 100 p.s.i.a. Meter readings were converted to actual pressures using the calibration curves.

Not all non-recording devices are this straightforward. Inouye, Bernstein, and Gaal (1970) discuss an advanced electromagnetic technique for deducing the depth of a watertable. The technique used the interaction of low-frequency electromagnetic waves with the earth. The two-coil tilt-angle electromagnetic method for measuring watertable depths was used to obtain field data. The 25-turn, 38 inch diameter, magnetic dipole transmitter was driven between 2 kHz and 200 kHz with a square wave generator. A 24-turn, 15 1/2 inch diameter, rotatable receiver was adjusted for a null output for each coil separation at several spot frequencies. The rotating axis of the receiving coil was horizontal and normal to the line between the transmitter and receiver. Signal frequency and transmitter-receiver spacing were varied to obtain the best data from the pertinent physical quantities.

The manual, non-recording methods of water level data collecting are adequate if frequent readings are not necessary or if readings are not required at multiple sites. However, the increased use of the personal computer allows more data to be analyzed to better describe an event or management practice. To take more data, reliable instrumentation to record water level readings at each site and methods for easy or automatic transfer of the data to a computer for analysis must be used.

B. Recording methods of water level monitoring

Many techniques have been devised to monitor and record a water level. Important advantages of recording gages over non-recording gages are: (1) a continuous record of fluctuations is provided, (2) maximum and minimum values and the time of their occurrence are definitely recorded, and (3) records can be obtained at points where observers are not always available. One of the simplest recording methods was developed by Ferguson (1942). It consisted of a 2 inch stilling well fastened to some support, a removable inside staff, and a marking substance (such as fine regranulated cork) that will float on water. The maximum stage height was shown by the highest level of cork dust. In addition the cork also marked successively lower crests, leaving a sharp, distinct line of grains at each crest stage. About 1 cubic inch of cork dust was used.

A popular and widely used water level recording system is the float-type chart recorder. The United States Bureau of Reclamation's, Water Measurement Manual (1974) defines a float-type chart recorder as consisting of a tape or cable that passes over a pulley equipped with a float on one end and a counterweight on the other. The float follows the rise or fall of the water surface and the stage or level may be read from the tape, or from a recorder connected to the pulley producing graphic or punched paper tape records of water surface elevation with time. The Water Measurement Manual states that, in general, graphic recorders consist of two main elements: a clock mechanism actuated by a spring, weight, or electric motor; and a gage height element actuated by a float, cable or tape, and counterweight. A gear reduction mechanism is usually also necessary in the height element. Four types of recorders use these elements. In a horizontal drum recorder the clock positions the pen along the drum axis and the gage height element rotates the drum. The vertical drum recorder, the time element again operates parallel to the drum axis and the height element rotates the drum according to the changes in stage. The third type of recorder also has a vertical drum, but the time and height elements have been reversed so that the clock mechanism rotates the drum and the water stage becomes a function of displacement along the drum axis. The above recorders are usually operated by 8-day spring driven clocks. For a continuous record of up to 9 months without changing the chart paper, a fourth type of graphic recorder can be used. The time element consists of a compensated, balanced, weight-driven clock which drives two parallel rolls, one of which holds the supply of paper. The float activates a pen which moves parallel to the axis of the rolls so that 1 inch of travel represents a change in the water level of one foot.

In addition to the graphic type recorder, a digital recorder may be used. The digital recorder is a paper-tape punch which records 4-digit numbers on a paper tape at preselected time intervals. Electronic translators are used to convert the tapes into suitable input for digital computers. To increase the time between rewinding the clock and changing the charts on a float-type recorder, Curtis (1960) developed an automatic triggering device to begin operation only when water begins to flow past the measuring station. Clocks need to be rewound and charts changed only after periods of flow. Hoff (1916) discusses the "evapormeter", a device used to monitor the change of the water surface in an evaporation tank to an accuracy of 0.01 inches. It resembles a vertical drum float-type recorder. The pen-point movement is ten times that of the float. The pressure on the pen required for a continuous record would put a load on the float which in consequence could not move gradually as the water surface does. To eliminate this problem, a rocker arm was developed. The rocker arm controls the pressure of the pen arm against the chart drum. Once every five minutes the rocker arm moves the pen from its normal position, in which it does not touch the chart, to the chart paper to make a mark as the cylinder moves. The pen arm remains free to move subject only to the float's action.

The float-type chart recorder is probably the most common method used to produce a water level-time relationship. However, to analyze the data, values have to be manually read from the chart or punched tape and entered into a computer, a time consuming task. For this reason, techniques to get the information to a computer automatically were developed. Several attempts at converting a float-type meter to give an electrical output have been tried. Boon and Harrison (1971) used a float-type system attached to a precision potentiometer to monitor watertable cycles in a tidal beach. The output voltage was proportional to the float position. A strip chart was used to record output voltage versus time. A large observation well was used but the high permeability of the beach sands minimized the time between the actual watertable and the water level in the observation well. Tromble and Enfield (1971) used the same idea with a vertical drum recorder. A 5K ohm, 10 turn linear potentiometer was connected to the float drive shaft of the recorder through a system of clock gears. Using a 4:7 gear ratio the full scale deflection was 17.5 feet. Van der Weerd (1977) designed a float-type system with an electrical output using thin nylon wire to transfer the float movement to the precision potentiometer. The wire is kept taut by means of a counterweight attached to a wire that runs over a smaller diameter pulley, keeping its vertical movement so small that it can be contained in a short tube built inside the meter case. The meter has a range of 1.25 meters and an accuracy of 0.5 centimeters, but can be increased with a larger diameter float. Talman (1983) developed a device consisting of a long float housed in a "self-contained" stilling well. Large variations in water level are reduced using a spring attached to the float so any range of water level can be recorded on any size clock drum and chart by changing the spring constant or the float size. The spring limits movement of the float and reduces the change of water level to a smaller change of float position while retaining a linear relationship. Data is stored in analog form on a chart recorder and digital form on a cassette tape. The biggest drawback of the system is the installation. Since the stilling well is self-contained, the 1500 millimeter range model requires an auger hole of 2650 millimeters, a potential problem in soils with high stone content. The mechanical impedance of the float-type system requires a large float and observation or stilling well which increases the time between the actual watertable and the water level in the observation well.

Another way to monitor and record a fluctuating water level is to use an electromechanical probe to physically follow the movement of the water surface. The probe can be connected to a chart recorder for a graphical output, or to a potentiometer for an electrical output. The observation wells can also be much smaller diameter.

Allman, Williams, and Stephenson (1969) used a commercially available Keck water level sensing device, with a precision of 0.003 foot, attached to a chart recorder for continuous output. The probe was small enough to fit inside a 5/16 inch pipe. Lovell et al. (1978) used a water level sensing probe consisting of a sensor and electric circuitry to control a 26 VDC permanent-magnet reversible 26-rpm electric motor that moves the sensor vertically. The sensor had three electrodes to activate microswitches that control the electric motor which moved the sensor up or down to determine the water surface. A 10-turn 50K ohm potentiometer gave a linear DC voltage out dependent on the vertical position of the sensor.

West and Black (1970) reported that the technique of measuring soil oxygen flux with the stationary bare platinum microelectrode has been applied to locating the watertable level in the field. With a potential of -0.4 volts to insure oxygen was the only element or compound reduced, near zero oxygen flux has been found at shallow depths while at a small distance above the saturated zone, the flux values were relatively high. From this the watertable level can be estimated.

Holbo, Harr, and Hyde (1975) measured water level using 32 platinum electrodes connected in parallel and placed at given intervals along a probe inserted into an observation well. The presence of water at a given electrode level provided a pathway for signal to flow to a common electrode running the length of the probe. The data was stored on a strip-chart recorder. This had the limitation of not being easily modified to give analog output as well as a problem with electrolysis.

Durham and Kohlmeier (1973) discuss the use of ultrasonic transducers to record the water level in observation wells during aquifer pumping tests. The device was placed in the bottom of the well and a sound pulse sent upward. The time required for the sound to be reflected back was measured, translated into a distance, and punched into paper tape at each site. Carter et al. (1984) introduced a device called a capacigage consisting of a stainless steel probe connected to a bridge circuit to measure the capacitance between the probe and a 5-cm diameter, perforated, galvanized pipe to be used as a stilling well. As the water level rose in the pipe, air, which has a lower dielectric constant than water, was displaced causing an increase in capacitance. The device was designed to output 4 to 20 milliamps, but was modified to output a DC voltage.

Bevier and Fausey (1979) tried placing a pressure transducer in a perforated cone machined from delrin inserted into the soil below the watertable. The perforations allowed the head from the watertable to be sensed by the pressure transducer. Some problems under field conditions were encountered, the perforations plugged and the transducers were damaged by overpressure during installation. The transducers were not hermetically sealed and displayed erratic results when exposed to humidity. MacVicar and Walter (1984) designed a probe similar to Holbo, Harr, and Hyde (1975) with the following goals in mind: simple, continuous operation, inexpensive, "large" DC signal out and low output impedance, and small in size to utilize a small observation well and minimize the time between the actual watertable and the water level in the observation well. The probe featured a series of resistors regularly spaced over the depth to be monitored and a ground wire opposite the contacts covering the same range of depths. To avoid electrolysis and rapid deterioration of the probe contacts, an AC input signal used to energize the probe was converted to DC prior to being recorded. A linear relationship between inverse resistance and depth was found.

A device to relate pressure in a tube to water level, called a bubble gage, was described by Barron (1960), Reinhart and Pierce (1964), and the United States Bureau of Reclamation's Water Measurement Manual (1974). The bubble gage was a mechanical instrument consisting of a pressurized gas supply, a sensitive pressure control system, a tube extending into the water, and either a non-recording or recording method of measuring the pressure in the tube. The non-recording method utilized a manometer to measure the pressure in the tube. The recording method automated the procedure using a servomotor that sensed the gas pressure and converted it into a shaft rotation was connected to a water stage recorder. The bubbler gage eliminated the need for a large stilling well and float. The principle of the gage is explained by the Water Measurement Manual (1974), "The gas is fed into the tube and it bubbles freely from the open lower end which is fixed at a known level under water. The gas pressure will be essentially equal to the head of water on the tube outlet and is read on the mercury-filled manometer." Barron (1960) claimed a sensitivity of 0.005 foot using a mercury manometer and a range of more than 120 feet.

C. Problems with current water level monitoring devices

The devices which utilize a float to monitor the watertable require a large observation well which increases the time between water level in the well and the actual watertable. All of the above devices output either an analog or digital signal at the observation well. From the observation well, the data must be transferred to a central location or one datalogger must be dedicated to each well. This is satisfactory if there are few sites or they are close together. When there are many sites spread apart in the field two choices exist, either one datalogger must be used at each site and the observer must walk to that site when the data needs to be dumped, or, wires must be run from each site to a central location at which the datalogger is located. The former would be very expensive and still time consuming. The latter appears more feasible, but shielded wire is expensive and the probability of picking up noise and transient electrical surges with a long data transmission wire is high. An inherent problem with a motorized probe device is that it is expensive, requires frequent maintenance, and the electric potential on the probe causes direct current flow through the groundwater resulting in electrolysis.

Most soil and water research is still done using a float-type chart recorder with the data either read off and entered into a computer by hand or through the use of a digitizer. Both are expensive and time consuming.

III. SYSTEM DESIGN

A. Design Objectives

The objective of this research was to design and test an electronic data aquisition system for collecting watertable elevation data with the following requirements: 1) low cost, 2) direct input of data into a computer for analysis, 3) a DC sensor output in the 5 volt range, 4) user error tolerant, 5) relatively simple and quick to assemble, 6) durable and reliable, 7) a majority of off the shelf items, 8) capability of monitoring watertable at eight locations, 9) a watertable elevation range of about 0 to 762 mm (0 to 30 inches), and 10) an overall accuracy of about ±3 mm (±0.1 inches).

B. Proposed System

Following recommendations by Merva and Fausey (1984) the system (Figure 1) used a small watertable observation well, approximately 191 mm (3/4 inches) I.D., to minimize the time between the actual watertable and the water level in the observation well. Into the observation well, a smaller diameter bubbler tube, 3.18 mm (1/8 inches) I.D. connected by flexible spaghetti tubing to a tank of pressurized nitrogen gas was inserted. Nitrogen gas was

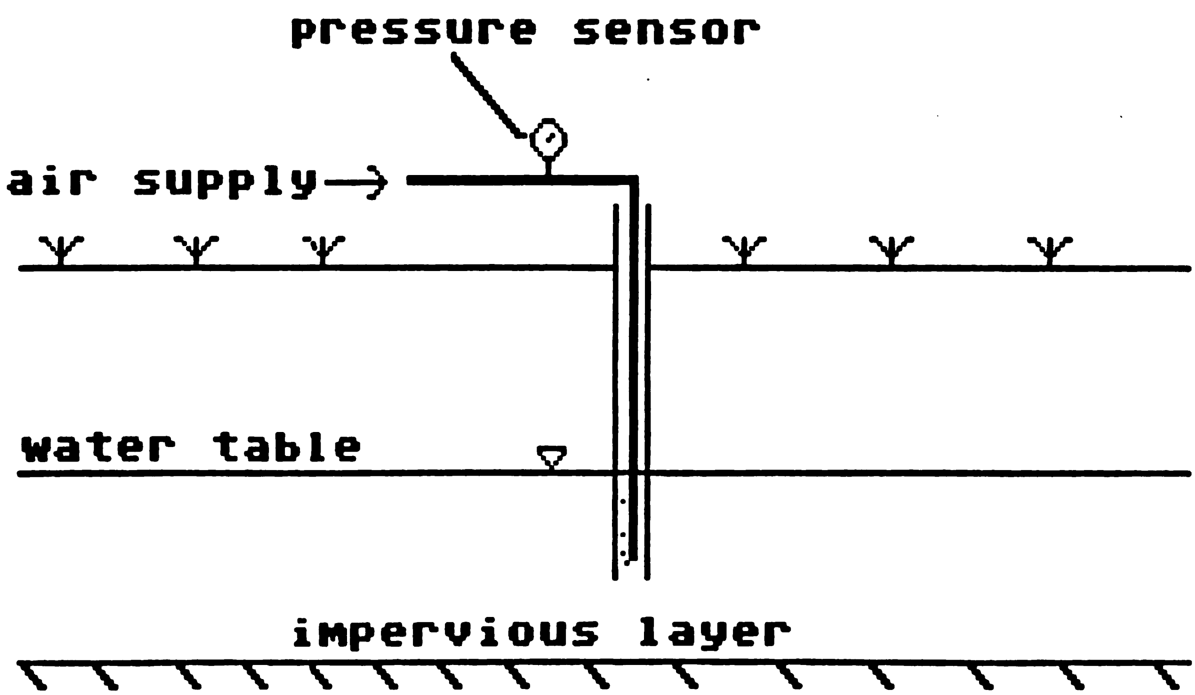

Figure 1: Proposed bubbler system.

used in the system because it is comparatively cheap and is inert and inorganic to retard algea growth at the end of the bubbler tube. The nitrogen gas was allowed to bubble slowly through the tubing into the observation well. The bubbling rate was controlled through an in-line needle valve. A pressure transducer connected to the supply line near the nitrogen gas source sensed the pressure required to force a bubble out of the bubbler tube, thereby sensing the water level surrounding the tube. The pressure transducer converted the pressure into a voltage. A datalogger converted the voltage from the pressure transducer into a digital output at some predetermined time interval.

C. Selection of Components

Components were chosen for the data aquisition system (DAS) because of their low cost, simplicity, reliability, and availability. The DAS had to be capable of monitoring at least eight pressure transducers, a range of approximately 0 to 762 mm (0 to 30 inches) of water pressure with a system accuracy of about ±3 mm (±0.1 inches). A brief description of the components is offered here (details of component specifications are given in Appendix A).

The pressure transducer chosen was a differential type with a range of 0 to 703 mm (0 to 27.7 inches) and a accuracy of ±1 mm (±0.04 inches). Internal signal conditioning produced a direct, linear output between 1 and 6 volts DC. Temperature compensation resulted in a predictable performance over the specified temperature ranges.

The data were logged on an 8 channel datalogger with 8 bit resolution resulting in a precision of ±2.8 mm (±0.11 inches). The datalogger had both analog(0 to 5 VDC) and digital input and digital output capabilities. The internal 2K bytes of random access memory (RAM) had the capacity of storing 1975 data points. The sampling interval was adjustable from 1 second to 18.2 hours. The datalogger utilized an RS232C port to initiate the data acquisition process and to retrieve the stored data.

A small, briefcase type, portable computer was used to communicate with the datalogger. The computer chosen had a screen, constant memory, an RS232 port, and built-in floating point BASIC. In addition, other built-in software including word processing and telecommunications, allowed the user to take notes, or send and receive information via a telephone line while in the field.

D. Data Transfer

1. Water level to pressure transducer

The position of the water level in the observation well was transferred to the pressure transducer via the 3.18 mm (1/8 inch) spaghetti tubing (Figure 2). As the water level in the observation well changed, the pressure needed to force a bubble out of the tube changed. When the water level increased, the pressure in the spaghetti tubing, which is sensed by the pressure transducer also increased. The pressure transducer continuously converted the pressure in the tube to a voltage.

2. Transducer to datalogger

The pressure transducer had a voltage output which varied linearly as the pressure changed from 0 to 6.89 kPa(0 to 1 psi or 0 to 27.7 inches of water). The datalogger converted the voltage (analog signal) to a digital number between 0 and 255. The numbers were stored in the 2K bytes of internal memory in the datalogger. A problem was encountered when matching the output of the pressure transducer with the input range of the datalogger. The datalogger converted a voltage in the range of 0 to 5 VDC, but the transducer had an offset of approximately one volt giving a full range output of 1 to 6 VDC. This meant the effective range of the pressure transducer and the

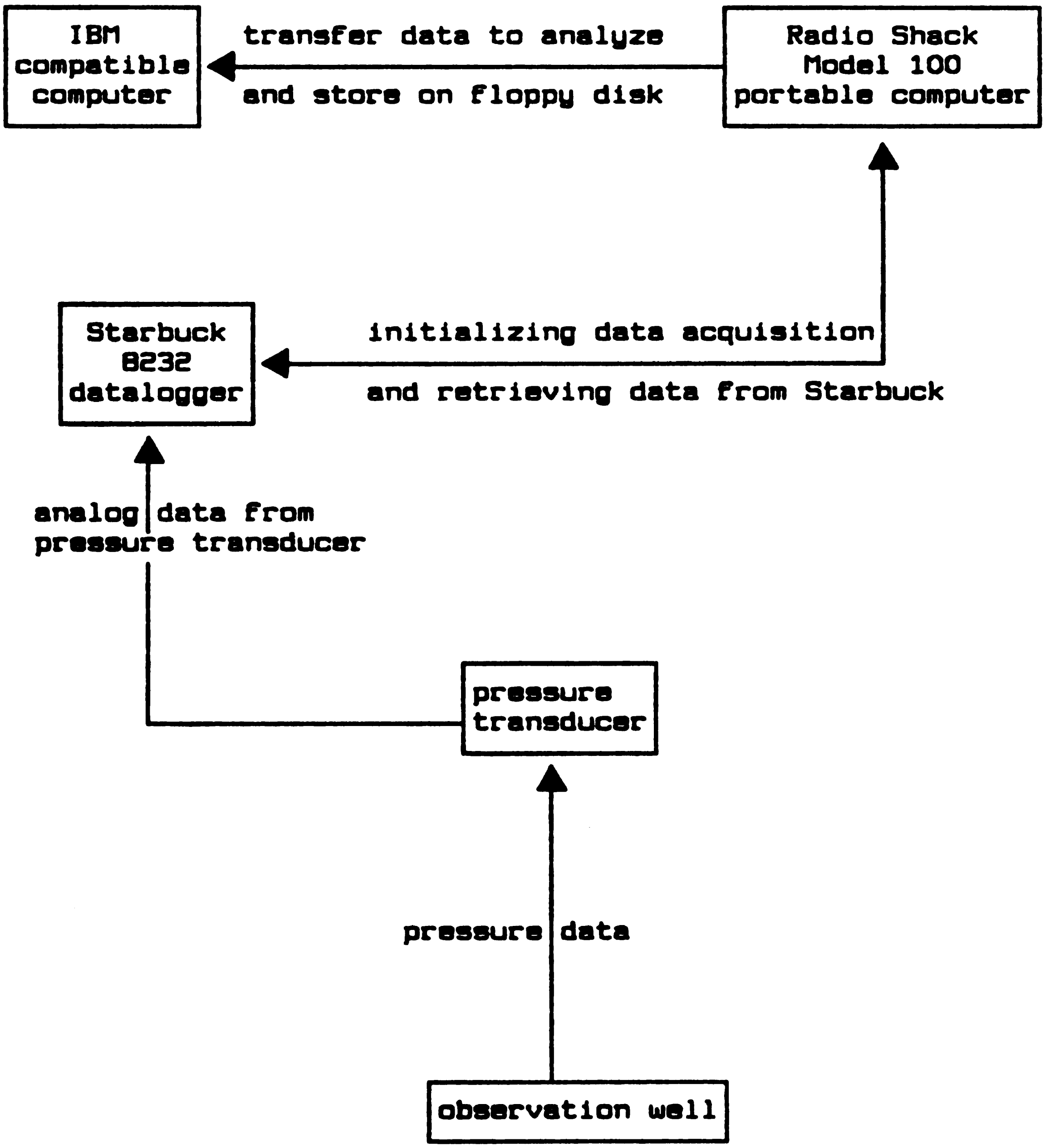

Figure 2: The transfer of information from observation well to floppy diskette.

datalogger together was 1 to 5 VDC [0 to 563.9 mm (0 to 22.2 inches) of water]. This problem is addressed in more detail in the "Recomendations" section of the text.

3. Datalogger to portable computer

With 8 channels, and a total of 1975 data points available in the datalogger, there were 246 data points available for each channel. The time interval used was 30 minutes, so the data had to be collected from the datalogger at least every 5 days. There were two possible methods to communicate with the datalogger using the portable computer. The first was with the memory based communication program. In this approach, the communication parameters (baud rate, data word length, parity, and stop bits) were set up the same as in the datalogger. The communication program worked well, but the operator had to manually enter each command. Since this technique allowed operator induced error, the second approach was used. In this approach, the datalogger was accessed from a BASIC program (Appendix B), where the operator needed only to "RUN" the program after connecting the computer to the datalogger. This allows statements in the BASIC program to make communication with the datalogger as user error tolerant as possible. The data from each channel was written to a separate file on the portable computer. It was then taken from the field to the office and transferred to a larger computer for further analysis.

4. Portable computer to IBM compatible computer

When the portable computer was connected to an IBM compatible computer to transfer data through the RS232C port, two problems were encountered. The first was that both computers wanted to send and receive information on the same wires. To solve this problem, the send wire on one computer was connected to the receive wire of the other computer and visa-versa. The second problem was that the IBM compatible expected a voltage on pin #8 of the RS232C connector(carrier detect). The portable computer did not use that pin and the IBM compatible never recognized that it was hooked up. To solve this problem, a wire was jumpered from pin #20 on the portable computer to pin #8 on the IBM compatible. The data could then be uploaded to the personal computer for further analysis.

Note: The IBM compatible computer needed a communication package to "talk" to the portable computer.

IV. Development of System

A. Test system I

To test the above system in the laboratory, a bubbler tube, consisting of a piece of spaghetti tubing taped on a meterstick, was inserted into a 5 gallon pail designed to fill to a predetermined level and then drain by siphon thus simulating watertable fluctuations (Figure 3). A Bausch & Lomb V.O.M. 5 strip chart recorder was initially used to log the data. The purpose of this test was not to determine the accuracy of the system but to check the system's ability to follow a fluctuating water level. The test was run for 19 days and the results were very encouraging (Figure 4).

B. Test system II

The second version of the test system (Figure 5) utilized an analog to digital converter (Starbuck 8232 datalogger) to record the data using the same test system described above. The test was run for about 10 days and the upper and lower as well as several intermediate values were checked with a meterstick to be within 2.5 mm(0.1 inches) of the recorded values. The results are shown in Figure 6. Both short [16 meters (50 feet)] and long [325 meters (1000

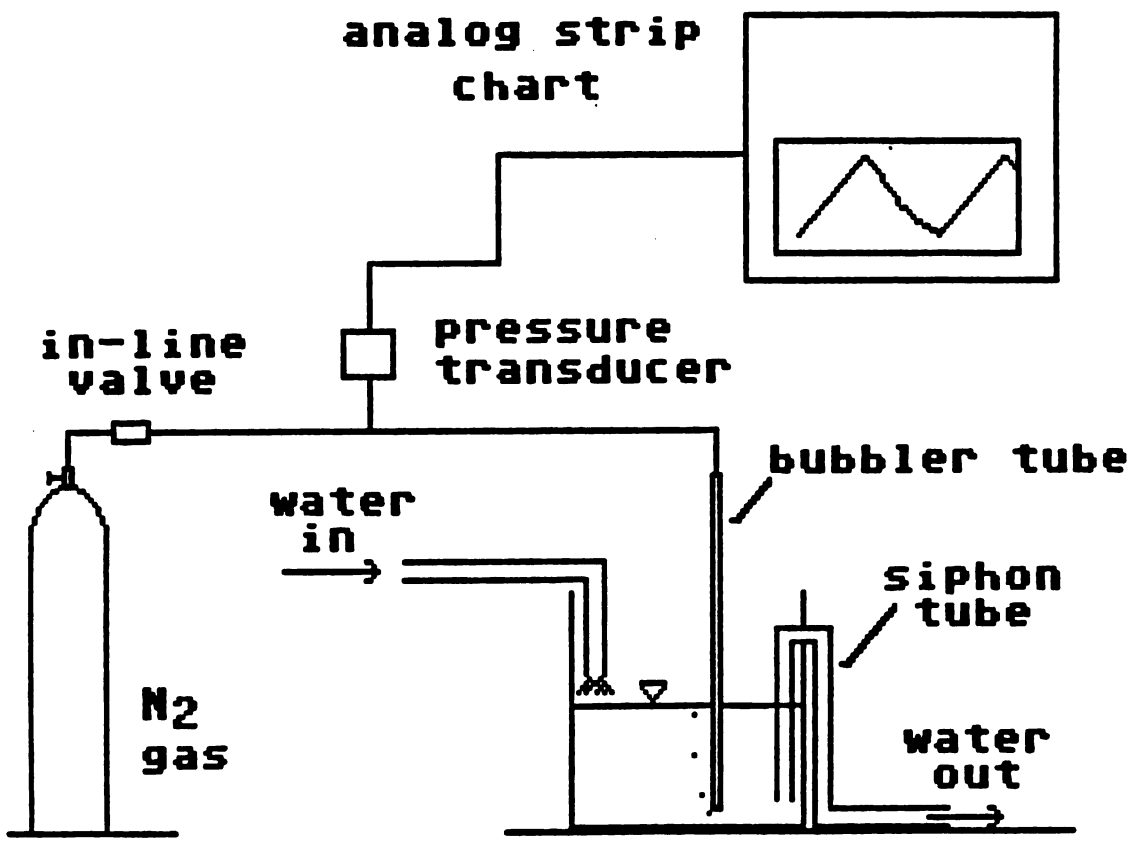

Figure 3: Test system I.

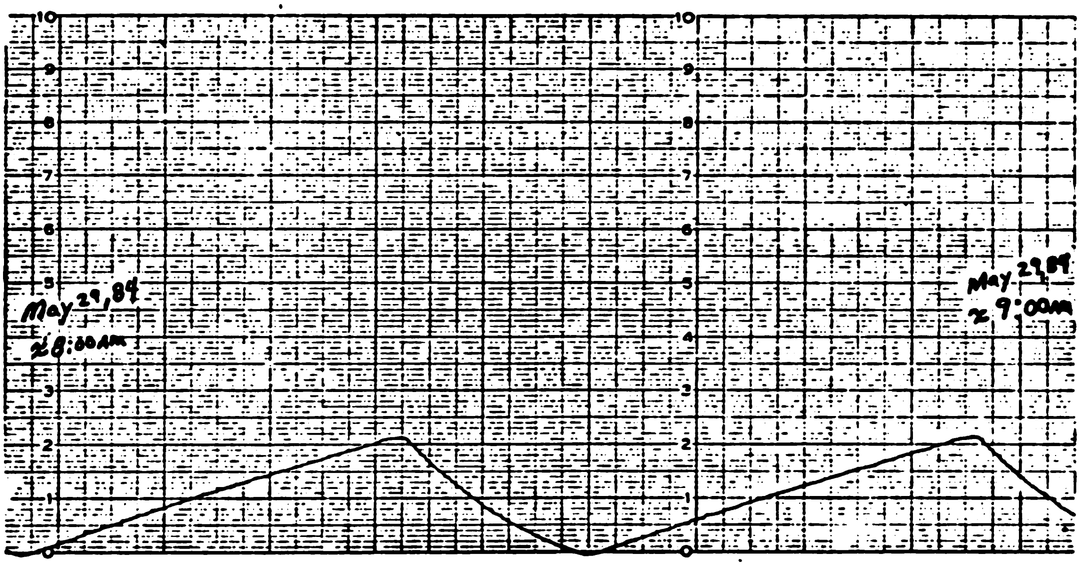

Figure 4: A one hour sample of the data from the test system I data as recorded by a strip chart recorder.

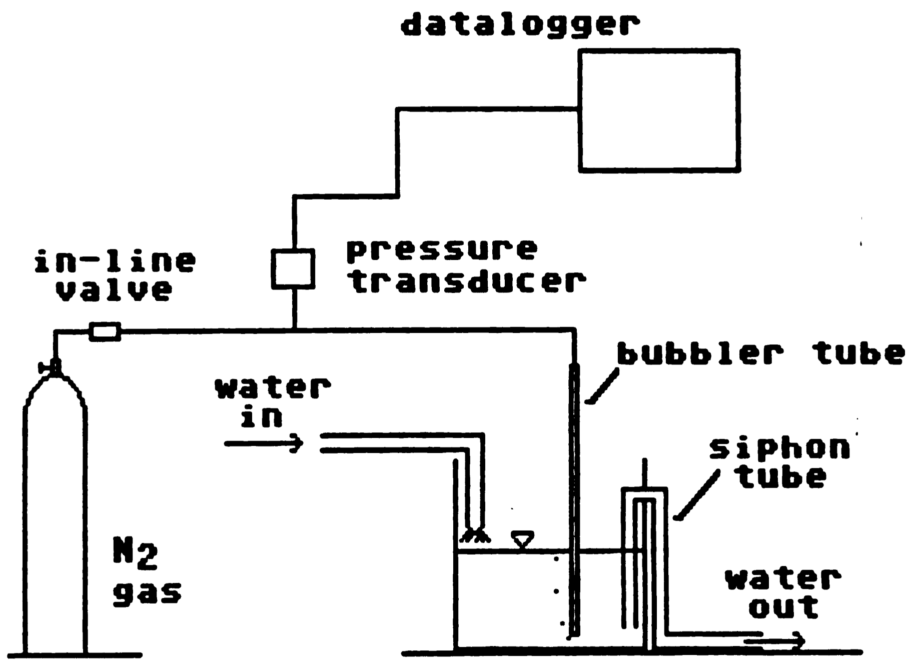

Figure 5: Test system II using a datalogger to collect the data.

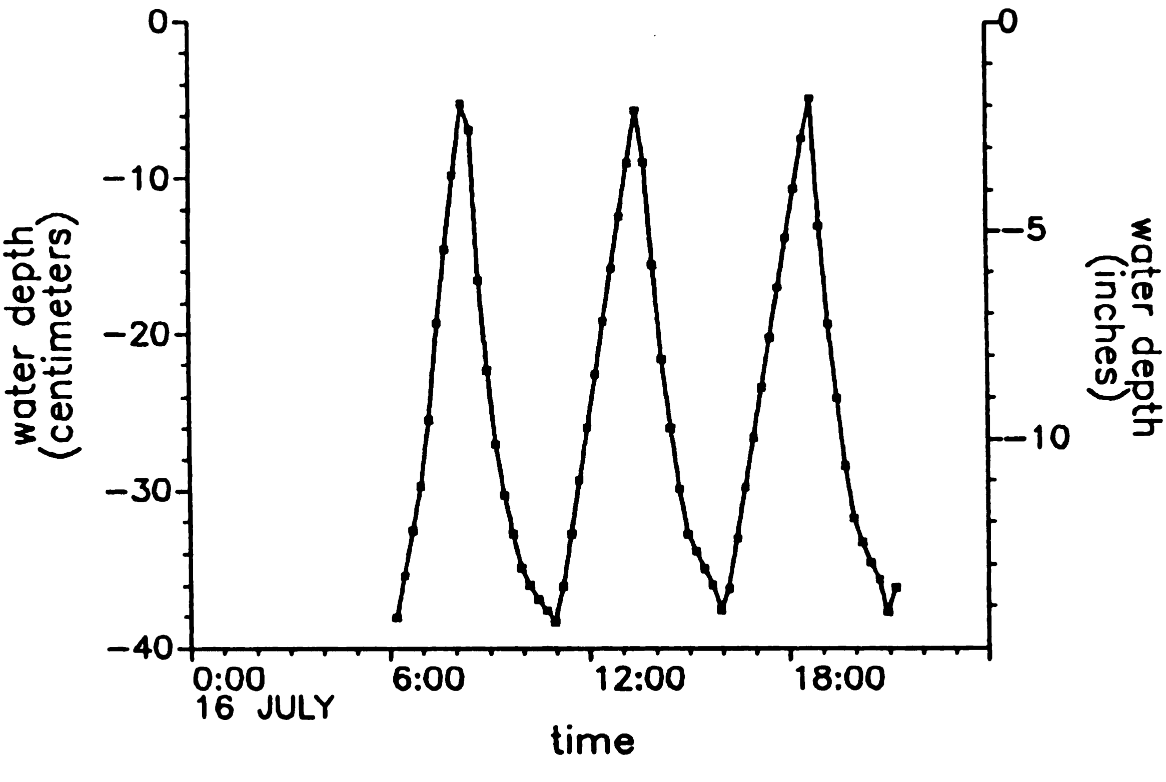

Figure 6: Fifteen hours of data from test system II.

feet)] bubbler tubes were tested with no noticeable difference in the accuracy of the system.

C. Field system installation

The data acquisition system (Figure 7) was installed in a 15 ha (37 acre) corn field being subsurface irrigated (Figure 8). The field was split in half so the watertable level could be controlled separately, allowing two management practices (a high and a low watertable level) to be tested. It was desired to monitor the watertable over a subsurface irrigation line and between a subsurface irrigation line on each end of the field for both management practices. The instrumentation equipment was housed in a pump house located between the two management practices on the edge of the field. The maximum length of a bubbler tube required for any observation well was about 389 meters (1200 feet).

The observation tubes were constructed from 25.4 cm (1 inch) O.D. PVC pipe with holes drilled randomly to admit water. The PVC pipe was wrapped in polyester cloth to retard soil accumulation in the pipe. The observation wells were drilled to a depth below the lowest expected watertable level using a 3 inch soil auger.

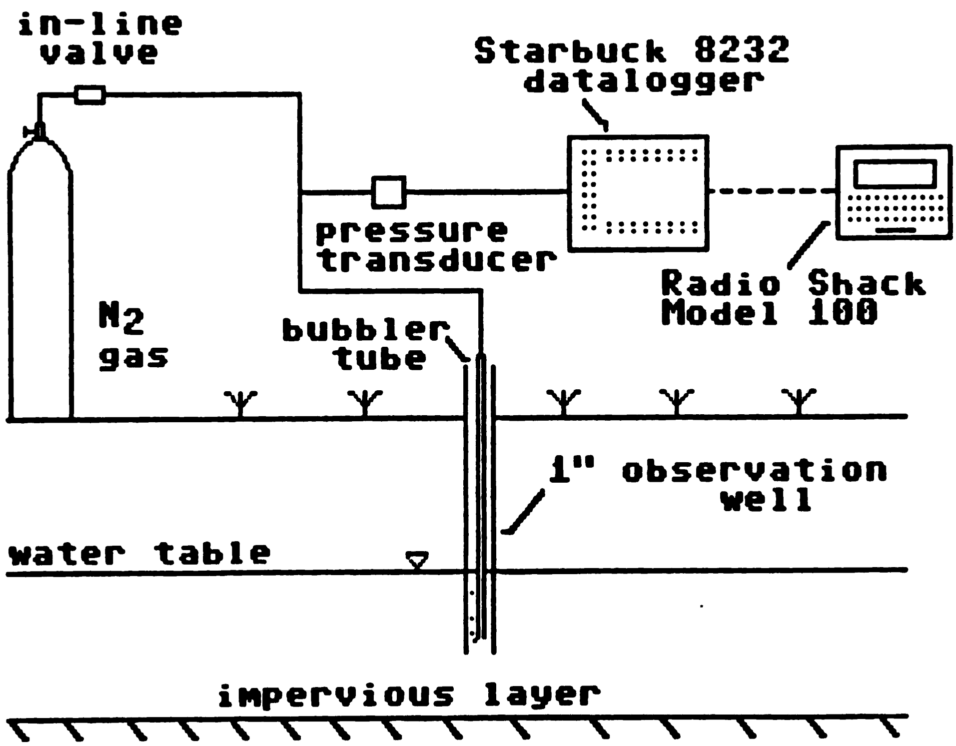

Figure 7: The first field system showing the datalogger, portable computer, and observation well.

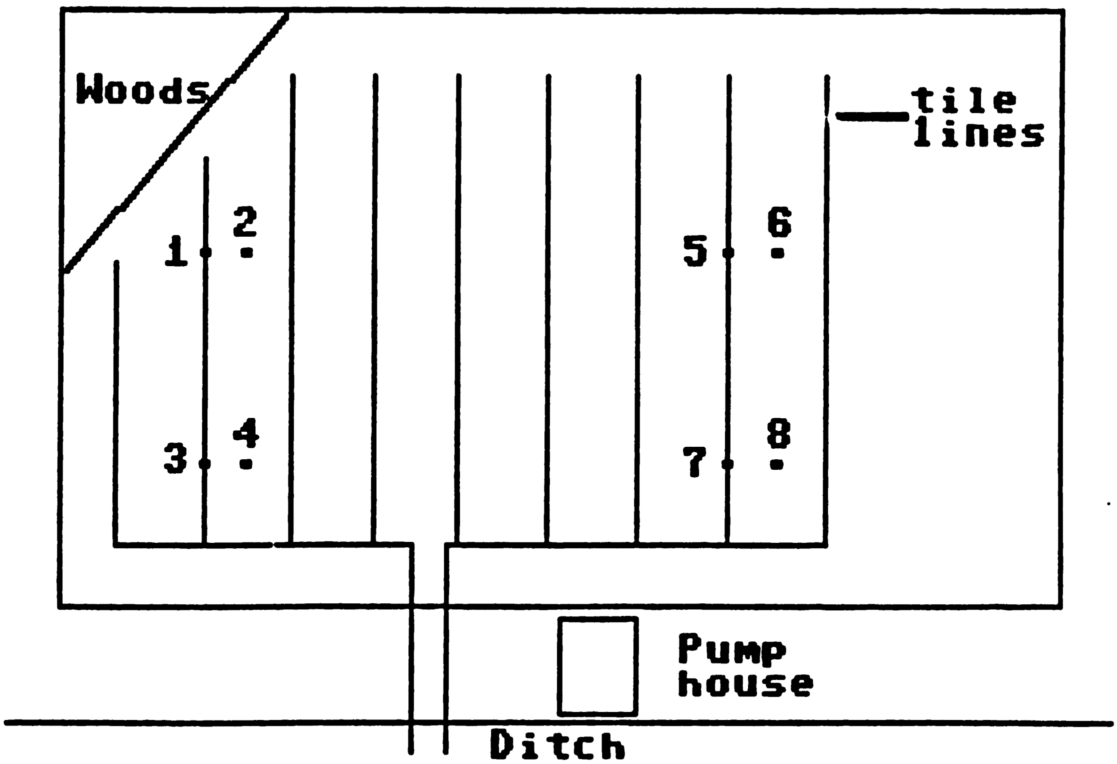

Figure 8: Bubbler system test field showing the observation well sites.

The bubbler tube consisted of 3.18 mm (1/8 inch) I.D. spaghetti tubing used in trickle irrigation. It was unrolled from the instrumentation station to each observation well. The bubbler tubes were inserted into the observation wells after the system was calibrated. Each tube was labeled to aid identification.

To set the bubbling rate for each bubbler tube, a calibration tube (a piece of spaghetti tubing about 163 meters (500 feet) long) was connected to the in-line valve of the bubbler tube to be adjusted. The other end of the calibration tube was inserted into a can of water. The in-line valve was opened until the bubbling rate was approximately one bubble every second. The actual bubbler tube was then reconnected to the in-line valve. The voltage reading at each of the pressure transducers was checked and recorded. This voltage was the transducer offset and differed depending on the transducer and bubbler tube length. The deviation in the offset is due to manufacturer's variations in the pressure transducers and slight differences in friction for different bubbler tube lengths. Finally, each observation well was checked to be sure it was bubbling. If not, the calibration spaghetti tubing was reconnected and the rate of bubbling was increased slightly. If this was done, it was necessary to recheck and record the new offset.

The bubbler tubes were installed in the observation wells by first determining the anticipated lower limit of the watertable from the soil surface. A #3 rubber stopper held in place with tygon tubing and hose clamps kept the bubbler tube at a constant depth below the soil surface. The rubber stopper was inserted into the observation tube and the distance from the top of the stopper to the end of the bubbler tube was measured and recorded as "b" (Figure 9). The distance from the top of the rubber stopper to the soil surface was measured and recorded as "a". The depth of the bubbler tube below the soil surface or (b - a) was recorded for each observation well. The value "c" in Figure 9 is the pressure transducer reading minus the offset. The equation for the distance to the watertable from the soil surface ("d") is therefore:

$$d = ((b - a) - c)$$

The system was now ready for data collection. The information recorded in the user's field manual was the value of (b - a), the offset for each pressure transducer, and the starting time and date of data aquisition.

D. Results of Field Test

1. Problems with Field System I

The data acquisition system was field tested for approximately three months. During this time, several things were learned about the system. The pressure

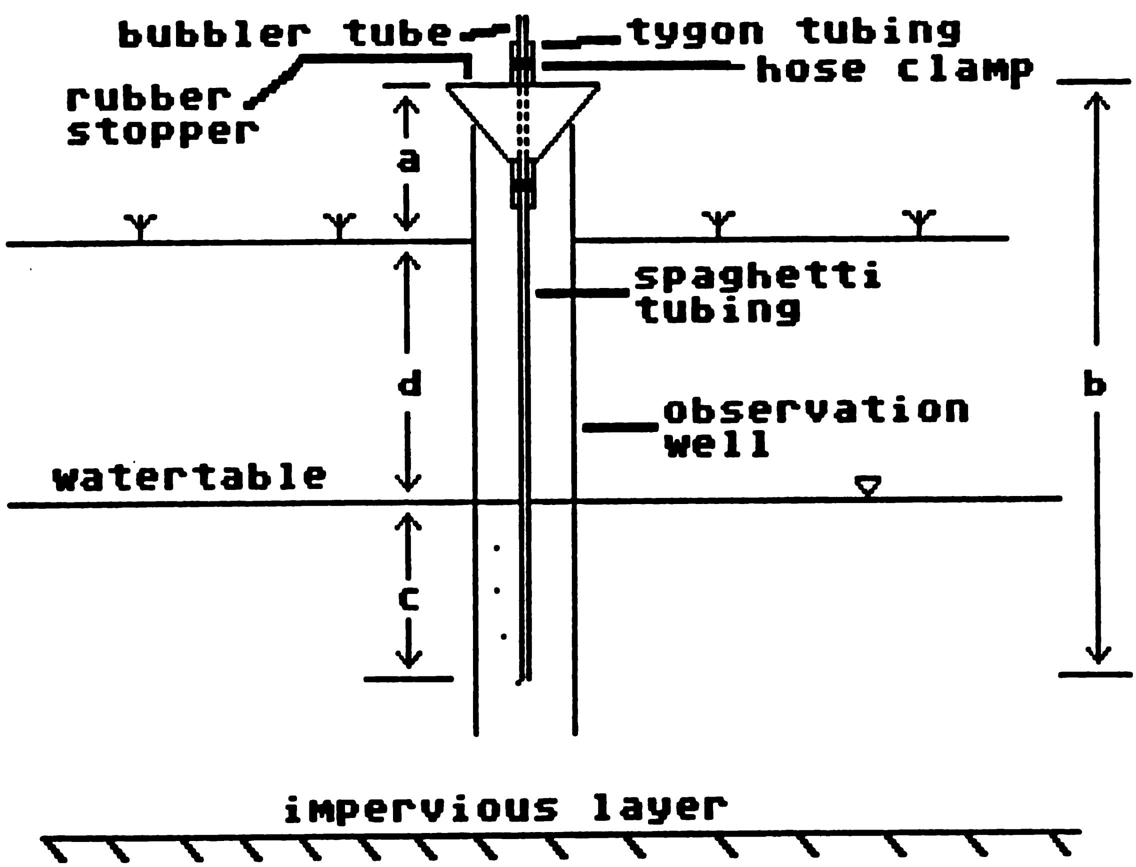

Figure 9: Bubbler tube installation into an observation well.

transducer's offsets remained constant. The bubbler tubes in the observation wells had to be moved down midway through the season when the watertable went below the estimated lower limit of the watertable. The new distance to the bottom of the bubbler tube was recorded and used later in the analysis of the data.

The first field system was powered completely from a 120 VAC powerline. The datalogger was plugged directly into the powerline while the pressure transducer's D.C. excitation voltage was supplied by a Heathkit IP-2718 Tri-power supply. The bubbler tube was strung on top of the ground to each observation well. Three problems arose from this set-up. The first was fluctuations in the pressure transducer's output. A pressure transducer was left open to atmospheric pressure as a reference. The output should have been a straight line, instead, the output was a diurnal-type fluctuation. A probable cause of this problem was powerline voltage variations. Since the pressure transducer output is linearly related to the excitation voltage at a constant pressure, powerline variations affected the pressure transducer's output directly. A software solution was used to solve this problem. The difference between each individual pressure transducer output and the output from the atmospheric reference transducer was taken to give the correct output of each pressure transducer.

The second power problem, power failure, affected both the pressure transducers and the datalogger. The output from the pressure transducers during a power outage was zero. The datalogger had no internal back-up batteries to power the memory, during a power failure all data and any program stored in memory were lost. The problem was solved by powering the datalogger with a 12 volt automotive battery kept charged by a battery charger. The battery would operate the datalogger for about a month without having to be recharged, but in most cases, the power outages lasted only for several hours at a time.

A third problem encountered was that rodents chewed on the bubbler tubes, puncturing or severing the tube. The problem could be checked for in the field and was indicated by a low reading as compared to the readings in nearby observation wells. To solve the problem the tubes were buried under one or two inches of soil.

A pressure transducer was left open to the atmosphere as a reference. The daily fluctuations, probably due to powerline voltage changes can be seen in the output (Figure 10). These fluctuations were subtracted from the raw data to give the corrected data.

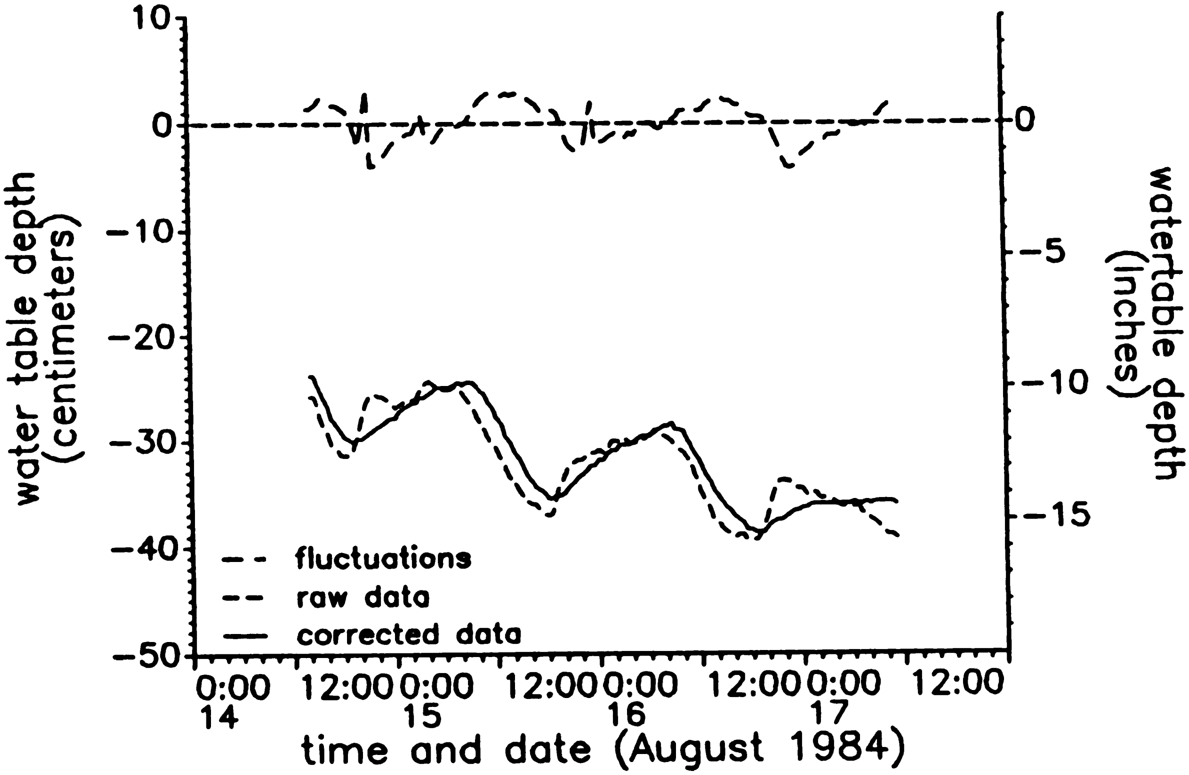

Figure 10: Fluctuations in the reference pressure transducer output. The uncorrected and corrected data sets are from observation well site #6.

2. Bubbler data compared to Steven's meter data

Data from a new system is not very meaningful unless it can be verified using another method. In the test field, float-type chart recorders (Steven's meters) were installed in the same area as were the bubbler tubes. Figure 11 shows the comparison between the bubbler system and the Steven's meter data sets. The difference in the extremes of the data is due to the greater sensitivity in the bubbler tube. This is a result of a smaller observation well for the bubbler system (1 inch versus 3 inch) which minimizes the time between the actual watertable level and the water level in the well [Merva and Fausey (1984)]. The diurnal fluctuations as well as the downward trend of the watertable can be seen in both Figures 10 and 11. The difference in the watertable depths between the two figures is due to the different management tests. Figure 10 is from the higher watertable side and Figure 11 is from the lower watertable side.

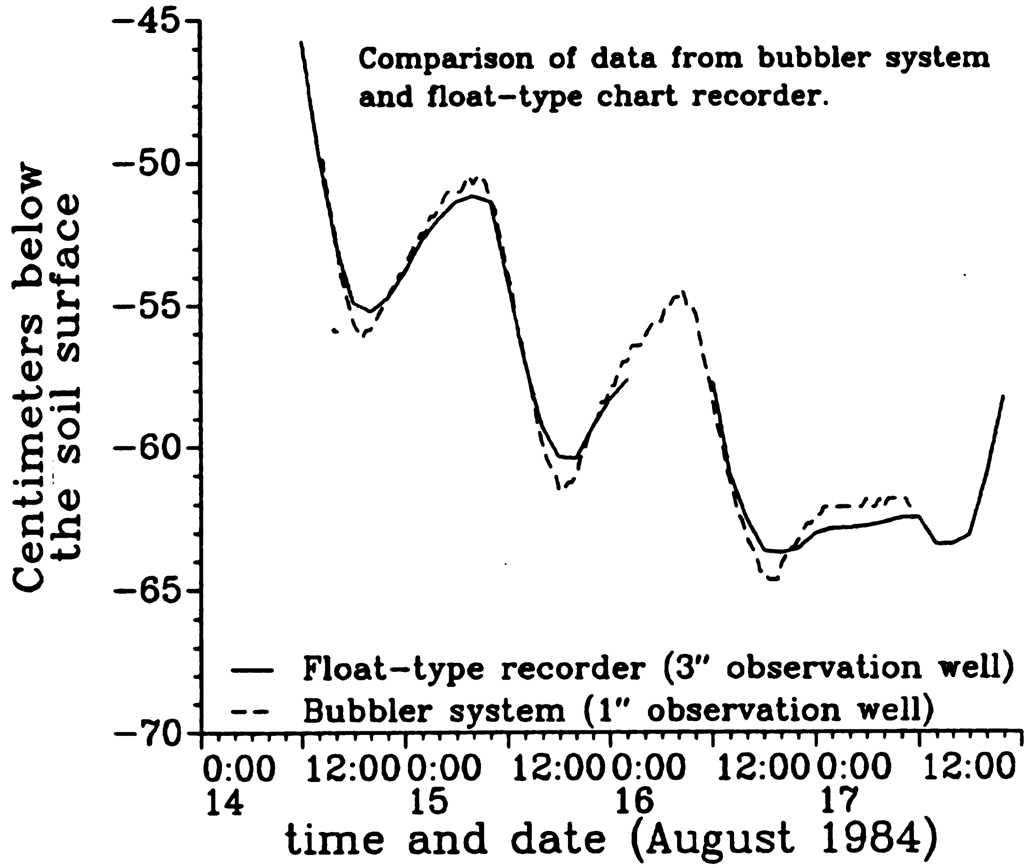

Figure 11: Sample of corrected data compared to float-type chart recorder data.

V. ERROR ANALYSIS

The error analysis performed on the bubbler system was mainly concerned with the static calibration of the system and to determine the lag time of the system as a function of bubbler tube length. Lag time is the it takes for the system to reach equilbrium after an increase of water depth at the end of the bubbler tube. A static calibration was chosen rather than a dynamic calibration because most watertable levels monitored in agricultural research tend to change slowly or a static change. The datalogger and pressure transducer were calibrated separately first, then together as a system with 5 different bubbler tube lengths (30.5, 152.4, 304.8, 457.2, and 609.6 meters). The datalogger and pressure transducer were kept at a constant temperature while the different bubbler tube lengths were tested at three different temperatures above 20°C (68°F). A constant bubbling rate of approximately one bubble per second was used for the entire calibration process.

A. Statistical method used

The data from the calibration of both the components and the system was statistically analyzed using the least squares method to determine the slope (M) in centimeters per datalogger unit or centimeters per volt and y intercept (YI) in centimeters. Data was colleced by the Starbuck 8232 datalogger and a Keithley 175 digital multimeter (DMM). In the calibration, datalogger reading or voltage was plotted on the x-axis and water depth on the y-axis. The calibration equation was used to calculate a Y value, in centimeters, given datalogger and DMM readings. The calculated Y value was subtracted from the measured Y value to give the residual. The bubbler tube was mounted on a meterstick and the measured y values were determined to the nearest millimeter. The residual squared was summed over the data set to yield the error sum of squares (SSE). The varience(s) and standard error with a 95% confidence interval were calculated for the slope (SE M), the y intercept (SE YI), the calculated y value (SE Y) using Student's t-distribution. An average standard error (SE Y Ave) and percent error of full scale (% err) for the calculated y were also determined. The complete data set and statistical output from the calibration can be seen in Appendix C. The data set and statistical output from the system calibration can be seen in Appendix D. The equations used in the statistical analysis are found in Table 1.

TABLE 1

Equations used for the statistical analysis

$$M = \frac{\sum_{i=1}^{n}(X_i * Y_i) - (n * \bar{X} * \bar{Y})}{\sum_{i=1}^{n}(X_i^2) - (n\bar{X}^2)} \qquad YI = \bar{Y} - M * \bar{X}$$

$$SSE = \sum_{i=1}^{n}(Y_i - YI - M * X_i)^2 \qquad s^2 = \frac{SSE}{n-2}$$

$$s^2M = \frac{s^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2} \qquad s^2YI = \left(\frac{1}{n} + \frac{\bar{X}^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2}\right) * s^2$$

$$s^2Y = \left(1 + \frac{1}{n} + \frac{(X - \bar{X})^2}{\sum_{i=1}^{n}(X_i - X)^2}\right) * s^2$$

$$SE\ M = \pm s^2M * t_{n-2,95\%} \qquad SE\ YI = \pm s^2YI * t_{n-2,95\%}$$

$$SE\ Y = \pm s^2Y * t_{n-2,95\%} \qquad \%\ err = \pm \frac{SE\ Y}{70.3\ \text{cm}} * 100$$

(full scale reading)

- n = number of data points
- X = datalogger or voltage reading
- Y = water depth
- t = Student's t distribution for n-2 points and a 95% confidence interval
- % err = percent error
- s = varience
- M = slope of line
- YI = y-intercept
- SE = standard error
- $\bar{X}$ = average of X values
- $\bar{Y}$ = average of Y values

X_i and Y_i = any given value of X and Y

B. Calibration of Components

1. Datalogger

The "factory-calibration" of the datalogger's full scale reading was checked by connecting a variable power supply and increasing the voltage until the datalogger output was just 255 units. The digital multimeter (DMM) reading was 4.997 VDC which agreed with the operator's manual indicated value of 5.00 ±0.02 VDC. Once the full scale reading was established, the datalogger was calibrated over the full range using a 4 1/2 digit, 12 bit resolution, Keithley 175 Autoranging DMM which is more accurate than the datalogger. The datalogger utilizes an analog to digital converter with 8 bit resolution. The expected full scale accuracy was (1/255) = ±0.392% or ±0.0196 VDC. The voltage was increased from about 1.25 to 5.00 VDC then decreased over the same range. The lower limit of the voltage range was chosen because of the power supply used. The average percent error over the full range was ±0.280% or ±0.0140 VDC.

2. Pressure transducer

The pressure transducer is capable of operating from a single, positive excitation voltage ranging from 7 to 16 VDC. At a given excitation voltage, the offset (output voltage at zero pressure) varies up to ±5% depending on the pressure transducer.

Each of the eight pressure transducers put in the field were calibrated separately. The difference was in the offset and not the slope of the calibration curve. Each pressure transducer used in the system should be calibrated. This error analysis was performed on one presure transducer. The pressure transducer was calibrated with an excitation voltage of 8 VDC, as suggested by the manufacturer. At this excitation voltage, the offset can vary from 0.95 to 1.05 VDC depending on the pressure transducer. The offset of the pressure transducer tested was 1.002 VDC. The output of the pressure transducer is dependent on the excitation voltage. The linear relationship between excitation voltage and output voltage at a constant pressure is shown in Figure 12.

The pressure transducer was calibrated by connecting a column of water above it. The water level in the column was increased and then decreased at approximately 50 mm intervals over the transducer range. The output voltage was monitored both by a 4 1/2 digit Keithley 175 Autoranging digital multimeter(DMM) as well as the calibrated datalogger.

Using the least squares method, the calibration curve (Figure 13) for the pressure transducer was determined from the DMM data. The slope, Y intercept, and the standard error for both the datalogger and the DMM are summarized in

Table 2. The calibration equation for the pressure transducer when using the datalogger was:

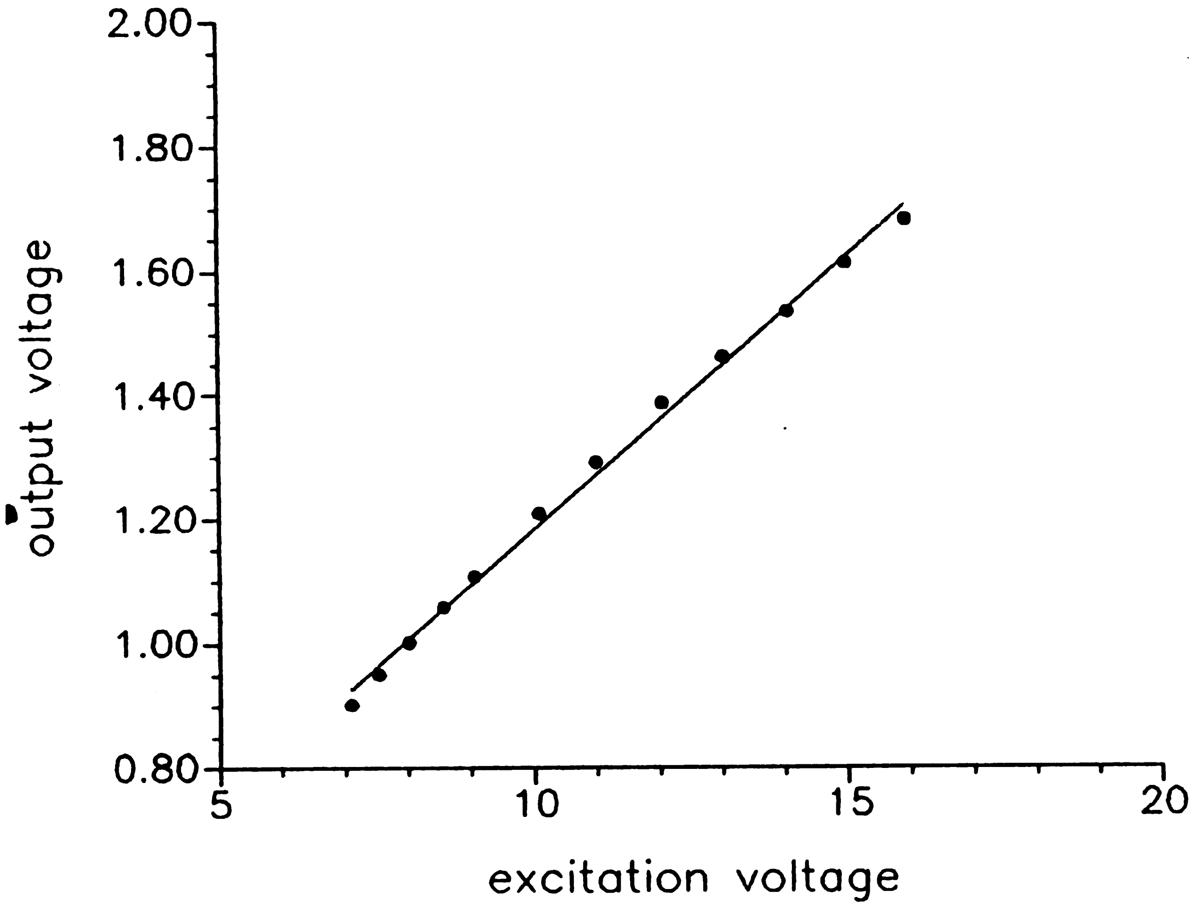

Figure 12: Excitation voltage versus output voltage for a pressure transducer.

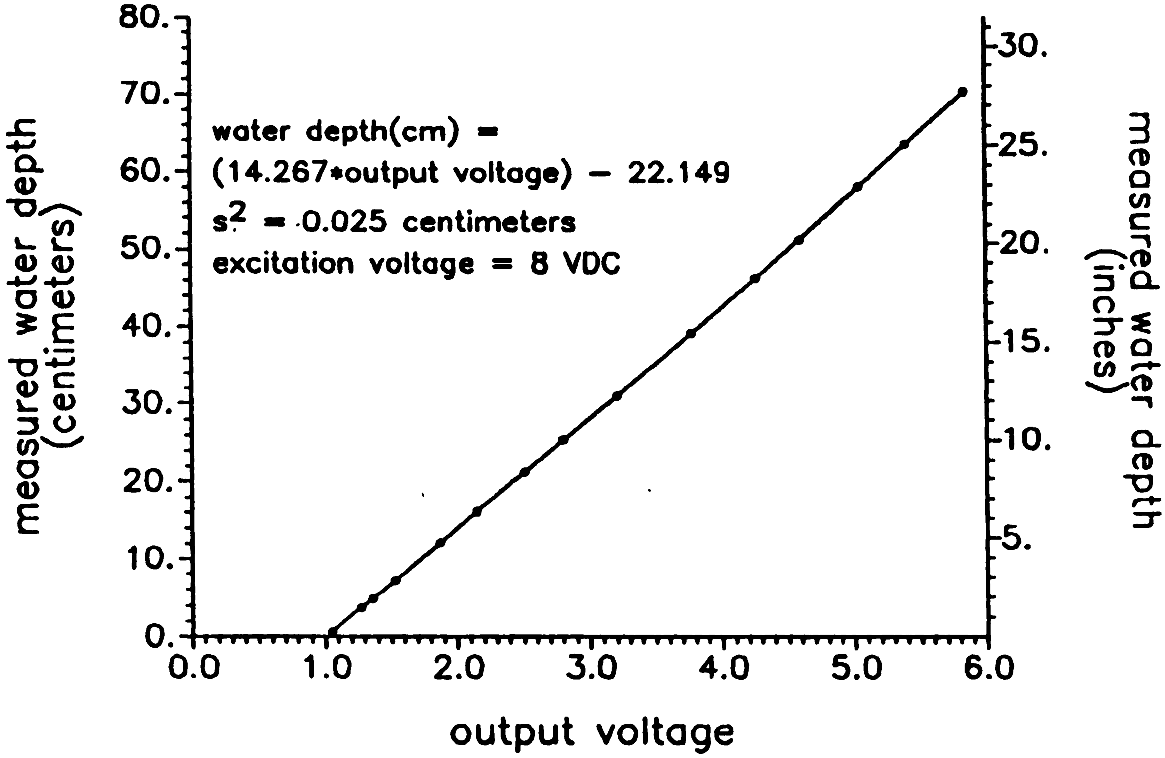

Figure 13: Calibration curve for the pressure transducer.

Water depth (cm) = ((0.279 * datalogger reading) - 21.875) [Water depth (inches) = ((0.110 * datalogger reading) - 8.612)].

When the output voltage is monitored, the equation was: Water depth (cm) = ((14.267 * voltage reading) - 22.149) [Water depth (inches) = ((5.617 * voltage reading) - 8.720)].

TABLE 2

Summary of the pressure transducer calibration

	M	SE M	YI	SE YI	SE Y Ave	s^2
Datalogger						
up	0.278	0.002	-21.730	0.337	0.297	0.114
down	0.279	0.002	-22.041	0.389	0.314	0.120
both	0.279	0.002	-21.875	0.351	0.403	0.176
Digital multimeter (DMM)						
up	14.260	0.037	-22.010	0.170	0.202	0.088
down	14.252	0.061	-22.211	0.262	0.281	0.118
both	14.267	0.048	-22.149	0.217	0.335	0.157

M = slope (cm/datalogger unit or cm/volt)
SE M = 95% standard error in the slope
YI = Y intercept (cm)
SE YI = 95% standard error in the Y intercept
SE Y Ave = average standard error (95%) in calculated Y (cm)
s^2 = variance

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3. Temperature effect

The temperature of the pressure transducer-datalogger system was changed from 20°C (68°F) to 60°C (140°F) at a constant excitation voltage and input pressure. The temperature range was chosen based on approximated field conditions and available labratory facilities. The output voltage changed 0.03 volts over this temperature change (Figure 14). From the slope of the line, the temperature coefficient for the system was calculated to be $713.33(10^{-6})$ volts per degree Celsius increase from 20°C. A temperature coefficient should be determined for each datalogger-pressure transducer combination put into the field.

C. Bubbler system calibration

The system, consisting of a portable computer, datalogger, pressure transducer, and bubbler tube, was calibrated using 5 different bubbler tube lengths at 3 temperatures using both the datalogger and the DMM to collect the data. A bubbling rate of one bubble per second was used for the entire error analysis. Nitrogen gas was bubbled through the bubbler tube which was rolled up into a 60 centimeter diameter roll. Each bubbler tube length was inserted into a oven. The end of the bubbler tube was taped to a meterstick and inserted into a 2 liter glass graduated cylinder. The end of the bubbler tube, the pressure transducer, the datalogger, and the portable computer were

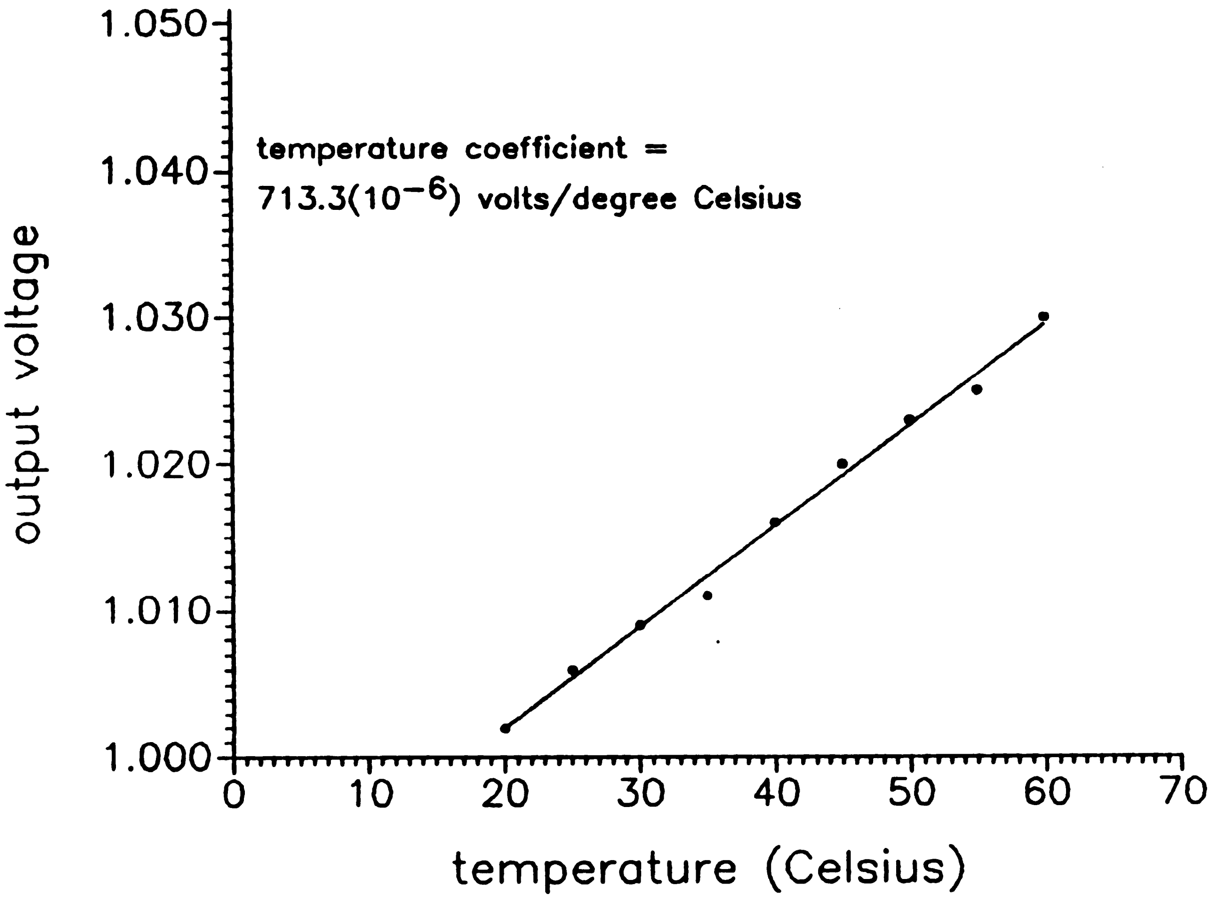


Figure 14: Determination of the temperature coefficient. Temperature versus output voltage.

outside the oven and at room temperature about 20°C. Water was added quickly into the graduated cylinder to increase the depth about 5 to 15 centimeters each time. The measured depth was taken from the meterstick. The increase in pressure in the bubbler tube was moniitored by the datalogger and the DMM until it reached an equilibrium. This value was used for the calibration of the system.

The slope (M), standard error of M (SE M), y intercept (YI), standard error of YI (SE YI), average standard error of the calculated y value (SE Y Ave), and variance (s) were calculated for each temperature and bubbler tube length. The calibration values were averaged over the temperature range for a given bubbler tube length. Overall averages were determined for M, SE M, SE Y Ave, and s. The values for YI and SE YI were excluded from the overall average since they change based on bubbler tube length and the bubbling rate. The slope and calculated y values are independent of tube length and bubbling rate and should remain constant. The summary of the calibration output is given in Table 3. Note that the slope of line stays relatively constant for the different bubbler tube lenghts and temperatures. The y intercept stays constant over the temperature range, but becomes more negative as the bubbler tube length increases. The reason the y intercepts are less for the 609.6 meter bubbler tube than the 457.2 meter bubbler tube is that the in-line valve was adjusted for the 609.6 meter tube to set the bubbling rate to 1 bubble per second.

TABLE 3

Summary of the bubbler system calibration

DATALOGGER

	M	SE M	Y-INT	SE YI	SE Y Ave	s
30.5 meter bubbler tube						
29°C	0.279	0.004	-15.926	0.579	0.407	0.108
44°C	0.276	0.002	-15.530	0.363	0.284	0.081
55°C	0.279	0.003	-15.932	0.480	0.292	0.078
Average	0.278	0.003	-15.796	0.474	0.328	0.089
152.4 meter bubbler tube						
29°C	0.278	0.003	-16.716	0.448	0.339	0.090
37°C	0.277	0.003	-16.683	0.386	0.306	0.060
51°C	0.277	0.004	-16.658	0.757	0.429	0.114
Average	0.277	0.003	-16.686	0.530	0.358	0.088
304.8 meter bubbler tube						
25°C	0.277	0.002	-19.215	0.424	0.287	0.076
32°C	0.276	0.001	-18.616	0.205	0.154	0.041
50°C	0.278	0.003	-19.097	0.556	0.416	0.111
Average	0.277	0.002	-18.976	0.333	0.286	0.076
457.2 meter bubbler tube						
28°C	0.281	0.002	-20.029	0.304	0.233	0.062
39°C	0.280	0.003	-20.020	0.466	0.346	0.092
53°C	0.279	0.002	-20.413	0.360	0.272	0.072
Average	0.280	0.002	-20.154	0.377	0.284	0.075
609.6 meter bubbler tube						
21°C	0.279	0.002	-19.707	0.328	0.319	0.139
28°C	0.277	0.003	-19.101	0.453	0.355	0.095
35°C	0.279	0.004	-19.446	0.692	0.465	0.124
53°C	0.281	0.003	-20.219	0.518	0.336	0.090
Average	0.279	0.003	-19.618	0.498	0.369	0.112
Overall Average	0.278	0.003	*****	***	0.328	0.090

TABLE 3 (cont'd.).

DMM

30.5 meter bubbler tube

29°C	14.073	0.104	-15.665	0.300	0.212	0.057
44°C	14.033	0.075	-15.531	0.217	0.170	0.045
55°C	14.063	0.033	-15.637	0.104	0.063	0.017
Average	14.056	0.071	-15.611	0.207	0.148	0.040

152.4 meter bubbler tube

29°C	14.045	0.167	-15.847	0.509	0.392	0.104
37°C	14.037	0.069	-16.546	0.210	0.167	0.045
51°C	14.102	0.119	-16.851	0.398	0.224	0.060
Average	14.061	0.118	-16.415	0.372	0.261	0.070

304.8 meter bubbler tube

25°C	14.130	0.053	-19.550	0.182	0.122	0.032
32°C	14.066	0.099	-18.759	0.315	0.236	0.063
50°C	14.046	0.125	-18.922	0.403	0.303	0.080
Average	14.081	0.092	-19.077	0.300	0.220	0.058

457.2 meter bubbler tube

28°C	14.290	0.150	-20.006	0.484	0.371	0.099
39°C	14.161	0.047	-19.929	0.152	0.113	0.030
53°C	14.163	0.135	-20.330	0.442	0.335	0.089
Average	14.205	0.111	-20.088	0.359	0.273	0.073

609.6 meter bubbler tube

21°C	14.156	0.083	-19.587	0.264	0.257	0.112
28°C	14.063	0.075	-19.074	0.234	0.184	0.049
35°C	14.168	0.062	-19.457	0.212	0.142	0.038
53°C	14.206	0.084	-19.969	0.288	0.188	0.050
Average	14.148	0.076	-19.522	0.250	0.193	0.062

Overall Average	14.113	0.093	*****	***	0.217	0.061

M = slope (cm/datalogger unit or cm/volt)
SE M = 95% standard error in the slope
YI = Y intercept (cm)
SE YI = 95% standard error in the Y intercept
SE Y Ave = average standard error (95%) in calculated Y (cm)
s = variance

D. Lag time determination

During the calibration of the system, the datalogger was programmed to store a voltage reading from the pressure transducer every 10 seconds. These data made it possible to calculate the rate of change of pressure in the bubbler tube for a water level change at the end of the bubbler tube. Data showed that time to equilibrium when the water level was being decreased was approximately halved as compared to when it was being increased. In most applications, the water level fluctuates both up and down so the increase would be limiting. For that reason, only the increasing water level was analyzed. Figures 15 to 19 show the relationship between the water depth changes and time for the pressure in the bubbler tube to equilibrate at 3 temperatures. Each step on the curve represents the addition of water to the graduated cylinder. Each temperature-bubbler tube combination was tested separately and the depth of each step was varied from about 5 to 15 centimeters. The flat part of the curves is when pressure in the bubbler tube is at a constant value. A change in the temperature of the bubbler tube did not noticably affect the rate of change of pressure (slope of the increasing line) for a given bubbler tube length as seen in Table 3. As the bubbler tube length increased, the time to equilibrium for a given change in water level also increased. Figure 20 shows the comparison between the five bubbler tube lengths at the lowest temperature. For a given water depth change

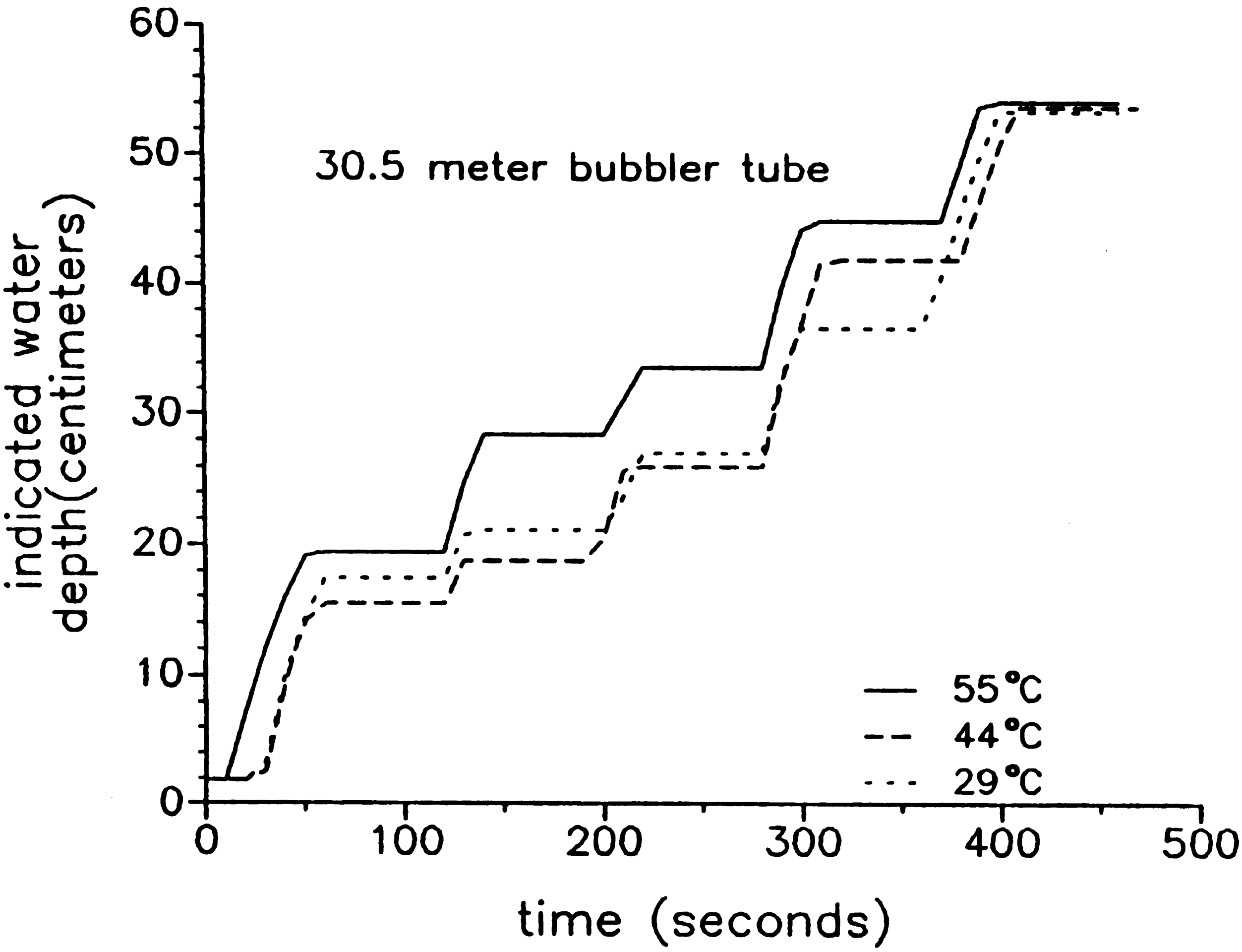


Figure 15: Time versus water depth for the 30.5 meter bubbler tube.

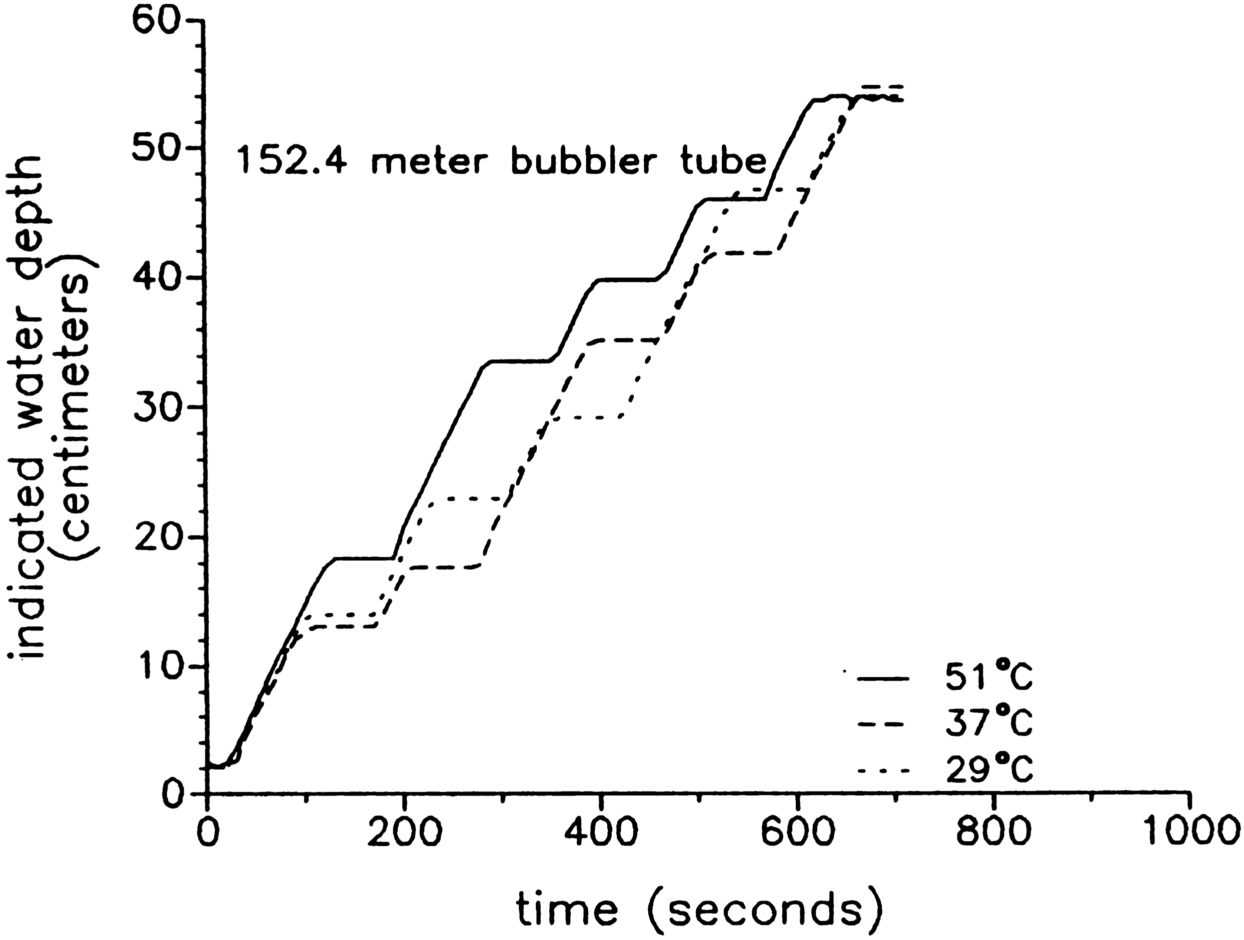


Figure 16: Time versus water depth for the 152.4 meter bubbler tube.

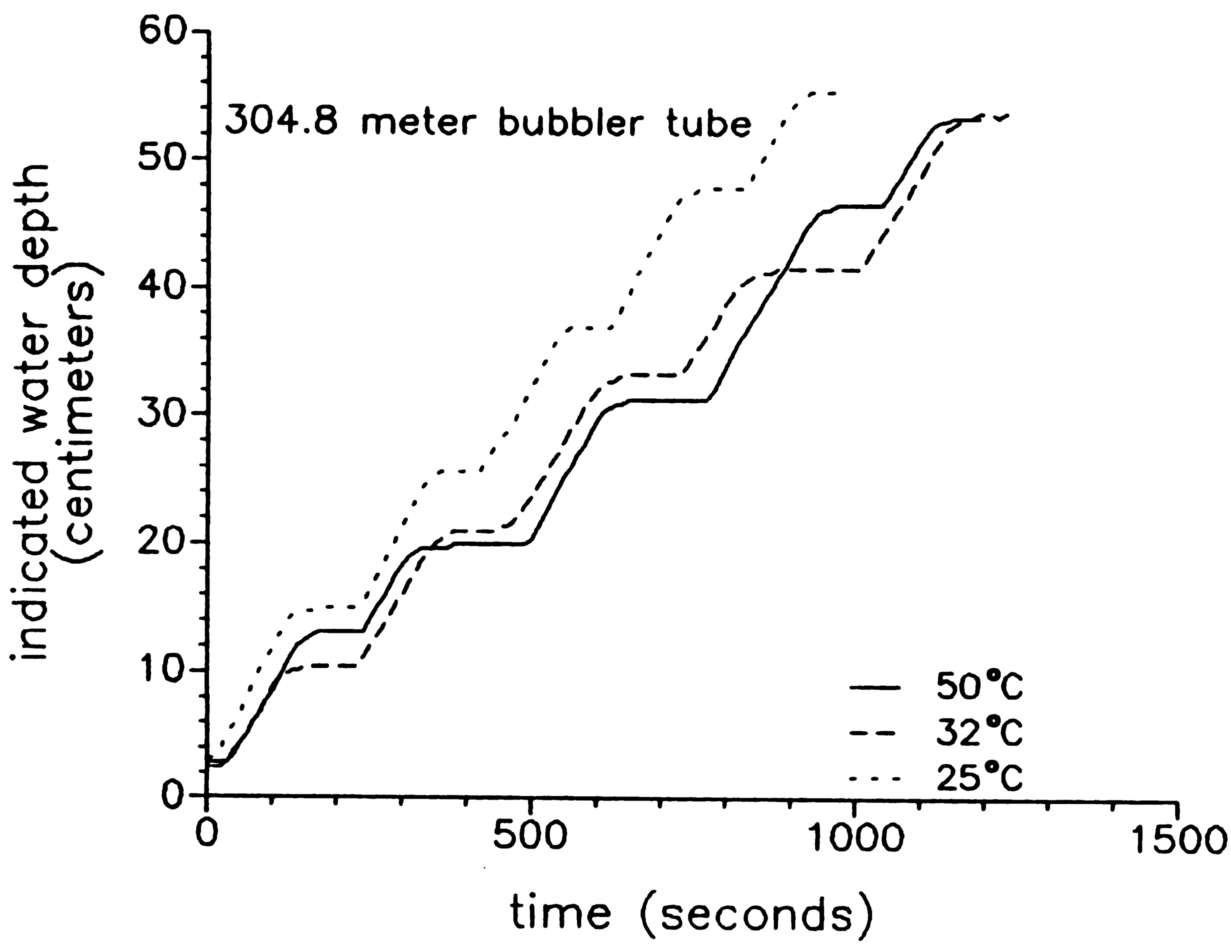


Figure 17: Time versus water depth for the 304.8 meter bubbler tube.

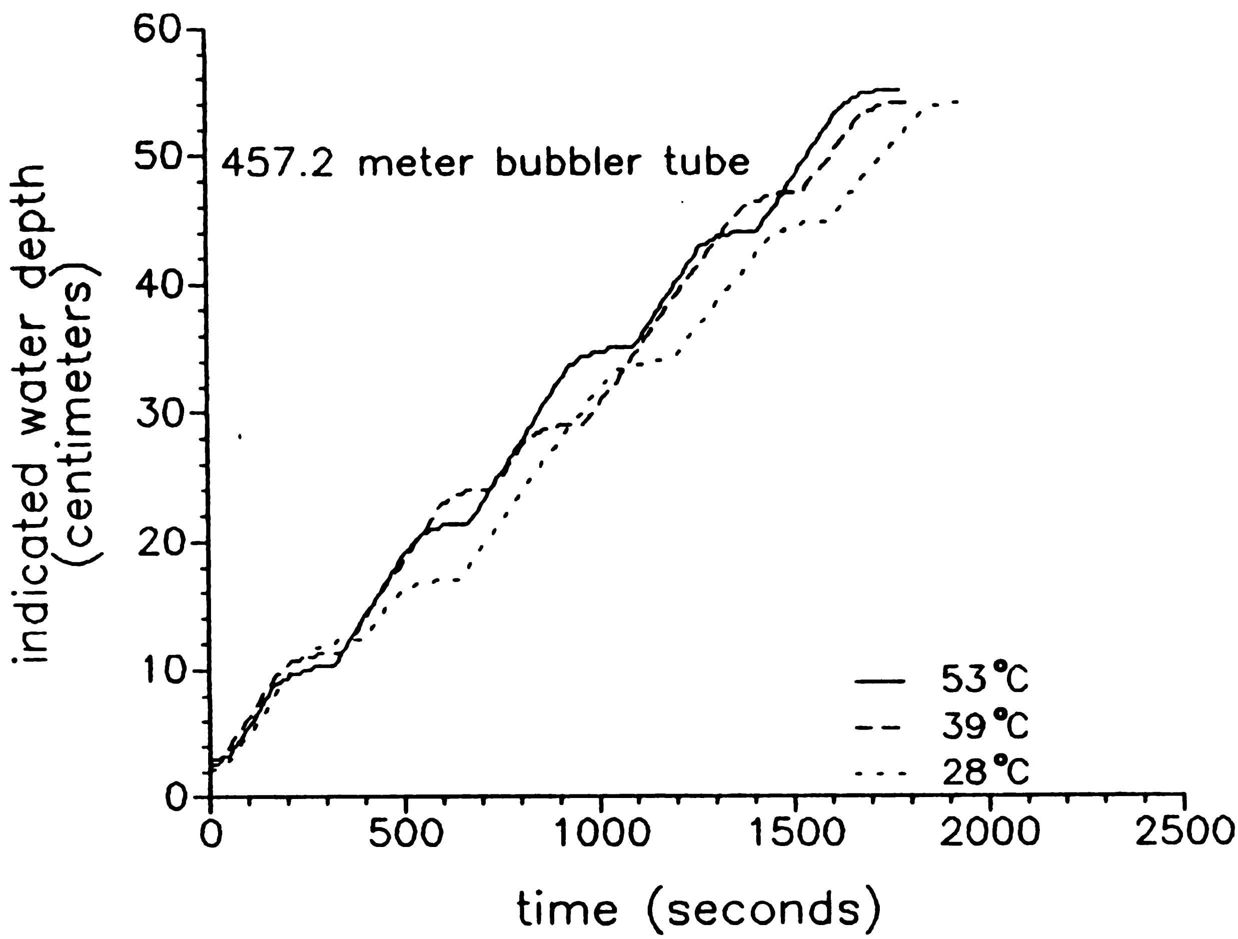


Figure 18: Time versus water depth for the 457.2 meter bubbler tube.

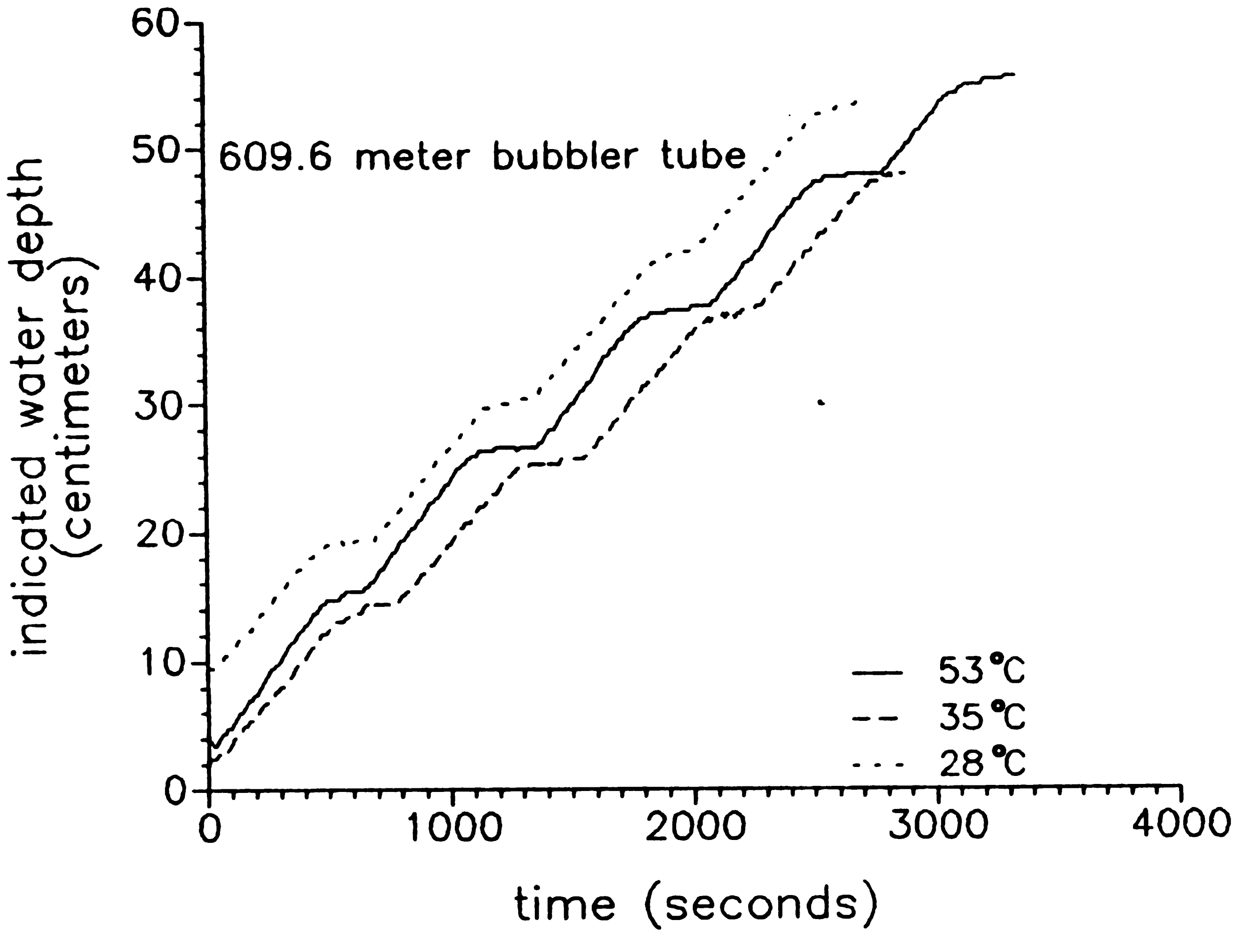


Figure 19: Time versus water depth for the 609.6 meter bubbler tube.

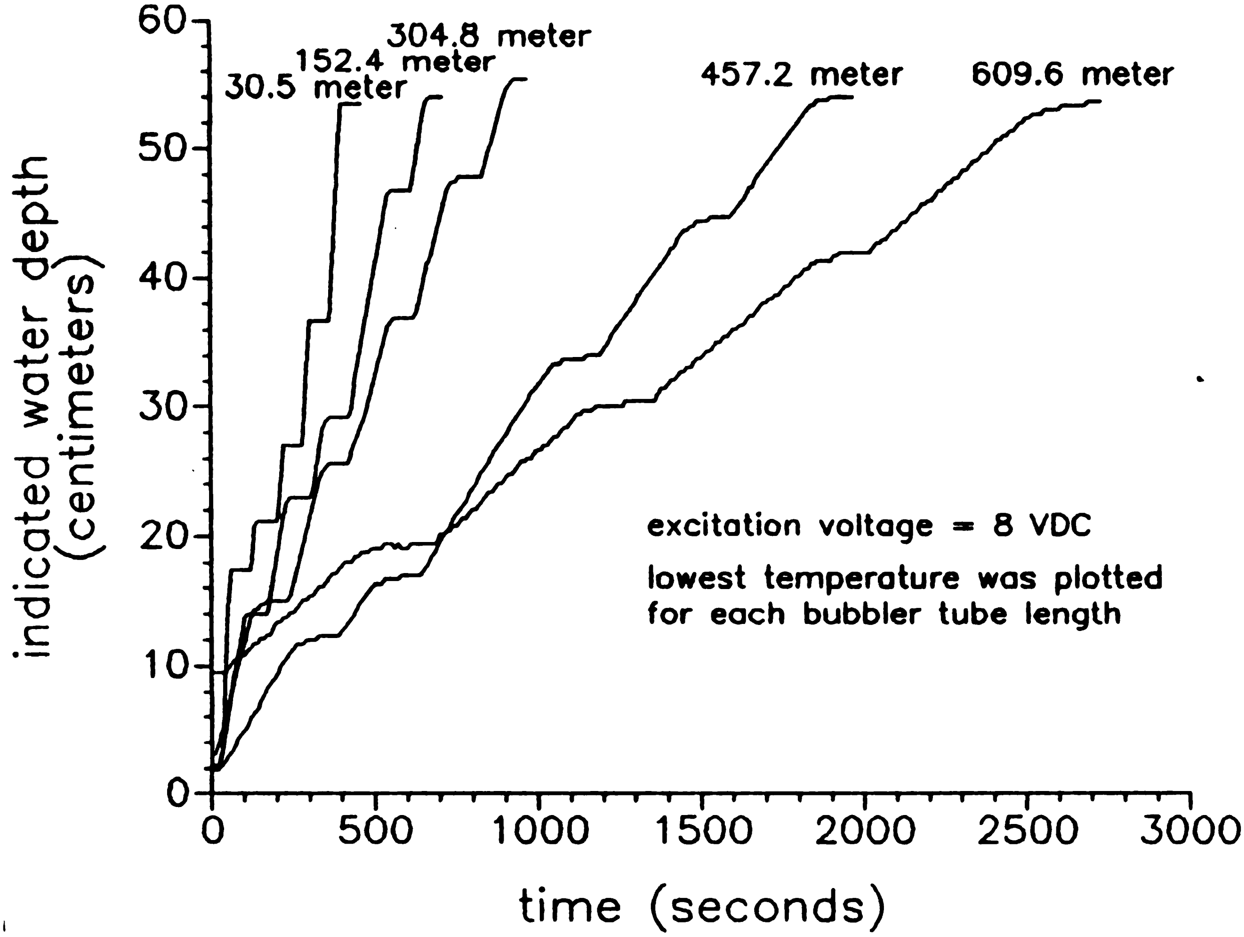


Figure 20: Comparison of Figures 16 - 19.

Figure 20 shows that as the bubbler tube length increase so does the time for the system to come ino equilibrium. The curves do not start at zero centimeters of water because the offset of the system is shown in the curves and it is different for each bubbler tube length.

To determine a relationship between water depth change and time for the system to come into equilibrium for each bubbler tube length, the data points on the slope of the calibration curve were extracted from the three temperatures for a given bubbler tube length, and the equation of a line forced through the origin was determined for the composite data set using the statistical-plotting program PLOTIT*. Figures 21 through 25 show the regression line and the data point scatter for each of the five bubbler tube lengths, while Figure 26 compares the regression lines for the five tube lengths. Table 4 summarizes the slope (seconds per centimeter of water depth change) and coefficient of determination (R^2) for the bubbler tube lengths. The output file from PLOTIT for these data can be seen in Appendix E.

* PLOTIT is a trademark of Computer Resource Services Holt MI

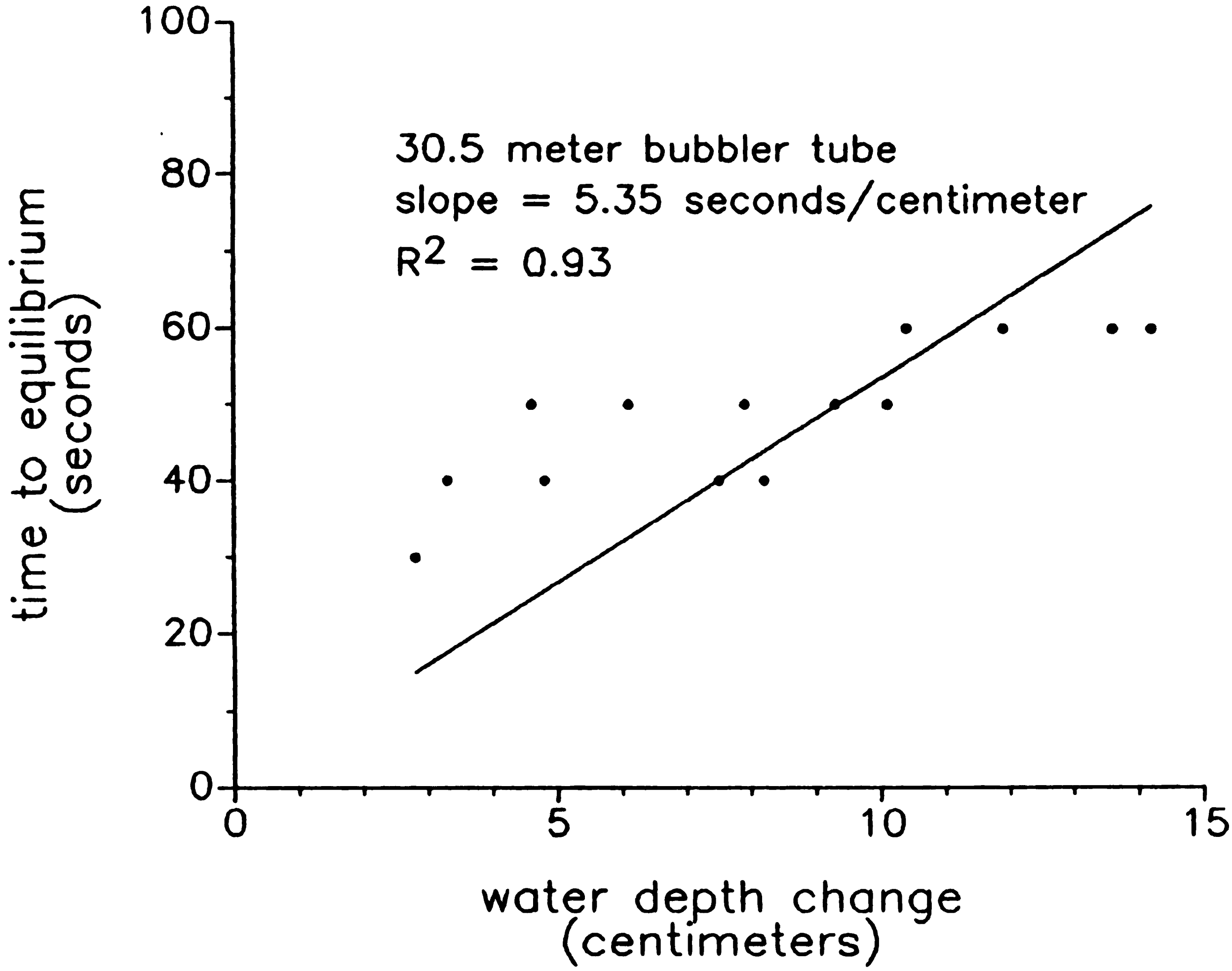


Figure 21: Water depth change versus time to equilibrium for the 30.5 meter bubbler tube.

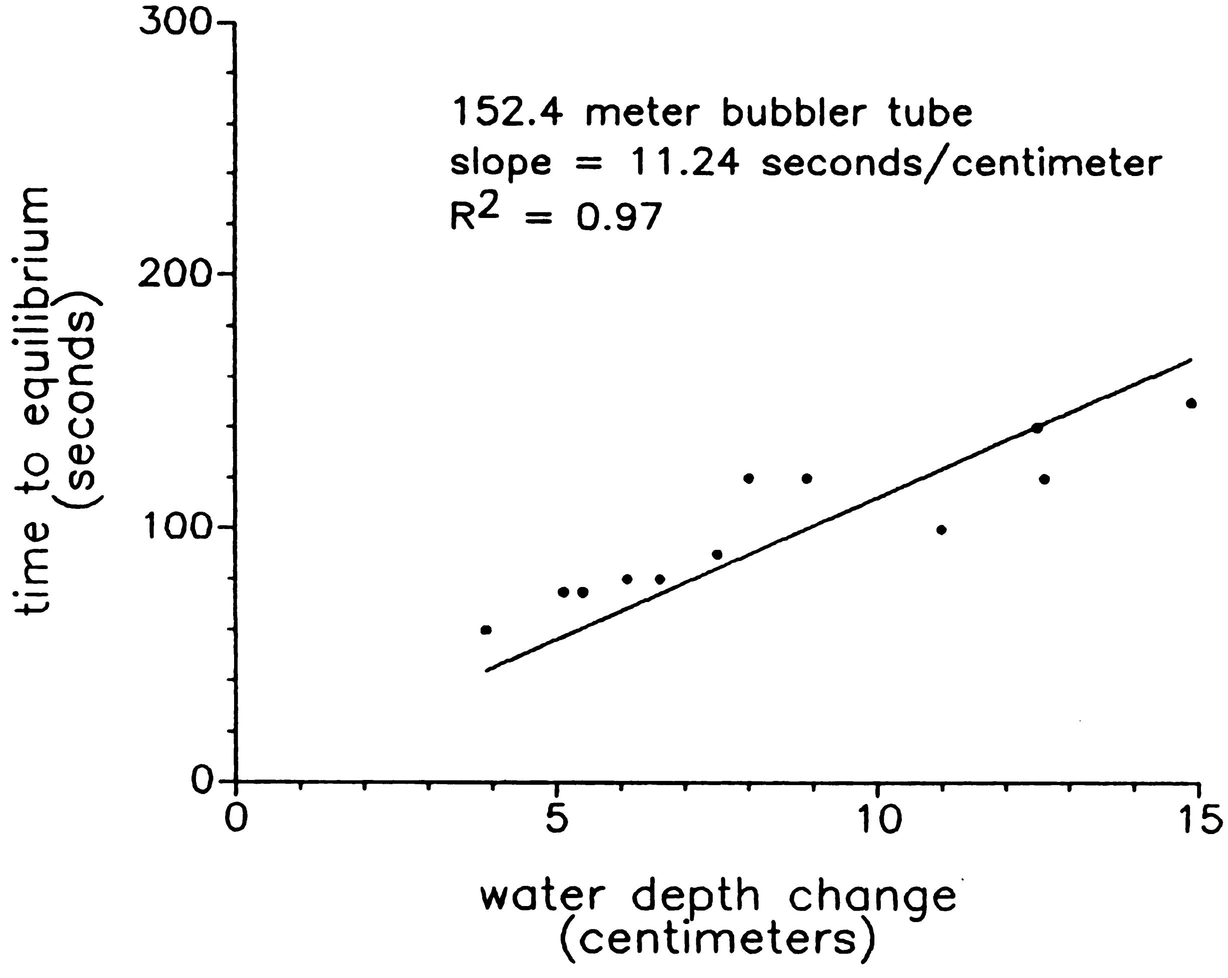


Figure 22: Water depth change versus time to equilibrium for the 152.4 meter bubbler tube.

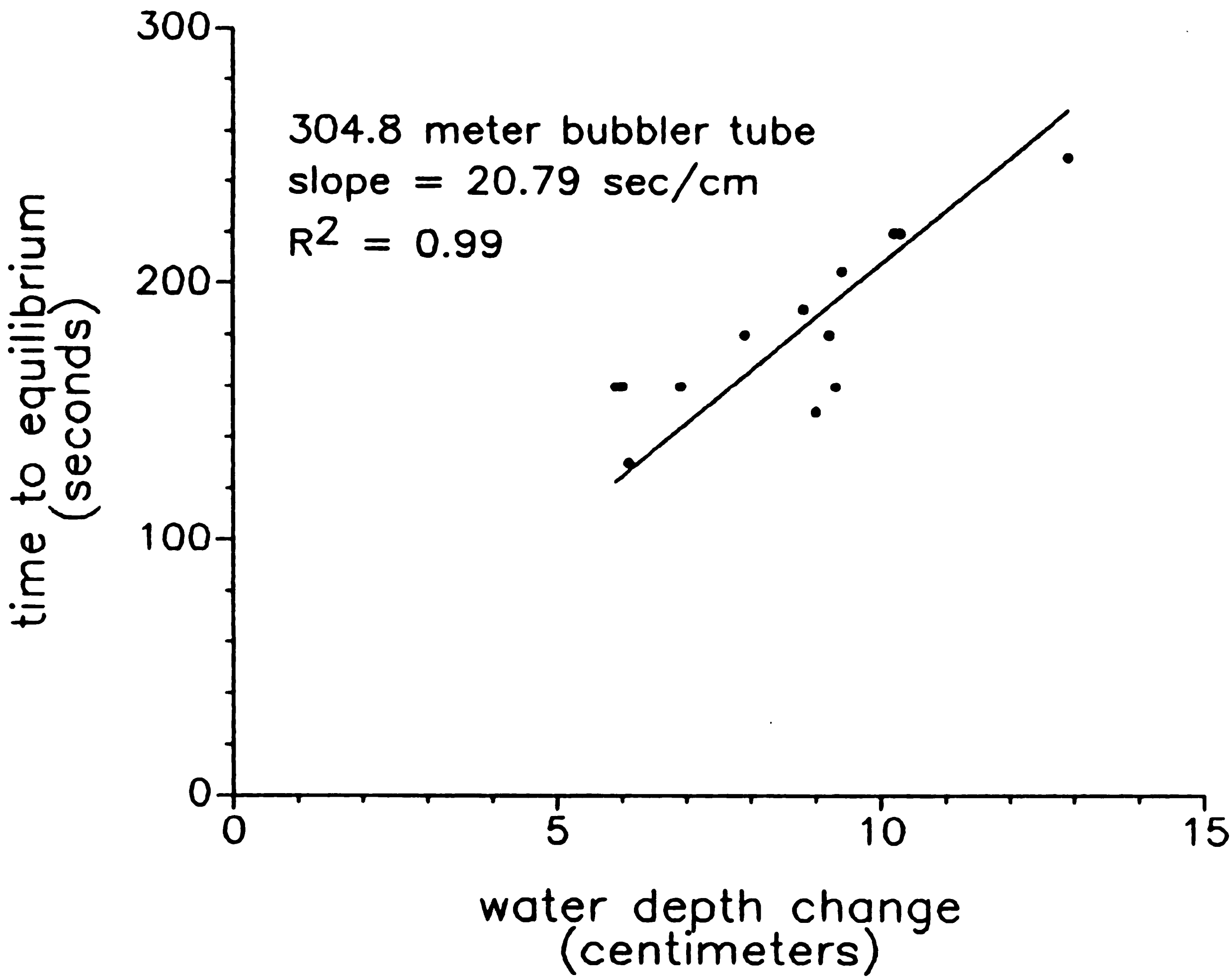


Figure 23: Water depth change versus time to equilibrium for the 304.8 meter bubbler tube.

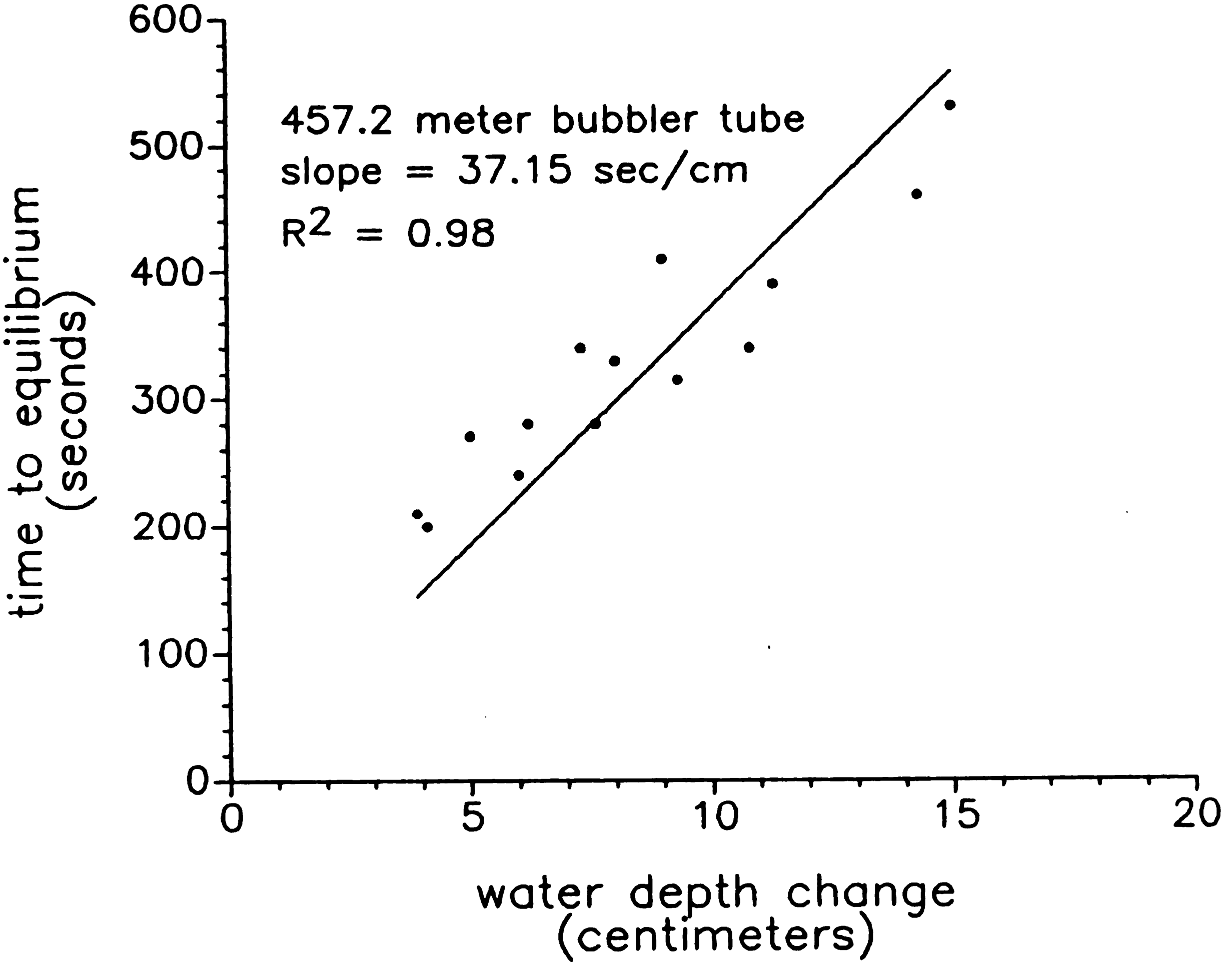


Figure 24: Water depth change versus time to equilibrium for the 457.2 meter bubbler tube.

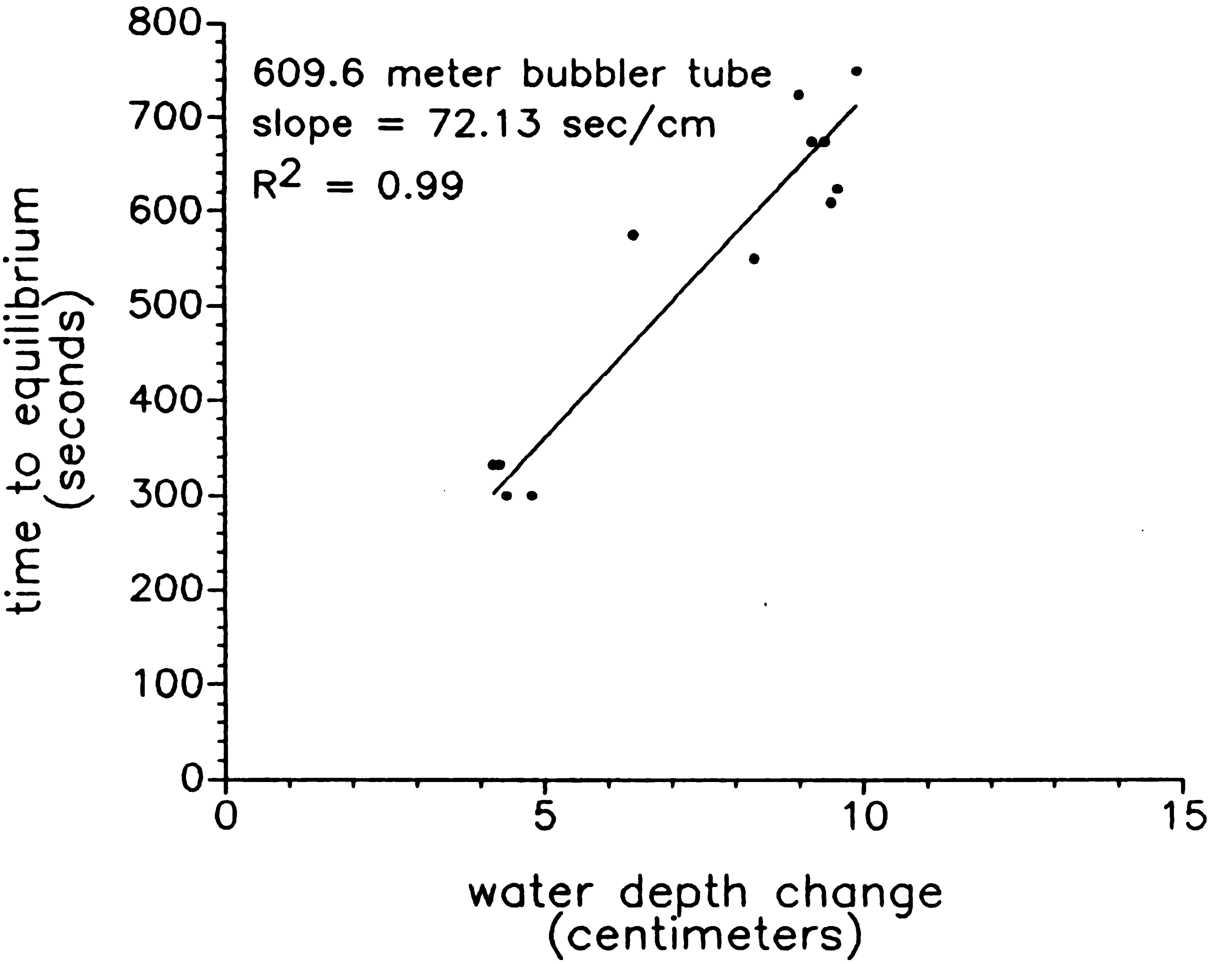


Figure 25: Water depth change versus time to equilibrium for the 609.6 meter bubbler tube.

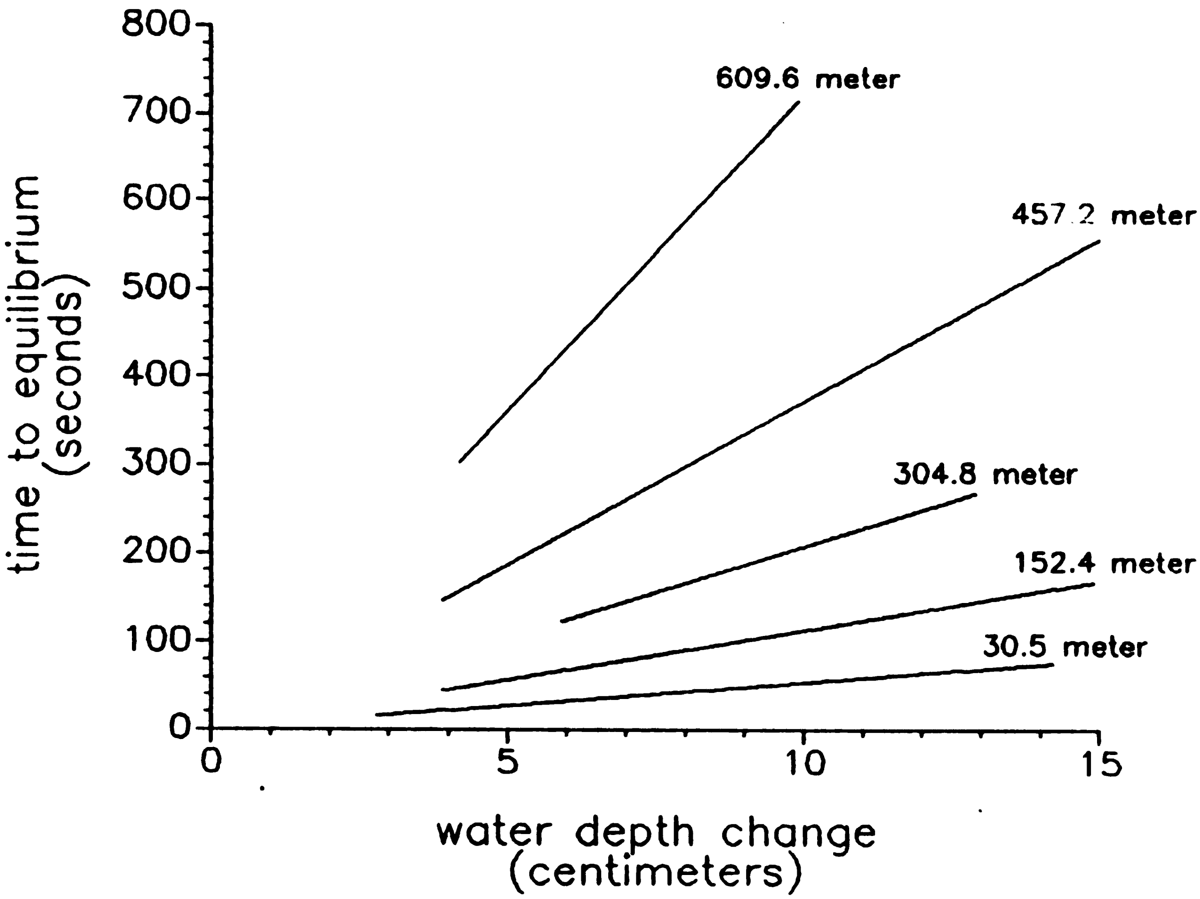


Figure 26: Comparison of Figures 22 - 25.

TABLE 4

Bubbler tube length versus slope of time to equilibrium line

Bubbler tube length (meters)		slope (seconds per centimeter water depth change)	R^2
30.5	(Figure 22)	5.35	0.93
152.4	(Figure 23)	11.24	0.97
304.8	(Figure 24)	20.79	0.99
457.2	(Figure 25)	37.15	0.98
609.6	(Figure 26)	72.13	0.99

The lag time for a change in water level is given by the product of the water level change and the appropriate slope as determined above. The relationship between the slope and bubbler tube length is shown in Figure 27. PLOTIT was used to determine the equation of the best fit. Table 5 summarizes the results. The output file from PLOTIT for these data is in Appendix F.

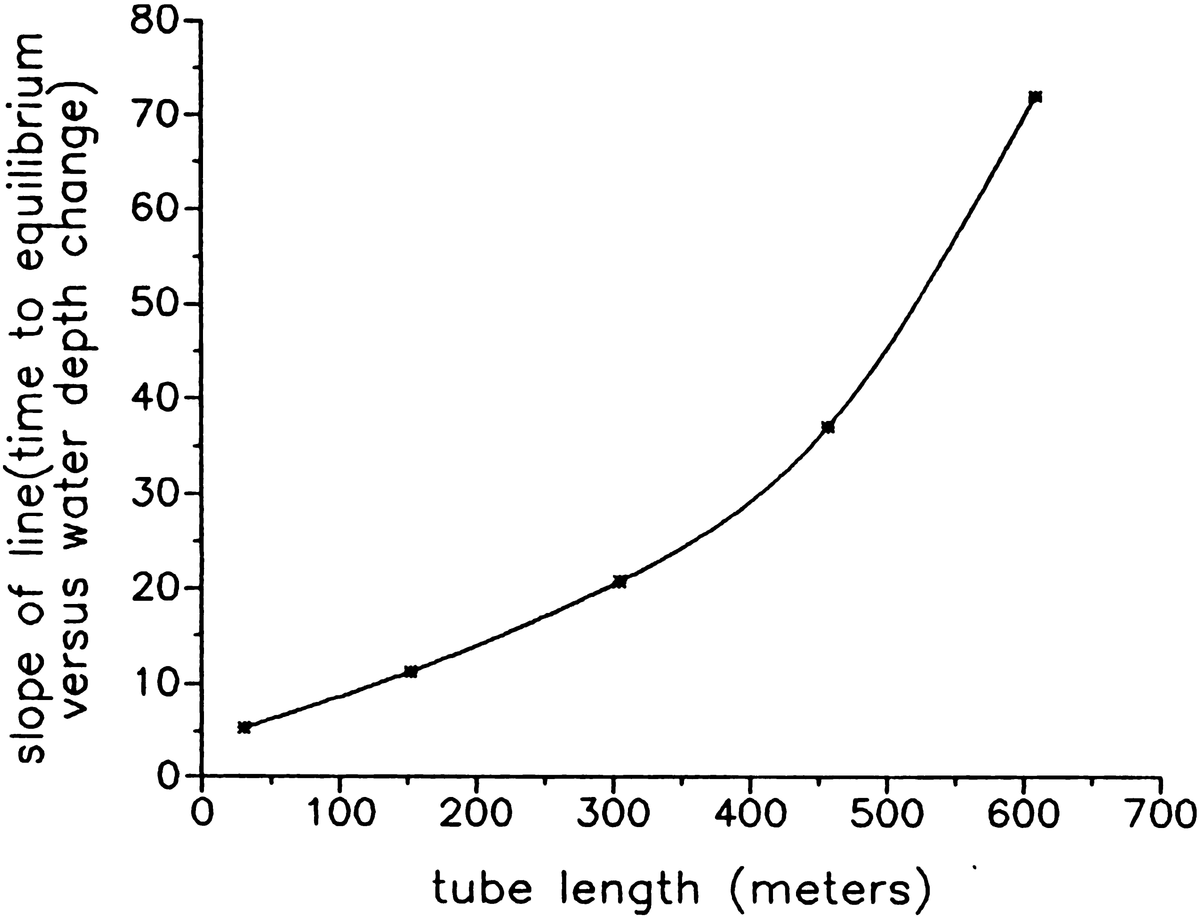


Figure 27: Bubbler tube length versus slope of time to equilibrium line.

TABLE 5

Best fit equations for the curve in Figure 27 as determined by PLOTIT

Equation	R^2
$Y = 0.030X$	0.96
$Y = 0.034X - 4.846$	0.90
$Y = 0.197(10^{-4})X^2 - 0.671X + 7.376$	0.99
$Y = 0.115(10^{-7})X^3 - 0.172(10^{-4})X^2 + 0.228X + 3.099$	0.99
$Y = -11.977(10^{-3})/(-1.894(10^3) + X)$	0.83
$Y = (38.484X)/(638.016+X)$	0.93
$Y = X/(33.55 + (0.228(10^{-2})X))$	0.02
$Y = 5.205(1.001^X)$	0.99
$Y = 0.106(X^{6.381})$	0.90

E. Analysis of system

The analysis of the system was performed using the data from one water depth increase (about 9 centimeters) from the time lag determination for the 609.6 meter (2000 foot) bubbler tube at 53°C. This data set was chosen since the 609.6 meter bubbler tube was the longest tested and would be the worst case. The following procedure could be used for any bubbler tube length. The order of the system was determined based on information given by Gerrish (1986)* and

* personal communication

Doebelin (1975). The order of an instrument gives an indication of it's dynamic characteristics. A zero order instrument responds instantaneously to an input and no dynamic characteristics exist. A first order instrument has one dynamic characteristic, a time constant. The time constant of a system is the physical time required to transmit signals from input to output. A second order has two dynamic characcteristics, a damping ratio and a natural frequency. The analysis of a second order instrument is much more complex than the analysis of a zero or first order instrument. Initially, the pressure transducer, datalogger, and total bubbler tube length, were considered together as the system. The system was tested by applying a step function at the end of the bubbler tube. A step function assumes the system is initially at equilibrium, the input quantity (water level in this case) is increased instantly an amount to give a "step". Figure 28 shows the expected output of a first and second order instrument after one step input (one water depth increase) and the actual output curve. The jagged line in the actual output curve is due to the resolution of the datalogger. The response is similar to the second order curve, but is different enough to justify further analysis to determine the order of the system and the test input function.

The next approach assumed the pressure transducer and datalogger to be the data acquisition system, the bubbler tube being used only as an information transfer system. In

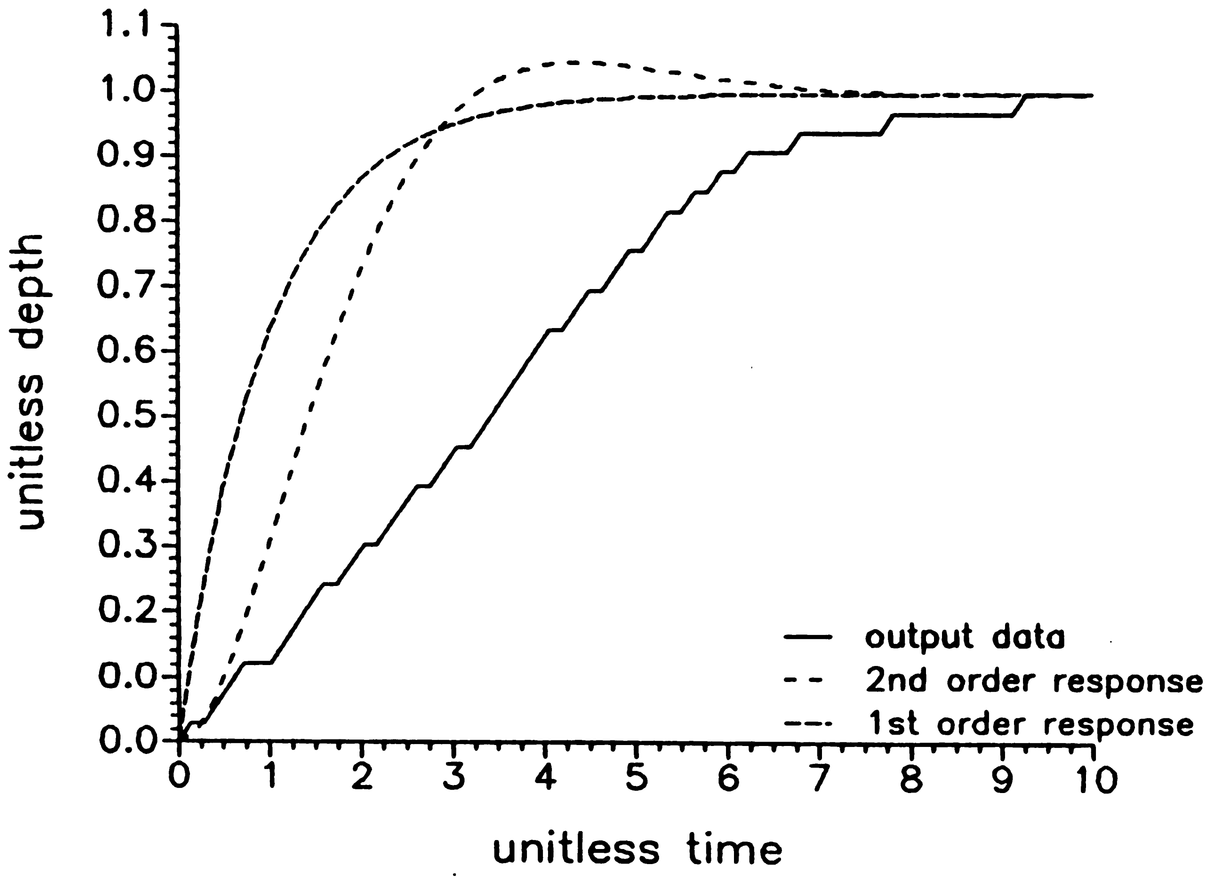


Figure 28: First and second order response to step input and the actual output curve.

this case, even though a step input was applied at the end of the bubbler tube, the data acquisition system "saw" a terminated ramp because of the bubbler tube's limitation of the flow of information. A terminated ramp assumes the system is initially in equilibrium then the input starts to change at a constant rate. At some value the ramp is terminated and the input is held at a constant value. A terminated ramp is shown as the dashed line in Figure 29. The output curve is very similar to the expected response to a terminated ramp function for a first order instrument (Figure 29). The terminated ramp at the data acquisition system was obtained by first applying a step change to the end of the bubbler tube. Immediately following the step input, water intruded into the end of the tube a distance equal to the step change minus some amount dependent on the tube length and the compressibility of the nitrogen gas. The distance is greater for a longer tube and less for a shorter tube. The pressure in the tube increased linearly until the first bubble was expelled from the end of the tube. From that time, water intruded less and less while the bubbling rate increased until at some time (equal to the time constant) very little or no water intruded into the tube and the bubbling rate remained constant.

Based on the above assumptions, the time constant was calculated as follows (Figure 30). The lower part of the actual data curve was assumed to have the same constant slope as the input ramp only offset by the time constant.

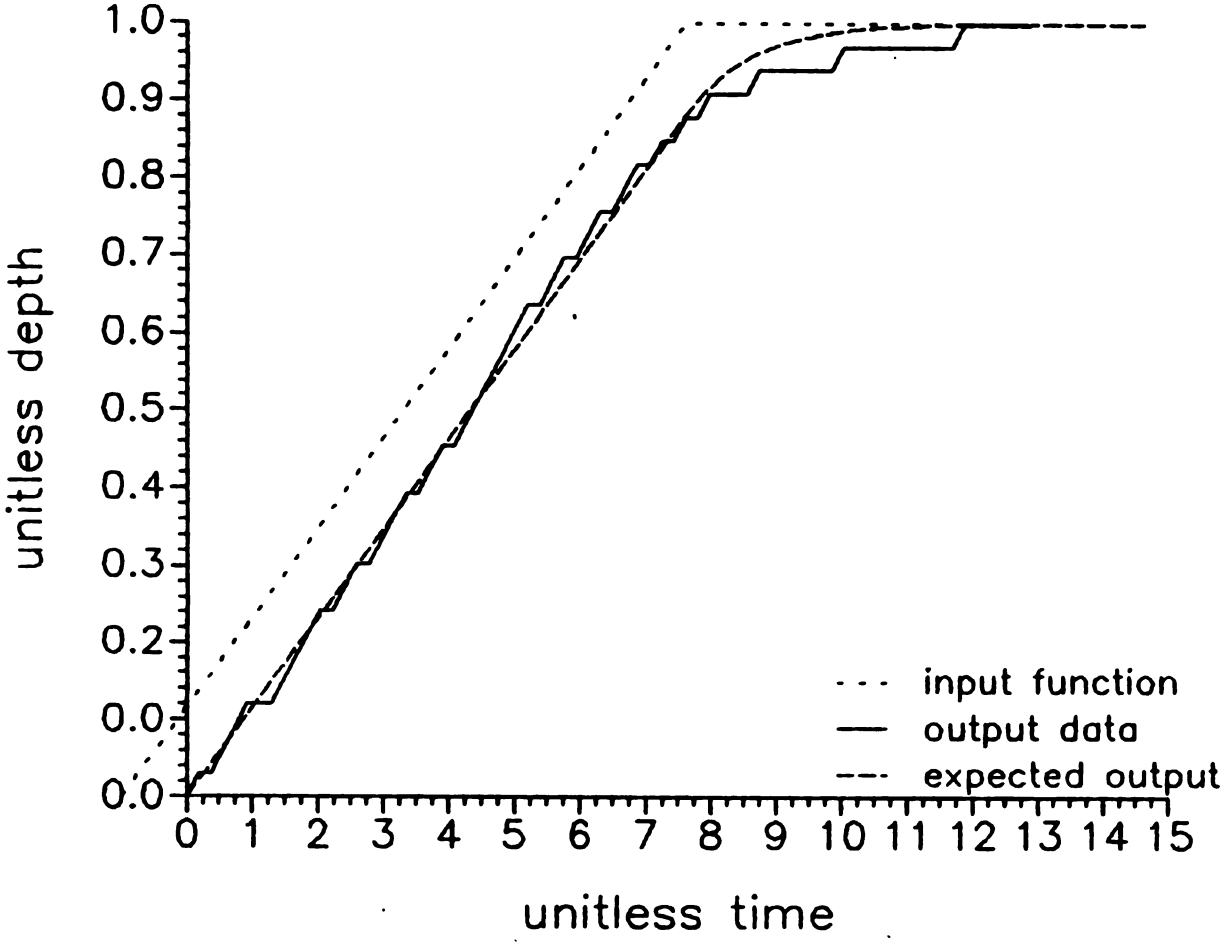


Figure 29: First order response to a terminated ramp and the actual output curve.

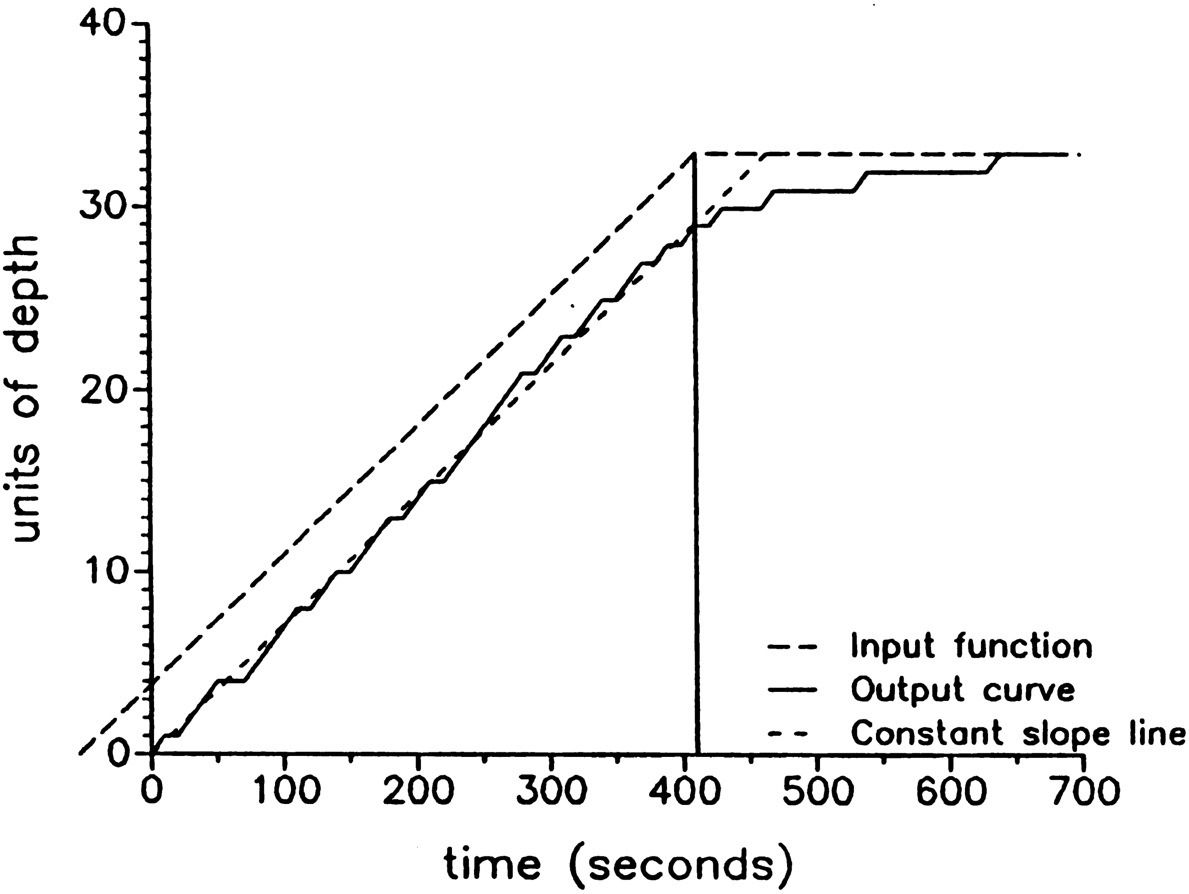


Figure 30: Determination of the time constant.

The slope was assumed to be constant from 0 to 20 units. For this constant slope, a line was extended to 33 units. The point where the output curve deviated from this line was considered to be the termination of the ramp and the time the first bubble emerged. From the termination of the ramp, a line parallel to the lower portion of the output curve was constructed. The distance between the two lines along the x axis was considered to be time constant and was found to be equal to 54 seconds.

The length of the bubbler tube, not the pressure transducer-datalogger combination, is the limiting factor in the response time of the system. When using the complete system, a more practical time constant other than that calculated above would be one relating the time to equilibrium to bubbler tube length for the whole system. A way to look at this is to determine the maximum rate of pressure change for a bubbler tube of a given length. The data used for the lag time determination and system analysis was the maximum rate since a large depth change was applied to the end of the bubbler tube and the system could not respond instantaneously. The maximum rate for each length was calculated by multiplying 3600 seconds per hour by the reciprocal of the slope (seconds per centimeter) of the lines in Figure 27. This gave a maximum rate of rise or fall of the field watertable in centimeters per hour. If the maximum rate is exceeded, the effects of lag time would be apparent in the output data. Table 6 summarizes the results. In the worst case, the 609.6 meter tube, the maximum rate of water level change is 49.9 centimeters per hour (19.7 inches per hour). This should not present a problem since most applications in watertable management do not exceed this rate. The slope of the output data, however, should be compared to the critical slope to be sure lag time is not affecting the data.

TABLE 6

Maximum water level rate of change for the tested bubbler tube lengths

tube length (meters)	maximum rate cm/hr(in/hr)
30.5	672.9(264.9)
152.4	320.3(126.1)
304.8	173.2(68.2)
457.2	96.9(38.2)
609.6	49.9(19.7)

---

1. Bubbling rate

The bubbling rate is an important parameter of the bubbler system, affecting the lag time of the system, offset of the calibration curve, and nitrogen gas use. The effect of altering the bubbling rate was not tested. The bubbling rate used for the entire error analysis was approximately 1 bubble per second.

A relationship between bubbling rate, bubble tube length, maximum expected rate of change in water level, and desired nitrogen gas use could be developed to give the optimum bubbling rate given the three other parameters. The maximum bubbling rate would be limited by excessive nitrogen gas use and turbulence at the bubbler tube outlet. The minimum bubbling rate would affect the time to equilibrium of the system. A change in bubbling rate should not alter the slope of the calibration curve, but it will move the curve up or down on the y axis by changing the pressure transducer offset at zero water depth.

The above analysis assumes a constant bubbling rate prior to the change in water level. In some applications, it might be beneficial to know the time to equilibrium from zero pressure in the bubbler tube. This could also be related to tube length and bubbling rate, as well as the starting head of water.

VI. RECOMMENDATIONS

A. Field system II

In the first version of the bubbler system, two problems related to power were discovered. The first was matching the output of the pressure transducer with the input of the datalogger. As mentioned before, the datalogger converts a voltage in the range of 0 to 5 volts, but the transducer has an offset of one volt giving an output of 1 to 6 volts. This means the effective range of the pressure transducer was 1 to 5 volts [0 to 563.9 mm(0 to 22.2 inches) of water]. Since this was a prototype version of the system, this range was determined to be adequate and no further attempts were made to correct the problem.

To take care of this problem, preliminary testing has been done using a difference amplifier (Figure 31). A difference amplifier utilizes an operational amplifier to output the difference between two voltages ($V_2-V_1=V_o$). V_2 is the actual signal voltage from the transducer, V_1 is a reference voltage equal to the pressure transducer offset, and V_o is the voltage, with the offset subtracted, which goes to the datalogger. V_2 ranges from 1 to 6 volts, V_1 is approximately equal to 1 volt, and Vo ranges from 0 to 5

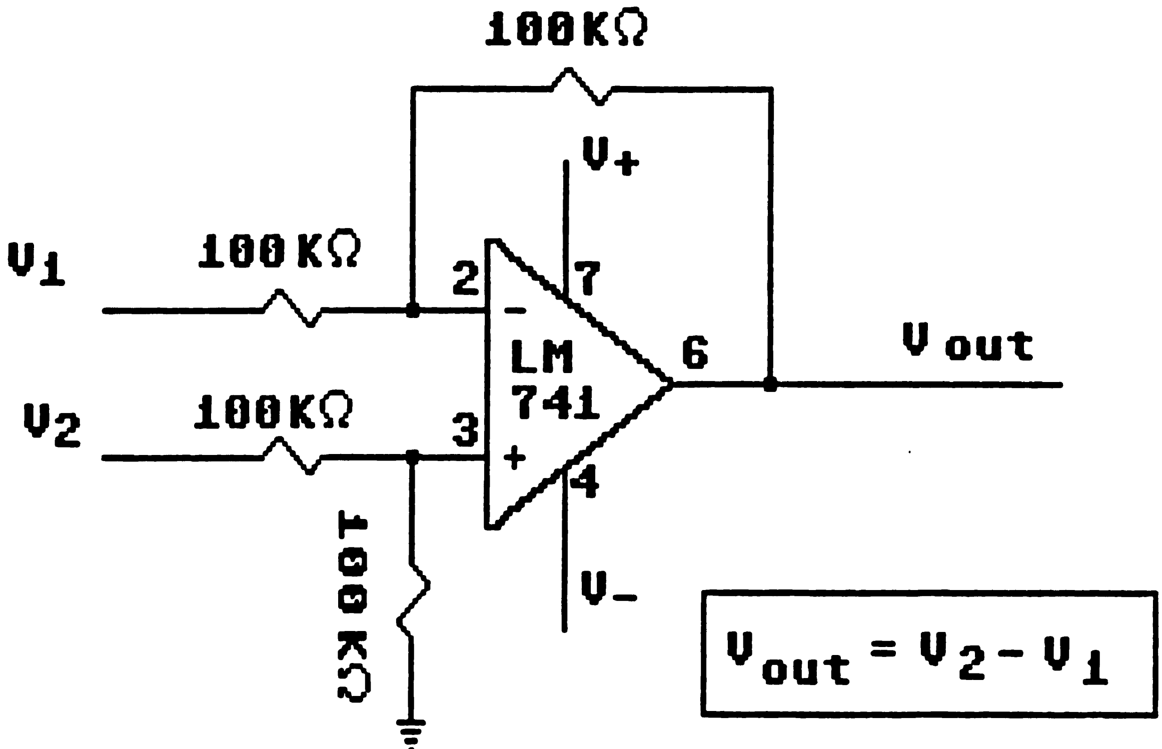


Figure 31: Difference amplifier.

volts. Two sources for a reference have been used. The first was a variable voltage regulator (Figure 32) connected to V_1 and adjusted until V_0 is zero at zero pressure. Since the offset changes with different pressure transducers and different bubbler tube lengths, the voltage regulator can be adjusted to give the maximum range with any bubbler tube length. The other reference voltage used another pressure transducer's output as V_1. This has the advantage of subtracting out fluctuations due to atmospheric pressure and slight input voltage changes but is a disadvantage since the offset is different for each transducer or $V_2-V_1 = 0 \pm 0.05$ volts. The user must record the remaining offset(the voltage at V_0 at zero pressure) so it can be subtracted from the raw data before analysis.

The second problem encountered had to do with powerline voltage fluctuations and power outages. The pressure transducer output is linearly related to the input voltage at a constant pressure. Since any changes in input voltage are directly transmitted to the output, the input voltage must be held relatively constant (±0.01 volts) to achieve accurate results.

Power outages affected both the pressure transducers and the datalogger. The pressure transducers did not output data during a power failure, while the datalogger lost all data and any program stored in memory even if the power went off for only a fraction of a second. The "quick fix"

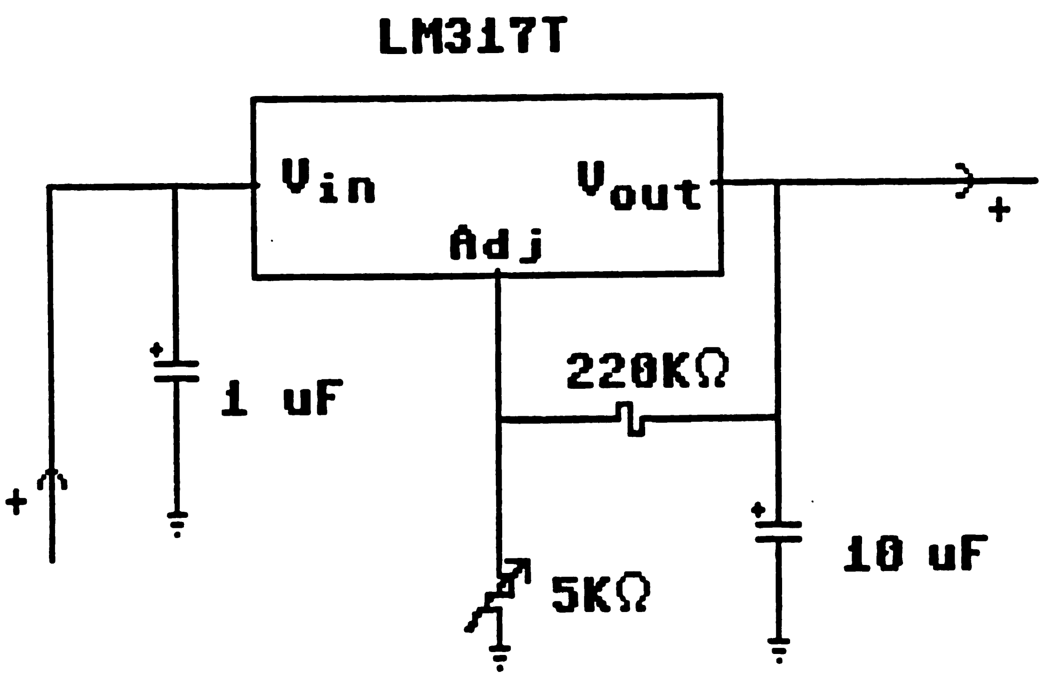


Figure 32: Variable voltage regulator.

solution was to connect the datalogger to a 12 volt automotive battery. The battery was kept charged with an AC battery charger to preserve the datalogger memory. The pressure transducer's output was zero for the duration of the power outage.

A better solution to both powerline fluctuations and power failures would be to power the entire data acquistion system using a 12 volt automotive battery to power two variable voltage regulators, one for the pressure transducers and one for the datalogger. Then the system could be installed at a remote site where AC power was not available. The pressure transducers require a maximum of 20 milliamps each and the datalogger requires about 500 milliamps, so a system with eight pressure transducers and one datalogger would require 660 milliamps or 0.66 amps. The proposed, modified system was not tested, but a fully charged battery should operate the system for at least a month. If AC power were available, a battery trickle charger could be used to keep the battery charged, and the battery would be used only when the AC power went off.

B. Other suggestions

There are several additional suggestions that would improve the system but have not been implemented or tested. First, it would be convenient to be able to set the bubbling rate at the instrumentation site rather than having to go out to each observation well to check it. This could be done by using a very accurate 0 to 1 psi pressure gauge connected to the in-line flow control valve. The in-line valve would be adjusted to a predetermined pressure for a given bubbler tube length.

A copper or stainless steel tube, smaller diameter than the bubbler tube, could be inserted into the observation well and connected to the bubbler tube. This would have the advantage of a straight tube which would be easier to install and would not curl up in the observation well. The smaller diameter tube might also decrease the amount of nitrogen gas used. The smaller tube would also allow the use of a smaller diameter observation well thereby decreasing the lag time between the actual watertable and the water level in the well.

Nitrogen gas was chosen because it is inert and inhibits algae growth at the end of the bubbler tube. The use of pressurized air in place of the nitrogen gas may be advantageous. An air compressor installed at the site would elimininate the need for transferring nitrogen gas tanks to the site. The potential problem with air is the time for algae to form at the end of the bubbler tube. Tests could be conducted to determine that time or some additive could be used occasionally to deter the growth of algae.

No test data has been developed for the operation of the system in cold weather. A possible effect is the increase in the time to equilibrium for a given bubbler tube length. The effects could be minimized by burying the bubbler tube to keep it at a relatively constant temperature all year long. The instrumentation mounted in an insulated box with a light bulb attached to a thermostat would keep it at a temperature above freezing.

VII. OTHER APPLICATIONS

The bubbler system was originally designed to simplify monitoring a watertable in the field, but the use of the bubble system is not limited only to monitoring a watertable. Several modified versions of the bubbler system were used to aid data collection at Michigan State University.

A. Monitoring pump output

Pump flow was monitored using an orfice meter. A pressure transducer was connected in place of the piezometer to measure the water pressure in the discharge pipe. The voltage from the pressure transducer was converted to a digital number and recorded in the datalogger. The digital number was converted to gallons per minute(gpm) in the field by the portable computer using the following equation:

$$Q = 8.02KA(h^{0.5})$$

where:

Q is flow rate in gallons per minute.
K is the discharge factor dependent on the ratio of orifice size to pipe diameter.
A is orifice area in square inches.
h is head in inches.

A problem encountered was fluctuations in the data due to slight variations in pumping rate. Since the pumping rate was relatively constant, the data values were averaged giving good results.

B. Run-off and pollutant monitoring

The instrumentation to monitor water flow and trigger pollutant samplers was improved using the bubbler system. The purpose of the research was to determine the nature of field pollutant losses from agricultural land where conventional tillage practices (moldboard plow) and conservation tillage practices (chisel plow) were used. Tile flow and surface runoff at the field site was measured utilizing flumes designed such that the volume of flow passing through the flume was uniquely related to the depth of flow in the flume. Tile flows were measured using three V-flumes while surface runoff was measured using two H-flumes.

In the past, float-type chart recorders were used to monitor depth of flow in the flumes. ISCO flow meters, based upon an air bubbling technique similiar to the bubbler system were used to totalize the flow through the flumes and initiate the pollutant samplers at a preset total. Both systems were troublesome and required chart readings to determine flow quantities. A modification of the bubbler system was used to monitor flow depth in both the tile and surface runoff flumes and trigger the pollutant samplers (Figure 33). Water level in the outlet ditch and a raingauge were also monitored. The system remained inactive until 0.25 or more inches of rain was received in the raingage. The ditch level was monitored to insure the tile outlets were not submerged. Instead of the portable computer and datalogger, a Campbell Scientific Model 21X micrologger was used to monitor the output voltage from the pressure transducers. The micrologger was used because of the ability to store many more points and the ease of connecting the system to a modem for data transfer over a phone line. When the rain gauge indicated over 0.25 inches of rainfall, the depth of water running through the flumes was stored and converted into a flow quantity using the appropriate equation for each flume. Individual pollutant samplers were triggered based on a preset cummulative flow quantity.

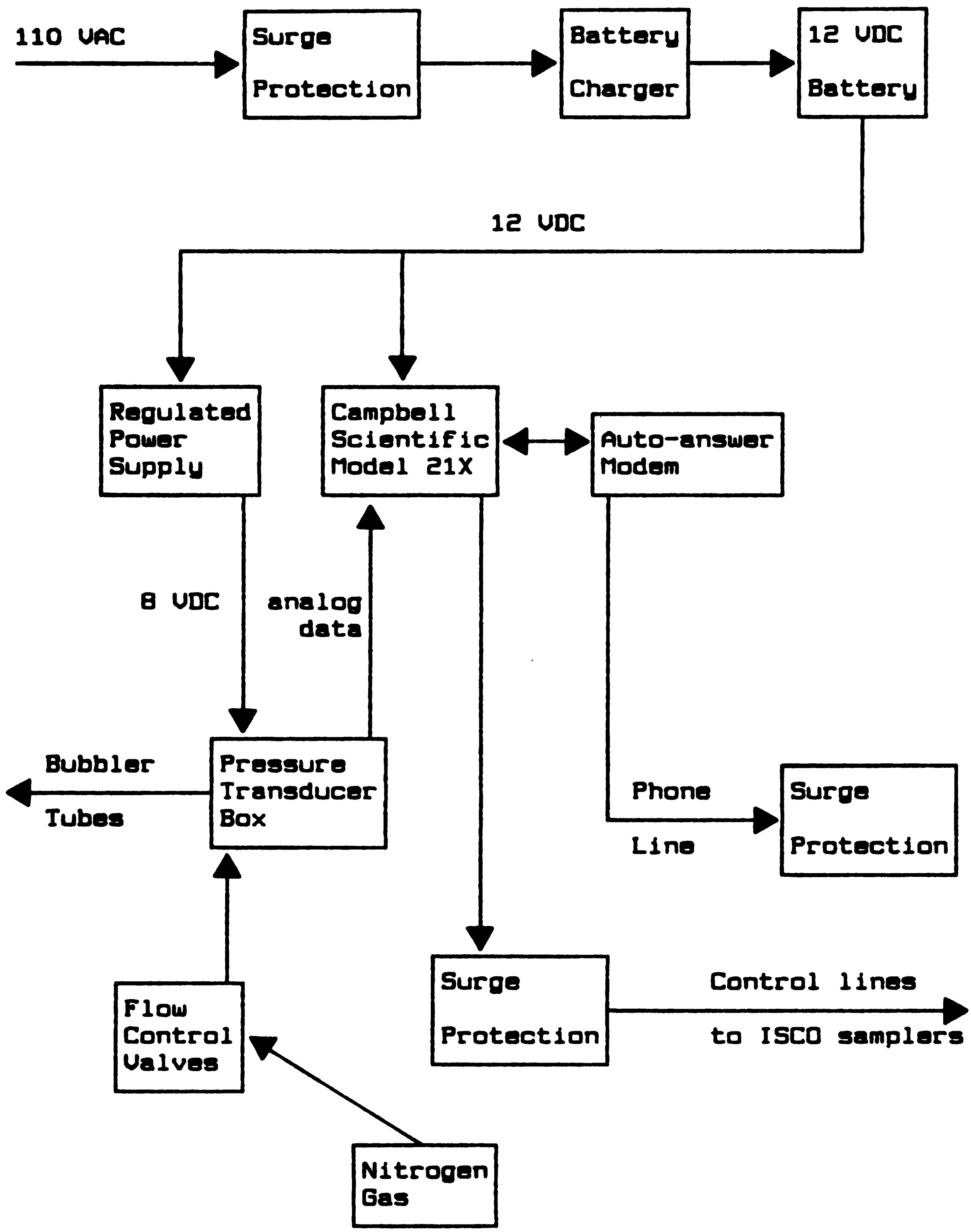


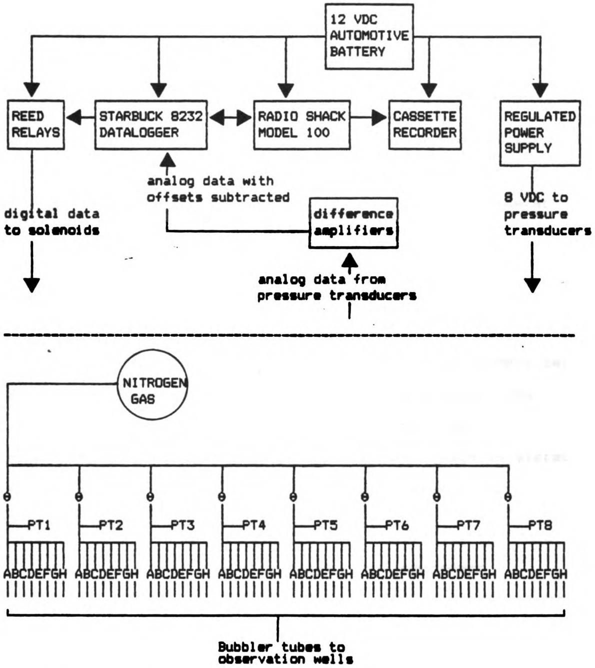
Figure 33: The Bubbler System layout using a Campbell Scientific Model 21X micrologger.

Time of day, day of year, raingage depth, ditch level, flow depth, actual flow, and cumulative flow were stored in the micrologger at five minute intervals. The system was reset if the flow through the flumes went below a given value.

The micrologger was capable of storing up to 23,348 data points. A telephone line installed at the site provided the ability to call the micrologger to monitor the system operation, check the number of samples taken, change the micrologger program, or retrieve the stored data. The data was retrieved from the micrologger approximately every 4 days. The use of the Campbell Scientific 21X micrologger was advantageous to the system for several reasons. The 21X has 13 bit precision while the other datalogger used has only 8 bit precision so that the accuracy of the system was limited by the accuracy of the pressure transducers rather than by the datalogger. The data storage capability was increased from 1975 to 23,348 data points and the system could easily be called to monitor operation or retrieve data. A disadvantage is the 21X must be programmed in a language similar to machine language, making the program harder to understand since no comment statements are allowed. The portable computer it replaced uses the familiar BASIC language which allows REMark statements to document the procedure within the program. Also, the 21X micrologger is about twice the cost of the other system. If accuracy is the most important criteria, the 21X system is recommended.

C. Watertable monitoring at 64 locations

This application is currently being developed. It involves monitoring the watertable at 64 locations in a 40 acre water management project. It is planned to develop the system using one 8 channel, 8 bit datalogger, 8 pressure transducers, 64 solenoid switches, and a portable computer. The entire system will be powered using a 12 volt automotive battery and will utilize difference amplifiers to subtract the transducer offset from the raw output. The nitrogen gas lines will be connected to the correct observation wells using eight banks of eight solenoids (A to H in Figure 34) switched sequentially by the digital output of the Starbuck 8232 datalogger. A set of solenoids consisting of one solenoid from each of the eight banks, e.g. all the A solenoids, will be opened to allow the nitrogen gas to bubble out. One pressure transducer will be connected to each of the eight solenoid banks so the pressure read by the pressure transducer is the pressure at the open solenoid. Each set of solenoids will be opened until all 64 observation sites are read. It will be designed to take a set of data points every 30 minutes. The data will first be stored in the datalogger, then transferred to the portable computer, and finally to a cassette tape.



θ => Flow control valves
PTn => Pressure transducers
A-H => Eight solenoids per bank

Figure 34: Schematic of bubbler system instrumentation (top) and solenoid banks (bottom) to monitor 64 observation wells for a watertable management research project.

VIII. CONCLUSIONS

The bubbler system is an electronic data acquisition system to measure the position of the water table for drainage and subirrigation. It uses a very small diameter observation well into which a smaller diameter bubbler tube connected by flexible tubing to a pressurized nitrogen gas tank is inserted. A pressure transducer connected to the supply line senses the pressure required to force a bubble out of the bubbler tube. The data acquisition equipment can be located in one central location with the bubbler tube transferring the water level information from the observation well to the pressure transducer. Data is stored in a datalogger and transfered to floppy diskette for further analysis and plotting.

The accuracy of the float-type chart recorders previously used was approximately ±3 mm (0.1 inches), so the bubbler system was designed to have about the same accuracy. The search for components was started by finding the pressure transducer, then the datalogger, and finally the computer. A Micro Switch Model 162PC01D pressure transducer, Starbuck 8232 datalogger, and a Radio Shack Model 100 portable computer were the components chosen for the data acquisition system.

The system was tested in the labratory and found to perform well. It was then installed in the field for further testing. Float-type chart recorders were installed along with the bubbler tubes for comparison of the data. The data from the bubbler system followed the digitized data from the chart recorder accurately. The difference was due to the increased time lag between the actual watertable and the water level in the observation well caused by a larger observation well diameter. The bubbler system used a 1 inch observation well while the float-type recorder used a 3 inch diameter well.

The datalogger and a single pressure transducer were calibrated separately, then the complete system was calibrated using five different bubbler tube lengths (100, 500, 1000, 1500, and 2000 feet) and three different temperatures above 20°C(68°F). The error analysis indicated that temperature had little effect on the system. Bubbler tube length did not effect the slope of the calibration curve, but the offset increased slightly as the tube length increased. There is a significant time delay from a given change in water level until the system is equillibrated. The time to equilibrium increases expotentially as the bubbler tube length increases.

APPENDIX A: Component specifications and prices.

APPROXIMATE COSTS FOR BUBBLER SYSTEM COMPONENTS

(Costs are typical retail prices in East Lansing, MI, 1986)

Radio Shack Model 100 portable computer(24K model)	$600.00
Starbuck 8232 datalogger	490.00
Micro-Switch Model 162PC01D pressure transducer	66.00
Bubbler tube(1/8" spaghetti tubing) per 1000 feet	19.82
In-line needle valve	10.47
Pressure regulator	64.00
Nitrogen gas (230 ft^3)	3.92
DB-25 ribbon cable for communications between Model 100 and Starbuck datalogger	20.00
Miscellanous tubing connections	10.00

COMPONENT SPECIFICATIONS

(All information given is based on 1986 data.)

Pressure Transducer (Micro-Switch Model 162PC01D)

*Size

59.6(2.35) x 30.0(1.18) x 28.5(1.14) mm(inches)

* Range

0 to 1 pound per square inch(psi) or 0 to 27.68 inches of water. The output from the transducer is between 0 and 6 volts DC, with a one volt offset, and is linear over the full range.

* Percent Error

Repeatability and hysteresis error of ±0.15% of full scale or ±1.05 mm of water (±0.0415 inches of water).

* Temperature compensated

Will operate accurately in temperatures from -40°C to +85°C (-65°F to +257°F).

Datalogger (Starbuck Model 8232)

* Size

228.6(9.0) x 279.4(11.0) x 50.8(2.0) mm(inches)

* Analog input range

0 to 5 volts.

* Resolution

Eight bit conversion with ±1 least significant bit(LSB) means precision of 1 part in 2^8(256) which equals (1/256)*100 = 0.39%. This gave an accuracy of ±2.79 mm (±0.11 inches) water.

* Number of channels

8 analog and 8 digital channels in and 8 digital channels out.

* Stand alone operation -- data transfer

The datalogger is independent of another device after the data collection process is started. Data collection is initiated via the RS232C port on a computer.

* Time interval control

Time base scans or time interval between data points is variable from 1 second to 18.2 hours.

* Local (internal) storage

It has the ability to store up to 1975 data points in the 2K of internal RAM.

Computer (Radio Shack Model 100)

* Size and weight

  300(11.8) x 215(8.4) x 50.8(2.0) mm(inches)
  1.361 kilograms(3 pounds 13.5 ounces).

* Temperature and humidity

  5°C to 40°C(41°F to 104°F) and 20% to 85% RH

* Screen

  An 8 line 40 column (240 x 64 full dot matrix) screen.

* Portable-Constant memory

  Rechargeable batteries protect the memory 40 days with 8K model and 10 days with 32K model. The operating batteries last 20 hours with all input/output devices disconnected.

* RS232C communications

  An RS232C port, accessible from a BASIC program, to communicate with the datalogger and the ability to upload or download information to or from an IBM compatible computer is supplied.

* Permanent memory based programs

  This computer has a word processor, a schedule and address organizing program, and a communication package.

* Floating point BASIC

  The Model 100 has an enhanced version of Microsoft BASIC available for possible field data manipulation.

* Communication capability

  It has a built-in modem with an automatic dialer. The Model 100 can communicate through the modem and RS232C port over a wide range of parameters. The baud rate can be varied from 75 to 19200 bits per second, the word length from 6 to 8 bits, ignore, odd, even, or no parity, 1 or 2 stop bits, and telephone parameters of line status enable or disable and a pulse rate of either 10 or 20 pulses per second.

* Bar code reader

  The built-in bar code reader interface along with an optional bar code reader allows the reading of product marking-code identifications.

* Cassette player interface

  The cassette interface to allow direct connection to a cassette player, for reading and writing programs and data, is also built-in.

* Parallel printer

  A parallel printer interface is built-in.

* Programmable function and cursor control keys

  There are eight fully programmable function keys. The Model 100 has individual cursor control keys and four command keys.

* Clock

  There is a real time clock, using military time, and a calendar with both day and date.

* Full size keyboard

  It also has a full size keyboard and a 10 key number pad.

APPENDIX B: Sample BASIC program and datalogger commands.

BASIC program for Radio Shack Model 100 to retrieve a set of data points from Starbuck 8232 datalogger.

```
100 OPEN "COM:37E1D" FOR INPUT AS 2
105 REM  Open communications for data received from
         datalogger.
110 OPEN "COM:37E1D" FOR OUTPUT AS 1
115 REM  Open communications for data transmitted to
         datalogger.
120 PRINT #1,CHR$(27);"01";
125 REM Start communications with datalogger.
130 PRINT #1, "MGP3";
135 REM Get number of data points on channel 3.
140 INPUT #2,A$:LE% = LEN(A$):A$ = RIGHT$(A$,LE%-3)
150 A = VAL(A$)
160 I% = INT((A-1)/10)+1
165 REM Number lines of data stored.
170 J% = A-10*(I%-1)
175 REM Number of points in last line.
180 J% = 4*J%
185 REM Characters in the last line.
190 PRINT #1,"MD3";
195 REM Start data transmission.
200 INPUT #2,B$
205 REM Throw away unit identification response.
210 FOR L% = 1 TO I%
220 IF L% = I% AND J% <> 0 THEN A$(L%)=INPUT$(J%,2):GOTO 240
230 A$(L%) = INPUT$(40,2)
240 NEXT L%
```

Sample communication session between Starbuck 8232 and Radio Shack Model 100.

Communications with <u>the Starbuck 8232</u>	Definitions and/or <u>explanation</u>
ESC 01 CR*	Start communications.
01:	Starbuck 8232 response.
MR CR	Reset monitor routine.
01:	
MB1-8:100 CR	Set aside 100 locations for each channel.
01:	
MI1-4:60 CR	One minute(60 second) time interval for channels 1-4.
01:	
MI5-8:900 CR	15 minute(900 second) time interval for channels 5-8.
01:	
MS1-8 CR	Start acquiring data on all eight channels.
01:	
ESC CR	Stop communications -- talk to you later! No response.
ESC 01 CR	Two hours later -- resume communications.
01:	
MGP1 CR	How many points have been acquired on channel 1?
01:100	100 points have been acquired.
MGP5 CR	How many points have been acquired on channel 5?
01:9	9 points have been acquired.
MD5 CR	Display the points on channel 5.
01:	
data data data	(9 data points)

*CR means press carriage return or enter key.

APPENDIX C: Component calibration data.

datalogger calibration (increasing water level)

X = datalogger reading (Units)   Y = DMM reading (Volts)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
64.0	1.247	1.246	0.001	0.0000	0.0148
90.0	1.760	1.757	0.003	0.0000	0.0137
107.0	2.094	2.091	0.003	0.0000	0.0137
129.0	2.520	2.523	-0.003	0.0000	0.0137
152.0	2.964	2.975	-0.011	0.0001	0.0137
174.0	3.405	3.407	-0.002	0.0000	0.0137
196.0	3.849	3.839	0.010	0.0001	0.0137
205.0	4.019	4.016	0.003	0.0000	0.0137
234.0	4.585	4.586	-0.001	0.0000	0.0137
245.0	4.800	4.802	-0.002	0.0000	0.0137
253.0	4.953	4.959	-0.006	0.0000	0.0137
254.0	4.987	4.979	0.008	0.0001	0.0137
255.0	4.997	4.998	-0.001	0.0000	0.0137

M = 0.020   SE M = 0.000   YI = -0.011
SE YI = 0.010   SE Y Ave = 0.0138   % err = 0.2760
s^2 = 0.006   SSE = 0.000   t(95%) = 2.201

datalogger calibration (decreasing water level)

X = datalogger reading (Units)   Y = DMM reading (Volts)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
254.0	4.988	4.984	0.004	0.0000	0.0138
242.0	4.743	4.748	-0.005	0.0000	0.0138
233.0	4.576	4.572	0.004	0.0000	0.0138
210.0	4.124	4.120	0.004	0.0000	0.0138
198.0	3.882	3.885	-0.003	0.0000	0.0128
173.0	3.392	3.394	-0.002	0.0000	0.0128
148.0	2.891	2.904	-0.013	0.0002	0.0128
115.0	2.261	2.256	0.005	0.0000	0.0128
99.0	1.942	1.942	0.000	0.0000	0.0138
90.0	1.770	1.765	0.005	0.0000	0.0138
78.0	1.533	1.530	0.003	0.0000	0.0138
64.0	1.252	1.255	-0.003	0.0000	0.0138

M = 0.020   SE M = 0.000   YI = -0.001
SE YI = 0.009   SE Y Ave = 0.0135   % err = 0.270
s^2 = 0.006   SSE = 0.000   t(95%) = 2.228

datalogger calibration (both data sets)

X = datalogger reading (Units)   Y = DMM reading (Volts)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
64.0	1.247	1.252	-0.005	0.0000	0.014
90.0	1.760	1.762	-0.002	0.0000	0.014
107.0	2.094	2.095	-0.001	0.0000	0.014
129.0	2.520	2.527	-0.007	0.0001	0.014
152.0	2.964	2.979	-0.015	0.0002	0.014
174.0	3.405	3.410	-0.005	0.0000	0.014
196.0	3.849	3.842	0.007	0.0000	0.014
205.0	4.019	4.019	0.000	0.0000	0.014
234.0	4.585	4.588	-0.003	0.0000	0.014
245.0	4.800	4.804	-0.004	0.0000	0.014
253.0	4.953	4.961	-0.008	0.0001	0.014
254.0	4.987	4.981	0.006	0.0000	0.014
255.0	4.997	5.000	-0.003	0.0000	0.014
254.0	4.988	4.981	0.007	0.0001	0.014
242.0	4.743	4.745	-0.002	0.0000	0.014
233.0	4.576	4.568	0.008	0.0001	0.014
210.0	4.124	4.117	0.007	0.0000	0.014
198.0	3.882	3.881	0.001	0.0000	0.014
173.0	3.392	3.391	0.001	0.0000	0.014
148.0	2.891	2.900	-0.009	0.0001	0.014
115.0	2.261	2.252	0.009	0.0001	0.014
99.0	1.942	1.938	0.004	0.0000	0.014
90.0	1.770	1.762	0.008	0.0001	0.014
78.0	1.533	1.526	0.007	0.0000	0.014
64.0	1.252	1.252	0.000	0.0000	0.014

M = 0.020   SE M = 0.000   YI = -0.005
SE YI = 0.007   SE Y Ave = 0.014   % err = 0.280
s^2 = 0.006   SSE = 0.001   t(95%) = 2.074

Temperature data [Vin = 8 VDC and constant pressure]

Temperature(°C)	Vout
20	1.002
25	1.006
30	1.009
35	1.011
40	1.016
45	1.020
50	1.023
55	1.025
60	1.030

Vin/Vout

X = voltage in Y = voltage out

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
7.09	0.903	0.927	-0.024	0.001	0.043
7.53	0.951	0.966	-0.015	0.000	0.043
8.01	1.002	1.008	-0.006	0.000	0.042
8.56	1.059	1.057	0.002	0.000	0.042
9.05	1.109	1.100	0.009	0.000	0.041
10.09	1.209	1.192	0.017	0.000	0.041
11.00	1.293	1.272	0.021	0.001	0.041
12.06	1.388	1.365	0.023	0.001	0.041
13.03	1.463	1.451	0.012	0.000	0.041
14.06	1.536	1.542	-0.006	0.000	0.042
14.99	1.614	1.624	-0.010	0.000	0.044
15.94	1.683	1.707	-0.024	0.001	0.045

M = 0.088 SE M = 0.004 YI = 0.302
SE YI = 0.044 SE Y Ave = 0.042
s^2 = 0.0175 SSE = 0.003 t(95%) = 2.228

pressure transducer calibration with DMM
(increasing water level)

X = DMM reading Y = water depth (cm)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.162	9.00	8.821	0.179	0.032	0.213
2.475	13.30	13.284	0.016	0.000	0.209
2.793	17.85	17.819	0.031	0.001	0.205
3.277	24.65	24.721	-0.071	0.005	0.200
3.604	29.30	29.384	-0.084	0.007	0.198
3.915	33.80	33.819	-0.019	0.000	0.197
4.226	38.20	38.254	-0.054	0.003	0.196
4.552	42.90	42.903	-0.003	0.000	0.196
4.866	47.30	47.381	-0.081	0.007	0.196
5.012	49.35	49.463	-0.113	0.013	0.197
5.347	54.15	54.240	-0.090	0.008	0.199
5.664	58.80	58.760	0.040	0.002	0.201
5.994	63.55	63.466	0.084	0.007	0.204
6.304	68.00	67.887	0.113	0.013	0.207
6.445	69.95	69.898	0.052	0.003	0.209

M = 14.260 SE M = 0.037 YI = -22.010
SE YI = 0.170 SE Y Ave = 0.202 % err = 0.287
s^2 = 0.088 SSE = 0.100 t(95%) = 2.160

pressure transducer calibration with DMM
(decreasing water level)

X = DMM reading Y = water depth (cm)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
5.908	62.10	61.988	0.112	0.0124	0.291
5.616	57.90	57.827	0.073	0.0053	0.285
5.344	54.00	53.951	0.049	0.0024	0.280
5.066	50.05	49.989	0.061	0.0038	0.276
4.989	48.70	48.891	-0.191	0.0365	0.275
4.654	44.00	44.117	-0.117	0.0137	0.272
4.295	38.90	39.000	-0.100	0.0101	0.271
3.914	33.70	33.571	0.129	0.0168	0.271
3.461	27.00	27.115	-0.115	0.0131	0.274
3.267	24.30	24.350	-0.050	0.0025	0.276
2.868	18.60	18.663	-0.063	0.0040	0.282
2.486	13.40	13.219	0.181	0.0327	0.289
2.258	10.00	9.970	0.030	0.0009	0.296

M = 14.525 SE M = 0.061 YI = -22.211
SE YI = 0.262 SE Y Ave = 0.281 % err = 0.399
s^2 = 0.188 SSE = 0.154 t(95%) = 2.201

pressure transducer calibration with DMM (both data sets)

X = DMM reading Y = water depth (cm)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.162	9.00	8.697	0.303	0.0921	0.345
2.475	13.30	13.162	0.138	0.0190	0.340
2.793	17.85	17.699	0.151	0.0228	0.337
3.277	24.65	24.604	0.046	0.0021	0.332
3.604	29.30	29.270	0.030	0.0009	0.330
3.915	33.80	33.707	0.093	0.0087	0.329
4.226	38.20	38.144	0.056	0.0032	0.329
4.552	42.90	42.795	0.105	0.0111	0.329
4.866	47.30	47.275	0.025	0.0006	0.330
5.012	49.35	49.358	-0.008	0.0001	0.330

5.347	54.15	54.137	0.013	0.0002	0.332
5.664	58.80	58.660	0.140	0.0197	0.335
5.994	63.55	63.368	0.182	0.0332	0.338
6.304	68.00	67.791	0.209	0.0438	0.342
6.445	69.95	69.802	0.148	0.0218	0.344
5.908	62.10	62.141	-0.041	0.0017	0.338
5.616	57.90	57.975	-0.075	0.0056	0.335
5.344	54.00	54.094	-0.094	0.0089	0.332
5.066	50.05	50.128	-0.078	0.0061	0.331
4.989	48.70	49.029	-0.329	0.1085	0.330
4.654	44.00	44.250	-0.250	0.0625	0.329
4.295	38.90	39.128	-0.228	0.0520	0.329
3.914	33.70	33.692	0.008	0.0001	0.329
3.461	27.00	27.229	-0.229	0.0526	0.331
3.267	24.30	24.462	-0.162	0.0261	0.332
2.868	18.60	18.769	-0.169	0.0286	0.336
2.486	13.40	13.319	0.081	0.0065	0.340
2.258	10.00	10.066	-0.066	0.0044	0.343

M = 14.267   SE M = 0.048   YI = -22.149
SE YI = 0.217   SE Y Ave = 0.335   % err = 0.4765
s^2 = 0.157   SSE = 0.643   t(95%) = 2.056

pressure transducer calibration with datalogger
(increasing water level)

X = datalogger reading   Y = water depth (cm)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
110.0	9.00	8.896	0.104	0.0109	0.316
126.0	13.30	13.350	-0.050	0.0025	0.303
142.0	17.85	17.805	0.045	0.0020	0.293
167.0	24.65	24.766	-0.116	0.0133	0.285
184.0	29.30	29.499	-0.199	0.0395	0.284
199.0	33.80	33.675	0.125	0.0156	0.286
215.0	38.20	38.130	0.070	0.0050	0.291
232.0	42.90	42.863	0.037	0.0014	0.301
248.0	47.30	47.317	-0.017	0.0003	0.314

M = 0.278   SE M = 0.002   YI = -21.730
SE YI = 0.337   SE Y Ave = 0.297   % err = 0.423
s^2 = 0.114   SSE = 0.091   t(95%) = 2.365

pressure transducer calibration with datalogger (decreasing water level)

X = datalogger reading   Y = water depth (cm)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
254.0	48.70	48.749	-0.049	0.0024	0.335
237.0	44.00	44.011	-0.011	0.0001	0.320
218.0	38.90	38.716	0.184	0.0340	0.309
200.0	33.70	33.699	0.001	0.0000	0.302
176.0	27.00	27.010	-0.010	0.0001	0.300
167.0	24.30	24.502	-0.202	0.0408	0.301
146.0	18.60	18.649	-0.049	0.0024	0.309
127.0	13.50	13.354	0.146	0.0213	0.321
115.0	10.00	10.010	-0.010	0.0001	0.330

M = 0.27   SE M = 0.002   YI = -22.041
SE YI = 0.389   SE Y Ave = 0.314   % err = 0.4467
s^2 = 0.120   SSE = 0.101   t(95%) = 2.365

pressure transducer calibration with datalogger (both data sets)

X = datalogger reading   Y = water depth (cm)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
110.0	9.00	8.760	0.240	0.0576	0.418
126.0	13.30	13.216	0.084	0.0070	0.408
142.0	17.85	17.672	0.178	0.0316	0.401
167.0	24.65	24.635	0.015	0.0002	0.394
184.0	29.30	29.369	-0.069	0.0048	0.393
199.0	33.80	33.547	0.253	0.0641	0.395
215.0	38.20	38.003	0.197	0.0389	0.399
232.0	42.90	42.737	0.163	0.0264	0.405
248.0	47.30	47.193	0.107	0.0114	0.415
254.0	48.70	48.864	-0.164	0.0270	0.419
237.0	44.00	44.130	-0.130	0.0169	0.408
218.0	38.90	38.838	0.062	0.0038	0.400
200.0	33.70	33.825	-0.125	0.0157	0.395
176.0	27.00	27.141	-0.141	0.0199	0.394
167.0	24.30	24.635	-0.335	0.1120	0.394
146.0	18.60	18.786	-0.186	0.0347	0.399
127.0	13.50	13.495	0.005	0.0000	0.407
115.0	10.00	10.153	-0.153	0.0233	0.415

M = 0.279   YI = -21.875   SE M = 0.002
SE YI = 0.351   SE Y Ave = 0.403   % err = 0.573
s^2 = 0.176   SSE = 0.495   t(95%) = 2.120

APPENDIX D: System calibration data.

DATALOGGER DATA

X = datalogger reading Y = measured water level (cm)

30.5 meter (100 foot) bubbler tube

29°C (84.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
100	11.9	11.985	-0.085	0.007	0.412
111	15.2	15.055	0.145	0.021	0.396
129	20.0	20.079	-0.079	0.006	0.381
158	28.2	28.173	0.027	0.001	0.383
209	42.4	42.408	-0.008	0.000	0.462

M = 0.279 SE M = 0.004 YI = -15.926
SE YI = 0.57 SE Y Ave = 0.407 % err = 0.579
s^2 = 0.108 SSE = 0.035 t(95%) = 3.182

44°C (111.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
94	10.4	10.420	-0.020	0.000	0.288
104	13.2	13.180	0.020	0.000	0.279
126	19.3	19.253	0.047	0.002	0.266
174	32.4	32.504	-0.104	0.011	0.275
210	42.5	42.443	0.057	0.003	0.312

M = 0.276 SE M = 0.002 YI = -15.530
SE Y Ave = 0.284
s^2 = 0.076 SSE = 0.017 t(95%) = 3.182
SE YI = 0.363 % err = 0.404

55°C (131°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
106	13.6	13.613	-0.013	0.000	0.310
133	21.1	21.138	-0.038	0.001	0.279
149	25.7	25.597	0.103	0.011	0.271
183	35.0	35.074	-0.074	0.005	0.282
211	42.9	42.878	0.022	0.000	0.316

M = 0.279　　SE M = 0.003　　YI = -15.932
SE YI = 0.480　　SE Y Ave = 0.292　　% err = 0.415
s^2 = 0.078　　SSE = 0.018　　t(95%) = 3.182

152.4 meter (500 foot) bubbler tube

29°C (84.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
92	8.9	8.853	0.047	0.002	0.356
119	16.4	16.357	0.043	0.002	0.327
138	21.5	21.638	-0.138	0.019	0.316
191	36.4	36.368	0.032	0.001	0.335
213	42.5	42.483	0.017	0.000	0.361

M = 0.278　　SE M = 0.003　　YI = -16.716
SE YI = 0.448　　SE Y Ave = 0.339　　% err = 0.482
s^2 = 0.090　　SSE = 0.024　　t(95%) = 3.182

37°C (98.6°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
89	8.0	7.995	0.005	0.000	0.319
103	11.9	11.877	0.023	0.001	0.305
156	26.6	26.574	0.026	0.001	0.285
176	32.0	32.120	-0.120	0.014	0.292
215	43.0	42.934	0.066	0.004	0.329

M = 0.277　　SE M = 0.003　　YI = -16.683
SE YI = 0.386　　SE Y Ave = 0.306　　% err = 0.435
s^2 = 0.081　　SSE = 0.020　　t(95%) = 3.182

51°C (123.8°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
105	12.5	12.441	0.059	0.004	0.481
151	25.1	25.189	-0.089	0.008	0.403
170	30.5	30.455	0.045	0.002	0.399
189	35.6	35.720	-0.120	0.015	0.412
212	42.2	42.095	0.106	0.011	0.449

M = 0.277	SE M = 0.004	YI = -16.658
SE YI = 0.757	SE Y Ave = 0.429	% err = 0.610
s^2 = 0.114	SSE = 0.039	t(95%) = 3.182

304.8 meter (1000 foot) bubbler tube

25°C (77°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
103	9.2	9.277	-0.0766	0.006	0.309
135	18.2	18.128	0.0717	0.005	0.277
169	27.6	27.533	0.0668	0.004	0.266
203	36.9	36.938	-0.0381	0.001	0.280
225	43.0	43.024	-0.0237	0.001	0.302

M = 0.277SE	M = 0.002	YI = -19.215
SE YI = 0.424	SE Y Ave = 0.287	% err = 0.408
s^2 = 0.076	SSE = 0.017	t(95%) = 3.182

32°C (89.6°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
89	6.0	5.969	0.0308	0.001	0.166
121	14.8	14.809	-0.0088	0.000	0.149
158	25.0	25.030	-0.0297	0.001	0.143
183	31.9	31.936	-0.0357	0.001	0.148
220	42.2	42.157	0.0434	0.002	0.166

M = 0.276	SE M = 0.001	YI = - 18.616
SE YI = 0.205	SE Y Ave = 0.154	% err = 0.219
s^2 = 0.041	SSE = 0.005	t(95%) = 3.182

50°C (122°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
97	7.9	7.832	0.068	0.005	0.437
119	13.8	13.939	-0.140	0.019	0.407
152	23.2	23.101	0.099	0.010	0.386
199	36.1	36.149	-0.049	0.002	0.411
220	42.0	41.979	0.021	0.000	0.440

M = 0.278 SE M = 0.003 YI = -19.097
SE YI = 0.556 SE Y Ave = 0.416 % err = 0.592
s2 = 0.111 SSE = 0.037 t(95%) = 3.182

457.2 meter (1500 foot) bubbler tube

28°C (82.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
97	7.3	7.262	0.038	0.001	0.243
111	11.2	11.201	-0.001	0.000	0.232
162	25.5	25.551	-0.051	0.003	0.216
194	34.5	34.554	-0.054	0.003	0.227
222	42.5	42.432	0.068	0.005	0.247

M = 0.281 SE M = 0.002 YI = -20.029
SE YI = 0.304 SE Y Ave = 0.233 % err = 0.331
s^2 = 0.062 SSE = 0.012 t(95%) = 3.182

39°C (102.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
94	6.2	6.267	-0.067	0.004	0.369
132	17.0	16.894	0.106	0.011	0.330
147	21.1	21.088	0.012	0.000	0.322
201	36.1	36.189	-0.089	0.008	0.341
222	42.1	42.062	0.038	0.001	0.366

M = 0.280 SE M = 0.003 YI = -20.020
SE YI = 0.466 SE Y Ave = 0.346 % err = 0.492
s^2 = 0.092 SSE = 0.025 t(95%) = 3.182

53°C (127.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
91	5.0	5.009	-0.009	0.000	0.292
124	14.3	14.229	0.071	0.005	0.264
165	25.6	25.685	-0.085	0.007	0.252
192	33.2	33.229	-0.029	0.001	0.262
225	42.5	42.449	0.051	0.003	0.289

M = 0.279 SE M = 0.002 YI = -20.413
SE YI = 0.360 SE Y Ave = 0.272 % err = 0.387
s^2 = 0.072 SSE = 0.016 t(95%) = 3.182

609.6 meter (2000 foot) bubbler tube

21°C (69.8°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
112.0	11.60	11.543	0.057	0.003	0.323
127.0	15.85	15.728	0.122	0.015	0.316
143.0	20.10	20.192	-0.092	0.009	0.311
158.0	24.40	24.378	0.022	0.001	0.310
173.0	28.60	28.563	0.037	0.001	0.312
189.0	33.00	33.027	-0.027	0.001	0.316
205.0	37.80	37.491	0.309	0.095	0.325
221.0	42.00	41.956	0.044	0.002	0.336
203.0	36.70	36.933	-0.233	0.054	0.323
188.0	32.70	32.748	-0.048	0.002	0.316
171.0	28.00	28.005	-0.005	0.000	0.311
158.0	24.40	24.378	0.022	0.001	0.310
143.0	20.00	20.192	-0.192	0.037	0.311
128.0	16.00	16.007	-0.007	0.000	0.316
111.0	11.10	11.264	-0.164	0.027	0.324
88.0	5.00	4.846	0.154	0.024	0.340

M = 0.279 SE M = 0.002 YI = -19.707
SE YI = 0.328 SE Y Ave = 0.319 % err = 0.454
s^2 = 0.139 SSE = 0.271 t(95%) = 2.160

28°C (82.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
87.0	5.00	4.994	0.006	0.000	0.378
117.0	13.30	13.302	-0.002	0.000	0.344
150.0	22.50	22.441	0.059	0.003	0.330
185.0	32.00	32.135	-0.135	0.018	0.343
220.0	41.90	41.828	0.072	0.005	0.382

M = 0.277　　SE M = 0.003　　YI = -19.457
SE YI = 0.453　　SE Y Ave = 0.355　　% err = 0.505
s^2 = 0.095　　SSE = 0.027　　t(95%) = 3.182

35°C (95°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
102.0	9.00	8.993	0.007	0.0000	0.504
136.0	18.40	18.473	-0.073	0.005	0.449
170.0	28.00	27.952	0.048	0.002	0.431
203.0	37.30	37.153	0.147	0.022	0.455
223.0	42.60	42.729	-0.129	0.017	0.487

M = 0.279　　SE M = 0.004　　YI = -19.446
SE YI = 0.692　　SE Y Ave = 0.465　　% err = 0.662
s^2 = 0.124　　SSE = 0.046　　t(95%) = 3.182

53°C (127.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
106.0	9.60	9.534	0.066	0.004	0.364
140.0	18.95	19.078	-0.128	0.016	0.324
172.0	28.10	28.060	0.040	0.002	0.312
203.0	36.80	36.761	0.039	0.002	0.328
226.0	43.20	43.217	-0.017	0.000	0.354

M = 0.281　　SE M = 0.003　　YI = -20.219
SE YI = 0.518　　SE Y Ave = 0.336　　% err = 0.478
s^2 = 0.090　　SSE = 0.024　　t(95%) = 3.182

DIGITAL MULTIMETER (DMM) DATA

X = DMM reading Y = measured water level (cm)

30.48 meter (100 foot) bubbler tube

29°C (84.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.958	11.9	11.890	0.00978	0.000	0.215
2.189	15.2	15.141	0.05888	0.003	0.207
2.539	20.0	20.067	-0.0667	0.004	0.199
3.119	28.2	28.229	-0.0292	0.001	0.200
4.124	42.4	42.373	0.02727	0.001	0.241

M = 14.073 SE M = 0.104 YI = -15.665
SE YI = 0.300 SE Y Ave = 0.212 % err = 0.302
s^2 = 0.057 SSE = 0.010 t(95%) = 3.182

44°C (111.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.848	10.4	10.402	-0.002	0.000	0.173
2.044	13.2	13.153	0.047	0.002	0.167
2.485	19.3	19.342	-0.042	0.002	0.159
3.418	32.4	32.435	-0.035	0.001	0.165
4.133	42.5	42.469	0.031	0.001	0.187

M = 14.033 SE M = 0.075 YI = -15.531
SE YI = 0.217 SE Y Ave = 0.170 % err = 0.242
s^2 = 0.045 SSE = 0.006 t(95%) = 3.182

55°C (131°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.079	13.6	13.600	0.000	0.000	0.067
2.613	21.1	21.110	-0.010	0.000	0.061
2.938	25.7	25.680	0.020	0.000	0.059
3.602	35.0	35.018	-0.018	0.000	0.061
4.162	42.9	42.893	0.007	0.000	0.069

M = 14.063　　SE M = 0.033　　YI = -15.637
SE YI = 0.104　　SE Y Ave = 0.063　　% err = 0.090
s^2 = 0.017　　SSE = 0.001　　t(95%) = 3.182

152.4 meter (500 foot) bubbler tube

29°C (84.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.768	8.9	8.985	-0.085	0.007	0.411
2.293	16.4	16.359	0.041	0.002	0.378
2.651	21.5	21.387	0.113	0.013	0.366
3.727	36.4	36.500	-0.100	0.010	0.388
4.152	42.5	42.469	0.031	0.001	0.418

M = 14.045　　SE M = 0.167　　YI = -15.847
SE YI = 0.508　　SE Y Ave = 0.392　　% err = 0.558
s^2 = 0.104　　SSE = 0.033　　t(95%) = 3.182

37°C (98.6°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.749	8.0	8.006	-0.006	0.000	0.174
2.024	11.9	11.866	0.034	0.001	0.167
3.075	26.6	26.619	-0.019	0.000	0.155
3.462	32.0	32.051	-0.051	0.003	0.160
4.239	43.0	42.958	0.042	0.002	0.180

M = 14.037　　SE M = 0.069　　YI = -16.546
SE YI = 0.210　　SE Y Ave = 0.167　　% err = 0.238
s^2 = 0.044　　SSE = 0.006　　t(95%) = 3.182

51°C (123.8°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.080	12.5	12.481	0.019	0.000	0.252
2.980	25.1	25.172	-0.072	0.005	0.211
3.353	30.5	30.432	0.068	0.005	0.209
3.721	35.6	35.622	-0.022	0.001	0.215
4.187	42.2	42.193	0.007	0.000	0.235

M = 14.102 SE M = 0.119 YI = -16.851
SE YI = 0.398 SE Y Ave = 0.224 % err = 0.319
s^2 = 0.060 SSE = 0.011 t(95%) = 3.182

304.8 meter (1000 foot) bubbler tube

25°C (77°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.033	9.2	9.176	0.02375	0.001	0.132
2.672	18.2	18.205	-0.0053	0.000	0.118
3.340	27.6	27.644	-0.0441	0.002	0.113
3.995	36.9	36.899	0.00077	0.000	0.119
4.425	43.0	42.975	0.02489	0.001	0.128

M = 14.130 SE M = 0.053 YI = -19.550
SE YI = 0.182 SE Y Ave = 0.122 % err = 0.174
s^2 = 0.032 SSE = 0.003 t(95%) = 3.182

32°C (89.6°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.757	6.0	5.955	0.0447	0.002	0.254
2.391	14.8	14.873	-0.0734	0.005	0.228
3.112	25.0	25.015	-0.0153	0.000	0.219
3.597	31.9	31.838	0.0625	0.004	0.226
4.335	42.2	42.219	-0.0185	0.000	0.254

M = 14.066 SE M = 0.099 YI = -18.759
SE YI = 0.315 SE Y Ave = 0.236 % err = 0.336
s^2 = 0.063 SSE = 0.012 t(95%) = 3.182

50°C (122°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.909	7.9	7.891	0.009	0.000	0.317
2.326	13.8	13.748	0.052	0.003	0.297
3.007	23.2	23.313	-0.113	0.013	0.281
3.913	36.1	36.039	0.061	0.004	0.298
4.338	42.0	42.008	-0.008	0.000	0.320

M = 14.046 SE M = 0.125 YI = -18.922
SE YI = 0.403 SE Y Ave = 0.303 % err = 0.431
s^2 = 0.080 SSE = 0.019 t(95%) = 3.182

457.2 meter (1500 foot) bubbler tube

28°C (82.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.909	7.3	7.273	0.027	0.001	0.387
2.185	11.2	11.217	-0.017	0.000	0.370
3.182	25.5	25.463	0.037	0.001	0.344
3.824	34.5	34.637	-0.137	0.019	0.361
4.368	42.5	42.411	0.090	0.008	0.393

M = 14.289 SE M = 0.150 YI = -20.006
SE YI = 0.484 SE Y Ave = 0.371 % err = 0.528
s^2 = 0.099 SSE = 0.029 t(95%) = 3.182

39°C (102.2°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.847	6.2	6.227	-0.027	0.001	0.121
2.605	17.0	16.961	0.039	0.002	0.108
2.897	21.1	21.096	0.004	0.000	0.105
3.958	36.1	36.121	-0.021	0.000	0.111
4.380	42.1	42.096	0.004	0.000	0.120

M = 14.161 SE M = 0.047 YI = -19.929
SE YI = 0.152 SE Y Ave = 0.113 % err = 0.161
s^2 = 0.030 SSE = 0.003 t(95%) = 3.182

53°C (127.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.782	5.0	4.909	0.091	0.008	0.361
2.451	14.3	14.384	-0.084	0.007	0.324
3.246	25.6	25.644	-0.044	0.002	0.311
3.782	33.2	33.236	-0.036	0.001	0.323
4.431	42.5	42.428	0.072	0.005	0.356

M = 14.163 SE M = 0.135 YI = -20.330
SE YI = 0.442 SE Y Ave = 0.335 % err = 0.477
s^2 = 0.089 SSE = 0.024 t(95%) = 3.182

609.6 meter (2000 foot) bubbler tube

21°C (69.8°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.204	11.60	11.612	-0.012	0.000	0.261
2.502	15.85	15.831	0.019	0.000	0.255
2.804	20.10	20.106	-0.006	0.000	0.251
3.106	24.40	24.381	0.019	0.000	0.250
3.407	28.60	28.642	-0.042	0.002	0.252
3.717	33.00	33.030	-0.030	0.001	0.255
4.036	37.80	37.546	0.254	0.065	0.262
4.357	42.00	42.090	-0.090	0.008	0.271
3.983	36.70	36.796	-0.096	0.009	0.261
3.690	32.70	32.648	0.052	0.003	0.255
3.359	28.00	27.962	0.038	0.001	0.251
3.111	24.40	24.452	-0.052	0.003	0.250
2.795	20.00	19.979	0.021	0.001	0.251
2.519	16.00	16.072	-0.072	0.005	0.255
2.182	11.10	11.301	-0.201	0.040	0.261
1.723	5.00	4.804	0.196	0.039	0.275

M = 14.156 SE M = 0.083 YI = -19.587
SE YI = 0.264 SE Y Ave = 0.257 % err = 0.366
s^2 = 0.112 SSE = 0.177 t(95%) = 2.160

28°C (82.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
1.710	5.00	4.973	0.027	0.001	0.195
2.301	13.30	13.284	0.016	0.000	0.178
2.961	22.50	22.566	-0.066	0.004	0.170
3.633	32.00	32.016	-0.016	0.000	0.177
4.333	41.90	41.860	0.040	0.002	0.198

M = 14.063 SE M = 0.075 YI = -19.074
SE YI = 0.234 SE Y Ave = 0.184 % err = 0.262
s^2 = 0.049 SSE = 0.007 t(95%) = 3.182

35°C (95°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.006	9.00	8.965	0.035	0.001	0.154
2.675	18.40	18.443	-0.043	0.002	0.137
3.351	28.00	28.021	-0.021	0.000	0.132
4.004	37.30	37.272	0.028	0.001	0.139
4.380	42.60	42.600	0.000	0.000	0.149

M = 14.168 SE M = 0.062 YI = -19.457
SE YI = 0.212 SE Y Ave = 0.142 % err = 0.202
s^2 = 0.038 SSE = 0.004 t(95%) = 3.182

53°C (127.4°F)

X	Y	CALCULATED Y	RESIDUAL	RESIDUAL SQUARED	SE Y
2.080	9.60	9.581	0.019	0.000	0.203
2.742	18.95	18.985	-0.035	0.001	0.181
3.381	28.10	28.063	0.037	0.001	0.174
4.000	36.80	36.857	-0.057	0.003	0.183
4.444	43.20	43.164	0.036	0.001	0.197

M = 14.206 SE M = 0.084 YI = -19.969
SE YI = 0.288 SE Y Ave = 0.188 % err = 0.267
s^2 = 0.050 SSE = 0.007 t(95%) = 3.182

APPENDIX E: PLOT-IT output for regression lines forced through the origin.

30.5 meter bubbler tube

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	48.57143	680.0000	34200.000000	1171.43000
X	8.192857	114.7000	1110.9100000	171.189400

Cross Product 5942.0000   Cor. Cross Product 370.85730

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	5.348768	.40915	13.07	.00	4.465	6.233

Model: Y = B(O) * X   REGRESSION LINE FORCED THROUGH ORIGIN

Coefficient of: Determination .929   Correlation .964

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Regression	1	31782.380000	31782.3800	170.9
Residual	13	2417.6220000	185.970900	
Total	14	34200.000000	Sig. of F Value:	.0000

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	8
Largest positive residual:	25.3957
Number of negative residuals:	6
Largest negative residual:	-15.9525
Number of sign runs:	8
Significance of sign runs test:	.6427
Average absolute residual:	10.5132
Residual sum of squares:	2417.62
Residual mean square:	185.971
Residual standard deviation:	13.6371
Durbin-Watson statistic:	.397147
Auto-correlation coefficient:	.759

157.4 meter bubbler tube

M E A N A N D S U M S T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	100.8333	1210.000	131050.00000	9041.66400
X	8.541667	102.5000	1008.6300000	133.109200

Cross Product 11337.500   Cor. Cross Product 1002.0830

R E G R E S S I O N S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	11.24049	.57049	19.70	.00	9.985	12.50

Model: Y = B(O) * X   REGRESSION LINE FORCED THROUGH ORIGIN

Coefficient of: Determination .972   Correlation .986

A N A L Y S I S O F V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Regression	1	127439.10000	127439.100	388.2
Residual	11	3610.8910000	328.262800	
Total	12	131050.00000	Sig. of F Value:	.0000

A N A L Y S I S O F R E S I D U A L S

Number of positive residuals:	8
Largest positive residual:	30.0760
Number of negative residuals:	4
Largest negative residual:	-23.6454
Number of sign runs:	2
Significance of sign runs test:	.0041
Average absolute residual:	15.3650
Residual sum of squares:	3610.89
Residual mean square:	328.263
Residual standard deviation:	18.1180
Durbin-Watson statistic:	1.01095
Auto-correlation coefficient:	.408

304.8 meter bubbler tube

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	181.9231	2365.000	444025.00000	13776.9400
X	8.607693	111.9000	1012.5100000	49.3091400

Cross Product 21051.000   Cor. Cross Product 693.80740

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	20.79091	.72325	28.75	.00	19.22	22.37

Model: Y = B(O) * X   REGRESSION LINE FORCED THROUGH ORIGIN

Coefficient of: Determination .986   Correlation .993

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Regression	1	437669.40000	437669.400	826.4
Residual	12	6355.6190000	529.634900	
Total	13	444025.00000	Sig. of F Value:	.0000

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	9
Largest positive residual:	37.3336
Number of negative residuals:	4
Largest negative residual:	-37.1182
Number of sign runs:	4
Significance of sign runs test:	.0795
Average absolute residual:	18.3387
Residual sum of squares:	6355.64
Residual mean square:	529.637
Residual standard deviation:	23.0138
Durbin-Watson statistic:	1.07333
Auto-correlation coefficient:	.389

457.2 meter bubbler tube

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	328.2143	4595.000	1623425.0000	115280.400
X	8.414287	117.8000	1147.8200000	156.617000

Cross Product 42641.500   Cor. Cross Product 3977.8540

R E G R E S S I O N   S T A T I S T I C S

Regression Coefficient		Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	37.14999	1.6228	22.89	.00	33.64	40.66

Model: Y = B(O) * X   REGRESSION LINE FORCED THROUGH ORIGIN

Coefficient of: Determination   .976   Correlation   .988

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Regression	1	1584131.0000	1584131.00	524.1
Residual	13	39293.860000	3022.60500	
Total	14	1623425.0000	Sig. of F Value:	.0000

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	8
Largest positive residual:	84.2501
Number of negative residuals:	6
Largest negative residual:	-71.2448
Number of sign runs:	4
Significance of sign runs test:	.0281
Average absolute residual:	47.3871
Residual sum of squares:	39293.8
Residual mean square:	3022.60
Residual standard deviation:	54.9781
Durbin-Watson statistic:	.828666
Auto-correlation coefficient:	.525

609.6 meter bubbler tube

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	537.5833	6451.000	3797003.0000	329053.000
X	7.416667	89.00000	722.80000000	62.7167400

Cross Product 52135.500   Cor. Cross Product 4290.5830

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	72.12991	2.1418	33.68	.00	67.42	76.84

Model: Y = B(O) * X   REGRESSION LINE FORCED THROUGH ORIGIN

Coefficient of: Determination .990   Correlation .995

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Regression	1	3760529.0000	3760529.00	1134.
Residual	11	36474.300000	3315.84500	
Total	12	3797003.0000	Sig. of F Value:	.0000

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	6
Largest positive residual:	113.369
Number of negative residuals:	6
Largest negative residual:	-75.2341
Number of sign runs:	7
Significance of sign runs test:	.6190
Average absolute residual:	45.6158
Residual sum of squares:	36474.0
Residual mean square:	3315.82
Residual standard deviation:	57.5832
Durbin-Watson statistic:	2.46890
Auto-correlation coefficient:	-.273

APPENDIX F: PLOT-IT output for Figure 28.

Curve fitting for Figure 28

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	29.33220	146.6610	7170.0970000	2868.20600
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 226931.40   Cor. Cross Product 77337.170

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	.3021723E-01	.32272E-02	9.36	.00	.2126E-01	.3918E-01

Model: Y = B(O) * X   REGRESSION LINE FORCED THROUGH ORIGIN

Coefficient of: Determination .956   Correlation .978

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Regression	1	6857.2390000	6857.23900	87.67
Residual	4	312.85810000	78.2145300	
Total	5	7170.0970000	Sig. of F Value:	.0007

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	2
Largest positive residual:	11.6955
Number of negative residuals:	3
Largest negative residual:	-9.42623
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	7.09850
Residual sum of squares:	312.858
Residual mean square:	78.2146
Residual standard deviation:	8.84390
Durbin-Watson statistic:	1.48856
Auto-correlation coefficient:	-.245

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	29.33220	146.6610	7170.0970000	2868.20600
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 226931.40   Cor. Cross Product 77337.170

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0)	-4.846272	7.7484	-.63	.58	-29.51	19.81
B(1)	.3350831E-01	.63224E-02	5.30	.01	.1339E-01	.5363E-01

Model: Y = B(0) + B(1) * X   INTERCEPT = B(0), SLOPE = B(1)

Coefficient of: Determination .904   Correlation .951

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	4301.8910000	4301.89100	
Regression	1	2591.4380000	2591.43800	28.09
Residual	3	276.76820000	92.2560900	
Total	5	7170.0970000	Sig. of F Value:	.0131

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	2
Largest positive residual:	9.95965
Number of negative residuals:	3
Largest negative residual:	-8.26619
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	6.72164
Residual sum of squares:	276.769
Residual mean square:	92.2563
Residual standard deviation:	9.60501
Durbin-Watson statistic:	1.59215
Auto-correlation coefficient:	-.184

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	29.33220	146.6610	7170.0970000	2868.20600
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 226931.40   Cor. Cross Product 77337.170

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0)	7.376336	3.7129	1.99	.19	-8.599	23.35
B(1)	-.6714135E-02	.86963E-02	-.77	.52	-.4413E-01	.3070E-01
B(2)	.1917730E-04	.40118E-05	4.78	.04	.1916E-05	.3644E-04

Model: Y = B(0) + B(1) * X + B(2) * X ** 2

Coefficient of: Determination .992

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	4301.8910000	4301.89100	
Regression	2	2845.9320000	1422.96600	127.8
Residual	2	22.274190000	11.1370900	
Total	5	7170.0970000	Sig. of F Value:	.0078

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	3
Largest positive residual:	2.42741
Number of negative residuals:	2
Largest negative residual:	-3.30405
Number of sign runs:	4
Significance of sign runs test:	.8850
Average absolute residual:	1.94068
Residual sum of squares:	22.2787
Residual mean square:	11.1394
Residual standard deviation:	3.33757
Durbin-Watson statistic:	2.64410
Auto-correlation coefficient:	-.458

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	29.33220	146.6610	7170.0970000	2868.20600
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 226931.40   Cor. Cross Product 77337.170

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0)	3.099960	.73918	4.19	.15	-6.292	12.49
B(1)	.2280798E-01	.35127E-02	6.49	.10	-.2183E-01	.6744E-01
B(2)	-.1715783E-04	.40463E-05	-4.24	.15	-.6857E-04	.3426E-04
B(3)	.1149531E-07	.12652E-08	9.09	.07	-.4580E-08	.2757E-07

Model: Y = B(0) + B(1) * X + B(2) * X ** 2 + B(3) * X ** 3

Coefficient of: Determination 1.000

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	4301.8910000	4301.89100	
Regression	3	2867.9440000	955.981200	3643.
Residual	1	.26244130000	.262441300	
Total	5	7170.0970000	Sig. of F Value:	.0122

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	3
Largest positive residual:	.545576
Number of negative residuals:	2
Largest negative residual:	-.410408
Number of sign runs:	5
Significance of sign runs test:	.9890
Average absolute residual:	.304139
Residual sum of squares:	.614384
Residual mean square:	.614384
Residual standard deviation:	.783826
Durbin-Watson statistic:	3.58554
Auto-correlation coefficient:	-.837

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	.7295807E-01	.3647904	.46094670000E-01	.194802700E-01
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 179.37740   Cor. Cross Product-192.70880

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0)	.1581240	.27117E-01	5.83	.01	.7182E-01	.2444
B(1)	-.8349599E-04	.22126E-04	-3.77	.03	-.1539E-03	-.1308E-04

Model: Y = A / (B + X) WHERE A = 1/B(1) AND B = B(0)/B(1)

Coefficient of: Determination .826   Correlation -.909

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	.26614400000E-01	.266144000E-01	
Regression	1	.16090410000E-01	.160904100E-01	14.24
Residual	3	.33898620000E-02	.112995400E-02	
Total	5	.46094670000E-01	Sig. of F Value:	.0326

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	2
Largest positive residual:	.371764E-01
Number of negative residuals:	3
Largest negative residual:	-.274159E-01
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	.239633E-01
Residual sum of squares:	.338986E-02
Residual mean square:	.112995E-02
Residual standard deviation:	.336148E-01
Durbin-Watson statistic:	1.59870
Auto-correlation coefficient:	-.225

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	.7295807E-01	.3647904	.46094670000E-01	.194802700E-01
X	.2833333E-02	.1416667E-01	.10569440000E-03	.655555600E-04

Cross Product .21204030E-02Cor. Cross Product .10868300E-02

R E G R E S S I O N   S T A T I S T I C S

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0)	.2598490E-01	.12536E-01	2.07	.13	-.1391E-01	.6588E-01
B(1)	16.57877	2.7265	6.08	.01	7.902	25.26

Model: Y = A * X / (B + X)   A = 1/B(0) AND B = B(1)/B(0)

Coefficient of: Determination .925 Correlation .962

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	.26614400000E-01	.266144000E-01	
Regression	1	.18018310000E-01	.180183100E-01	36.97
Residual	3	.14619640000E-02	.487321500E-03	
Total	5	.46094670000E-01	Sig. of F Value:	.0089

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	2
Largest positive residual:	.298176E-01
Number of negative residuals:	3
Largest negative residual:	-.204104E-01
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	.141407E-01
Residual sum of squares:	.146196E-02
Residual mean square:	.487319E-03
Residual standard deviation:	.220753E-01
Durbin-Watson statistic:	1.46414
Auto-correlation coefficient:	.127

MEAN AND SUMS TABLE

	Mean	Sum	Sum of Squares	SS Deviations
Y	35.87548	179.3774	7040.4870000	605.236300
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 188228.00 Cor. Cross Product 5262.9940

REGRESSION STATISTICS

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(O)	33.54955	11.344	2.96	.06	-2.552	69.65
B(1)	.2280327E-02	.92562E-02	.25	.82	-.2718E-01	.3174E-01

Model: Y = X / (A + (B * X)) WHERE A = B(O) AND B = B(1)

Coefficient of: Determination .020 Correlation .141

ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	6435.2510000	6435.25100	
Regression	1	12.001340000	12.0013400	.6069E-01
Residual	3	593.23500000	197.745000	
Total	5	7040.4870000	Sig. of F Value:	.8213

ANALYSIS OF RESIDUALS

Number of positive residuals:	3
Largest positive residual:	12.2679
Number of negative residuals:	2
Largest negative residual:	-15.0825
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	10.1860
Residual sum of squares:	593.235
Residual mean square:	197.745
Residual standard deviation:	14.0622
Durbin-Watson statistic:	1.50608
Auto-correlation coefficient:	-.160

MEAN AND SUMS TABLE

	Mean	Sum	Sum of Squares	SS Deviations
Y	1.305005	6.525027	9.2887330000	.773536700
X	1020.000	5100.000	7510000.0000	2308000.00

Cross Product 7987.2750   Cor. Cross Product 1331.7480

REGRESSION STATISTICS

	Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0)	.7164515	.33262E-01	21.54	.00	.6106	.8223
B(1)	.5770136E-03	.27140E-04	21.26	.00	.4906E-03	.6634E-03

Model: Y = A * B ** X WHERE A = 10**B(0) AND B = 10**B(1)

Coefficient of: Determination .993 Correlation .997

ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	8.5151960000	8.51519600	
Regression	1	.76843650000	.768436500	452.0
Residual	3	.51001640000E-02	.170005500E-02	
Total	5	9.2887330000	Sig. of F Value:	.0002

ANALYSIS OF RESIDUALS

Number of positive residuals:	2
Largest positive residual:	.458466E-01
Number of negative residuals:	3
Largest negative residual:	-.458803E-01
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	.281026E-01
Residual sum of squares:	.509993E-02
Residual mean square:	.169998E-02
Residual standard deviation:	.412308E-01
Durbin-Watson statistic:	2.00005
Auto-correlation coefficient:	-.365

M E A N   A N D   S U M S   T A B L E

	Mean	Sum	Sum of Squares	SS Deviations
Y	1.305005	6.525027	9.2887330000	.773536700
X	2.835218	14.17609	41.268790000	1.07647700

Cross Product 19.366290   Cor. Cross Product .86641470

R E G R E S S I O N   S T A T I S T I C S

Regression Coefficient	Standard Error	Student's T Value	Sig	Confidence Limits Lower	Upper
B(0) -.9769520	.44129	-2.21	.11	-2.381	.4274
B(1) .8048613	.15360	5.24	.01	.3160	1.294

Model: Y = A * X ** B   WHERE   A = 10**B(0)   AND   B = B(1)

Coefficient of: Determination   .902   Correlation   .949

A N A L Y S I S   O F   V A R I A N C E

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Mean	1	8.5151960000	8.51519600	
Regression	1	.697343700000	.697343700	27.46
Residual	3	.76192990000E-01	.253976600E-01	
Total	5	9.2887330000	Sig. of F Value:	.0135

A N A L Y S I S   O F   R E S I D U A L S

Number of positive residuals:	2
Largest positive residual:	.178197
Number of negative residuals:	3
Largest negative residual:	-.144540
Number of sign runs:	3
Significance of sign runs test:	.5434
Average absolute residual:	.109479
Residual sum of squares:	.761964E-01
Residual mean square:	.253988E-01
Residual standard deviation:	.159370
Durbin-Watson statistic:	1.38597
Auto-correlation coefficient:	-.027

APPENDIX G: Bibliography

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APPENDIX H: Index of authors.