GROUNDWATER ANALYSIS WITHIN HIGHWAY CONSTRUCTION ZONES

by

Adam B. Scheller

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This thesis was presented

by

Adam B. Scheller

It was defended on

July 25th, 2007

and approved by

Dr. J.S. Lin, Associate Professor, Civil and Environmental Engineering Department

Dr. J.D. Monnell, Assistant Professor, Civil and Environmental Engineering Department

Dr. R.D. Neufeld, Professor, Civil and Environmental Engineering Department

Thesis Advisor: Dr. R.G. Quimpo, Professor, Civil and Environmental Engineering Department

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Adam Scheller, M.S.

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Highway construction can adversely affect the natural environment, including the quality and behavior of valuable groundwater resources. Investigation was undertaken in order to identify these effects and evaluate possible mitigation measures. Monitoring devices were strategically placed within small watersheds that were representative of the entire construction zone. These devices included groundwater wells, rain gages, and surface water flumes. The wells were arranged in networks aligned along the assumed direction of groundwater flow and were designed to capture both deep and shallow groundwater behavior. The installed equipment was monitored for over one year, during which time the collected data was processed into easy to understand formats that would be accessible to all organizations involved with the construction project. Hydrologic phenomena such as groundwater table fluctuation, recharge quantities, and flow rate were all analyzed and used to represent the conditions within the aquifer. After studying the behaviors observed within each watershed, inferences were made as to the effectiveness of the mitigating structures utilized by the contractor to reduce the environmental impacts of highway construction.

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PREFACE

I would like to extend special thanks to my thesis advisor, Dr. Rafael Quimpo. Over the past six years his guidance and encouragement as a professor, project manager, and mentor has helped to focus my ambitions and plan my future. Without his expertise and dedication to this research I would not have been able to reach this goal. I would also like to thank the other members of the faculty within the Civil and Environmental Engineering Department including Dr. Jeen-Shang Lin, Dr. Ronald Neufeld, and Dr. Jason Monnell, whom each served on my advising committee. I would also like to acknowledge the others students and engineers that I have worked with over the past three years, including Weizhe An, Sujaya Kalainesan, and Majid Khazaei. Lastly, I would like to thank my family and friends, whom have always encouraged me to do my best.

1.0 INTRODUCTION

Highway construction can alter both the surface and ground water hydrology of an area. Excavation and filling can affect the permeability of the soil and modify the flow paths that water takes on the surface and within the soil. The use of certain construction techniques and the unearthing of hazardous materials may cause pollutants to drain into streams and percolate into the groundwater. In environmentally sensitive zones, such as wetlands, these effects must be monitored closely and attempts should be made to minimize them.

Due to the increasing emphasis on sustainable development and the concerns of the public, it has become necessary to identify potential problems that may result from highway construction. One aspect of this situation is the effect of construction on the groundwater resources of the surrounding area. In order to identify potential problems and suggest methods of improvement, a system of data collection and analysis must be developed and implemented. This system should be well organized, simple to utilize, and capable of being transported from one application to the next.

Monitoring groundwater can be a daunting task, as there are many unseen variables that may affect its behavior. A dense network of monitoring devices is best to attain the most accurate results. For large construction projects, with limited budgets and resources for environmental investigation, these dense networks are not an option. Due to these limitations, a system will be presented in this study that relies on minimal equipment and is designed to be effective over small representative areas within larger construction zones.

A large highway construction project taking place in central Pennsylvania serves as the case study within which this investigative process will be developed and tested. This site is an excellent staging ground for the research, as it is located within a very environmentally sensitive zone, where the influences of construction are potentially serious. The terrain at this location includes mountains, which drain into wide fertile valleys containing clean streams and wetland areas. The construction is taking place on the upslope of these mountains and may affect the down slope wetlands, as well as Bald Eagle creek, into which the wetlands drain.

In order to limit the impact that this construction project will have on the region, many mitigating structures have been utilized. In addition to drains, detention basins, and silt fences located below the construction zone to deal with changes in surface runoff, an infiltration gallery has been installed beneath the roadway to intercept dirty water and filter its flow to the wetland areas.

To evaluate the effectiveness of these methods, the construction zone was monitored at two representative sites along the highway. The instrumentation system consists of three monitoring wells within each small watershed, a flume to measure surface water discharge, and two rain gages located near the sites. This framework was in operation for over one year and many analysis techniques were used to estimate its effectiveness at representing the hydrologic responses within the area.

Specifically, attempts are made to determine the response of the groundwater level to meteorological events and to ascertain how these responses correlate with the surface water behaviors. Other means of analysis include monitoring the recession curves during dry periods and estimating the direction and speed of the groundwater flow.

This report identifies the equipment and methodology used to monitor and interpret the groundwater hydrology of a watershed located within a large highway construction zone.

Although the results of the case study by which the methodology was tested will be presented, emphasis is placed on the organization of the method and not on the findings of the analysis. Suggestions will be presented on how the method can be improved for future implementation.

2.0 RESEARCH OBJECTIVES

The main goal of this research was to devise, implement, and test a system of hydrologic monitoring equipment that could be utilized to capture the effects of highway construction on valuable groundwater resources. Based on this general framework, the research was divided into two main areas of concentration. The first area deals with the structure of the monitoring system. This includes the monitoring equipment itself, procedures and schedules for data collection, and methods of organizing and manipulating the findings. The second aspect of the research was concerned with interpreting the data that was collected and using it to represent the conditions present at the test locations. Focus was placed on using applicable knowledge of hydrology and hydraulics to examine key groundwater behavior that could be utilized to show the effects of highway construction. Each of these two areas is comprised of many minor objectives, which are outlined next.

2.1 INSTRUMENTATION AND DATA ORGANIZATION

The first objective of this research is to organize and implement a system of monitoring devices capable of collecting detailed hydrologic data over a long term period. The equipment must be able to capture the hydrologic regime within small watersheds, including surface water discharge, deep and shallow groundwater fluctuation and flow, and meteorological conditions.

The small watersheds will be selected to represent the average conditions throughout the construction zone. To meet this requirement, the test sites must contain many of the construction practices that were utilized during the project. These include drainage channels, sedimentation basins, and infiltration galleries. Also, the sites should be representative of the average topographical and geographical conditions found within the construction zone. An investigation into the subsurface properties of the test areas must be completed to determine what these conditions are. It is particularly important to design a monitoring system capable of demonstrating the effects of highway construction on the groundwater flow. This entails monitoring the conditions above and below the highway cut zone throughout the construction process. Since the equipment will be in operation for a long term period and be collected by different organizations, a schedule for data collection will be devised and followed. It is also required that the equipment be low cost, low maintenance, and capable of being transported to other sites and future projects.

The data gathered from the system of monitoring equipment must be organized in such a fashion that it may be easily distributed to and understood by multiple organizations. This means that the data should be formatted so that common data processing tools, such as spread sheets, can be used to analyze and relay the information. The data must not only be interpreted by the scientific community, but also by construction companies, consultants, and the public. It is crucial that information can be exchanged efficiently and effectively.

2.2 DATA ANALYSIS

The second objective of the research is to utilize hydrologic and hydraulic principles and theories to interpret the data collected by the monitoring system. This entails identifying the phenomena that most effectively represents the groundwater conditions present at the test sites and determining how their behavior may be affected by the construction. A review of groundwater processes and of past research will be undertaken to select these phenomena and to develop appropriate methods of analyzing the collected data. Response patterns will be identified which will give insight into the general behavior of the aquifer. Detailed analyses of deep and shallow water level fluctuations, groundwater recharge, and flow rates will be undertaken. Recharge analysis will attempt to utilize the water table fluctuations to quantify the amount and rate of water entering the ground. Flow rates will be estimated based on soil properties and by conducting tracer studies at each test site.

The data will then be used to model the groundwater conditions and predict the reactions to storms and other events. Based on the success of this analysis, suggestions will be made on how to improve the monitoring system for future implementation and on how the highway construction has affected the area. Depending on the degree of confidence placed on the method, focus between these two areas will differ. If it is believed that the system was very effective, then suggestions will be provided on the highway construction procedures. If the system has many shortcomings, then focus will be placed on how it can be improved for future use.

3.0 GROUNDWATER BACKGROUND

In order to fully appreciate the methods and findings of this research, it is important to have a thorough understanding of the groundwater mechanisms which govern the phenomena that have been investigated. It is crucial to understand how groundwater interacts with the other facets of the hydrologic cycle and how it factors into the total hydrologic budget. Groundwater flow mechanisms and their subsequent methods of measurement must be outlined and understood for use in the research. In order to interpret the readings from wells and other gages, knowledge of how and where groundwater is stored must be gained. With this information, an effective investigative system can be developed, and a clear picture can be constructed of what occurs beneath the surface and why.

This section outlines some of the key concepts needed in the study of groundwater hydrology. It also includes some common methods and observation techniques used in groundwater investigations. Details of these techniques are limited to those methods which have been adopted for use in this research. Information regarding how the techniques were specifically used will be included in the analysis section of the report.

3.1 HYDROLOGIC CYCLE

The hydrologic cycle describes the continuous process which circulates water all over the planet, from phase to phase, and from the air to the surface to within the ground. A graphical representation of this process is shown in Figure 1. Many mechanisms power the hydrologic cycle, including evaporation, precipitation, infiltration, runoff, and subsurface flow. Based on these processes and other factors, the cycle can be broken down into three main systems, Atmospheric Water, Surface Water, and Sub-Surface Water (Todd and Mays, 2005). The Atmospheric system contains evaporated water vapor stored in the form of clouds, which condenses and falls as precipitation. The surface water system represents the rainfall that has fallen to the earth and is comprised of surface runoff and water which is stored in lakes, ponds, and other depressions. The sub-surface water system includes all water that has infiltrated into the soil and is either recharging the groundwater or flowing just beneath the surface as interflow. Each of these three systems interacts continually and it is very important to limit any actions that disrupt their balance.

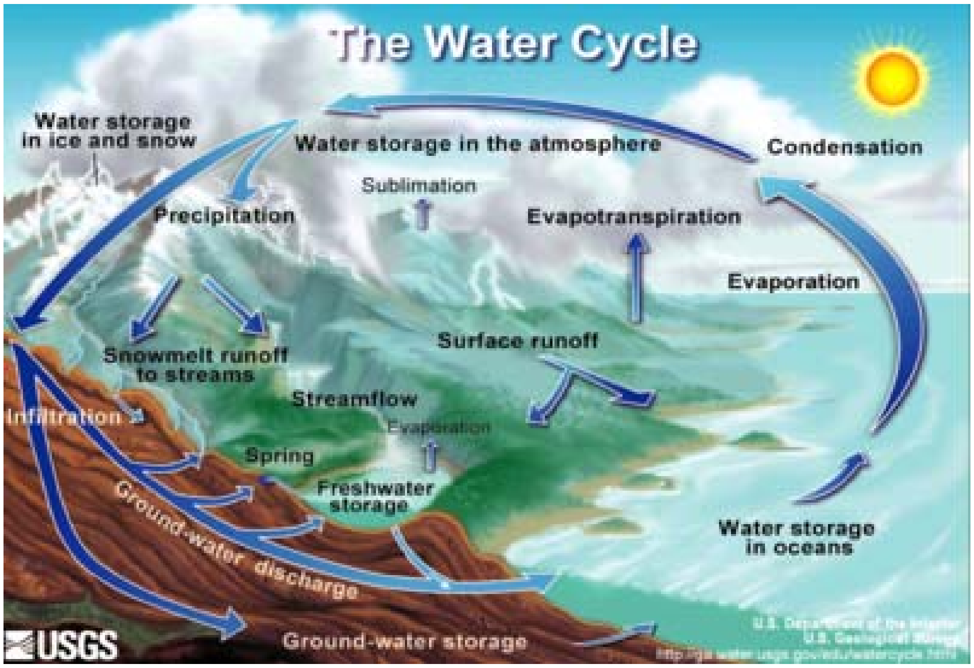


Figure 1: Hydrologic Cycle (USGS)

3.1.1 Groundwater System

It is impossible to consider one part of the hydrologic cycle without examining the others. For this research however, focus is placed on the sub-surface water system. This not only consists of the groundwater itself, but also the geologic media which stores and transports the water, flow boundaries, water sources, and water sinks (Todd and Mays, 2005). In this report, the term groundwater is used to refer to all water that is stored beneath the ground surface. Deep and shallow portions of the groundwater system will be identified when appropriate.

Input into the groundwater system usually comes from surface water, which infiltrates into the soil and is stored within the voids and small fractures that exist in most geologic formations. This infiltrated water may either be stored in shallow soil formations, which will be utilized by plant life and contribute to interflow, or recharge the water table, located deeper within the ground. The shallow groundwater is contained in an area referred to as the Vadose zone, or zone of aeration, meaning that the voids within the soil are partially occupied by water and partially by air. As water infiltrates further into the ground, it enters the zone of saturation, where all of the available interstices are filled with water. Recharge amounts and rates are variable and depend on many parameters. Understanding the recharge process is important to any hydrological investigation. A detailed examination of groundwater recharge is presented within this report.

Once water has entered the ground, it may take many different paths. In general, ground water is always flowing, but at speeds that vary from more than a meter per day to less than a meter per year. Groundwater will usually return to the surface by drainage into rivers, lakes, or oceans. It may also be utilized by plant life, lost to the atmosphere by evaporation, or be removed through mechanical pumping.

3.1.2 Hydrologic Budget

As stated earlier, no single part of the hydrologic cycle may be analyzed without consideration of the others. One of the ways in which all of the aspects of the cycle can be examined is by the application of a hydrologic budget. A hydrologic budget, or water balance, is a mass balance analysis based on the continuity of water flow and is applicable to any hydrologic system. Simply stated; the water budget accounts for all water inputs, outputs, and storage within a designated area. The water budget has many applications in the study of hydrology. It will be utilized in this research to estimate recharge and to correlate the findings with a surface water model that was developed for the same test watersheds.

The water budget method of analysis has been used by many researchers to account for the amount of water entering and exiting a particular geographic area. Rasmussen represented the water balance for a hydrologic system in the following manner, assuming that no artificial inputs or withdrawals occur (Rasmussen and Andreasen, 1958):

$$P = R + ET + \Delta SW + \Delta SM + \Delta GW$$

where:

P	= Precipitation
R	= Runoff
ET	= Evapotranspiration
ΔSW	= Change in Surface Water Storage
ΔSM	= Change in Soil Moisture
ΔGW	= Change in Groundwater Storage.

The above equation was utilized in a study of the hydrologic budget within the Beaverdam Creek Basin in Maryland. This study provided insight into some of the methods required for the groundwater investigation posed by the research presented in this report. The formulation of the hydrologic budget shown above will be used in conjunction with fluctuations of groundwater levels and other measurements to determine the storativity of the soil and quantify the groundwater recharge.

In his report, Rasmussen alluded that too frequently hydrologists theorize on the water cycle but do not adequately measure the factors involved (Rasmussen and Andreasen, 1958). He also stated the fact that the water budget equations are practically unsolvable and that only rough estimates can be made concerning water volumes. This is important to keep in mind because in most situations, as in the presented case study, data is often limited and difficult to interpret. A balance must be achieved between the complexity and cost of the measurement methods and the desired use and required accuracy.

3.2 AQUIFERS

Any subsurface geologic formation capable of storing and transmitting significant amounts of water may be termed as an aquifer. There are many different classifications of such water holding formations, based on the properties of the soil and the arrangement of the sub surface materials. These parameters designate how water moves through the media and how much of this water can be stored within the formation. In general, two primary types of water bearing formations exist, confined and unconfined aquifers. These two generalizations are widely used to describe the natural state of groundwater resources. Before any detailed investigation of groundwater hydrology can begin, it is imperative to determine which of these aquifer types, or variation there of, exists within the area. The behavior of the groundwater differs significantly between these two major categories. Thus, different techniques may be required for monitoring and analyzing their responses.

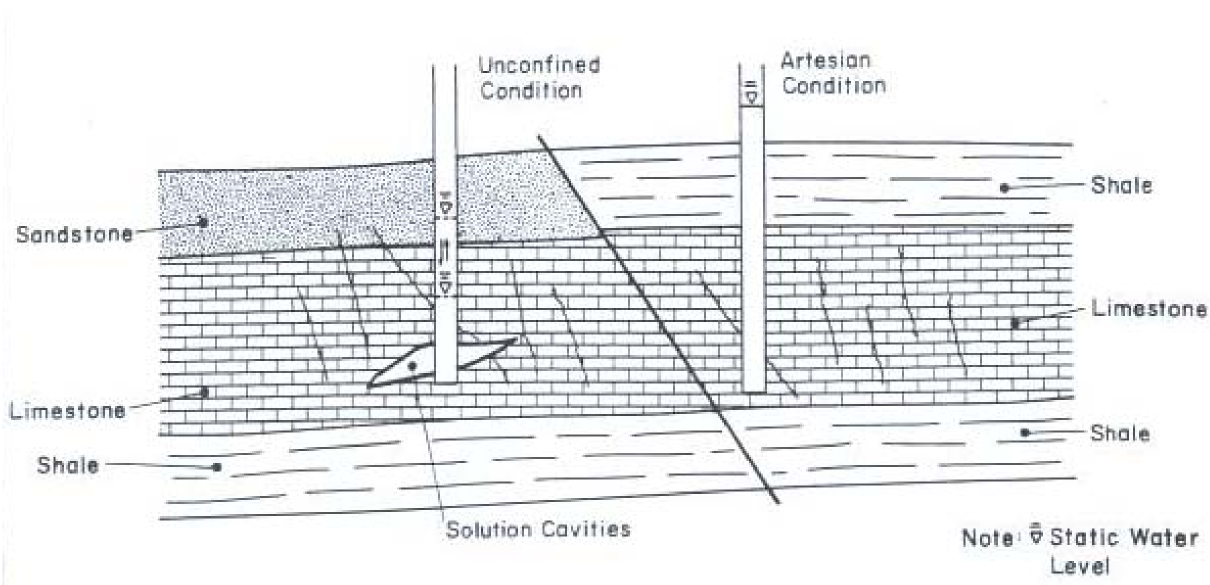


Figure 2: Confined and Unconfined Aquifers (Skelly and Loy Inc.)

3.2.1 Confined Aquifers

A confined aquifer is one that is confined between layers of soil or rock which are effectively impermeable to water and air. This means that water stored within these formations is held under pressure greater than atmospheric. This pressure gradient becomes an issue when installing wells into the aquifer, either for observation purposes or for pumping. Due to the piezometric head, the level of water within the well will rise above the level of the upper confining bed, and possibly even above the ground surface. This water level is referred to as the piezometric surface. An example of a confined, or artesian, aquifer is shown in the right side of Figure 2. This figure was obtained from a hydrogeologic classification survey conducted within the same area investigated by this report. The displayed formations are an estimated representation of the actual conditions present beneath the construction zone. Details of this subsurface structure will be discussed later on in the report.

Observation wells in confined aquifers react significantly to changes in pressure as opposed to direct changes in water storage. This reliance of the water table on pressure makes the analysis of recharge quantities and rates difficult. Although rises in water level may not be directly related to the volume of water entering the aquifer, there may be a relationship between the two. This potential relationship will be exploited in this research.

3.2.2 Unconfined Aquifers

Whereas confined aquifers are completely encapsulated within impermeable materials, unconfined aquifers possess a free surface by which the actual water level within the formation may fluctuate with increases in storage volume. An example of this formation is shown in the left side of Figure 2.

This type of water bearing formation allows estimates of groundwater storage volumes and recharge rates to be made through the direct analysis of groundwater level fluctuations and comparisons to input amounts. The Water Table Fluctuation (WTF) method, introduced in section 3.6, in conjunction with analysis of the water budget, will be utilized to study these relationships. This method will also be extended for use within the confined aquifers.

3.3 SUBSURFACE PROPERTIES

The realm of groundwater is quite different from its surface water counterpart. Water beneath the surface is not free to flow, but is instead contained within a variety of rock and soil formations. Although groundwater does move within this media, flow rates range from extraordinarily slow, as in the case of densely packed clay, to relatively rapid, as when traversing small fractures in hard rock. The subsurface properties that determine the groundwater environment must be investigated to understand the mechanisms which determine how it will behave. This knowledge is gained by implementing various techniques designed to estimate these properties. Although there are many important parameters to consider, only the most important ones, which were utilized in this research, will be examined. These properties include porosity, hydraulic conductivity, and specific yield. The methods used to measure and calculate these values are also presented.

3.3.1 Porosity

Only a percentage of the material contained within geologic formations is capable of storing and transmitting water. This percentage can be estimated by examining the porosity of the sample. The porosity, α, of a soil or rock sample represents the amount of voids contained within that sample in reference to the total volume of the sample. This ratio can be expressed in the form:

$$\alpha = \frac{Vv}{V_T}$$

where:

Vv = Volume of the voids
V_T = Total volume of the sample

Porosity becomes very important in groundwater investigations because the volume not occupied by soil particles may be filled with water. These voids, if interconnected, may then serve as the means by which water travels through the soil. To represent this particular interconnected network of voids, the term effective porosity is used (Todd and Mays, 2005).

Porosity is a function of the type and condition of a particular formation. Reference values are available for certain materials, but more precise estimates should be obtained from testing the material, usually in the laboratory. Porosity serves as an important parameter when visualizing the amount of water that a particular sample can retain. Effective porosity provides insight into estimating how water flows within the sample. Although these are good starting points, soil porosity is more of a theoretical term and represents the maximum amount of water that can be stored and conveyed. More specific properties are required to analyze the actual mechanics of the in situ formations.

3.3.2 Specific Yield

Although water can theoretically occupy all of the available space within a formation, as represented by the porosity, this saturated state is often never achieved or is only temporary. A more realistic estimate of the water holding capacity of a sample must be defined. The specific yield, S_y, is the ratio of the volume of water a soil sample will release against the force of gravity, to its own volume (Todd and Mays, 2005).

This ratio will become very important in the analysis of recharge posed by this research. The specific yield is generally treated as a property of soil storage which is independent of time (Heally and Cook, 2002). Estimating specific yield is a very difficult task however, because it is actually a function of the depth to the water table, which may change over time. Because of this, laboratory methods are often ineffective at estimating this property. In order to obtain accurate values of the specific yield, a method should be applied which utilizes the actual water table fluctuations within the aquifer along with estimates of the groundwater recharge determined by analysis of the water budget (Diiwu, 2003). Based on this, the specific yield takes the form:

$$S_{ya} = \frac{RECHARGE}{WTC}$$

In this equation, recharge is assumed to be a uniform depth over the aquifer and WTC (Water Table Change) represents the fluctuation in the water level during the recharge period. Details on this investigation will be presented in the analysis chapter of this report.

3.3.3 Hydraulic Conductivity

To further analyze how water flows through the pathways contained within an aquifer, hydraulic conductivity must be defined. The hydraulic conductivity, K, is a measure of the permeability of a particular fluid, which is usually water, through any media (Todd and Mays, 2005). This value is a very important constant when determining flow through a porous media, such as in the application of Darcy's Law.

Many of the properties that determine groundwater flow can be expressed by the hydraulic conductivity constant. Numerous methods and models have been developed in order to understand and replicate this flow. One of the earliest, simplest, and probably most widely used theories in groundwater flow modeling is the application of Darcy's Law. This Law can be stated many ways, but basically means that the flow rate through a porous media is proportional to the head loss and inversely proportional to the length of the flow path (Todd and Mays, 2005). This statement serves as the basis for numerous groundwater flow equations and analysis techniques, from travel time and velocity estimates, to the determination of dispersion of a pollutant through the ground. Darcy's Law can be represented in equation form as:

$$Q = -KA\frac{dh}{dl}$$

where:

Q	=	Discharge
K	=	Hydraulic Conductivity
A	=	Cross Sectional Area of Flow Path
dh/dl	=	Hydraulic Gradient

This equation is fundamental to the study of all groundwater hydrology. It will be used in this research to estimate flow rates and travel times within the test zones. Darcy’s Equation will later be applied to analyze the results of a tracer study to obtain more accurate estimates of hydraulic conductivity.

3.4 SUB-SURFACE INVESTIGATIONS

Many types of investigations can be performed to determine what geological conditions are present at the test site. It is important to determine the general structure of the formations as well as what specific properties they exhibit. This includes identifying the rock and soil elements that compose the aquifer and determining the orientation of these elements. For instance, an aquifer may consist of only two materials, but they may be layered in a multitude of arrangements. Along with visually identifying the subterranean structure, testing is required to determine classifying properties, including those introduced in the previous sections. The analysis methods and tools utilized for these classifications are presented next.

3.4.1 Soil Borings and Drilling Logs

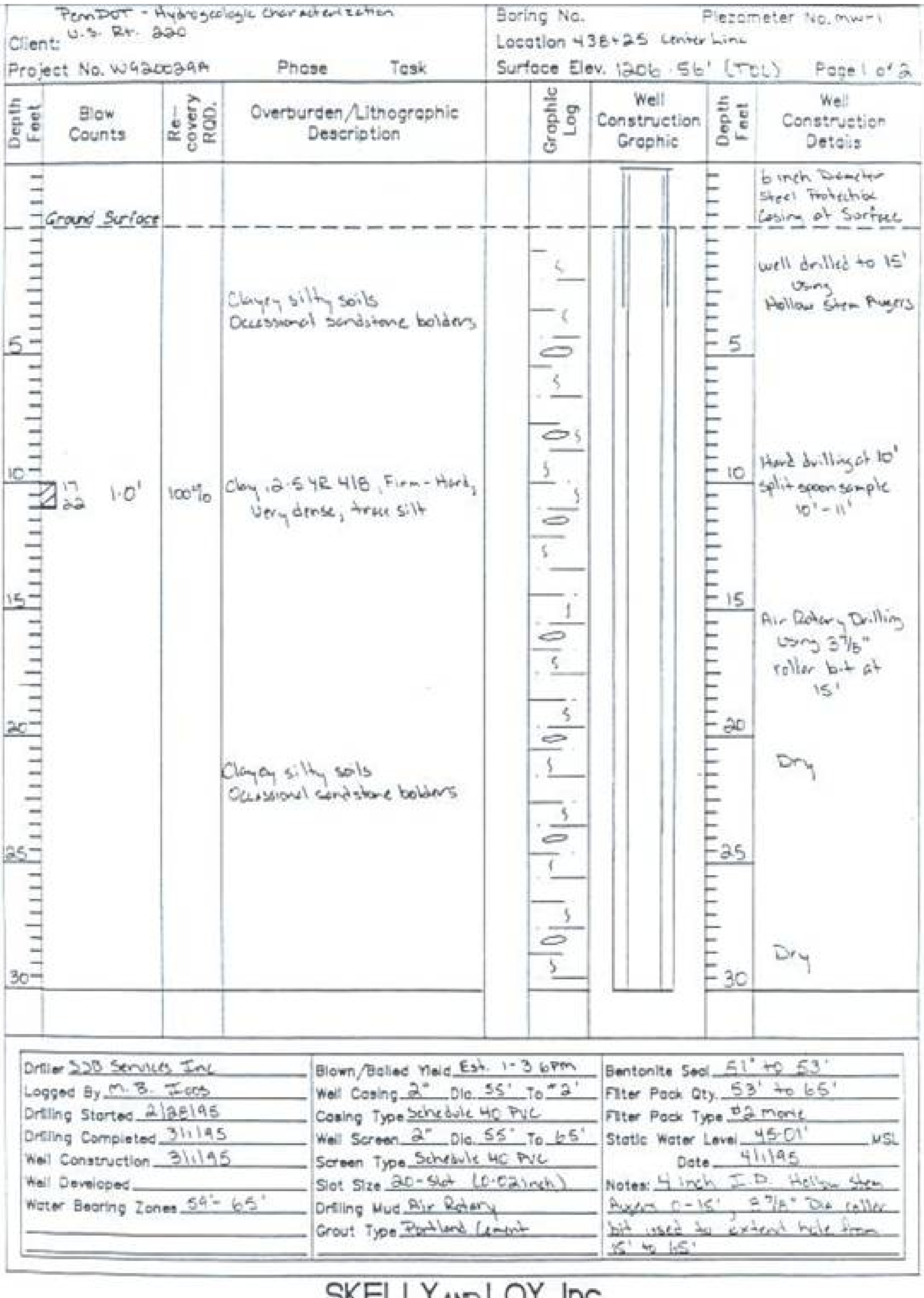
A common practice used to investigate what lies beneath the ground surface is to sample and record the materials encountered during the drilling of wells, or by conducting separate soil borings. These drilling logs provide valuable information on the composition and structure of the aquifer.

Many times this procedure is costly, and requires the knowledge of experienced geologists. For these reasons, drilling logs were not completed in the course of the presented research. However, logs from previous investigations at nearby locations were found. A sample from these logs is shown in Figure 3.

As pictured, the logs contain the locations, thicknesses, and descriptions of the encountered material, including the presence of water. Interpretation of drilling logs may lead to the determination of the aquifer type and the location of the water table or piezometric surface. These logs provide an excellent reference when deducing the hydrologic behaviors encountered within any aquifer

3.4.2 Slug Tests

After a well has been dug and completed, certain tests can be performed to determine specific properties. One very common procedure is called a slug test, which may be used to estimate the hydraulic conductivity of an aquifer. Slug tests measure how water levels within a well respond after a specified volume of water or other material is introduced or removed from the water column. Due to the nature of the test, the calculated hydraulic conductivities are only representative of an area very near to the well. This may pose problems for aquifers which are not homogeneous, as was the case of the tested sites.


Client: PennDOT - Hydrogeologic Characterization U.S. Rt. 220
Project No. W9200399A Phase Task
Boring No. Piezometer No. MW-1
Location 438+25 Center Line
Surface Elev. 1206.56' (TOL) Page 1 of 2

Depth Feet	Blow Counts	Re-covery RQD.	Overburden/Lithographic Description	Graphic Log	Well Construction Graphic	Depth Feet	Well Construction Details
	Ground Surface						6 inch Diameter Steel Protective Casing at Surface
			Clayey silty soils Occassional sandstone bolders				well drilled to 15' using Hollow Stem Augers
5						5	
10	17 22 1.0'	100%	Clay, 2.5YR 4/8, Firm - Hard, Very dense, trace silt			10	Hard drilling at 10' split spoon sample 10' - 11'
15						15	Air Rotary Drilling using 3 7/8" roller bit at 15'
20			Clayey silty soils Occassional sandstone bolders			20	Dry
25						25	
30						30	Dry

Driller SDB Services Inc
Logged By M. B. Foos
Drilling Started 2/28/95
Drilling Completed 3/1/95
Well Construction 3/1/95
Well Developed
Water Bearing Zones 59'- 65'

Blown/Bailed Yield Est. 1-3 GPM
Well Casing 2" Dia. 55' To +2'
Casing Type Schedule 40 PVC
Well Screen 2" Dia. 55' To 65'
Screen Type Schedule 40 PVC
Slot Size 20-Slot (0.02inch)
Drilling Mud Air Rotary
Grout Type Portland Cement

Bentonite Seal 51' to 53'
Filter Pack Qty. 53' to 65'
Filter Pack Type #2 morie
Static Water Level 45.01' MSL
Date 4/1/95
Notes: 4 inch I.D. Hollow Stem Augers 0-15', 8 7/8" Dia roller bit used to extend hole from 15' to 65'

SKELLY AND LOY, Inc.

Figure 3: Drilling Logs (Skelly and Loy Inc.)

Slug testing was not implemented in the case study, but previous tests at nearby locations, provided applicable information. A sample result from one of these slug tests is shown in Figure 4. The figure includes a graphical representation of how the water level decreases after a slug has been introduced into the water column. The Bouwer and Rice method was used to analyze the data and estimate the hydraulic conductivity. Details of this calculation method are not important for this research.

The slug tests provided early estimates of the hydraulic conductivity within the aquifer. As mentioned, these estimates only represent the conditions very near to the test wells. They were used only to select appropriate data collection schedules for designing and implementing tracer studies. The tracer studies themselves would refine the estimates of conductivity.

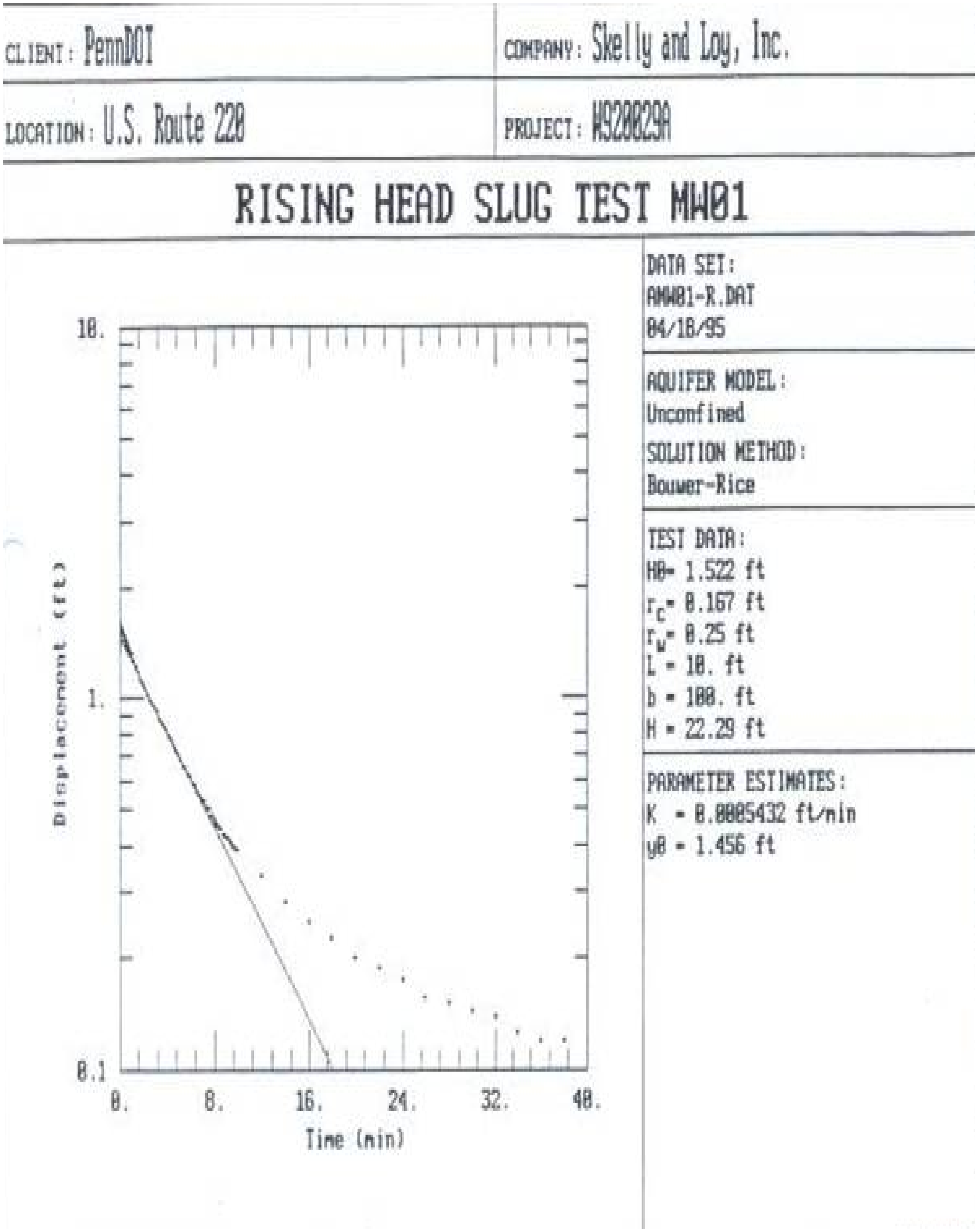


Figure 4: Slug Tests (Skelly and Loy Inc.)

3.4.3 Tracer Tests

Another method of estimating hydraulic conductivity in the field is by conducting a tracer study. This is accomplished by injecting an environmentally friendly tracer dye into an upstream well and monitoring its travel time and dispersion towards a downstream location. The monitoring is done by selecting and adhering to a sampling schedule at the downstream well. Collected samples are analyzed to determine the travel time and concentration of the dye. It is assumed that the dye will arrive in various concentrations over a certain time period. Based on an average of these times and the distance between the wells, estimates of the average interstitial velocity, V_a, may be obtained. Darcy's Law may then be used to estimate the hydraulic conductivity:

$$K = \frac{\alpha L^2}{ht}$$

In this equation, L is the distance between the wells and h is the difference in water level elevation recorded at the individual wells. The porosity, α, of the soil must be estimated for the entire flow path.

Although this test is based on simple principles and is easy to execute, three significant limitations are encountered (Todd and Mays, 2005). First, due to the generally slow nature of groundwater travel, the wells need to be fairly close together to provide for realistic data collection schedules. This limits the estimates to small spans which may not be representative of the entire aquifer. Secondly, the direction of water flow within the ground must be accurately determined or else the tracer dye may not arrive at the downstream monitoring well. Lastly, depending on the stratification of the aquifer, different portions of the dye may arrive at different times. Due to dispersion and the presence of fractures and other unknown variables, the first identification of the dye is generally not representative of the average travel time. This must be accounted for when determining the average conductivity.

This test procedure was carried out during the current research. It was utilized at both test locations, with varying results. These findings and the details of the conducted procedure are stated in greater detail in the analysis section of this report.

3.5 GROUNDWATER FLUCTUATIONS

Although the previously discussed testing methods and properties may be used to model a given aquifer, the behavior taking place within the formation is very complex and not predictable by purely theoretical means. Groundwater levels may respond to phenomena other than changes in water storage. Responses may demonstrate seasonal patterns or react only to significant storm events. The patterns may be different within the same drainage area depending on subsurface formations and the direction of water flow. In order to view these behaviors and begin to interpret them, direct measurement of groundwater levels is required. This is done by drilling observation wells into the aquifer at varying depths and continuously recording the level of the water surface. Detailed analysis of these levels is presented throughout this report. A general understanding of what the data will represent will be introduced in this section.

Since it is impossible to view exactly what is occurring beneath the surface throughout the entire watershed, it is required to correctly interpret what is happening at the monitoring wells by using hydrologic theories and reason. Sometimes it is easy to infer the factors causing groundwater fluctuation. For instance, one would expect the water table to slowly recede during periods of draught, or rise sharply after a heavy rainfall event. Many times however, the readings taken by equipment in the field can defy reason until further investigation is completed. In this research and that of many others, anomalies in groundwater response are common and a few key issues are of particular interest. These include the interpretation of very large and rapid increases and decreases in water levels, as well as the failure of some wells to immediately react to rainfall input. When these phenomena are present, it becomes very difficult, if not impossible to interpret the fluctuations in a hydrologic sense.

3.5.1 General Patterns

The fluctuation of groundwater levels can be a very difficult mechanism to effectively interpret for scientific use. Although many methods have been developed for relating the groundwater responses to precipitation, evaporation, and other factors, there is great uncertainty to the application of these methods in varying conditions. A previous study, (Moon et al, 2004), shows the variable nature of groundwater behavior, displayed by water table fluctuations. Each of the wells used in this study were located within the same watershed, yet many different response patterns were observed. The patterns that were identified in the study are shown in Figure 5.

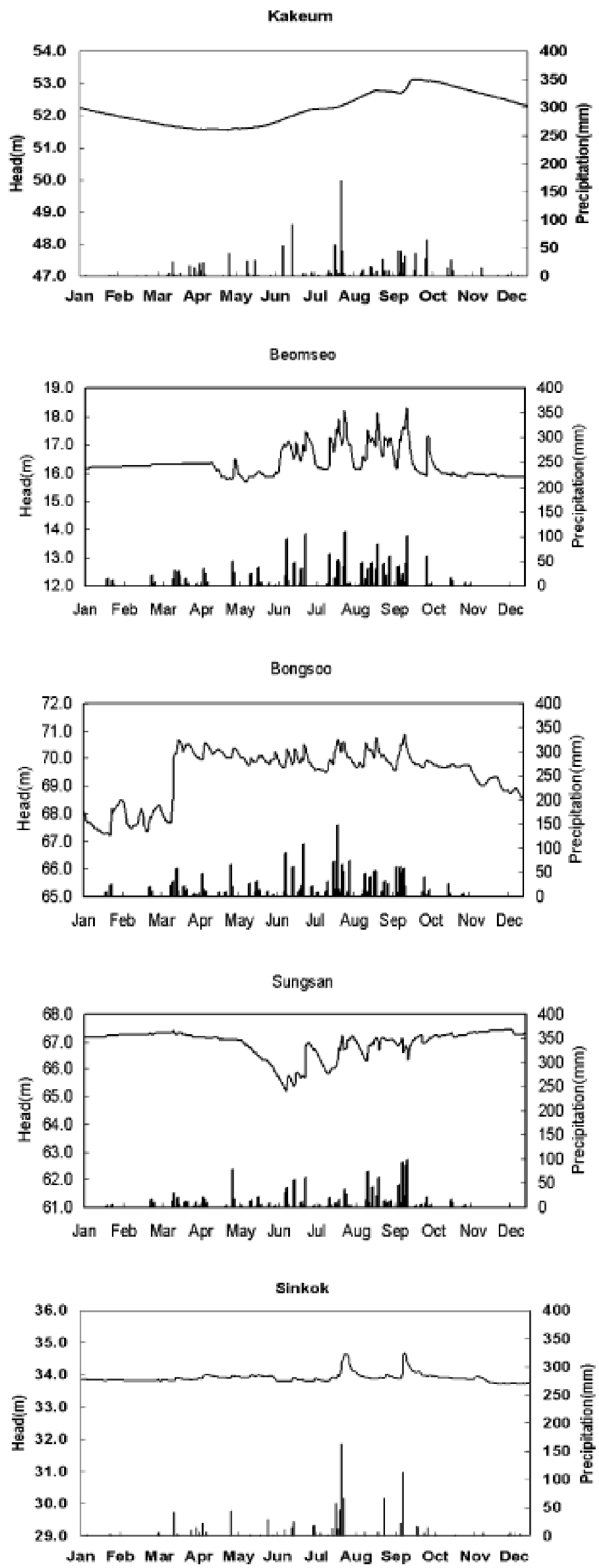


Figure 5: Variations in Groundwater Fluctuation (Moon et al, 2004)

The first pattern in this figure displays a seasonally dependent response, as the water level declines in the winter, recharges in the spring and summer, and begins to recede again in the fall. The study also relates this response pattern to the location and composition of the vadose zone. In this case, the vadose zone is deep and made from dense materials, which minimizes the effect of individual rainfall events on the groundwater level. The second and third plots demonstrate a groundwater table that responds significantly and immediately to precipitation events. From this it can be deduced that the underlying formations are very permeable or contain fractured rocks. The fourth pattern shows a negative correlation with rainfall events, suggesting that some other variable is causing the fluctuation, such as mechanical pumping or a large amount of evapotranspiration. The final plot is puzzling because the level is only affected by the two most intense rainfall events.

Each of these general patterns was encountered in one form or another during this research. Previous investigations, such as the Moon study, have been used to interpret the observed patterns. Original theories have also been presented to attempt to explain some of the responses.

3.5.2 Special Considerations

Apart from the great number of short term and long term fluctuations that are indicative of groundwater behavior, there are also numerous phenomena which create unusual and unexpected readings. It is often times very difficult and quite frustrating to determine which specific device is causing a particular response. During this research, many such devices have been investigated and tested with the collected data. One of the most interesting and potentially applicable processes, dealing with inordinate water level rises, will be examined next. It is important to identify such devices because they create responses which are not representative of the actual behavior of the groundwater.

Rises in water level are usually not directly related to precipitation inputs in a naturally occurring aquifer. They can sometimes be explained by the interaction of rainfall amount and intensity, soil properties, and present conditions, such as the soil moisture. In some instances, one variable may drastically affect the behavior recorded by monitoring wells. For instance, in one study, ground water levels raised an average of 2.75 feet in a single week, although there was only 3.25 inches of precipitation (Rasmussen and Andreasen, 1958). Other similar occurrences have been noted, including many within this research. One possible explanation for this is a phenomenon known as the Lisse Effect. This consists of a rise in water level caused by an increase in air pressure in the unsaturated zone between an infiltrating wetting front and the actual water table (Diiwu, 2003). The mechanisms and conditions required to cause this event are shown in Figure 6. The upper soil layer, when saturated, acts as a confining layer, which temporarily pressurizes the water beneath it. This causes the water levels within monitoring wells to rise significantly. An example of this effect on water levels is shown in Figure 7. The rise produced by the Lisse effect is not indicative of an increase in groundwater storage, and its influences must be filtered out if the data is to be used for calculating water depths in response to rainfall. After researching conditions within the I-99 construction site and analyzing the response patterns, it is evident that this effect may account for some of the inconsistencies encountered in the groundwater level data. Methods for dealing with this situation and its impact on recharge calculations will be examined in greater detail in the analysis section of the report.

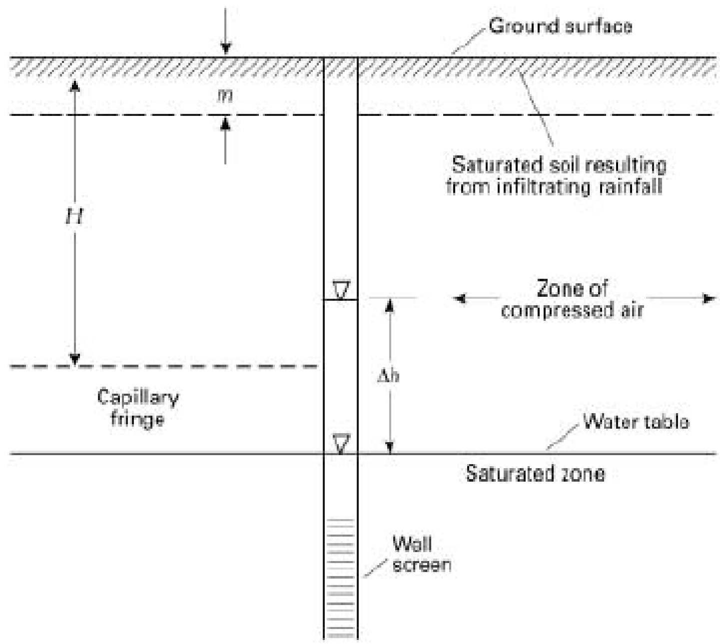


Figure 6: Conditions Causing the Lisse Effect (Heally and Cook, 2002)

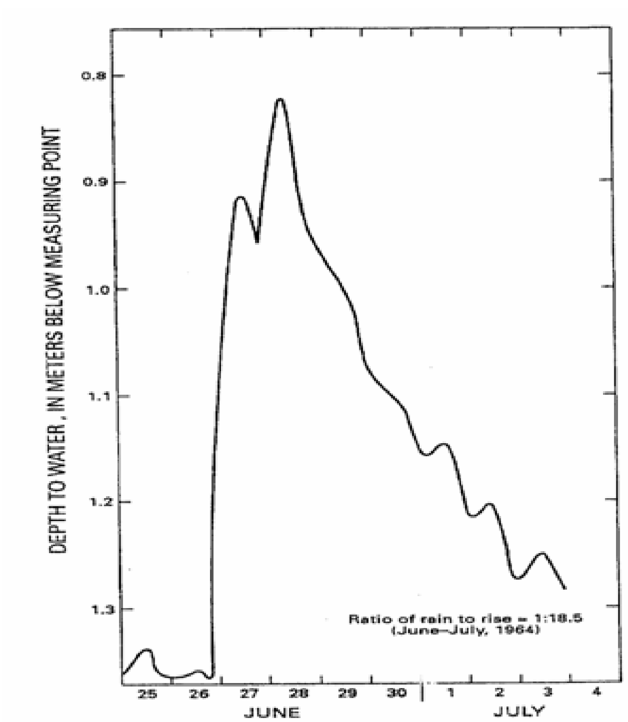


Figure 7: Example of the Lisse Effect (Weeks, 2002)

3.6 GROUNDWATER RECHARGE

Recharge can be defined as water that percolates into the lower limits of the vadose zone, reaches the water table, and causes a major rise in the groundwater level (Jan et al, 2007). Groundwater recharge is a key component in any model of groundwater flow or contaminant transport and its accurate quantification is imperative to proper management and protection of valuable groundwater resources (Heally and Cook, 2002; Diiwu, 2003).

A major focus of this research is to successfully interpret and forecast groundwater fluctuations and determine recharge quantities. As previously explained, the levels represented by groundwater tables and piezometric surfaces fluctuate in response to many variables above and below the ground surface. Rainfall amounts alone are not accurate indicators of groundwater recharge (Todd and Mays, 2005). Factors such as soil moisture, topography, rainfall intensity, and subsurface characteristics all cause recharge to be variable in both time and space. To obtain accurate estimates of recharge rates and quantities, these factors should be examined to some degree.

Due the complexities stated above, numerous methods have been devised in order to simplify the groundwater system and allow for general estimates of recharge to be made. Some of these methods are based on hydraulic principles whereas others depend on the general ideas of mass balance and the continuity of hydrologic systems. The hydraulic approach, which is dependent on Darcy's equation, offers the most direct measurement of recharge. This method is very laborious, expensive, and site specific, making it a poor candidate for this research (Jan et al, 2007). A simpler approach was needed. Based on the installed equipment and the level of accuracy required, it was determined that recharge would be estimated based on the fluctuations of the water table in conjunction with the application of a simplified water budget. After investigating the techniques commonly used for such purposes, a modified version of the Water Table Fluctuation (WTF) method was chosen. The key principles and assumptions of this method are examined next.

3.6.1 Modified Water Table Fluctuation Method:

The Water Table Fluctuation method is the most common technique used to estimate groundwater recharge. This method requires knowledge only of the groundwater level fluctuations within the aquifer and an estimate of the specific yield of the soil. This method's simplicity and non reliance on the mechanisms of water transport makes it the ideal candidate for this research. Due to the methods dependence on water table fluctuations, it is best applied to unconfined aquifers. When used in conjunction with a reliable water budget model, as the modified version requires, it can also be applied to confined aquifers in a limited sense (Sophocleous, 1991).

The Water Table Fluctuation method operates by measuring the increase in groundwater level in response to a rainfall event. Based on this increase, a volume of infiltrated water can be estimated by multiplying the rise by the storage capability of the soil. As mentioned earlier, the specific yield will be utilized as the storage property of the formation. Rasmussen has expressed this concept in the following form:

$$\Delta GW = \Delta H \text{ x } S_y$$

where:

ΔGW = Change in Groundwater Storage
ΔH = Change in Groundwater Stage
S_y = Specific Yield

This formulation allows for the amount of water entering the aquifer to be quantified over the entire area of the watershed, assuming a homogeneous nature. Once calculated, this volume of water may be compared with the volume of rainfall that has caused the rise, as well as with other factors such as pressure and temperature. Based on these findings, ratios between water level rise and the potential causing factors can be developed. Since rainfall is the predominant cause for water level rise in most aquifers, the Recharge Ratio will be representative of the water level rise compared with the rainfall amount. This ratio will serve as the main predictive tool used to estimate future groundwater fluctuations. The other considerations mentioned earlier will also have to be investigated before this ratio can be applied with confidence.

Although only two main parameters, the water level change and specific yield, are required to utilize this method, there are still many shortcomings and difficulties associated with the WTF method. First of all, specific yield is a very difficult property to measure in the field. Although small samples can be tested in the laboratory, these samples are usually not representative of entire watersheds, especially in fractured or stratified aquifers. There are also two important assumptions that must be taken into account when using the WTF method (Heally and Cook, 2002). First, it is assumed that all water arriving at the water table goes directly into storage. Second, during periods of recharge, it is assumed that there is no base flow, evapotranspiration, or subsurface flow. This limits the use of the WTF method to short time periods, where these losses can be neglected. This makes the method best applicable to individual storm events. Further modifications are required in order to extend the concepts to long term and seasonal behaviors

The WTF method, when applied in isolation, is not reliable unless accurate values of aquifer effective storativity are available (Jan et al, 2007). To be more effective and to eliminate the difficult estimation of the specific yield directly, many researchers have combined the WTF method with application of the groundwater basin water budget. Based on this approach, recharge volumes are estimated based on the water budget. The soil water balance derived recharge is divided by the corresponding water table rise to obtain an estimate of the fillable porosity of the soil, which is in essence an estimate of the specific yield. The water budget method is the most widely used technique for estimating specific yield in fractured rock systems because it does not require assumptions about the flow processes.

3.7 BASE FLOW AND RECESSION RATES

During drier periods, when no water is entering the aquifer, groundwater levels within the wells should recede slowly. The recession occurs as a combination of evapotranspiration losses and the sub-surface flow of the water towards a discharge area. This decrease in elevation will eventually reach a constant rate that is governed by the physical properties of the storage media. When the groundwater reaches the discharge area, it surfaces as base flow. Many techniques have been developed for extracting base flow from surface water data, but little work has been done concerning the determination of base flow from observation well fluctuation. Since the base flow curve is also indicative of the drainage rate of groundwater storage, it should follow that groundwater recession rates can be used to deduce, or at least relate to base flow (Todd and Mays, 2005).

A very simple relationship can often times be used to represent the shape of recession curves in stream flow hydrographs. It takes the shape of the following equation:

$Q = Q_oK^t$

where:

Q	= Discharge
Q_o	= Given Initial Discharge
K	= Recession Constant
T	= Time

This relationship has been used with great success in representing the recession of streams after rainfall events, but is not as effective when applied to the very slow nature of groundwater recessions. This equation was used in the research, but a simple linear relationship worked better at modeling the groundwater behavior. That is, the groundwater level within the wells decreased linearly during periods of no rainfall. Details of this relationship and its significance will be discussed later on in the report.

4.0 CASE STUDY: INTERSTATE 99 CONSTRUCTION

The research project was implemented and tested on portions of the Interstate 99 construction corridor located in central Pennsylvania. This construction was undertaken by the Pennsylvania Department of Transportation (PENNDOT) and is being completed to extend the current I-99 corridor further northwest towards Interstate 80. Research related to this construction project has been going on for many years due to numerous concerns as to how the surrounding environment will be effected. The location, topography, and geology of the construction zone are discussed in this section of the report. A summary of the utilized methods of construction, which are pertinent to this research, will also be presented.

4.1 GEOGRAPHIC INFORMATION

The construction zone runs parallel to the existing Route 220 in central Pennsylvania, between the towns of Tyrone in the southwest and Port Matilda in the northeast. Route 220 is currently the main road utilized to traverse this pathway, which gets many travelers heading toward Penn State University. The proposed roadway extension will provide a much faster multilane alternative to the current route and will alleviate traffic on other local roads. The construction area, along with the location of the new highway, designated by the red line, is pictured in Figure 8.

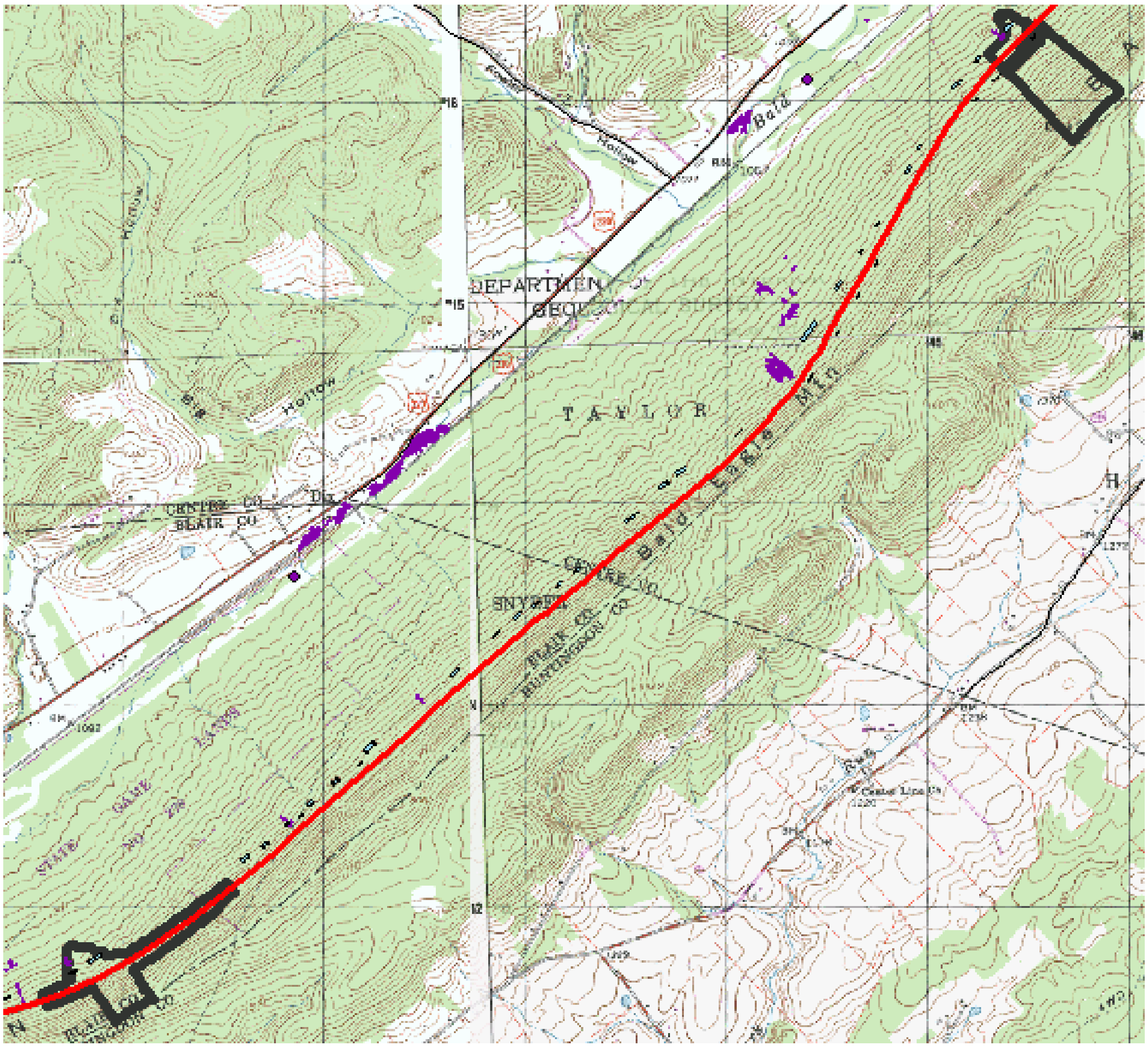


Figure 8: Highway Construction Zone

The topography around the proposed alignment makes the construction particularly important to the ecology of the area. As shown in the map, the highway is being cut through the mid portion of a large mountain. At the base of this mountain is a fertile valley, containing numerous wetland areas surrounding Bald Eagle Creek, which was once a trophy trout stream. Although it has become somewhat degraded over the years, it is still part of a delicate ecosystem which provides a habitat for many aquatic species. The mountain on which the roadway is being constructed drains directly into this waterway. Due to the steep slope of this formation, the hydraulic gradient from the ridge top to the valley floor is quite large, creating rapid flows of both surface water and groundwater. Because of this arrangement, any negative effects created by the construction will immediately affect this natural area.

4.2 GEOLOGIC CONDITIONS

A general idea of the subsurface conditions located along the construction corridor was obtained from a study conducted by Skelly and Loy Inc. During this study, soil borings were taken, nested well pairs were installed and monitored, slug tests were conducted, and soil and rock samples were analyzed in laboratory tests. Much information was gathered from this research. Most importantly, insight was gained into the composition and arrangement of the materials beneath the surface.

A review of the Skelly and Loy study revealed that the formations beneath the construction zone are very diverse. Thirty two separate rock and soil formations were discovered, as well as numerous faults and rock joints. Based on the study of these variations, it was estimated that on average, the area is underlain by three main geologic intervals. The first of these intervals is very dense, low permeability clay, which is present in varying thicknesses on the surface of the area. This layer is underlain by a narrow band of weathered bedrock, which has a slightly larger permeability than the soil layer. Beneath this material is a fractured bedrock interval. The fractures contained within this formation serve as conduits for water flow, and thus results in a relatively high average permeability. These three geologic intervals are shown in Figure 9.

Based on the type and arrangement of these formations, it was concluded that water is stored in both unconfined and confined aquifers within the construction area. The low permeability soil overlaying the bedrock is generally believed to be of little importance to water flow in the area. If this layer becomes thick enough, as at the base of the ridge, it may even serve as a confining layer (Skelly and Loy Inc., 1995, 1997).

It is also possible that the soil layer may act as a confining layer only after heavy rainfall events. This is due to the wetting front caused by storms not allowing air to escape the formation. When analyzing the water table fluctuations, it will be necessary to keep in mind this unique situation, as it may be indicative of the previously mentioned phenomena known as the Lisse Effect, and greatly affect how the measurements are interpreted

The weathered and fractured bedrock intervals are more crucial formations for storing and transporting volumes of water, and because of the potential confining nature of the soil interval, this water may become pressurized.

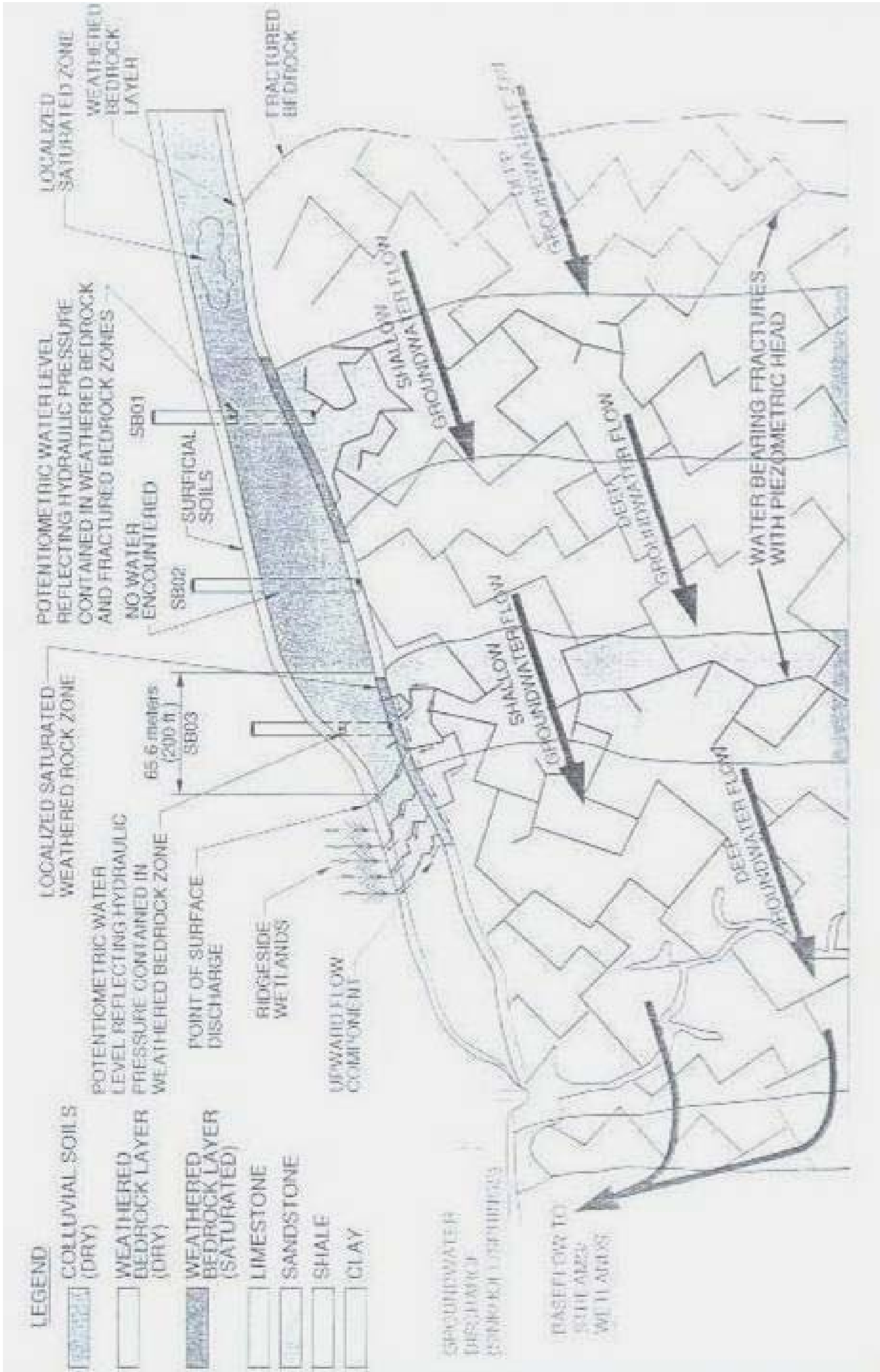


Figure 9: Geologic Formations Found in the Construction Zone (Skelly and Loy Inc.)

4.3 METEORLOGICAL CONDITIONS

Central Pennsylvania is located in a temperate climate zone. It is part of the northeast climate region as presented by the National Climatic Data Center (NCDC). The area receives an average of 40 inches of precipitation each year. During the thirteen months that rainfall data was collected, 35 inches of precipitation had fallen near the test sites. Average temperatures in this region are about 60 degrees Fahrenheit with highs in the low nineties and lows near zero. Detailed weather data recorded near the sites during the research period will be examined in the analysis section of this report.

4.4 CONSTRUCTION DETAILS

The construction of the roadway utilized many features which are common to highway construction, and others which are fairly new technology. In order to efficiently handle the polluted runoff that results from the construction and later use of the roadway, separate drainage systems were used to route the clean and dirty discharges through the work zone. The area above the construction zone is classified as clean water zone. Water quality in this area is not affected by the runoff from any part of the construction. This water is collected in drainage channels and piped beneath the roadway where it will resurface and continue to flow towards the wetlands. The drainage that occurs in the area of the roadbed and the construction zone is classified as dirty water. This water is also collected by drainage ditches and is then piped or channeled into sedimentation basins. These basins are designed to provide enough storage time to allow contaminants to settle. They also serve as storm water management devices to account for excess runoff occurring because of increases in impermeable area. Once the dirty water has been allowed to settle, it is released back into the natural drainage network, where it will eventually flow into the stream. The sedimentation basins will reduce the peak flows recorded at the watershed outlet and increase the duration of the storm hydrographs.

On the subsurface level, an infiltration gallery was constructed in order to filter and maintain sufficient shallow groundwater flow to the wetlands. A diagram showing this device is included as Figure 10. This structure was implemented because of numerous concerns that the completed road surface would not only cause pollutants to permeate into the groundwater, but also that the impervious surface would decrease groundwater flows towards the wetlands. The effectiveness of this structure at alleviating these concerns will be examined.

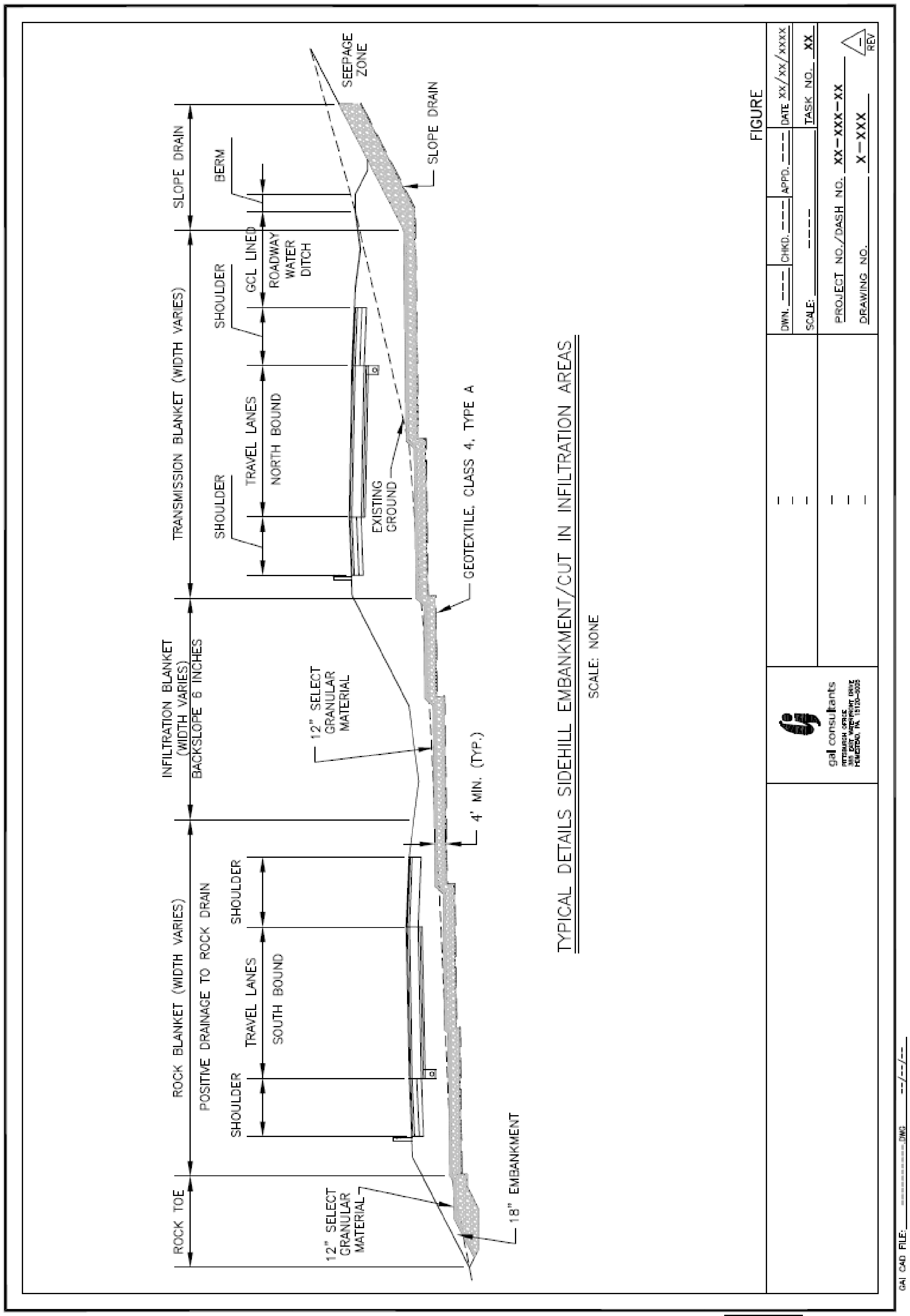


Figure 10: Roadway Cross Section Showing Infiltration Gallery (GAI Consultants)

4.5 TEST WATERSHEDS

It was decided that two test sites would be selected to represent the average conditions present within the construction zone. This was done to reduce costs and to limit the volume of data that would need to be analyzed. The two watersheds are outlined in Figure 11, along with the installed monitoring equipment and that equipment which was from previous investigations. Watershed 1 is located in the southwest corner of the map and is shown in detail in Figure 12. This watershed is 46.1 acres. Watershed 2 is located in the northeast corner and is represented in Figure 13. This watershed is 54.4 acres

Six groundwater wells have been installed and observed over the course of the research. Within each test watershed there are two deep wells and one shallow well. This equipment is shown in the respective figures of each watershed.

The watershed denoted as Watershed 1 includes sedimentation basins 10 and 11. It is located in the vicinity of station 183 + 50. Deep wells located within this watershed are referred to as Well A (Downstream) and Well B (Upstream). Also at this site is a shallow well located in the downstream wetlands. It will be referred to as Watershed 1 Shallow Ecotone. Throughout the report, these references will be used to identify the watersheds and the instruments contained within them. A similar naming scheme is used for test Watershed 2, containing SB-111, which is located at station 400 + 00. A summary of this equipment is presented in Chapter 5.

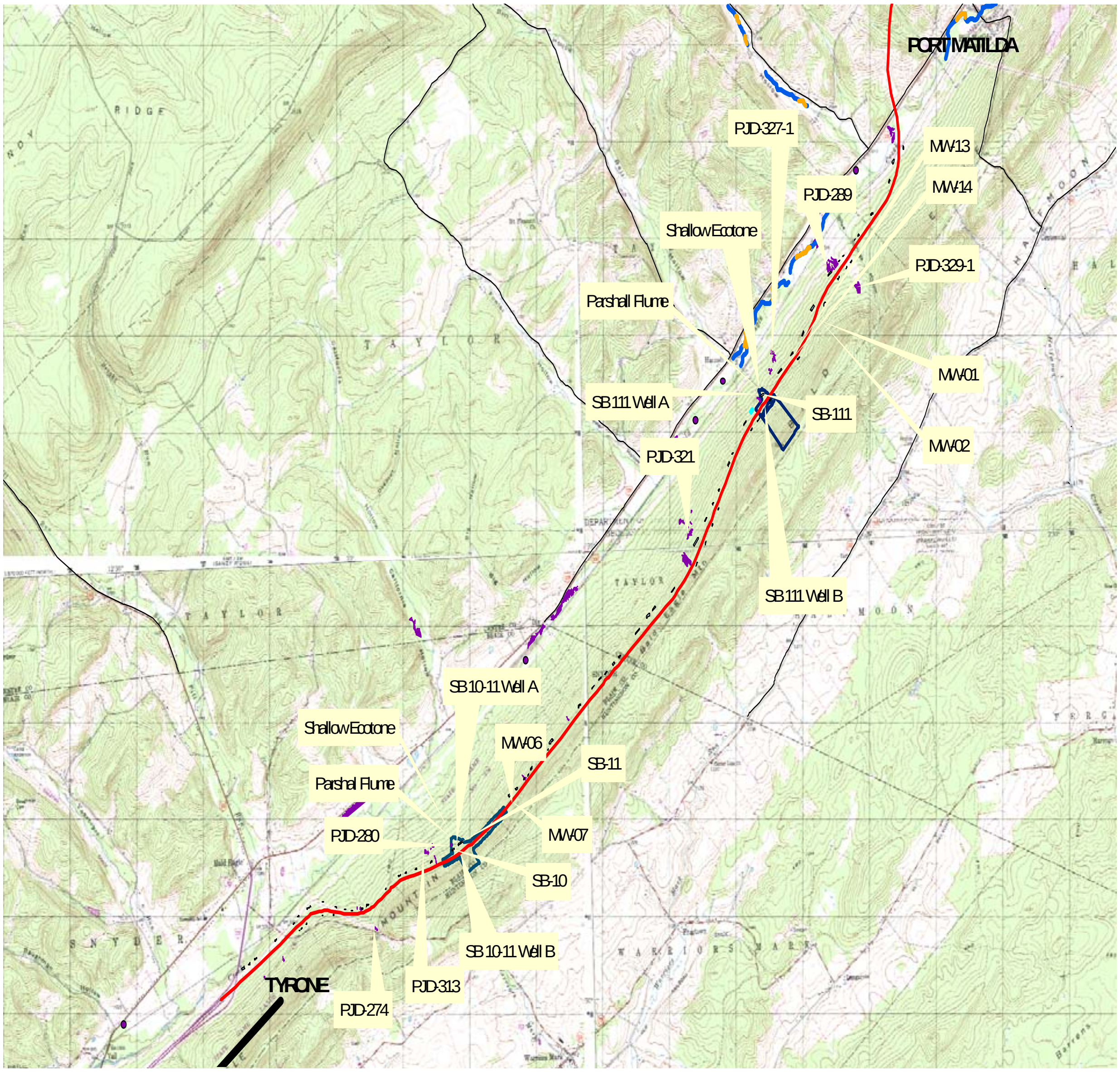


Figure 11: Location of Test Watershed and Monitoring Equipment

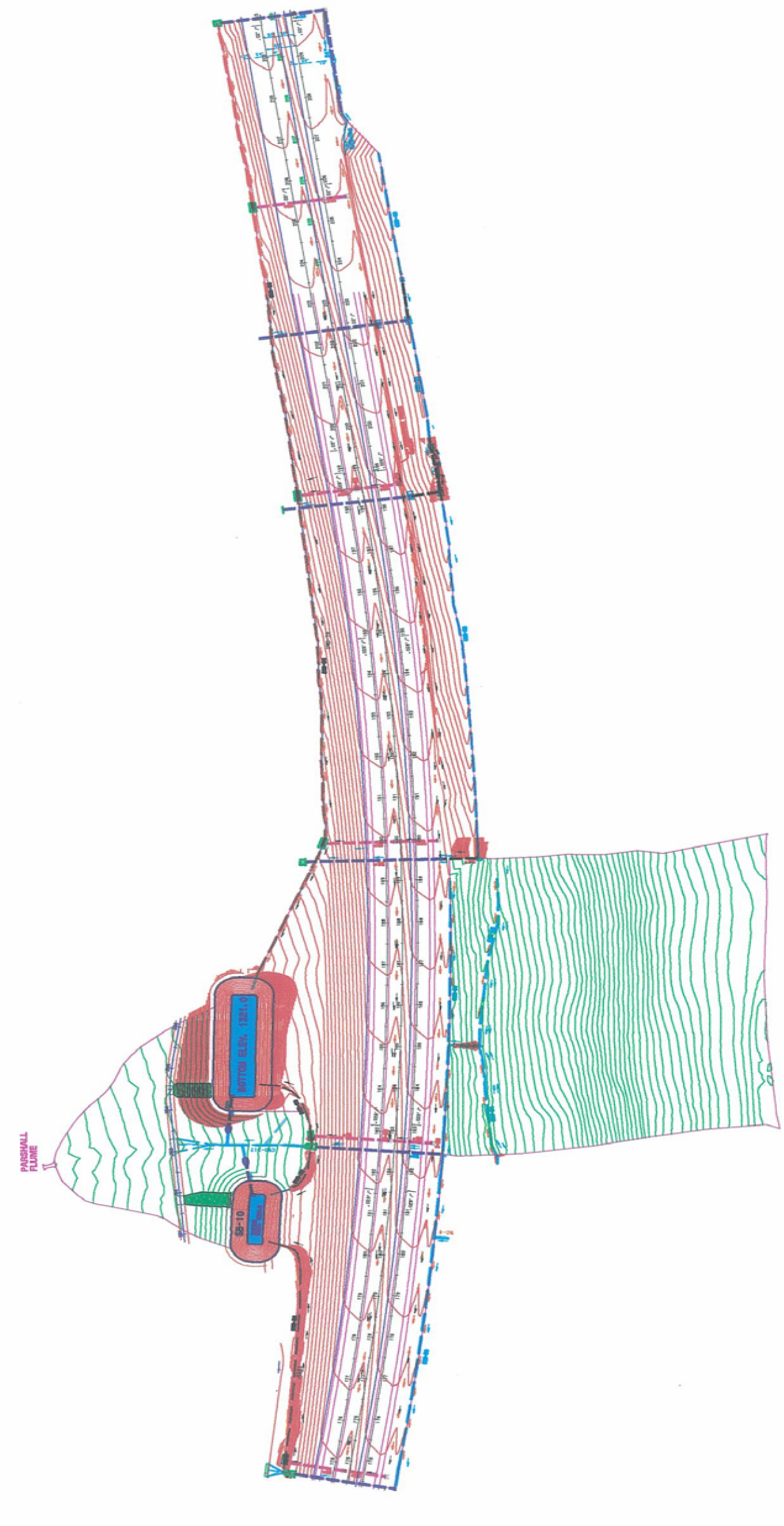


Figure 12: Watershed 1

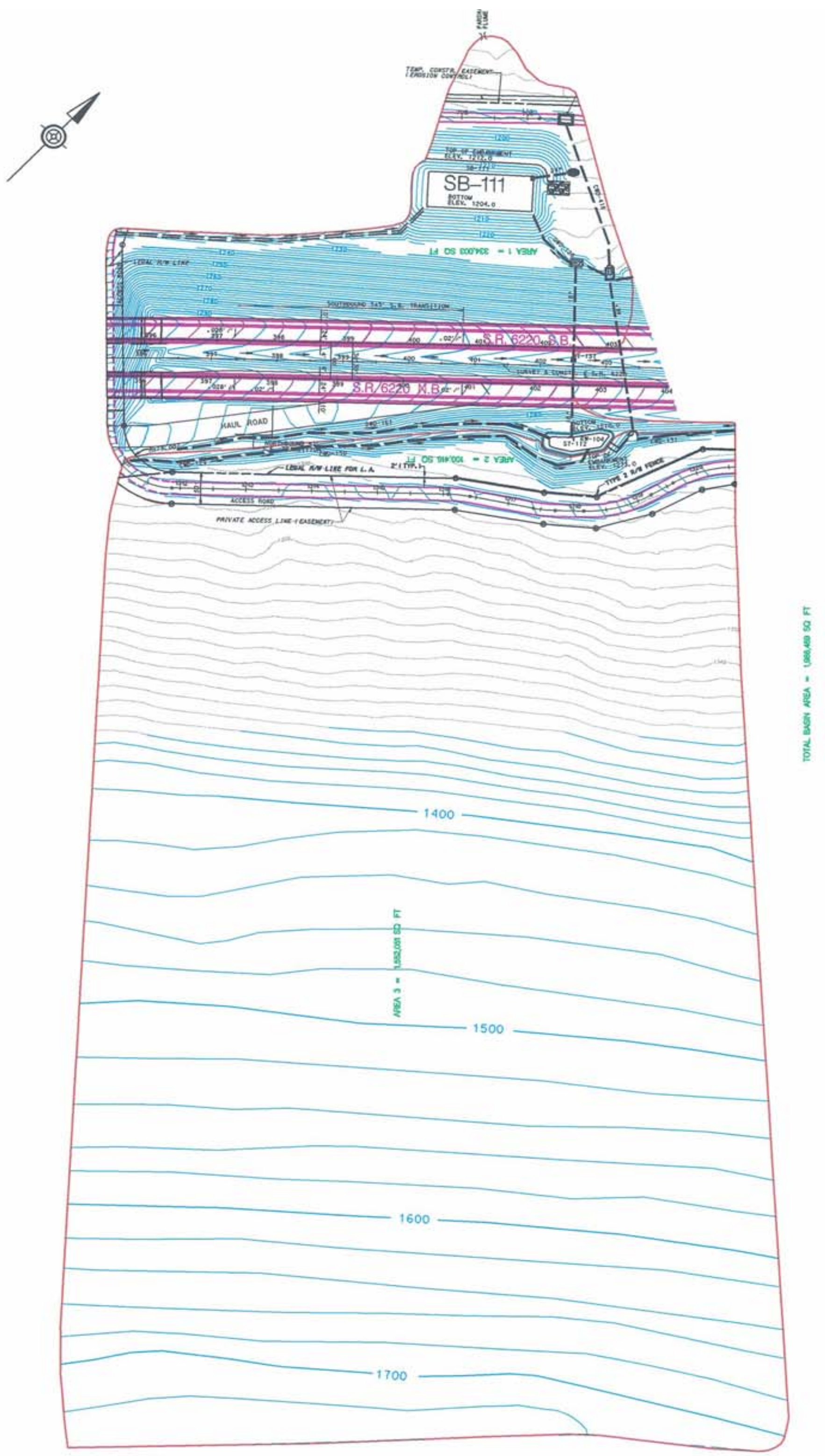


Figure 13: Watershed 2

4.6 GROUNDWATER RESOURCES

Groundwater is a very important resource in this area of Pennsylvania. Numerous groundwater wells have been drilled in the area in order to withdraw water to be used for irrigation, drinking, and other purposes. This pumping would significantly alter the response patterns displayed by the monitoring equipment. Figure 14**,** created with GIS and based on information provided by the USGS, shows the locations of over 50 groundwater wells within 2 miles of the test watersheds. It is almost certain that the use of these wells will influence the behavior of the water table. The pumping schedules and discharges of the wells is not known, thus they cannot be directly related to any responses shown by the installed monitoring equipment. Throughout the analysis however, it is important to keep in mind that non natural forces may be influencing the observed conditions.

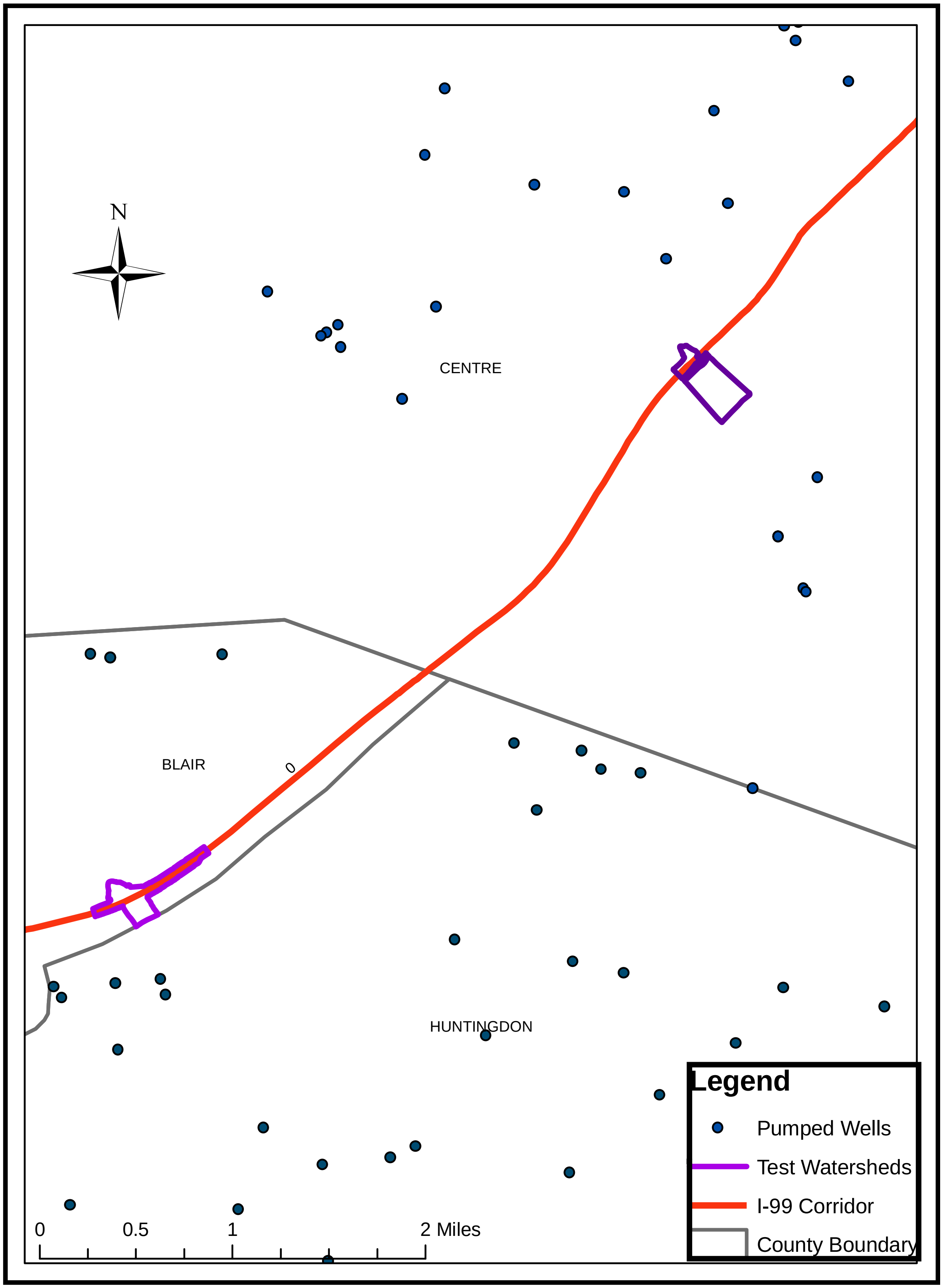


Figure 14: Groundwater Wells Near the Test Sites

5.0 MONITORING EQUIPMENT AND DATA COLLECTION

Groundwater movements and fluctuations all have one thing in common, they occur beneath the surface. Due to this concealed environment, equipment must be used that has the ability to determine what is occurring within the aquifer and transmit this information to the surface. Many tools exist for this sort of investigation, including dug wells, piezometers, lysimeters, and more advanced devices such as radar and other geophysical or electromagnetic methods. One of the main objectives of this research was to determine a simple and cost effective method that could be applied by construction firms in an attempt to identify problems and improve their own practices. It was decided that the most appropriate system would be based upon a small network of shallow and deep monitoring wells, used in conjunction with rain gages, and surface water flumes. The measurements taken from these devices are manageable, easy to understand, and should be accurate enough for this purpose.

Due to the nature of many highway designs, drainage areas from the roadway and surrounding lands are generally narrow to avoid flooding of the road surface. This feature allows for the assumption that a limited number of monitoring devices are required to represent an entire drainage zone. Based on this assumption, and on watershed delineations made by a consulting engineering firm, the test areas selected were instrumented in the following manner. One deep well is located on the upslope, just above the roadway cut. This device is intended to represent the natural groundwater response. A second deep well is drilled down slope, below the cut, in order to observe any disturbances which construction may have caused. From the levels in these two wells, a water table profile can be interpolated below the roadway. Further down the slope, a shallow well is installed. Adjacent to this structure is a surface water flume, which is strategically placed to capture the outflow from the entire watershed. The equipment is installed transversely through the center of the watershed in order to recreate a single cross section, intended to capture the direction of water flow.

Although the exact equipment used in the case study may be modified for future implementation of the proposed measurement system, an overview of these devices is necessary to understand the type of data that should be gathered and to develop an acceptable retrieval schedule for optimum effectiveness. Table 1 Provides an overview of the groundwater monitoring devices installed at each of the test watersheds for this investigation

Table 1 : Installed Monitoring Equipment

Monitoring Device	Station	Coordinates	Bottom Elevation (ft)	Total Depth (ft)	Bore Diameter (in)	Inside Diameter (in)
SB 10-11Watershed 1						
Well A (downstream)	183 + 50	40° 43.406' N 78° 8.936' W	1281	31	4	2
Well B (upstream)	183 + 50	40° 43.336' N 78° 8.866' W	1400	15.3	4	2
Shallow Ecotone	183 + 50	40° 43.429' N 78° 8.948' W	1265	8	6	
SB 111 Watershed 2						
Well A (downstream)	400+ 00	40° 45.808' N 78° 5.573' W	1170	31	4	2
Well B (upstream)	400 + 00	40° 45.751' N 78° 5.491' W	1269	40.5	4	2
Shallow Ecotone	400 + 00	40° 45.867' N 78° 5.562' W	1170	8	6	

5.1 DEEP WELLS

The easiest way to determine the location of the water table for an unconfined aquifer, or piezometric surface for a confined aquifer, is to dig a well into the ground and allow it to fill with water. This simple principle is what governs the four deep wells installed in the case study. The level shown within these wells should be representative of an area of at least several square meters around the well, which makes this much more of an integrated approach than more sophisticated methods such as soil moisture measurement devices (Heally and Cook, 2002).

The deep wells installed at the two test sites are shown in the construction cross sections in Figures 15 and 16. In both cases, the upstream well was installed just up slope of an infiltration gallery and the downstream well is located just below this structure. This was done in order to identify how the roadway cut and the infiltration gallery affects the groundwater flow and quality.

5.1.1 Installation

Each of the deep wells was installed using an off-road drilling rig. The borehole size and depth of each well are displayed in Table 1. Wells were drilled until refusal of the auger, indicating the presence of solid bedrock, or the less desirable large boulder. Although notes were made during the drilling process, no sampling or soil identification and classification was recorded. The installation of these wells did not provide insight into soil characteristics such as porosity or conductivity. These values were estimated from the results of other studies and through later experiments.

Figure 15: Cross Section of Watershed 1

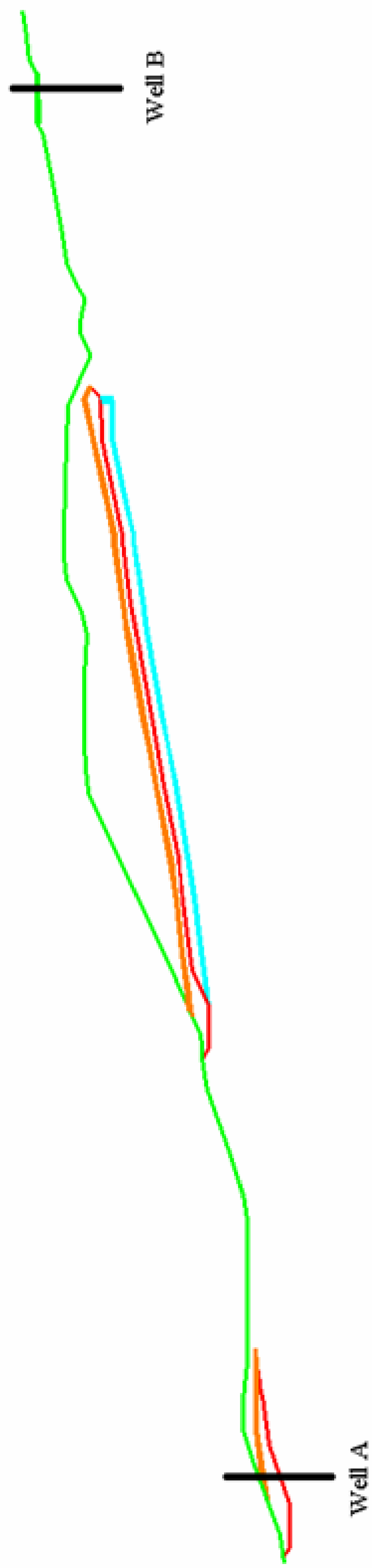


Figure 16: Cross Section of Watershed 2

It is recommended that more detailed information be taken during the drilling process. This information would provide the best insight into the subsurface properties of the area. Although pertinent data was discovered by researching previous studies, the accuracy of this information cannot be judged and the information is not from an ideal location.

5.1.2 Data Collection

Located within each deep well is a continuous logging device which records and stores the groundwater elevation in reference to a datum selected by the installers. The device takes data readings at one hour increments and maintains a continuous record from the start of the monitoring period. In order to retrieve this record, field visits are made to download the data via a notebook computer. This setup can be seen in Figure 17. The output data is in text format which can later be imported into a spreadsheet for further organization.

The wells keep continuous records of data and have substantial battery life. Thus, it is not necessary to make many site visits for data downloading and maintenance. Schedules should be based on how quickly the data can be organized and analyzed. During the case study, data was retrieved every one to two months.

Figure 17: Downloading Data from Monitoring Wells

The upstream wells at each test watershed were installed prior to the downstream wells and contain slightly less sophisticated devices. In addition to the level of the groundwater, the downstream wells have the capability to measure and record the temperature. Temperature may be important in shallow water table environments where it may cause significant water level fluctuations or affect the performance of the equipment. The locations of the monitoring wells were determined from construction drawings and verified with a GPS device. The surface and well bottom elevations were obtained from records made during the drilling procedure. Figure 18 shows a detailed schematic of one of the deep wells.

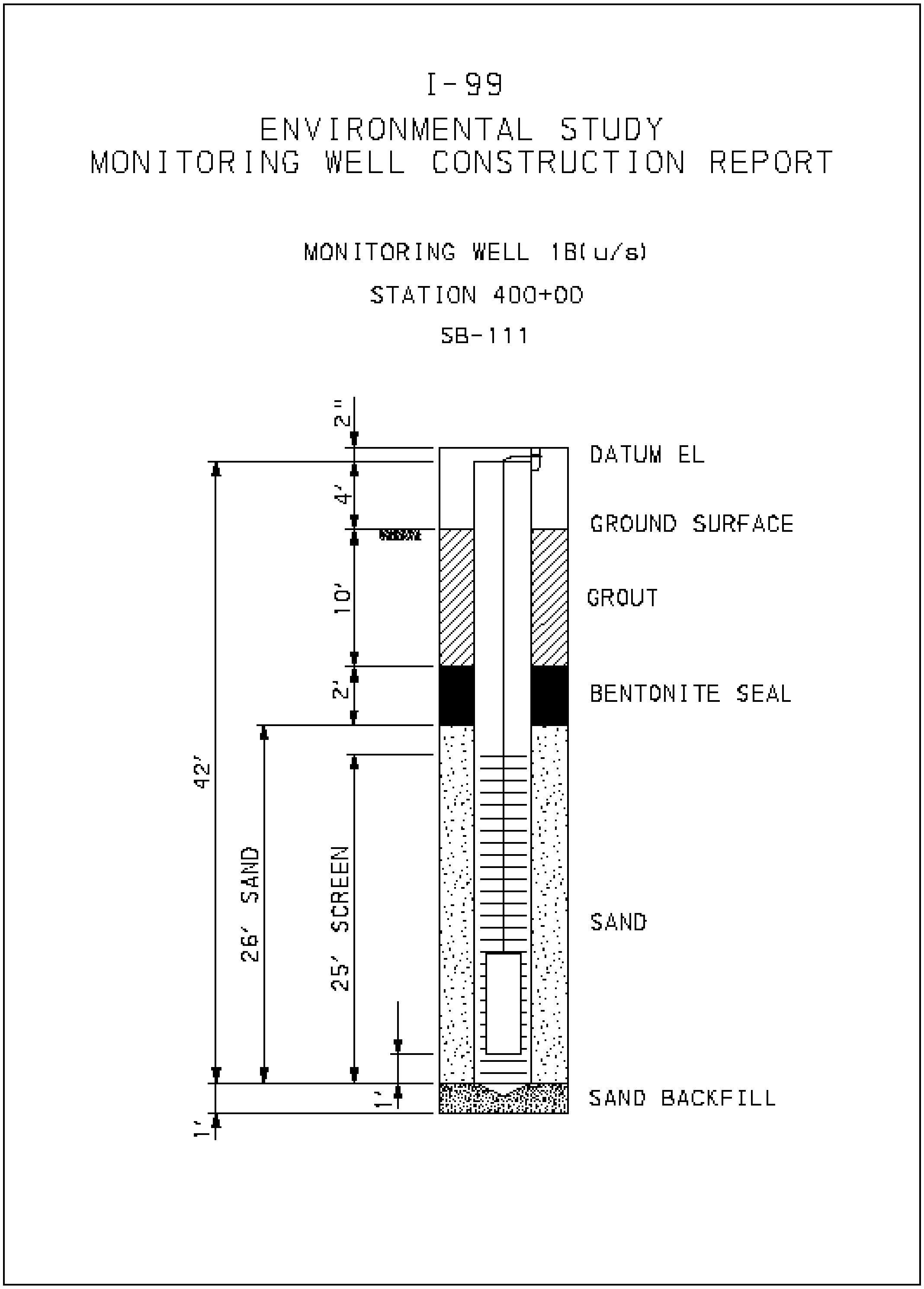


Figure 18: Deep Well Schematic (AWK Engineers)

5.2 SHALLOW WELLS

Another important factor of the groundwater hydrology within the construction zone is the response within the unsaturated or vadose zone. To monitor this aspect of the hydrologic cycle, shallow wells have been installed at the test sites. The main area of concern for these effects is within the downstream wetland areas near the watershed outlets. These devices have been utilized to measure the interflow levels through the wetlands and to determine if the construction process has disrupted this flow in any way. These wells are eight feet deep and should be more sensitive to rainfall events and water losses, including evapotranspiration, than the deep wells, which are designed to measure the location of the water table and other deeper interactions.

5.2.1 Installation

The shallow wells were installed with the same equipment used to install the deep wells, without logging drilling data. These wells were located a few feet from the outlet flume that is used to measure surface water discharge. Thus, the interflow values at this point can be directly compared with the outflow of surface water. A schematic of an installed shallow device is shown in Figure 19.

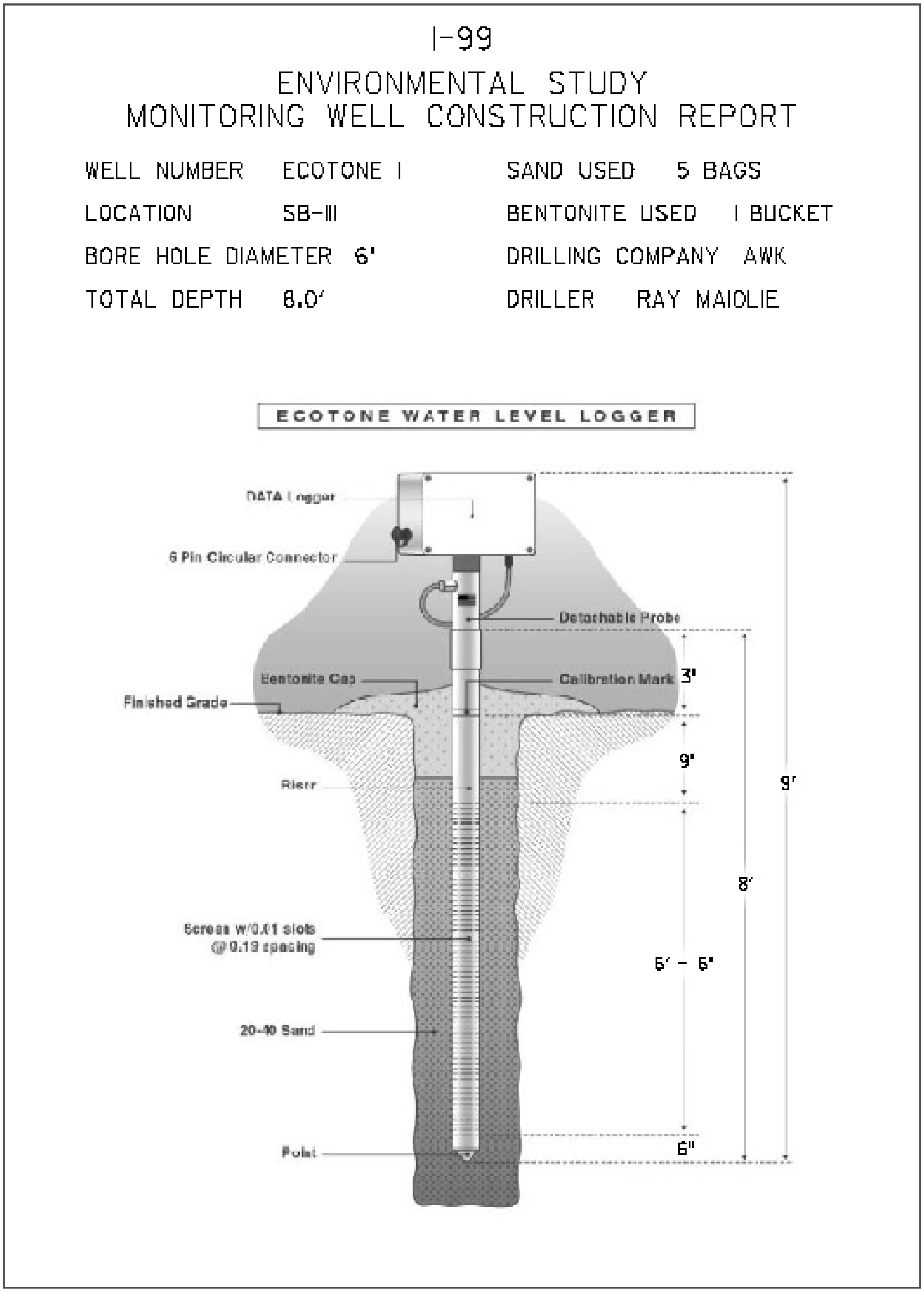


Figure 19: Shallow Well Schematic (AWK Engineers)

5.2.2 Data Collection

A measurement device, known as an Ecotone, is used to record and store water surface elevation data within the wells at hourly intervals. The datum elevations for these devices were provided by the installers and reference elevations were verified from construction drawings. In order to retrieve the information from the shallow wells, data is downloaded via a hand-held palm pilot device. This setup is shown in Figure 20.

Figure 20: Shallow Well and Palm Pilot

As with the deep wells, the shallow loggers store the entire range of data and have a fairly long battery life. They are more fragile than the deep wells however, and may require more maintenance based on exposure to the elements. For instance, the equipment may be very ineffective under cold and icy environments. On many occasions, these devices simply stopped recording data. To ensure proper function, they should be checked at lease once per month, especially during cold and wet periods.

5.3 METEOROLOGICAL GAGES

Rainfall is the primary source of recharge within the selected test watersheds, as is the case at many locations. It is very important to maintain a detailed record of the precipitation events at the site since groundwater responses relative to these events are to be examined in a time sensitive fashion. Storms may be spatially varied to a great extent, thus it is crucial to obtain data that is as close to the investigated site as possible. Due to time and budget constraints, it may be required to use previously installed gages. In the current project, the test watersheds were located between two meteorological gages that were continuously monitored. This greatly reduced costs and effort, but may have resulted in slightly less accurate data, as will be explained below.

Measurements from two different gauging stations were used to estimate rainfall within the test areas. The first is located in Port Matilda PA, a few miles northeast of the test watersheds. It is operated by a consulting firm and provides continuous readings of rainfall, temperature, pressure, and wind speed. The second station is maintained by the National Oceanographic and Atmospheric Administration (NOAA), and is located a few miles southwest of the construction zone, in Tyrone PA. This device provides hourly rainfall amounts.

Initially, only the gage at Port Matilda was used for the research. While analyzing the data, an inconsistency was observed concerning the timing of groundwater and surface water responses to some rainfall events. Although a small time gap between these responses and the rainfall events causing them is expected since the gage is a few miles from the test sites, there was a very significant delay in some instances. This concern prompted the investigation into another gage to compare values.

A difference between the timing of certain rainfall events as recorded by the two gages was observed as shown in Figure 21. It was determined that for some storm events, the NOAA gage correlated with the groundwater and surface water response patterns more closely. After further investigation, an error was found with the computer clock that was synchronized with the rain gage at Port Matilda. Since the rainfall amounts are very similar for most storms and these gages are only about 12 miles apart, the NOAA gage data was used when it appeared to better correlate with the groundwater response. Due to the spatial difference between the location of the gages and the hydrologic monitoring equipment, detailed analysis could not be made between the response time of the wells and the timing of significant rainfall events.

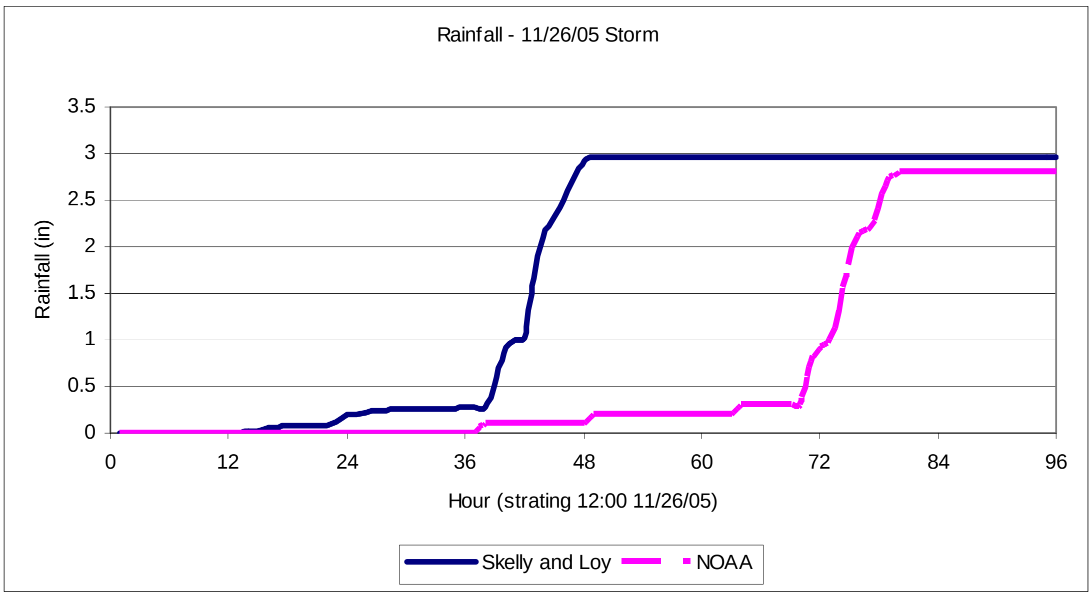


Figure 21: Time Gap Displayed by Rain Gages

Due to the occurrence of this sort of error, it is recommended that numerous gages be used if cost and resources permit. Also, the gages should be as close to the investigation sites as possible. On site gages would be best, but this may not be justified if installation costs are high and data retrieval becomes a problem.

5.4 SURFACE WATER EQUIPMENT

Although surface water is not the main focus of this research, its measurement is essential in order to determine the effects of construction on the hydrology of the area. As stated in chapter three, the interaction between surface water and groundwater is very important to maintain a balanced water budget and complete the hydrologic cycle. In particular, the surface runoff volumes calculated will be used directly in the water budget balance to estimate groundwater recharge.

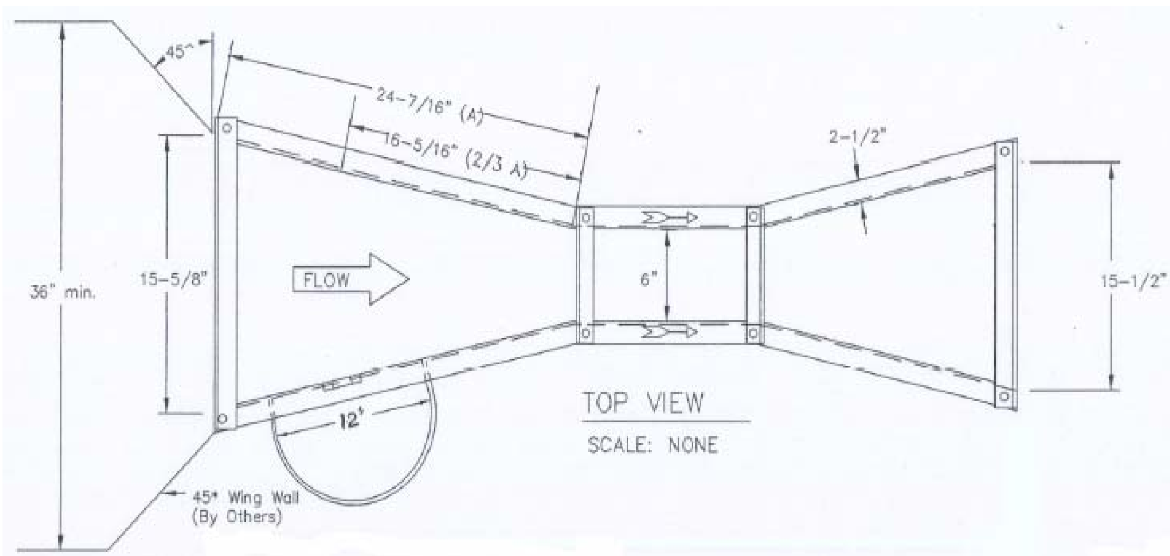


Figure 22: Parshall Flume Schematic

To determine the surface water characteristics of the test watersheds, Parshall flumes were installed at the outlets of each drainage areas. A diagram of this piece of equipment is shown in **Figure 22**. The Parshall flumes are outfitted with the same monitoring devices which are included within the shallow wells. These devices measure the level of water passing through the flume. Based on this level, and a calibration curve provided by the manufacturer, the discharge can be determined. This analysis was completed as part of a separate task undertaken during the research. Its findings will be referenced in this report.

Because the outflow data is recorded every hour, a smooth curve can be produced representing storm hydrographs in response to rainfall. This data can be compared with the interflow rates and deep groundwater fluctuations and be used to determine discharge volumes.

5.5 EQUIPMENT OF OTHER INVESTIGATIONS

Since the I-99 project has been going on for many years and many consultants have worked on the project, there is a wealth of data available which was assessed to determine some properties and behaviors that were not measured in this research. The construction site is very large and the previous sampling sites were scattered across this entire area. Because of the unique topography within this region and the disturbed subsurface geology, it was essential to identify data that was taken only very close to the test watersheds. To supplement the water level measurements, data recorded from previously installed equipment was obtained and studied. This equipment consisted of nested pairs of piezometers and deep wells similar to those of the current study.

5.5.1 Piezometers

Eleven sets of piezometers were installed throughout the construction site between 1995 and 1997 as part of subsurface investigations and hydrologic characterization studies conducted by Skelly and Loy Inc. These were installed in nested pairs along the construction site in order to analyze the movement of groundwater through the aquifer and to determine the difference between the deep and the shallow groundwater responses. Those pairs nearest to the test watersheds of this investigation were selected in order to gain an understanding of the subsurface conditions. Data from these devices (the locations are shown in Figure 11) are summarized in Table 2.

Table 2: Previously Installed Equipment

Device	Location (station)	Surface Elev. (ft)	Total Depth (ft)	Screened Depth (ft)	Depth to rock (ft)	Casing Dia. (in)	Est. Yield (GPM)	Water Bearing Zones (ft)	Screened Interval	Rising Head K (ft/min)	Falling Head K (ft/min)
MW - 06	216 + 00	1572.5	83	73 - 80	5	2	0.5	30-50, 80-83	Shale	8.803 E -5	1.369 E -5
MW - 07	216 + 00	1571.6	50	5 - 50	5	2	0.5	5-50	Shale	1.067 E -5	4.811 E -5
MW - 01	438 + 25	1206.6	65	55 - 65	60	2	1 - 3	59-65	Limestone	5.432 E -4	5.854 E -4
MW - 02	438 + 25	1207.1	15	2 -15	None	2	0.5	3-5	Silty Clay	6.122 E -5	5.177 E -5
MW - 13	412 + 00	1406.7	98	87 - 97	55	2	2 - 3	31, 55, 88-89	Sandstone	5.566 E -3	6.382 E -3
MW - 14	412 + 00	1409.5	37	6.5 - 35.5	None	2	0.25	26-27	Silty Clay	1.463 E -5	1.566 E -5

The boreholes for these piezometers were constructed using conventional air rotary drilling procedures. During drilling, core samples were taken and detailed descriptions of the subsurface geology were included in the drilling logs. These provided the only detailed information available on the formations occurring below the test sites.

The piezometers from these investigations also provided some insight into the hydraulic conductivity of the aquifers through the completion of both rising and falling head slug tests. These tests involved adding or removing a specific volume of water from the wells and monitoring the rates at which the water receded or rose. Slug tests typically provide estimates of the hydraulic properties adjacent to the wells and may not be representative of the entire aquifer.

5.5.2 Monitoring Wells

Six monitoring wells were also located in the proximity of the test sites. They are labeled as PJD in the map in Figure 11 and were installed by Skelly and Loy, Inc. Details on the method of drilling and soil characteristics were not available. For each of the six wells, the monthly average levels were recorded during the year of 2005. The exact datum elevations are not known, and only the levels as measured from the well cap were recorded. Due to the limited detail of this information, these will be used only for comparison to the trends seen in the data.

6.0 DATA ORGANIZATION AND FORMATTING

In order for the collected data to be effective at both representing the conditions clearly and being easy to use and transfer, it must first be organized and properly formatted. This aspect of the research is critical because large highway construction projects typically consist of many separate entities, each utilizing the collected information for different purposes, and each possessing a limited number of tools for data analysis. A method has been proposed to address these concerns. It involves, aside from the monitoring devices previously presented, the use of common computing hardware and software. These tools have been selected in order to facilitate simple and rapid exchange of data and to provide a clear and precise way of presenting the information for analysis. Tables and time series plots, created and managed in spreadsheets, are the basis of the system. The use of Geographical Information Systems (GIS) and more advanced graphics tools have also been investigated as an aid in transferring and displaying the data.

Due to the nature of the monitoring equipment used, a lengthy record of data was collected over one year. Most of the data was converted from raw formats into spreadsheets. Some of the data had to be calibrated based on construction drawings and visualizations were made clearer through the use of drawing programs. The readings were organized in such a way that groundwater fluctuations could be directly compared to rainfall events by way of graphical analysis. In order to visualize relationships, both rainfall and groundwater data were broken down into hourly, weekly, and monthly time increments. A brief overview of this simple data manipulation is presented in this chapter.

6.1 WELLS AND STAGE RECORDERS

When data is downloaded from the deep wells and shallow stage recorders, it is stored in text format showing the date and time of each reading. The readings relate to the height of the water column within the well shaft. An example of this file is shown in the screenshot of Figure 23. In the upstream wells, the temperature is also included as another column within the file. For each well, these files were imported into Excel, where they were calibrated and organized. The large amount of data, even from only 6 wells, was very overwhelming at first. It is important to keep very organized tables throughout the analysis or data could become misplaced or incorrectly interpreted. It is suggested that one spreadsheet be used to store all of the raw data and others be used for examining the readings.

In order to normalize the data from each of the wells, it was necessary to assign an absolute elevation to the groundwater levels. This was done by using surveyed bottom elevations and the depth of each well. The level of the groundwater was then expressed in reference to the surface topography. By doing this, estimates of the water table elevation and hydraulic gradient within each test watershed could be made at any time.

Once an absolute elevation was determined for all of the groundwater levels, the values were organized and viewed in many ways. For this study, the data was organized into two main groups, continuous and averaged. Within these two groupings, groundwater levels were studied over many different time scales and compared with many other measured variables.

B00680-SB010-0002A-Jul282005-134523.txt - Notepad

File Edit Format View Help

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Unit Of Measure: FT
Calibration Factor #1: 1964
Calibration Factor #2: 2142
Logger ID: #B00680
Job Number: SB010
Well Number: 0002A
Depth Below Datum : 0032.00
Sampling Interval: HR
Start Date: 05/07/28 13:45:23
   Date          Time         Uncomp. HT. WTR  Depth Of Water         Water Depth Rel.
                              Above Transd.     Below Datum          To Mean Sea Level
05/07/28   13:45:23              32.28            31.91                  968.09
05/07/28   14:00:00              45.88            18.31                  981.69
05/07/28   15:00:00              45.87            18.32                  981.68
05/07/28   16:00:00              45.85            18.34                  981.66
05/07/28   17:00:00              45.85            18.34                  981.66
05/07/28   18:00:00              45.85            18.34                  981.66
05/07/28   19:00:00              45.85            18.34                  981.66
05/07/28   20:00:00              45.85            18.34                  981.66
05/07/28   21:00:00              45.87            18.32                  981.68
05/07/28   22:00:00              45.87            18.32                  981.68
05/07/28   23:00:00              45.88            18.31                  981.69
05/07/29   00:00:00              45.88            18.31                  981.69
05/07/29   01:00:00              45.90            18.29                  981.71
05/07/29   02:00:00              45.90            18.29                  981.71
05/07/29   03:00:00              45.90            18.29                  981.71
05/07/29   04:00:00              45.88            18.31                  981.69
05/07/29   05:00:00              45.90            18.29                  981.71
05/07/29   06:00:00              45.90            18.29                  981.71
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05/07/29   08:00:00              45.93            18.26                  981.74
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05/07/29   10:00:00              45.95            18.24                  981.76
05/07/29   11:00:00              45.97            18.22                  981.78
05/07/29   12:00:00              45.98            18.21                  981.79
05/07/29   13:00:00              45.97            18.22                  981.78
05/07/29   14:00:00              45.97            18.22                  981.78
05/07/29   15:00:00              45.97            18.22                  981.78
05/07/29   16:00:00              45.97            18.22                  981.78
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05/07/29   19:00:00              45.95            18.24                  981.76
05/07/29   20:00:00              45.97            18.22                  981.78
05/07/29   21:00:00              45.97            18.22                  981.78
05/07/29   22:00:00              45.98            18.21                  981.79
05/07/29   23:00:00              46.00            18.19                  981.81
05/07/30   00:00:00              45.98            18.21                  981.79
05/07/30   01:00:00              45.98            18.21                  981.79
05/07/30   02:00:00              45.98            18.21                  981.79
```

Figure 23: Well Data in Text Format

Continuous data is merely the calibrated water level readings that were recorded each hour. These data points represent the actual fluctuation of groundwater, as recorded by the wells, on an hourly basis. This method of organization is used to examine both long term trends in the data as well as individual response events. The continuous record of groundwater level data for

Well A in Watershed 1 is shown in Figure 24. Due to the large number of data points and its inherent sensitivity to instantaneous events, continuous organization of the data is best suited for analyzing local events, such as the immediate response to storms.

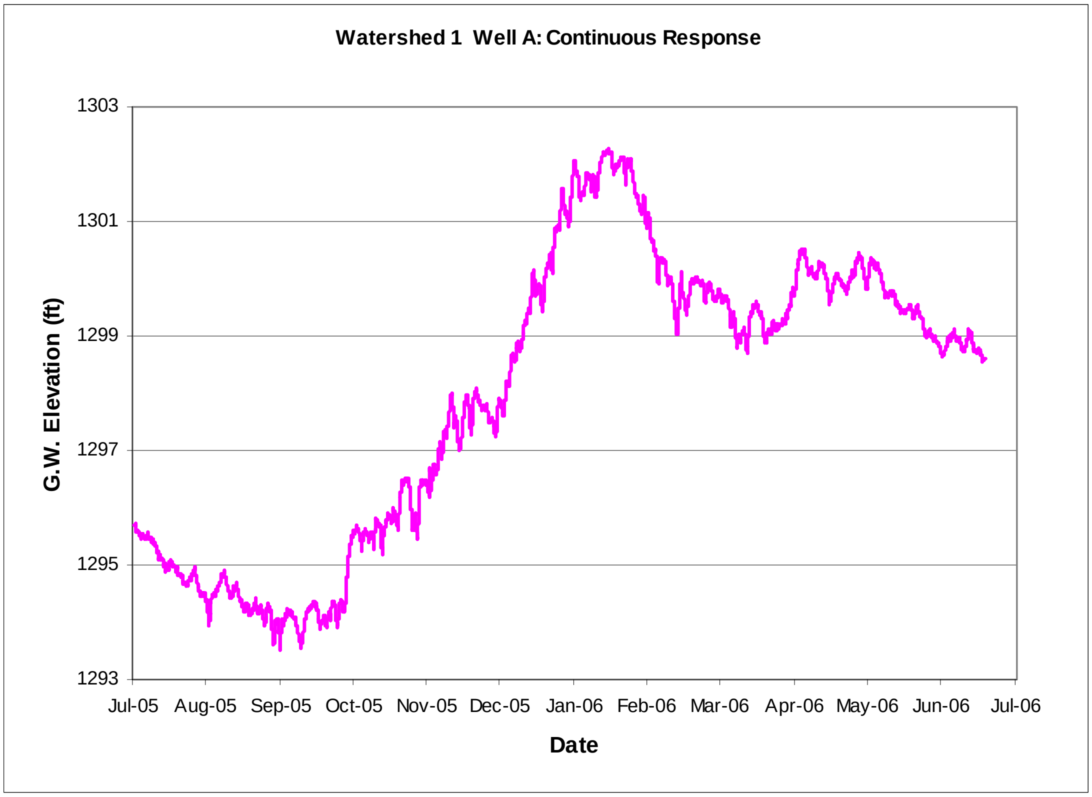


Figure 24: Continuous Response Data

To more clearly visualize and begin to understand the long term trends often observed in groundwater behavior, the data values may be averaged over time. For this study, averaging was done on a weekly, monthly, and seasonal basis. This form of data organization reduces the effects of localized extremes and possible errors in the readings. Figure 25 shows a representation of the same groundwater level record that was previously introduced. In this case however, the data points represent weekly averages, providing for a smoother curve that is less dependent on individual readings.

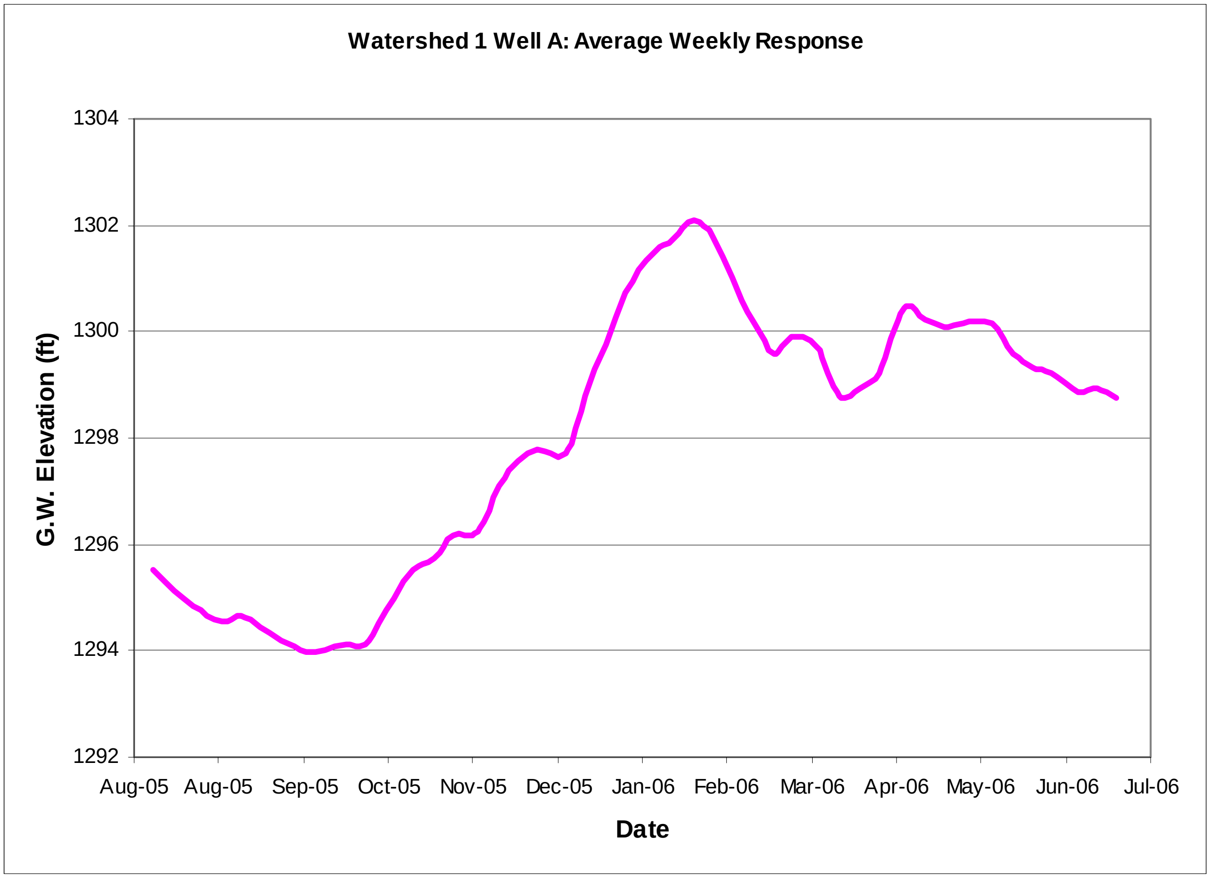


Figure 25: Average Weekly Response Data

6.2 METEOROLOGICAL DATA

To gain insight into the response behavior of the groundwater, the rainfall data, along with temperature and pressure readings, must be organized properly. The data from Skelly and Loy Inc. is available in Excel spreadsheet format and all data forms (rainfall, temperature, and pressure) can be requested in any time interval because the station has a continuous recorder. The rainfall data from the NOAA gage is available in text format. It is only provided on days which rainfall occurs and attention must be made to the organization of the file containing the data so that it is imported correctly into the spreadsheet.

The rainfall data were organized into hourly, weekly, monthly, and seasonal groupings. These values were then represented as either incremental amounts, which could be displayed as bar charts, or cumulative totals, which are best represented by line graphs. Each of these methods has its strengths and weaknesses for analyzing different aspects of the groundwater response. The hourly incremental rainfall readings allowed for detailed examination of individual storms. Hourly cumulative organizations work well at looking at long term rainfall patterns. The weekly and monthly values are best suited for bar charts. Figure 26 shows an example of the monthly precipitation totals from both rain gages, represented as a bar chart over the entire study period.

The temperature and pressure data was arranged in similar ways. As with the groundwater level data, these values were used as either continuous records or averaged on a weekly or monthly basis.

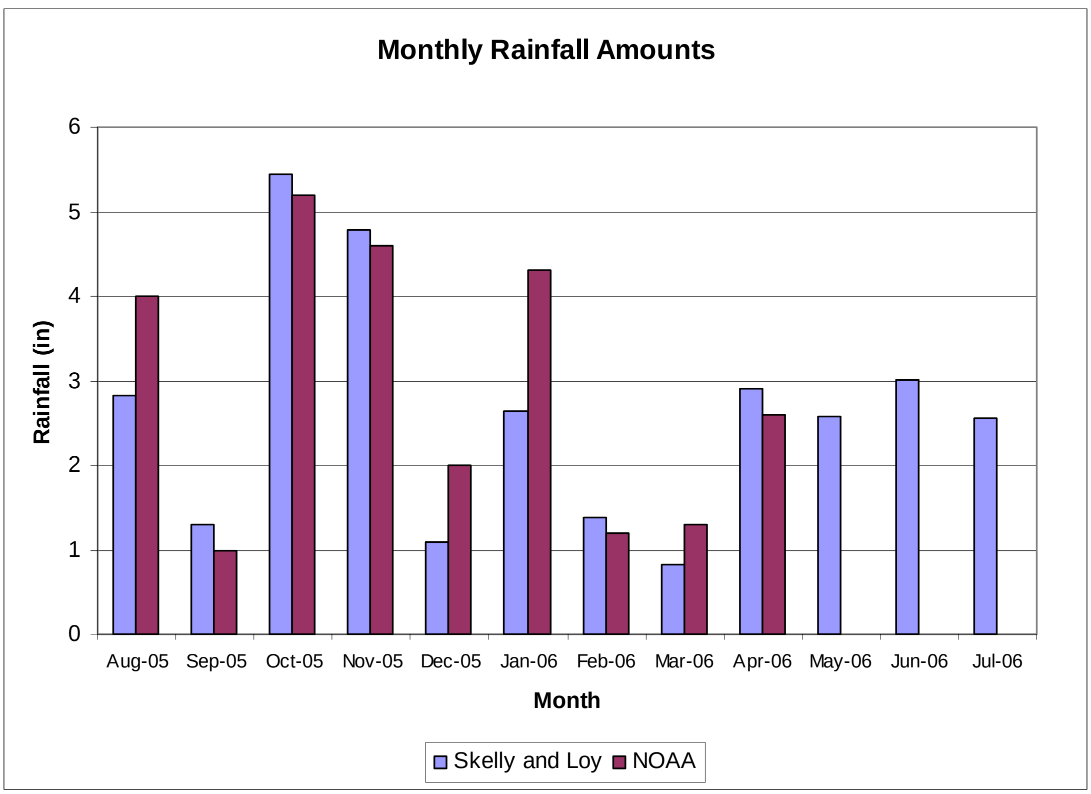


Figure 26: Monthly Rainfall Amounts

6.3 SURFACE WATER DATA

The surface water data was not dealt with directly in this research. Information was obtained from another investigator and included storm hydrograph data and water volumes that had been calculated from the hydrographs. The data was available in spreadsheet format and organized into hourly values of flow rate expressed in cubic feet per second. These data could be plotted against time for an individual storm event, as shown in Figure 27**.** Long term trends in the discharge pattern were not examined because during periods of no rainfall, no data was available.

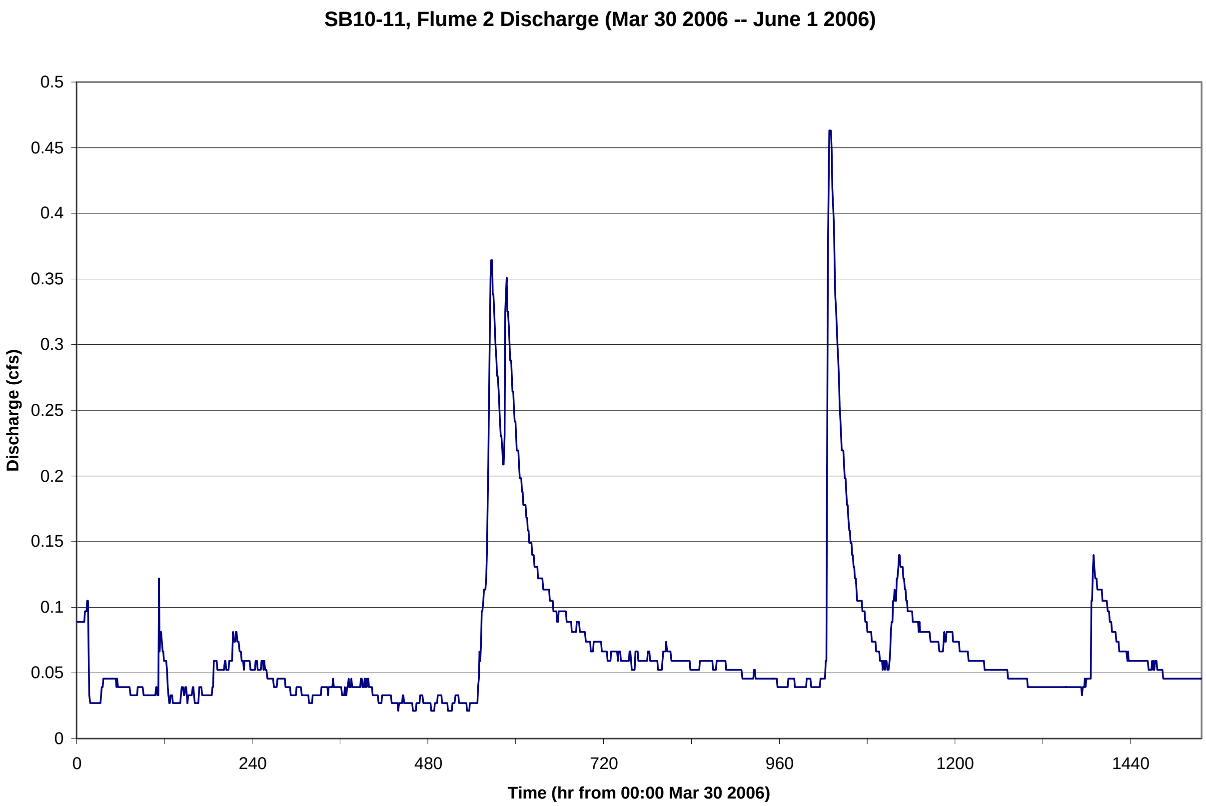


Figure 27: Storm Hydrograph

6.4 DATA INTEGRATION

The data gathered from each of the devices is not very meaningful when it is examined separately. In order for the system to be effective at modeling the response of a watershed to natural and unnatural stimulation, all of the data must be integrated and compared.

Because the data were organized into similar groupings and intervals, integration was simple. Tables were prepared which contain each measured variable at each time interval. These data were then plotted on the same graph for visualization and analysis. An example of this data integration is shown in Figure 28, which combines the hourly rainfall increments and continuous groundwater level data to monitor the aquifers response to a specific storm. After integration, the data can be viewed and analyzed in many ways, including the development of regression equations, the determination of ratios between the variables, and the ability to identify expected or unusual behaviors. These topics will be discussed in the next chapter.

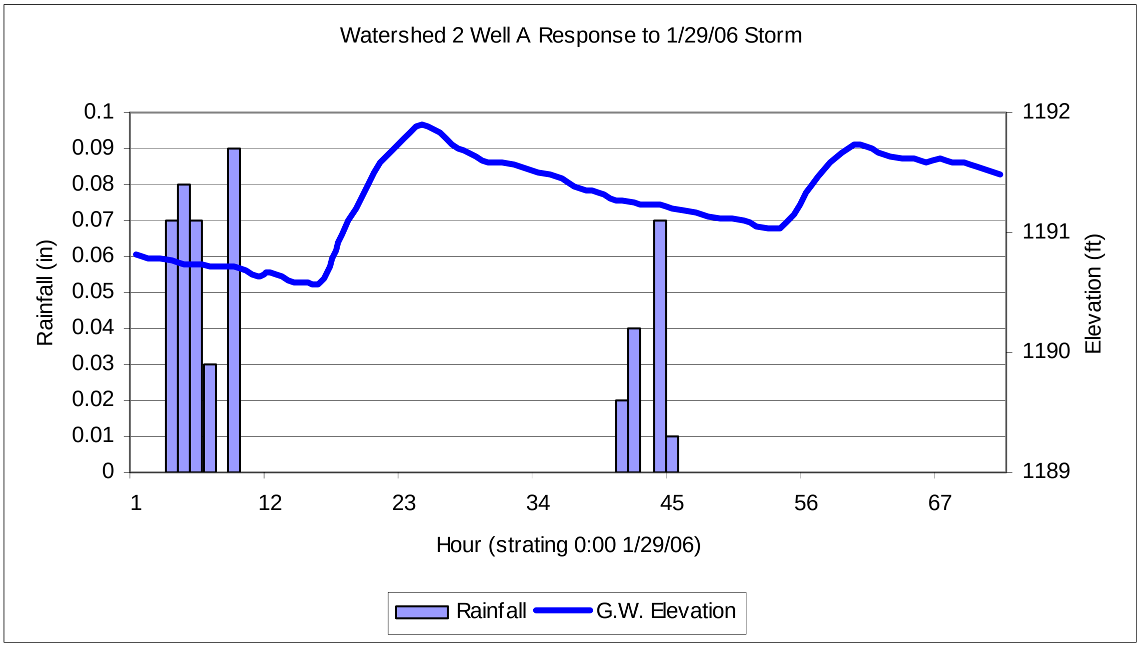


Figure 28: Integrated Rainfall and Groundwater Level Data

6.5 OTHER METHODS

During this research, numerous other tools were investigated to organize and view the measured values. The project requirements of simplicity and availability, as well as the benefit versus cost ratio of these tools, prevented their full use. Some of these tools are worth mentioning in this report, as they do have great potential for better representing the collected groundwater data.

GIS stands for Geographical Information System, and it is one of the newest and fastest growing tools available for database management. It effectively combines spatial data with attribute data in a user friendly graphical interface. The possible applications of a GIS to this project were abundant, yet time and data constraints limited its use. GIS, under the ArcView platform, was used to successfully display the locations of the monitoring equipment used at each of the test watersheds on interactive maps. Three of these maps are shown in chapter 4. The benefit of maps created within a GIS is that data can be stored for each location on the map. This allows, for instance, all of the well data for watershed 1 to be linked directly to the actual wells on the map. This would be a very powerful method of organizing and viewing the information. Transfer of the data would also be facilitated, as the entire database would be stored as a single bundle of files. Because of the spatial aspect, there would be no uncertainty as to where the data belonged or what it represented. GIS was applied in a limited sense in the construction of a project webpage by another member of the research team. The website provided public access to the interactive spatial data.

Although the two dimensional plots created in Excel and based on the spreadsheet data are very effective at representing the groundwater point data over time at each well, these data are actually intended to estimate the behavior of the entire aquifer. In order to estimate and visualize this response, a tool with three dimensional capabilities is required. Matlab, a numerical computing and advanced graphics program, was investigated for this purpose.

This program is capable of displaying the groundwater point data at each well on a three dimensional mesh, created from the topographic maps of the construction zone. From this, the point data would be interpolated between the wells to develop an estimate of the water table beneath the watershed. This could be taken a step further, and the levels could be animated to show the change in water table surface over time. This would be a powerful presentation tool.

This was not implemented for two major reasons. First, the data available was not detailed enough to make the effort worthwhile. Since only two deep wells were included in each watershed, the three dimensional surface would simply be a plane connecting the two point sources. Secondly, although the plots and animations may benefit presentations, it is very limited as an analysis tool. This is because very little was known about the subsurface properties of the watersheds. Also, an analysis of this type of data would be very complicated and difficult to interpret.

7.0 DATA ANALYSIS

After the data was properly organized, it was analyzed by both qualitative and quantitative methods in an attempt to understand and possibly predict the behavior of the watersheds. The qualitative analysis consisted of examining the plots of groundwater response over time for each of the monitoring locations and attempting to identify patterns or trends in the data. This simple visualization of the information was crucial for deducing the mechanisms that govern the response. The quantitative analysis involved further investigating these patterns, along with the magnitude and durations of the responses, to determine relationships that can be used to model future aquifer behavior. The methods of other researchers (Rasmussen and Andreasen, 1958; Jaber et al, 2005) have been adapted and implemented for these purposes. Using these findings, correlations between the upstream and downstream responses were identified. All analyses were done using the computing tools presented in the previous chapter in conjunction with the hydraulic and hydrologic methods presented in chapter 3. Prepackaged groundwater modeling programs were considered but not utilized due to limited data and other factors.

For the model to be effective at representing and later predicting the highway watersheds behavior, three detailed analyses were conducted to calculate specific properties and understand certain processes that are characteristic of aquifers. First, estimates of the groundwater recharge within the test zones were made based on elements of the water budget and fluctuations of the groundwater level. Second, recession rates and base flow were examined by studying the rate of groundwater level decline during dry periods. Finally, travel times and hydraulic conductivities were estimated by conducting tracer studies, which also ensured that flow was passing through the aquifer.

The analysis took many different paths and used numerous theories in order to best fit the requirements of this research. Although all of the methods used will not be presented in this report, many of them are included in order to show how the analysis evolved over time. Due to the large amount of data that was analyzed, only the details from the investigation of Watershed 1 will be included in this report. Both the surface and ground water equipment at this test site showed the most consistent and reasonable results.

7.1 QUALITATIVE ANALYSIS OF GROUNDWATER RESPONSE

Examples of groundwater response patterns, as observed by monitoring wells in previous studies, were included in chapter 3. The explanations of these patterns, coupled with the collected data, were used to analyze groundwater behavior at the test watersheds. This section identifies the patterns that were observed and determines which variables are most crucial to building an effective groundwater model.

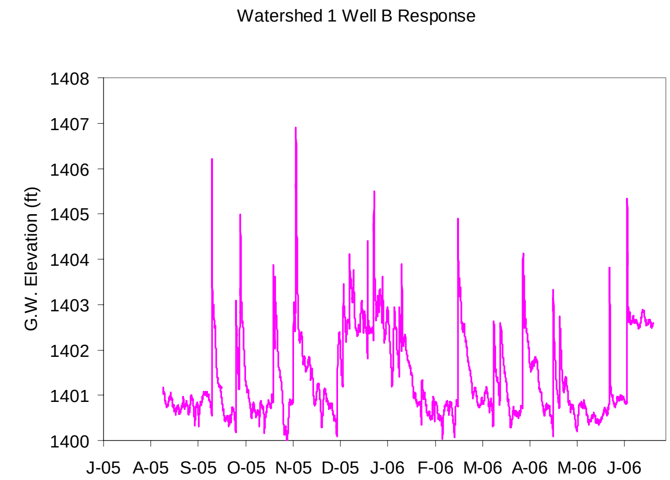
It is impossible to examine all of the parameters that might effect groundwater fluctuations. In order to select the most pertinent variables, a qualitative overview of the response patterns was undertaken by plotting the groundwater levels against time on the same graph as all of the other measured variables. Groundwater level was plotted alongside rainfall, temperature, barometric pressure, and surface water discharge.

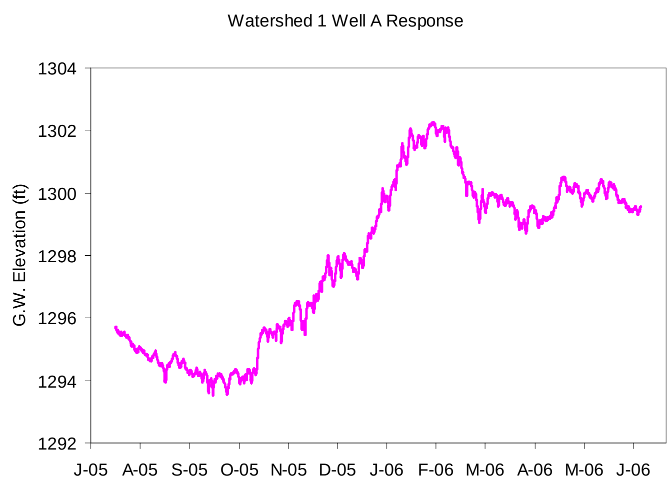
After analyzing the effects of barometric pressure and temperature, it was decided that these variables did not have a significant effect on the levels measured in the observation wells. If they did have an influence, it was greatly masked by the overriding influence of precipitation. Because of this, the details of the pressure and temperature analyses will not be included in this report.

As introduced in chapter 4, both of the test watersheds are located in a region that relies heavily on groundwater resources. Detailed information has not be obtained regarding the pumping schedules or rates of the withdrawal wells near the test sites, thus correlation between groundwater discharges and observation well fluctuation can only be speculated upon.

7.1.1 Long Term Response Patterns

Figure 29 shows the continuous water level record for the 3 wells in Watershed 1. Note that the horizontal scales for the plots are the same, but the vertical scales have been adjusted in each graph in order to capture greater detail. As shown in the figure, each well exhibited its own unique behavior. The differences between the two deep wells and one shallow well bring up many concerns and clearly show that even within a very small watershed; the subsurface behaviors may be vastly different.





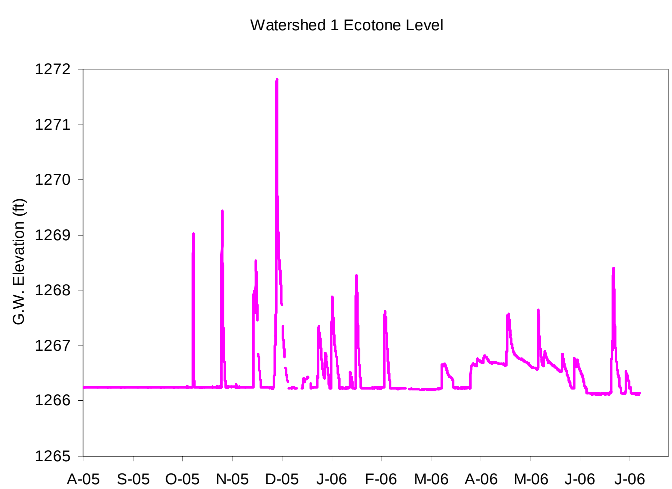


Figure 29: Continuous Record of Groundwater Levels at Watershed 1

Well B of Watershed 1 is located in the upstream portion of the watershed. The first noticeable characteristic of the response at this well is the dramatic and apparently instantaneous rises and recessions, which will later be shown to correlate with precipitation events. The seasonal level does not fluctuate much over the course of the study period. Once the water level rises, it returns to nearly the same level, indicating that this portion of the aquifer does not hold significant volumes of water. Also note that the bottom elevation of this well is 1400 feet, which means that many times the well is completely dry. The following explanation will be used to account for the behavior of this well for the remainder of the report.

Well B was only drilled fifteen feet into the ground due to the auger encountering solid rock. The encountered formation is assumed to be fractured bedrock, which was discussed in chapter 4, and is common throughout the area of Bald Eagle Creek. This formation may allow water to flow beneath the bottom of the well, which would explain why it only records significant levels immediately following rainfall events. The fractures in the formation may completely fill with water during these events, indicated by the dramatic rises, and then recede just as quickly and dramatically. It is also important to note that this observation point is on the upslope of a large hill, and should not retain large amounts of groundwater throughout the year. The precipitation that falls on this area will infiltrate into the soil, but immediately begin to flow downstream due to a steep hydraulic gradient. This upstream zone is classified as a groundwater recharge area, and its function is very important to the downstream wetlands. Aside from the very high readings, such as the 8 foot spike in the month of November, it will be assumed that the level recorded within the well shaft is representative of water entering the deep groundwater table and contributing to recharge.

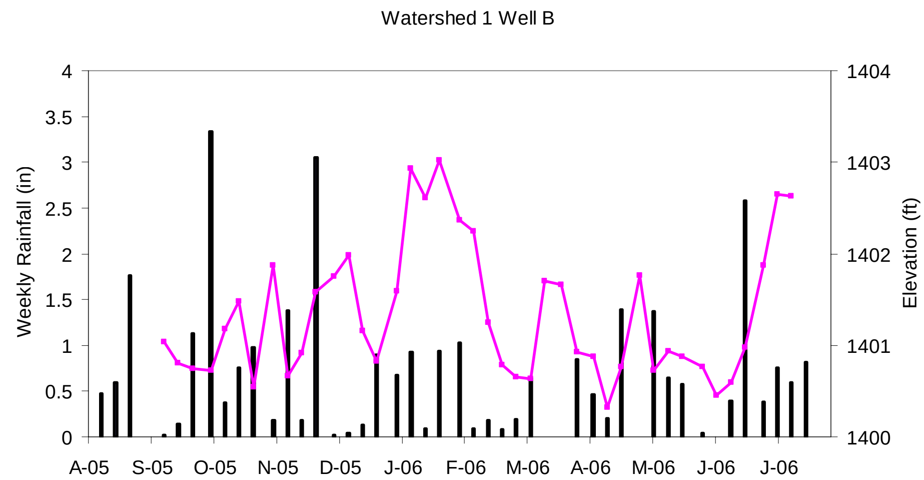
Unlike the upstream well, Well A is deep and is believed to capture all of the ground water fluctuations. The well bottom elevation is 1281 feet, meaning that there are significant amounts of water in the well shaft throughout the entire monitoring period. One reason for this may be that the well is located in a low lying wetland area, and thus should have a continuous supply of water during most of the year. As shown, this well records long periods of constant rise or recession throughout the timescale, with the recharge period lasting from October to March. This correlates with the fact that in the United States, water tables tend to be high in the spring due to recharge from winter precipitation (Rahn, 2002). The levels receded in the late spring and summer months due to less precipitation, higher temperatures, and the requirements of plant life within these very fertile areas. The downstream well response is also immediate, but not nearly as extreme as Well B, and it does not recede as quickly. As with Well B, it will be assumed that the increase in groundwater level is indicative of the amount of water recharging the aquifer.

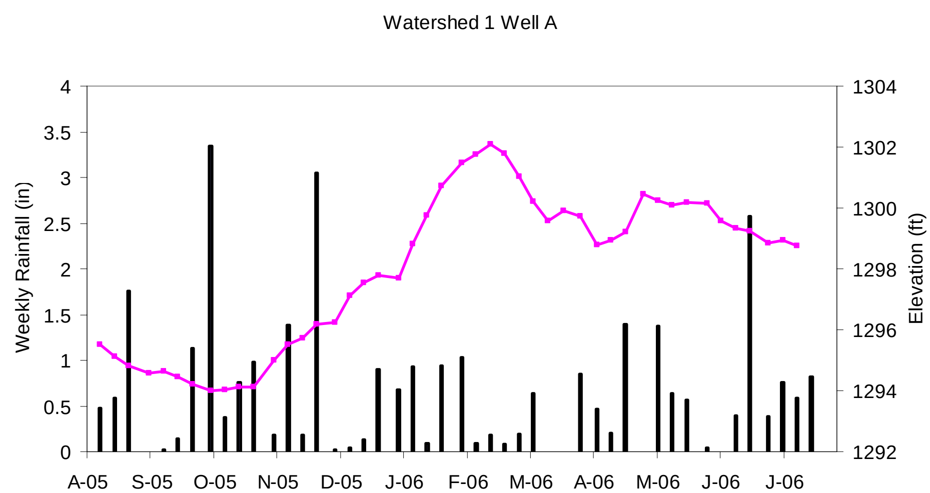
The patterns recorded by the shallow stage recorders at both watersheds were troubling. For Watershed 1, the well did not display responses that are characteristic of wetland areas. As shown in Figure 29, instead of displaying moist soil conditions, the well is predominately dry most of the year and experiences large rises and recessions, similar to those exemplified by the upstream well. This behavior could be representative of a fractured subsurface structure or be the result of nearby pumping, keeping the levels low accept during recharge events

7.1.2 Variables Effecting Long Term Response

Even before data was collected and analyzed, it was expected that precipitation amount and intensity would be the main variables affecting groundwater fluctuation. It has already been shown that one of the wells exhibits a seasonal pattern, which is partially reliant on precipitation amounts and types. In an attempt to better understand the relationship between the two, weekly and monthly rainfall amounts were compared to the weekly and monthly average groundwater levels. The weekly values are plotted in Figure 30. Although analyses of these plots are not immediately conclusive, there does appear to be a connection between the long term trends in groundwater fluctuation and the rainfall amount.

As with groundwater fluctuation, surface water discharge occurs in response to precipitation input. Studying this relationship will add confidence to the model and allow for the later calculation of groundwater recharge. Figure 31 displays the long term continuous records of groundwater fluctuation and surface water discharge. As shown, the responses are very similar, especially when comparing the discharge pattern to Well B and to the shallow Ecotone, which increases the assurance that both types of equipment functioned correctly. The response timing and magnitude of these events should correlate better with one another than each does individually with the rainfall. This is because the rain gages are located far from the test sites. Long term quantification of the surface water runoff will not be undertaken because, as shown in the plots, the streams generally run dry unless a rainfall event occurs





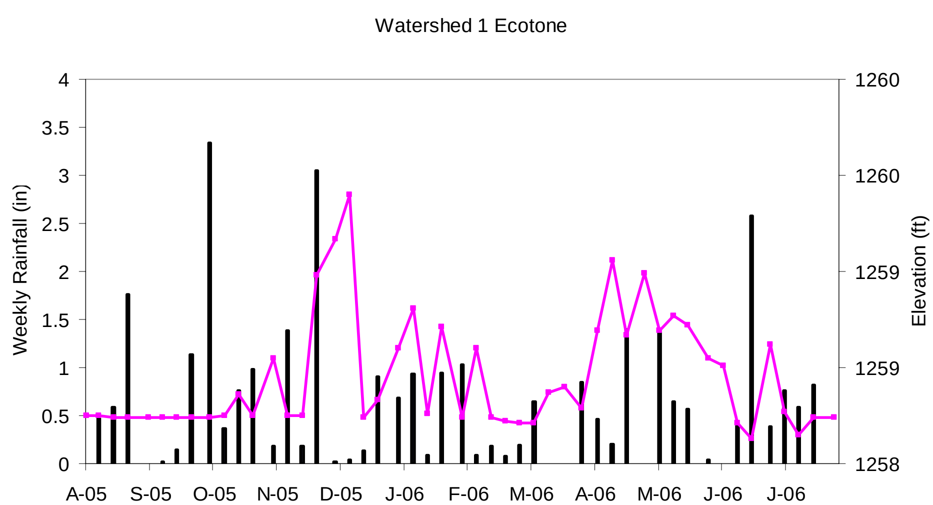


Figure 30: Weekly Rainfall and Average G.W. Elevations

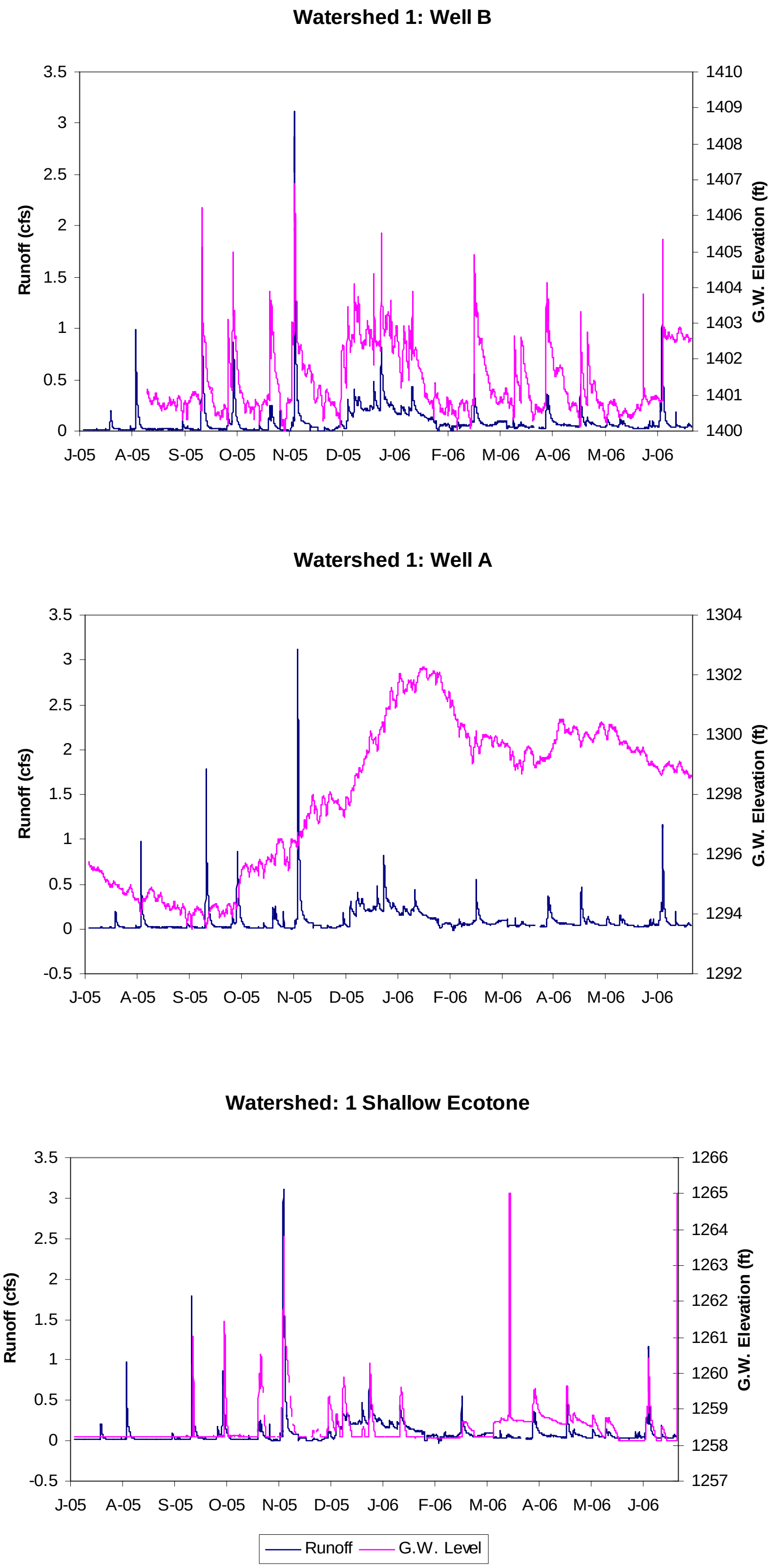


Figure 31: Watershed 1 Runoff and G.W. Elevation

7.1.3 Event Based Responses

Although seasonal patterns are present in the data, these are actually aggregate responses that result from localized storm events in conjunction with other factors. Understanding these short term responses, which can be classified as recharge events, is critical because they are the building blocks of any hydrologic model and are required for comparison to storm event based surface water models.

Individual storm records provide a much more detailed look at the rates at which groundwater levels rise and fall in response to rainfall. Over 50 individual storms were analyzed during this research. Many different response durations and magnitudes were identified for each well. Two main categories will be presented. First, there were events where both Well A and Well B responded in a similar fashion. An example of this is shown in Figure 32. Note that during this event the shallow well failed to respond. Secondly, there were many events where Well B responded dramatically, as shown in Figure 33. It is clear that the wells are responding to the rainfall, but it is unclear why they often respond differently.

As discussed in chapter 3, the Lisse effect is one of the possible explanations for the dramatic responses. The Lisse effect occurs as a result of intense rainfall that entraps air and pressurizes the groundwater, leading to an increase in the observed well level. To determine if this theory is valid, the rainfall intensity was compared with the readings. If it is determined that the Lisse effect is present, it will not be possible to develop relationships between rainfall amount and groundwater table rise for these events.

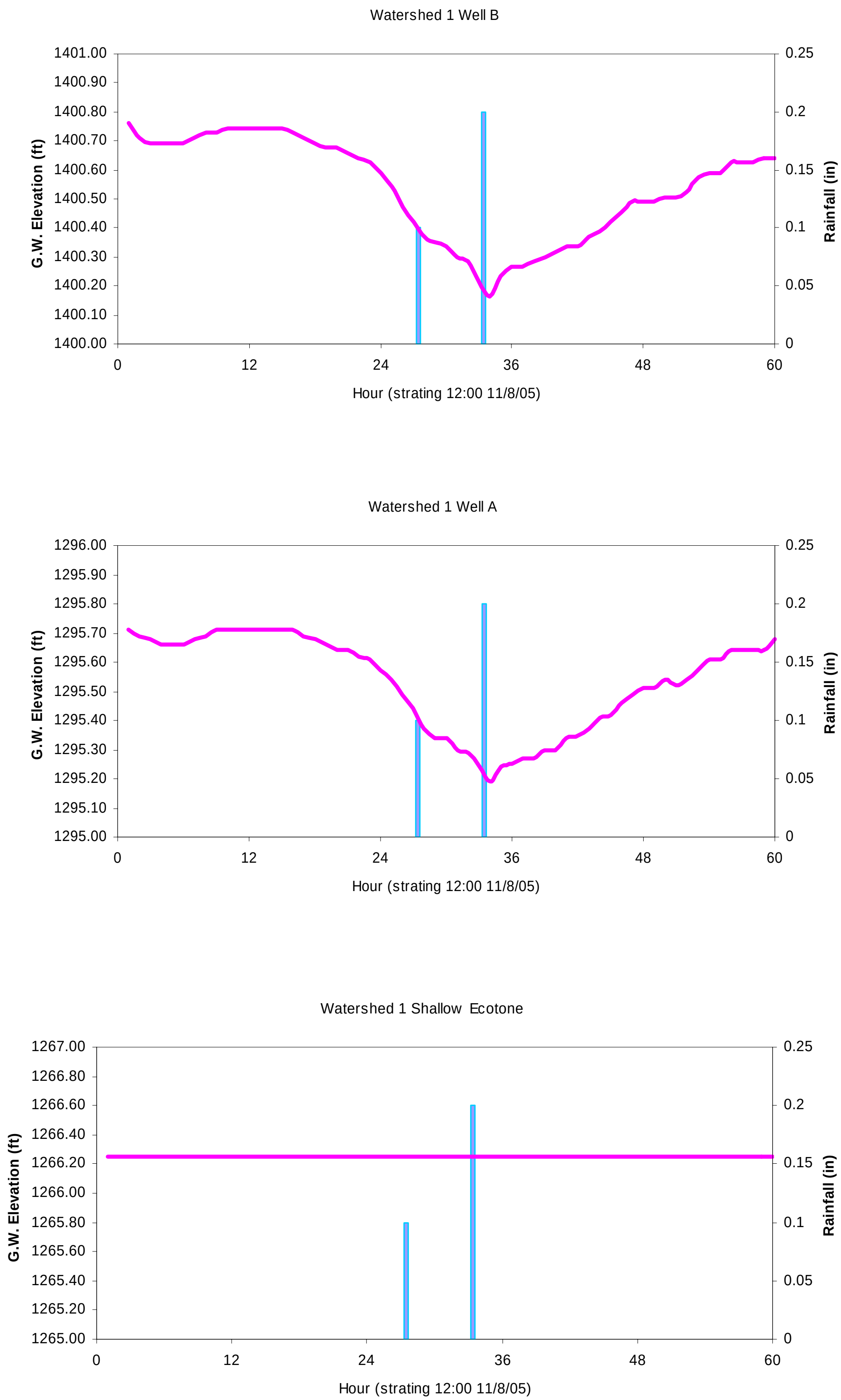
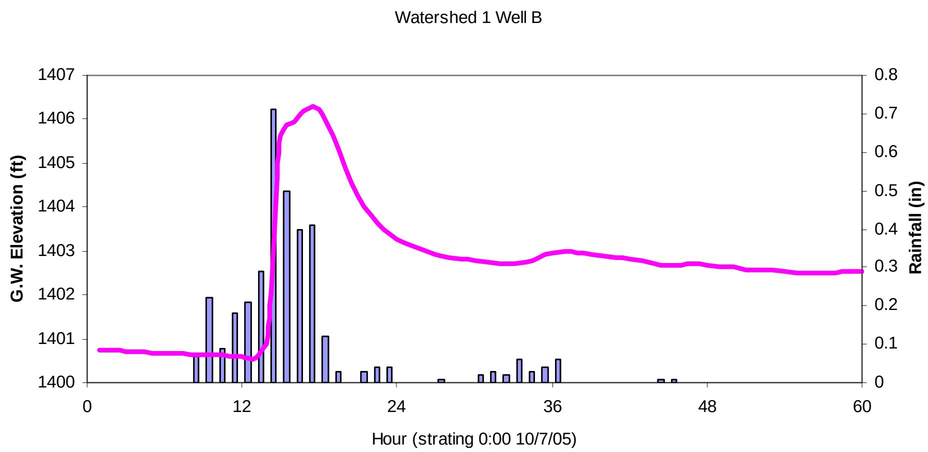
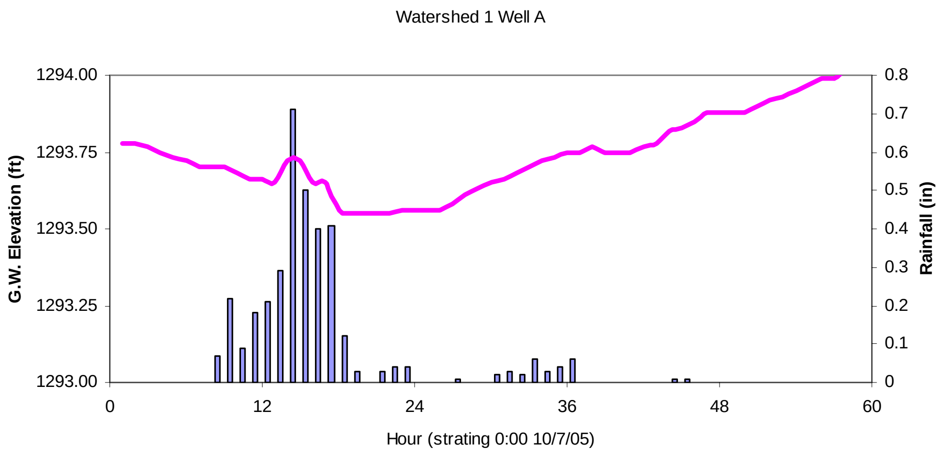


Figure 32: 11/8/05 Incremental Rainfall and G.W. Response





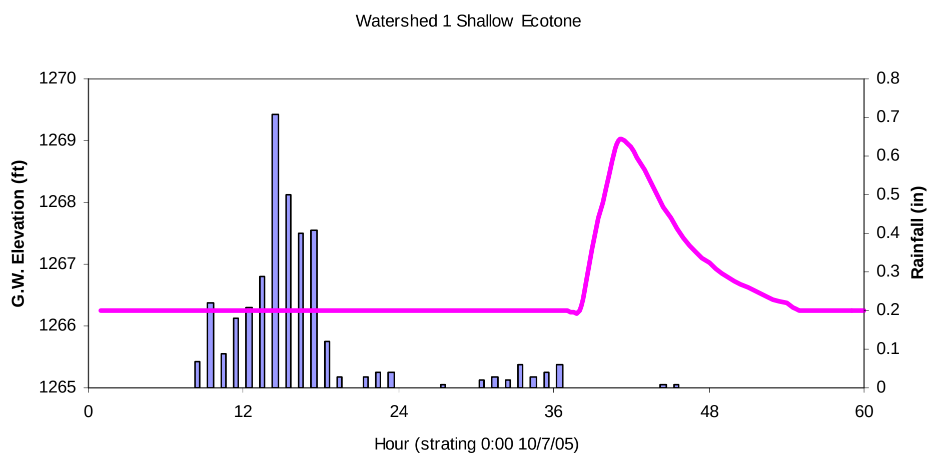


Figure 33: 10/7/05 Incremental Rainfall and G.W. Response

7.2 QUANTITATIVE ANALYSIS OF GROUNDWATER RESPONSE

To create a groundwater model based on the collected data, attempts were made to develop numerical relationships between the significant variables identified in the previous sections. These relationships include correlations between rise in groundwater levels and precipitation depth, precipitation intensity, and runoff volumes. These relationships stand as the basis for the groundwater model. Effort has been taken to ensure that the data used to develop these relationships is reasonable. This was often a difficult task due to irregularities and inconsistencies in the readings.

7.2.1 Groundwater Rise V.S. Rainfall Amount

Although rainfall amount is not the sole indicator of groundwater fluctuation, it is a major factor. The collected data demonstrated that most significant rainfall events resulted in increases in the groundwater levels. Past studies (Jaber et al, 2005) have indicated that the relationship between these two variables is often linear, and takes the form of the following equation:

$$WTC = a \times P$$

where:

WTC = Water Table Change
a = Regression Coefficient
P = Precipitation Depth

To develop this relationship, the groundwater rises must be accurately determined. To do this, the decline of water level prior to the rainfall event was extrapolated to the time of the peak of the subsequent rise in order to account for the natural drainage of the aquifer (Rasmussen and Andreasen, 1958). This process is shown in Figure 34 and was done using the trend line feature in Excel.

Since the rain gauging stations are not located directly at the test sites, it was impossible to determine exactly how long the wells took to react to each storm event. In general, all responses occurred within 12 hours of the rainfall, which allowed for the ability to match up each response event with the correct corresponding storm. There is also uncertainty regarding the amount and intensity of the rainfall. For this reason, only those events where the rainfall between the two gages was similar was utilized.

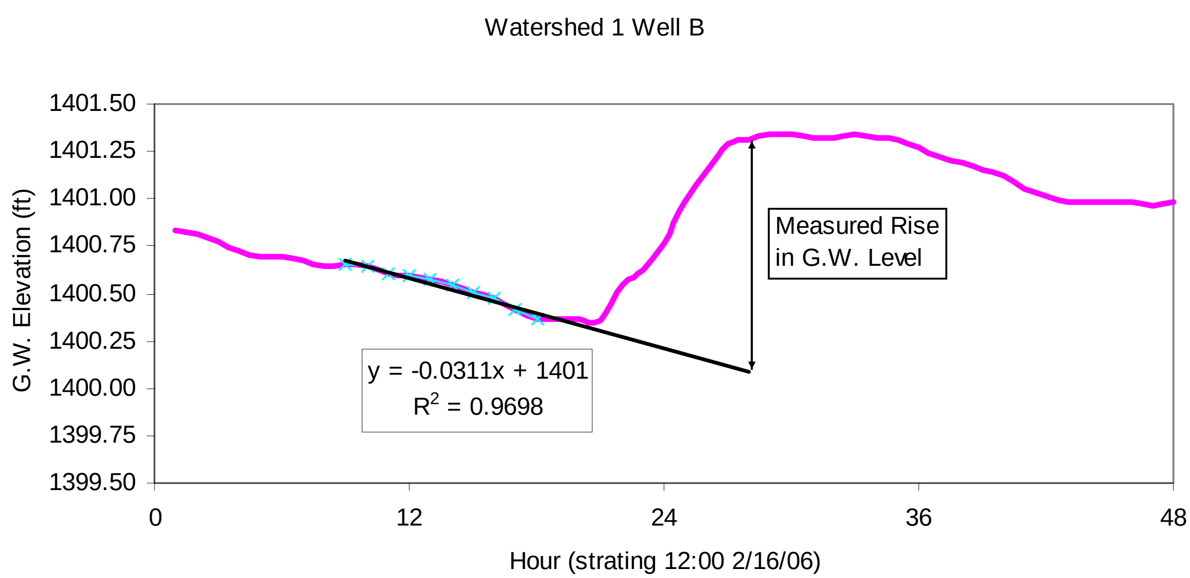


Figure 34: Method of Extending G.W. Recession to Measure Rise

Twenty six separate rainfall events were selected for this analysis. The number of storms was reduced from the original set of fifty based on irregularities in the rain gage records and the lack of response from some wells to certain storms. The very extreme rises that occurred at Well B were also screened out of this analysis. Table 3 shows the storms that were analyzed, the rainfall amounts recorded at each gage, and the measured groundwater response. Based on these values, linear regression equations were constructed, correlating the average rainfall amount with the ground water response. The plots of these analyses are shown in Figure 35.

It is apparent from the plots that there is a relationship linking the rainfall amount with the magnitude of the groundwater rise in all three of the monitoring wells. When a linear regression line was fit to the data, the results were not as conclusive. The low R-squared values of 0.392 and 0.292 for Well A and Well B show that the linear trend in the data is very weak. This is partially due to the fact that the line of best fit was forced to intersect the origin. This was done because it was assumed that zero inches of rainfall should result in zero inches of groundwater rise. Since all events that were selected display periods of groundwater recession prior to the rise in response to rainfall, it would not be justified to assume otherwise. Thus, although a better fit could be achieved by selecting a regression line with a y-intercept value; this value could not be physically justified.

The shallow well data seemed to show a more linear trend, with an R squared value of 0.726. This is surprising, as it was mentioned earlier that the patterns displayed by these devices at both test sites were very different and irregular. It is believed that the data seems to fit better because even fewer storms were available for analysis and many times, for small rainfall events, the level rise was zero.

Table 3: G.W. Rises and Rainfall Amounts

	Rainfall (in)		Watershed 1 Rise in G.W. Level (ft)			Watershed 2 Rise in G.W. Level (ft)		
Storm Event	Skelly and Loy	NOAA	Well A	Well B	Ecotone	Well A	Well B	Ecotone
9/25/2005	0.64	0.7	0.74	0.78	0.01	0.63	0.49	NA
9/29/2005	0.46	0.3	1.66	1.70	0.01	1.27	1.18	NA
10/20/2005	0.76	1	1.04	2.93	NA	1.82	1.35	3.08
11/8/2005	0.38	0.3	NA	2.82	NA	1.96	1.81	0.17
11/14/2005	0.82	0.8	NA	3.04	1.74	2.81	NA	0.50
11/15/2005	0.36	0.3	NA	1.80	0.95	4.10	NA	0.12
11/26/2005	2.97	2.8	2.07	4.82	5.50	6.59	4.56	0.65
1/2/2006	0.58	0.6	NA	1.63	1.64	2.12	NA	0.17
1/11/2006	0.28	0.3	0.73	0.55	0.26	0.96	0.45	0.20
1/13/2006	0.63	0.5	NA	2.59	2.01	2.63	1.25	0.27
1/23/2006	0.3	0.4	0.26	1.42	0.00	1.57	NA	0.12
1/24/2006	0.4	0.3	3.22	3.52	0.00	1.53	NA	0.14
1/29/2006	0.34	0.3	0.54	2.43	0.00	1.49	NA	0.14
1/30/2006	0.14	0.1	0.58	NA	0.00	0.73	NA	0.08
2/2/2006	0.33	0.3	0.58	1.59	0.00	1.36	0.33	0.14
2/3/2006	0.67	0.7	2.62	2.17	1.39	2.35	0.91	0.25
2/16/2006	0.18	0.1	0.12	1.24	0.00	0.51	0.21	0.00
3/1/2006	0.17	0.3	0.83	1.36	0.00	1.37	0.62	0.07
3/11/2006	0.41	0.8	0.44	4.15	0.40	1.43	0.27	0.19
3/31/2006	0.11	0.1	0.93	0.95	0.03	1.15	0.37	0.03
4/3/2006	0.56	0.3	0.63	2.42	0.13	1.59	0.29	0.25
4/7/2006	0.25	0.4	1.39	2.01	6.32	0.96	0.43	0.16
4/21/2006	1.47	1.4	NA	3.34	0.96	2.62	NA	0.33
5/11/2006	1.35	1.1	1.04	3.24	1.07	1.15	0.69	0.78
5/14/2006	0.44	0.5	NA	2.12	0.27	0.58	NA	0.17
5/26/2006	0.35	0.2	1.04	1.09	0.32	0.70	0.30	2.77
7/12/2006	0.71	0.5	0.11	1.71	NA	NA	0.12	NA

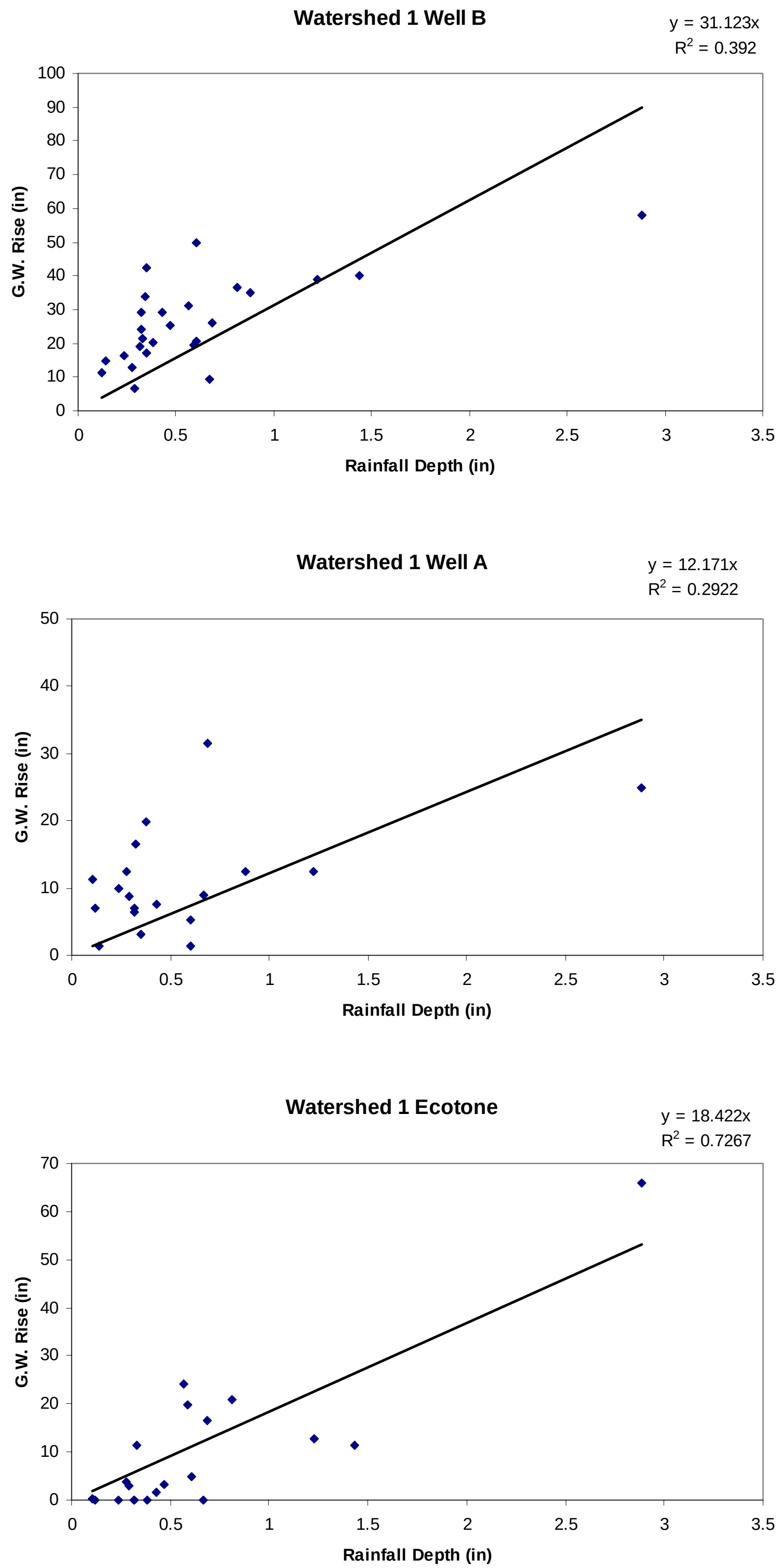


Figure 35: Linear Regression of Groundwater Levels and Rainfall Depth

A major deficiency in the collected data was a lack of information on small storm events. It is believed that these small storm events shape the relationship between rise and rainfall near the origin. Due to the spacing of the rain gages, it was not possible to link very small rainfall events with their subsequent responses. This issue will need to be addressed in future research.

7.2.2 Rainfall Intensity

Rainfall intensity is known to be a factor in the amount of recharge an aquifer receives, and thus the amount of groundwater fluctuation that is observed. To achieve a stronger relationship between the rainfall amount and groundwater rise, the events were sorted based on their intensity. The maximum intensities from each of the storms were used and the events were divided into two groups. Low intensity storms were classified as below 0.15 inch per hour and high intensity storms were above this level. When the data were plotted, the relationships between rise and rainfall amount were actually weaker than the unsorted events. For this reason they have not be utilized.

For a select number of storm events, the rainfall intensity was very high; greater than half an inch per hour. For these events, both wells responded dramatically. Due to the concerns related to the Lisse effect and other factors, these events were excluded from the set of storms.

7.2.3 Surface Water Discharge

Since the groundwater model was designed to be based on rainfall amounts in conjunction with estimates of the water budget, it is important that the other significant factor of the water budget also be related to rainfall. To check this relationship, Runoff volumes were calculated by computing the areas under the hydrographs for each storm event. Due to unknown reasons, possibly related to freezing temperatures, runoff data was only available for 15 of the 26 storms. The calculated volumes were then compared to the rainfall depths. As shown in Figure 36, runoff increases with increases in rainfall. This matches the results of the groundwater levels and should be adequate for the recharge calculation.

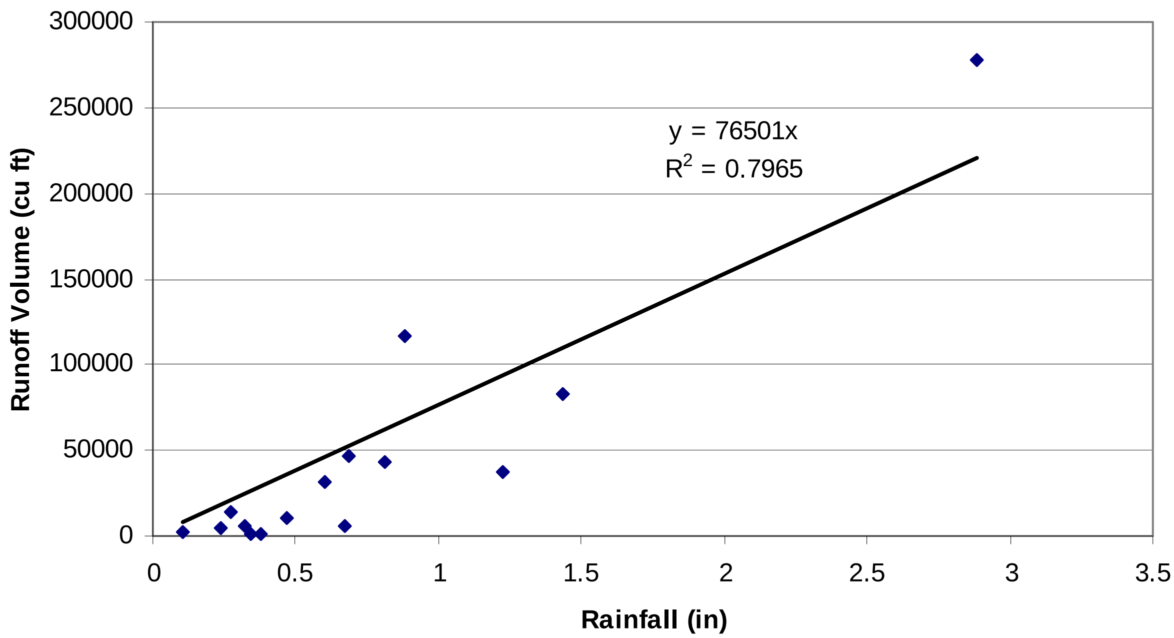


Figure 36: Watershed 1 Discharge and Rainfall Depth

7.3 UPSTREAM – DOWNSTREAM CORRELATIONS

One of the objectives of the groundwater study was to identify relationships between the upstream and downstream response patterns within each watershed. This includes the short term reactions to rainfall events as well as the long term seasonal patterns. These relationships may shed some light on how effective the infiltration gallery is at maintaining groundwater flow through the highway cut zone.

The upstream and downstream continuous responses for Watershed 1 over the course of a year are re-plotted in Figure 37. Aside from the broad differences that have been explained in the previous sections, there are some striking similarities between the two wells. Five distinct time periods are identified in Figure 37. During these time periods, the wells have nearly

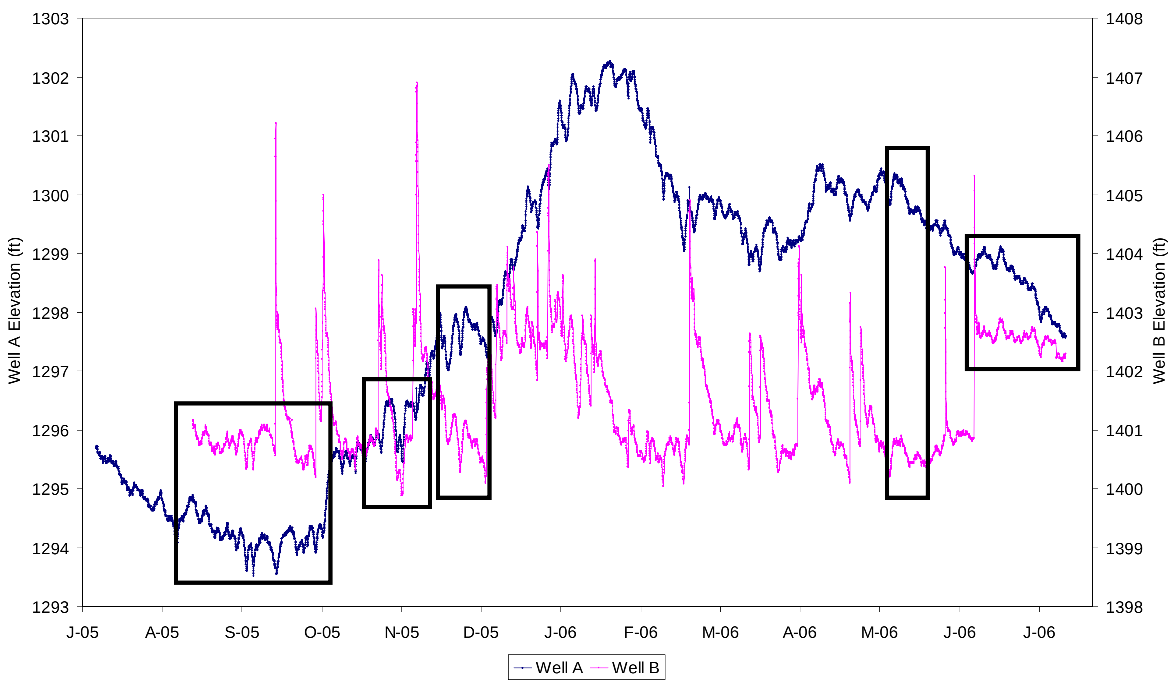


Figure 37: Upstream and Downstream Correlations for Watershed 1

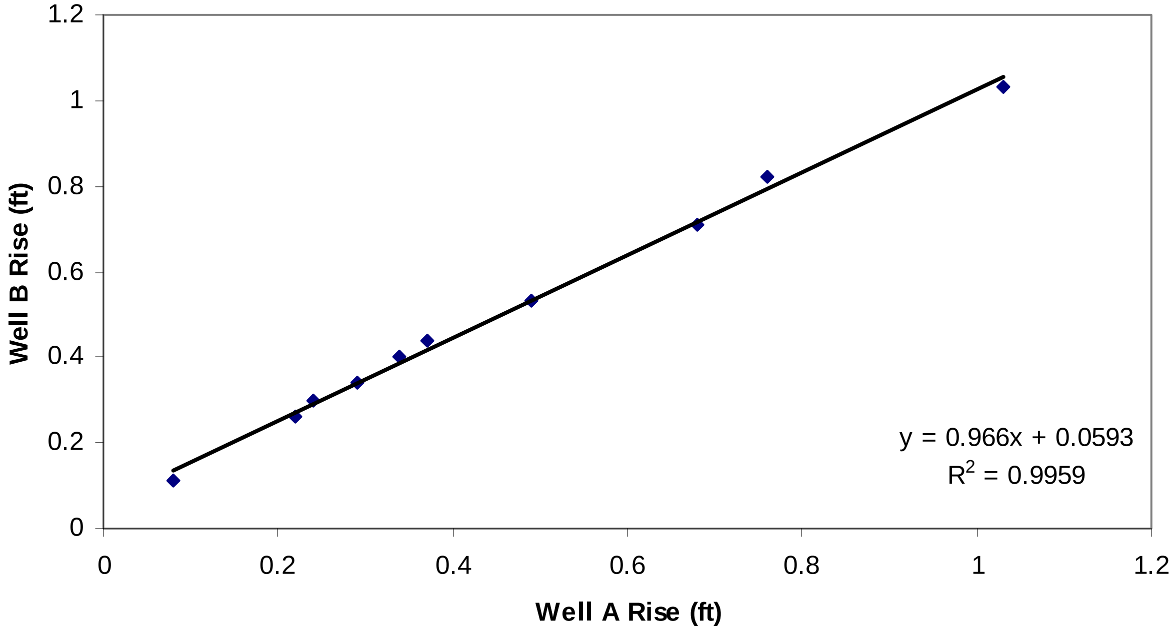


Figure 38: Upstream-Downstream Correlation for Watershed 1

identical responses. Figure 38 shows this correlation as a linear plot. This is quite interesting, as it clearly demonstrates that for extended periods of time, the two sections of the aquifer reacted similarly.

Beyond these areas however, the responses are vastly different. Figure 39 shows the average weekly changes in groundwater level in the two wells. Note that often times one well actually shows an average increase in level, whereas the other shows an average decrease. These differences make it very difficult to use the data to infer on the effectiveness of the infiltration gallery and construction measures.

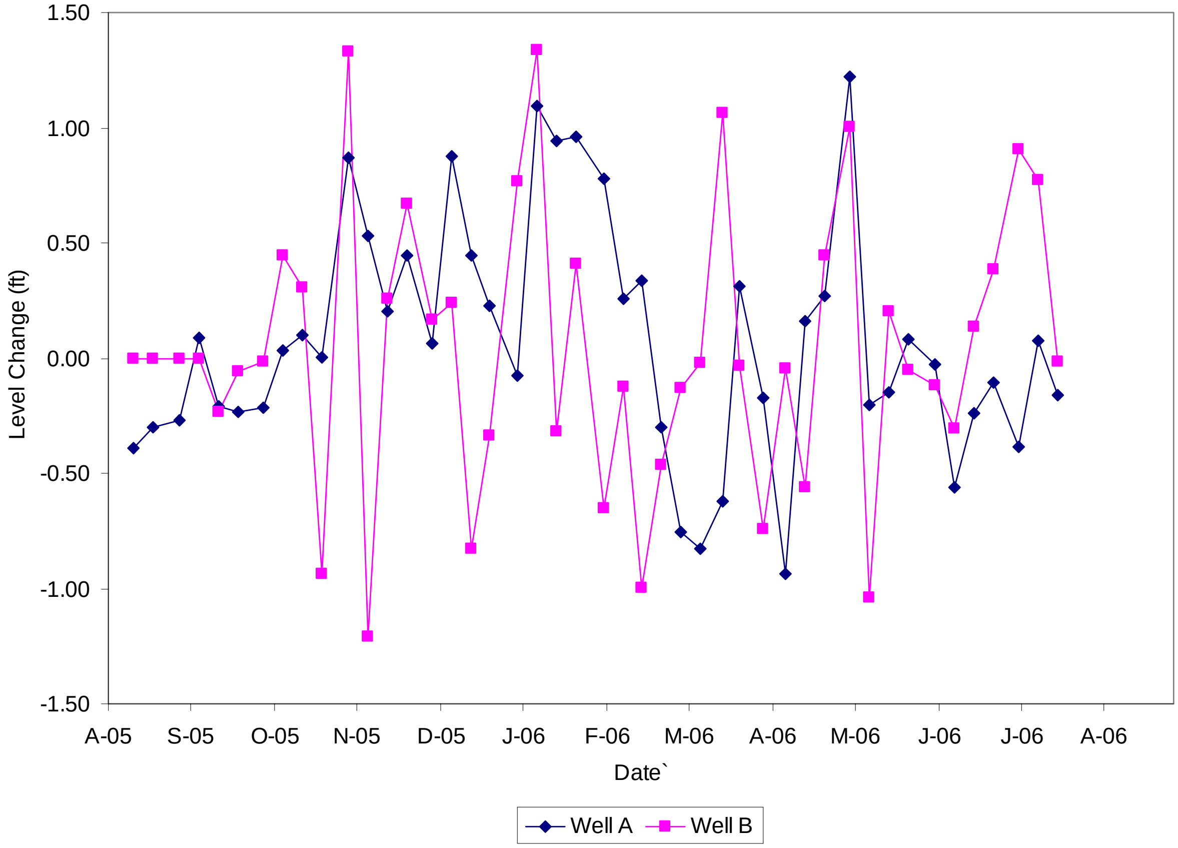


Figure 39: Weekly Changes in Groundwater Level at Watershed 1

One theory that had been explored regarding the behavior and interaction of the wells was that the downstream well not only contains its immediate response, but also will demonstrate a lagged version of the upstream response. This may be why the downstream well shows a constantly rising level even after the upstream well has receded. Based on the groundwater levels alone however, no clear evidence was discovered that would support this theory.

In order to further develop the theory, a tracer study was completed to provide estimates of how long groundwater takes to move from one well to the next. This value was intended to be used in conjunction with the timing of the level changes in order to correctly partition the data.

7.4 RECHARGE ANALYSIS

Understanding the recharge process and its relationship with rainfall is of critical importance to the management of groundwater systems (Todd and Mays, 2005). This being said, recharge estimation is one of the most difficult tasks undertaken in groundwater modeling. Many studies have been conducted in order to find a correct and efficient method of quantifying recharge. The most accurate methods consist of measuring all aspects of the hydrologic budget, including rainfall, evapotranspiration, and soil moisture. Other methods rely on broad estimates of these parameters and on the changes in groundwater level. As discussed in chapter three, the main technique employed for the estimation of recharge in this research was to combine a limited quantification of the hydrologic budget with groundwater level fluctuations. The end result of this analysis was to estimate the recharge volumes for individual storm events and over a long term period.

As discussed in the analysis of the groundwater fluctuations, difficulties were encountered when attempting to relate the groundwater level change to rainfall amounts and discharge volumes. Because of these shortcomings, recharge analysis was hindered. A great deal of effort was placed on researching the method that was applied during this study and many attempts were made to manipulate the measurements in order to determine accurate values of recharge.

7.4.1 Event Based Estimates of Recharge

To determine how much water is recharging the aquifer, water level rises will be used to estimate the average rise across the test watershed. Based on this rise, the recharge depth should take the form:

$$R = WTC \times S_y$$

where:

R = Recharge Depth
WTC = Fluctuation of the water table shown in the wells
S_y = Specific Yield of the aquifer.

The specific yield was estimated by analyzing the hydrologic budget of the watershed based on rainfall and runoff volumes in accordance with the assumptions presented in chapter 3. The simplified water budget can be stated as:

$$\text{Recharge} = \text{Rainfall} - \text{Runoff}$$

Evaporation and transpiration can be left out of the budget at this level, because their effects are minimal on a short term basis. Table 4 shows the quantification of the water budget for Watershed 1. Volumes were calculated based on the area of the watershed and an equal depth of water. Estimates of specific yield were determined by dividing the estimated recharge depth by the measured groundwater level rise. These estimates were then averaged and used to predict future recharge volumes based on groundwater fluctuation alone. This will be utilized in the long term analysis of recharge.

Table 4: Runoff and Specific Yield Estimates

					Estimated Specific Yield		
Storm Event	**Precipitation Volume (cf)**	**Runoff Volume (cf)**	**Recharge Volume (cf)**	**Recharge Depth (ft)**	**Well B**	**Well A**	**Ecotone**
9/25/2005	132,300	5,400	126,900	0.054	0.069	0.072	
9/29/2005	75,000	1,200	73,900	0.031	0.018	0.019	
10/20/2005	173,800	117,000	56,700	0.024	0.008		
11/8/2005	67,100	1,600	65,500	0.028	0.010		
11/14/2005	160,000	42,700	117,300	0.049	0.016	0.023	0.028
11/26/2005	569,700	278,200	291,500	0.123	0.026	0.059	0.022
2/3/2006	135,300	46,200	89,000	0.038	0.017	0.014	0.027
3/1/2006	46,400	4,800	41,600	0.018	0.013	0.021	
3/11/2006	119,500	31,100	88,400	0.037	0.009	0.085	0.093
3/31/2006	20,700	2,400	18,400	0.008	0.008	0.008	0.258
4/7/2006	64,200	5,500	58,600	0.025	0.012	0.018	0.004
4/21/2006	283,400	83,100	200,200	0.084	0.025		0.088
5/11/2006	241,900	37,800	204,100	0.086	0.027	0.083	0.080
5/14/2006	92,800	10,400	82,500	0.035	0.016		0.129
5/26/2006	54,300	13,600	40,700	0.017	0.016	0.016	0.054
				Average:	0.019	0.038	0.078

From the analysis of the water budget and the amounts of recharge occurring in response to each storm event, it is clear that significant amounts of water are entering the groundwater table. Fifty to ninety five percent of rainfall volumes have been found to permeate into the ground. From this it can be assumed that the construction has not significantly impeded the amount of water reaching the wetland areas.

Values of specific yield are estimated to be between .03 and .08 for silt and clay (Todd and Mays, 2005). Although these values are obtained from laboratory tests and are not effective at representing conditions at the site, they do show that the estimated values are reasonable.

7.4.2 Long Term Estimates of Recharge

Similarly to the short term recharge analysis; this method involves comparing the amount of precipitation input with the groundwater levels. Figure 40 shows the technique employed by Rasmussen and Andreasen to quantify recharge on a monthly basis. The average levels were plotted and the recession slopes were extrapolated to the peak of the subsequent rise. Since the specific yield values calculated for the short term events are a property of the aquifer, they should hold in the long term as well. Thus, the recharge for each week is equal to the specific yield times the observed rise.

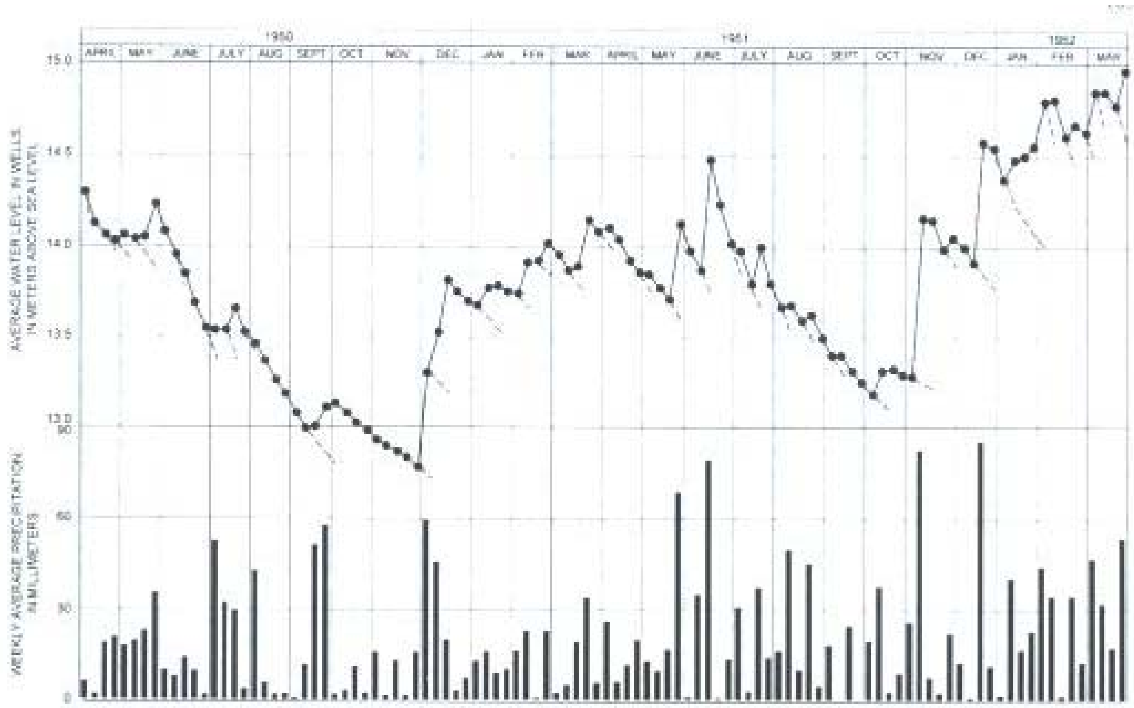


Figure 40: Method Used to Interpret Recharge Periods (Rasmussen and Andreasen, 1958)

Table 5 shows the results of this calculation for the entire observation period at each well. The groundwater fluctuation was taken as the sum of the weekly rises during the month, and the recharge depth was determined by multiplying the fluctuations by the estimated specific yield for that part of the aquifer. Again, it is clear that there is a constant supply of water recharging the aquifer. Even in the driest months and those with the lowest groundwater levels, there are measurable amounts of recharge.

Table 5: Monthly Recharge for Watershed 1

		Groundwater Fluctuation (ft)		Recharge Depth (in)	
Month	**Rainfall**	**Well A**	**Well B**	**Well A**	**Well B**
Aug	2.82	0.15	NA	0.07	NA
Sept	1.29	0.25	0.24	0.11	0.06
Oct	5.45	0.60	0.32	0.27	0.07
Nov	4.79	1.20	2.40	0.55	0.56
Dec	1.09	1.55	1.52	0.71	0.35
Jan	2.64	3.45	2.20	1.58	0.51
Feb	1.38	0.60	1.08	0.27	0.25
Mar	0.83	0.90	1.32	0.41	0.31
Apr	2.90	2.25	3.04	1.03	0.71
May	2.58	0.25	1.00	0.11	0.23
June	3.01	0.35	1.68	0.16	0.39
July	2.55	0.10	0.00	0.05	0.00
totals:	31.33	11.65	14.80	5.29	3.45

7.5 RECESSION ANALYSIS

The ability of an aquifer to drain its contents is based on properties that are unique to the formation and the rate by which it does so can be used as a defining parameter to model the response. In order to effectively estimate the recession rates, periods were selected with limited rainfall, as precipitation input alters the levels represented in the observation wells. This was done by selecting the recession curves that were extrapolated in order to determine the groundwater rises. Care was taken to only select those events that were not closely preceded by other events or were interrupted by rainfall input.

Table 6 shows the recession rates that were calculated for each well. Although these values only represent how quickly the levels recede vertically, they can be compared to the estimates of hydraulic conductivity through the test watershed. Table 7 shows the estimates of K from the slug tests preformed near the test sites. Hydraulic conductivity was also calculated during the tracer study. Table 8 shows the estimates of K from this analysis. Note that the values here are much greater. This is because they represent an average for the entire area instead of a small zone around the well. This makes sense based on the fractured nature of the aquifer.

Table 6: Recession Rates for Watershed 1

	Recession Rate (ft/min)	
Date	**Well A**	**Well B**
9/25/2005	2.875E-05	2.681E-05
10/20/2005	1.611E-05	1.778E-05
11/8/2005	2.111E-05	2.333E-05
11/14/2005	1.514E-05	5.333E-05
11/26/2005	1.486E-05	1.542E-05
1/2/2006	2.444E-05	7.806E-05
1/11/2006	3.236E-05	4.667E-05
1/13/2006	3.333E-05	1.528E-05
1/23/2006	3.694E-05	3.528E-05
1/29/2006	7.222E-06	5.764E-05
2/2/2006	3.389E-05	4.861E-05
2/16/2006	4.569E-05	4.569E-05
3/1/2006	2.014E-05	4.319E-05
3/11/2006	3.306E-05	4.292E-05
3/31/2006	3.444E-05	8.889E-06
4/3/2006	2.528E-05	3.167E-05
4/7/2006	1.944E-05	3.194E-05
4/21/2006	NA	3.819E-05
5/11/2006	NA	2.639E-06
5/14/2006	NA	7.347E-05

Average	2.601E-05	3.684E-05
Standard Deviation	9.967E-06	2.015E-05

7.6 FLOW ANALYSIS

7.6.1 Tracer Study

In order to estimate the hydraulic conductivity of the aquifers underlying the test watersheds and the time it takes water to pass under the roadway, a tracer study was conducted. This type of test measures the time required for water to travel between two points within the aquifer. Rhodamine dye was used as the tracer dye and was injected at the upstream observation wells as a single slug. Water samples were then taken at the downstream observation well and analyzed.

The first time this experiment was carried out, the goal was only to determine whether the dye would appear at the downstream sampling location. Prior to running the experiment, calculations were made using Darcy's Law to estimate the travel time between the wells. For this estimate, values of hydraulic conductivity determined from slug tests in nearby areas were utilized. A summary of these values is shown in the Table 7. These values of K are very low and not applicable to the whole system. From them it was calculated that the dye would not reach the lower well for thousands of years. Since it is clear that this estimate is much too large, a weekly sampling scheme was constructed three weeks after injection.

Table 7: Slug Test Estimates of Hydraulic Conductivity

Site Name	Located Near	Rising Head K (ft/min)	Falling Head K (ft/min)
MW-06	Watershed 1	8.803×10^{-5}	1.369×10^{-5}
MW-07	Watershed 1	1.067×10^{-5}	4.811×10^{-5}
MW-01	Watershed 2	5.432×10^{-4}	5.854×10^{-4}
MW-02	Watershed 2	6.122×10^{-5}	5.177×10^{-5}
MW-13	Watershed 2	5.566×10^{-3}	6.382×10^{-3}
MW-14	Watershed 2	1.463×10^{-5}	1.566×10^{-5}

After it was determined that the tracer passed from one well to the other, a more detailed investigation was conducted. Dye was injected into the upstream well and samples were taken in the downstream well three times a week to determine the time of travel.

The average velocity, v_a, the dye will have through the aquifer is based on the hydraulic gradient (h/L), porosity of the soil (α), time of travel (t), and the hydraulic conductivity (K). Since the average system porosity is not known, this value will be estimated as a range based on common values.

$$v_a = \frac{K}{\alpha}\frac{h}{L}$$ Velocity based on hydraulic parameters

$$v_a = \frac{L}{t}$$ Velocity based on distance and travel time

$$K = \frac{\alpha L^2}{ht}$$ Hydraulic Conductivity

In order to solve these equations, the groundwater surface elevations were noted from the loggers and an average difference in height was determined. A yearly record of water surface elevations is shown in Figure 41.

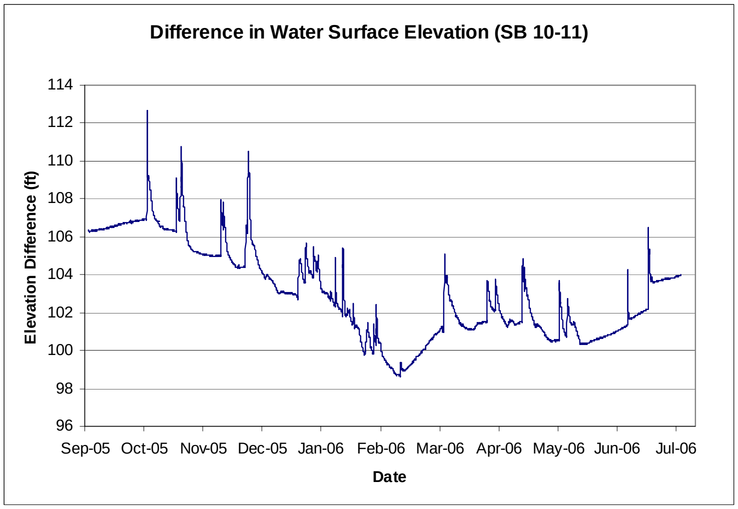


Figure 41: Fluctuating Hydraulic Gradient in Watershed 1

The dye injection date and time was recorded and a log was kept of downstream dye concentration over time. Based on this data, the dye plume moved very quickly past the downstream well. The travel time was 21 days. The following quantities were determined:

$t = 21$ days

$L = 600$ feet

$h = 104$ feet

$v_a = 28.5$ ft/day

From these data, the values of conductivity shown in Table 8 were determined for a range of possible porosity values.

Table 8: Hydraulic Conductivity from Tracer Tests:

α	**(ft/min)**
0.25	.0286
0.3	.0344
0.35	.0401
0.4	.0458

8.0 SUMMARY AND CONCLUSIONS

The two main objectives set forth at the onset of this research will be addressed in this chapter. The first objective, to devise, implement, and test a system of hydrologic monitoring equipment, was accomplished within the budgeted time and cost of the project. An assessment of the equipment and tools used to collect, organize, and transmit the data will be presented in this chapter. The second objective, interpreting the collected data to represent and model the present and future conditions, was achieved with varying degrees of certainty. Separate sections are included for each aspect of the analysis. Each section summarizes the findings, expresses a level of confidence, and attempts to evaluate the construction techniques. A final section is included which makes specific suggestions on how the monitoring system and data analysis techniques can be improved upon.

8.1 INSTRUMENTATION AND DATA ORGANIZATION

The methods of data collection and organization utilized during this research were effective, in as the data was efficiently gathered, transferred, and organized through the cooperation of multiple organizations. All pieces of equipment functioned throughout the monitoring period, with some minor exceptions.

8.1.1 Installed Equipment

The four deep monitoring wells continuously recorded data over the course of the research. One of the wells was damaged while taking measurements, but it was fixed within weeks. Although it is difficult to determine if the values the wells recorded were accurate, it is certain that they were consistent and continuous. The shallow wells did display some problems recording data. This was identified by time periods where no data was recorded. It is believed that much of this problem may be due to the affects cold temperatures, causing water to freeze in the shallow pipe or the equipment to improperly function. Despite these apparent short term malfunctions, the shallow wells also seemed to respond consistently, if not accurately. The surface water flumes experienced some of the same problems as did the shallow Ecotones. This is understandable, as they are basically the same device. In the future, these devices may need to be modified to deal with the extreme conditions since they are more likely to be exposed to the elements than the deep wells. The rain gages also seemed to function correctly, aside from the timing error that was explained in chapter 5. The accuracy of the equipment will be addressed in the data analysis portion of the conclusion.

This network of equipment met the requirement of measuring the hydrologic regime within the small watersheds, including surface water runoff, groundwater fluctuation, and meteorological conditions.

8.1.2 Test Watersheds

Each watershed contained the required features that were needed to represent the construction zone. Most importantly, both watersheds contained the infiltration gallery, which was of particular interest. Sedimentation basins and drainage networks were also included. Limited data was available as to the schedule of the ongoing construction during the research period. This includes the grading and paving of the roadway, re-routing of drainage channels, and the failure of certain structures. For instance, it was discovered that one of the sedimentation basins failed during a significant storm. In the future, it is recommended that better communication be made between the construction personnel and the researchers.

Based on the available information, it appeared that the test watersheds were representative of the average geologic conditions present throughout the construction zone. Not much confidence in placed in this conclusion however, as the conditions were merely assumed to be similar to that of locations located miles from the actual site. This information was based on soil borings and slug tests. It was assumed that the three intervals of low permeability clay, weathered bedrock, and fractured bedrock underlay the area. This seemed reasonable based on some of the response patterns. For instance, the possibility that the surface material may act as a confining layer pressurizing the aquifer coincided with the dense clay. Also, the rapid rises and recessions of the water levels seemed to be a reasonable property of the fractured bedrock interval.

8.1.3 Data Organization

Through the collaboration of all firms involved in the project, including The University of Pittsburgh, PENNDOT, AWK Engineers, GAI Consultants, and Skelly and Loy Inc., an effective schedule for data collection and transmittal was successfully devised and followed throughout the research period. Data was collected, on average, once a month. Maintenance trips were also scheduled periodically to check the performance of some equipment.

Data was effectively transmitted and presented through the use of text editing programs, spreadsheets, and GIS. Spreadsheets served as the main tool for data storage, delivery, and analysis. GIS was mainly used as a visual aid, but its potential for providing an integrated approach to data analysis and visualization was clearly demonstrated. Other tools were investigated for implementation. The benefits of these tools were not deemed significant enough to devote further effort at this time.

8.2 DATA ANALYSIS

The collected data was analyzed by various methods in an attempt to model present conditions, predict future responses, and use the results to evaluate the construction measures. Effort was placed on developing a relationship between groundwater rise and rainfall amount. This was achieved, but with a low degree of certainty. Despite this uncertainty, conclusions could still be drawn from the data regarding the environmental stability of the test sites.

8.2.1 Long Term Response Patterns

The long term analysis of the response patterns demonstrated that even when studying small areas, the behavior of the aquifer across the site can be very different. It was shown that the upstream deep well and the downstream shallow well did not display seasonal trends. The patterns indicated a groundwater level that was reliant on event based input. Three possible explanations were identified for this behavior. First, in regard to the upstream locations, the well might not have been drilled deep enough into the aquifer. This would have prevented a complete view of the groundwater table. Second, the response pattern indicates that the upslope portion of the mountain does not hold significant levels of groundwater. This water may immediately be conveyed to the downstream wetlands. Third, fractured formations may create individual channels for water to flow, reducing the amount of water that comes in contact with the well shaft, especially in the upstream portion of the aquifer.

The downstream deep well did display a seasonal pattern. It was also clear that this seasonal pattern was reliant on individual input from storm events. Over the entire study period, this well contained significant depths of water. This pattern is comparable to many wetland areas in the United States and indicates that the wetlands have a sufficient supply of water despite the possible reductions in infiltration due to the roadway surface.

8.2.2 Short Term Response Patterns

Fluctuations in groundwater levels did show moderate correlations with rainfall amounts. The ratio of rise in groundwater level to depth of precipitation ranged from 12 to 31. The lack of stronger relationships is attributed to the inability of the rain gages to estimate the precipitation depth at the test sites and also to the lack of response data occurring from small magnitude events. It was also determined that rainfall intensity was not a major factor in the fluctuation pattern.

Based on the analysis of the inordinately large rises associated with some rainfall events, it was decided that these responses could not be correlated with input. It is still unclear as to what value or ratio should be used as a threshold to make the distinction between reasonable and unreasonable response. Although it was not explicitly proven that the Lisse effect was responsible for any of these events, it stands as the best explanation to date.

8.2.3 Upstream Downstream Correlations

Comparison of upstream and downstream responses was intended to display the effectiveness of the infiltration gallery by providing a means of deducing the groundwater flow mechanisms beneath the road surface. It was theorized that response of the wells on the upstream and downstream side of the roadway would indicate an immediate local response to rainfall. In addition to this, the downstream well should show a lagged response due to the down slope flow of the groundwater. These responses could then be analyzed to indicate the flow rate beneath the road.

The lagged response was not able to be separated from the local response at the downstream well. For the majority of the monitoring period the wells responded uniquely with no discernable correlation. Based on this, inferences about the infiltration gallery could not be made.

For a select few time periods however, response in the wells appeared to be identical. It can be concluded from this that these different portions of the aquifer do have the ability to respond similarly, indicating that the subsurface properties may be comparable. It also demonstrates that certain variables must change drastically over time between the two locations. These dynamic properties could not be identified, but may include soil moisture, abstractions such as evapotranspiration, and changes in the topography due to the construction.

8.2.4 Recharge Analysis

Short term and long term estimates of recharge provided a means of evaluating the constructions effect on the environment. The estimation of recharge depth by way of water budget analysis clearly demonstrated that significant amounts of water were infiltrating into the ground. It was shown that 50 to 95 percent of the rainfall was estimated to be recharging the groundwater and eventually the wetland areas. The specific yield values that were determined from the modified WTF method ranged from 0.019 to 0.078, which are reasonable based on published values. Using the methods studied to analyze the long term recharge process, it was shown that both the upstream and downstream wells experienced net total increases in groundwater level through the year. Again, this seems to show that the construction practices have not hindered the recharge process.

Because of the weak correlation between recharge and rainfall depth for individual storm events, it was not possible to use the groundwater recharge estimates to further calibrate the surface water model.

8.2.5 Recession Analysis

A linear relationship was shown to best represent the collected groundwater recession data. The slopes of this relationship ranged from 2.6×10^{-5} to 3.68×10^{-5} ft/min. These relationships were very strong, with R-squared values greater than 0.9. The average recession rate over the course of the monitoring period was fairly constant. Based on this, it does not appear that the construction created significant changes in the way water recedes or travels through the area.

The calculated recession rates of flow compare very well with the estimates of hydraulic conductivity from the slug tests near watershed 1. These recession values are indicative of the natural drainage of the aquifer and thus comparable to base flow.

8.2.6 Flow Analysis

The analysis of flow rates based on tracer studies provided valuable information regarding the hydraulic conductivity of the aquifer as well as the flow path of water through the test site. First of all, it was found that water did flow along the assumed travel route between the wells. This was a very beneficial piece of information, as it was one of the major assumptions that most of the other analyses were based upon. The analysis also provided for a more reasonable value of hydraulic conductivity, ranging from .02 to .05 ft/min. These values are more representative of the entire aquifer than the slug tests and recession analysis, and thus better account for the effects of the fractured formations, which tend to increase flow rates.

In regards to the construction techniques, the relatively expedient passage of the dye through the construction area shows that the roadway cut and infiltration gallery appear to be working well at maintaining groundwater flow.

8.3 FUTURE WORK

Numerous opportunities are available to improve upon the methods set forth by this research. The monitoring system itself is open to the most modification, as lack of pertinent data was a major issue during the study period. Improvements can also be made on the analysis techniques that were utilized to evaluate the data.

The best way to increase certainty in the system and obtain a better view of the subsurface behaviors is to add more monitoring wells. It is suggested that at least two wells be included at each monitoring location for redundancy. This would increase the confidence level and show that well records were actually indicative of groundwater response, and not of equipment malfunctions. In order to better show the effects of the infiltration gallery, it is recommended that shallow recorders be placed around this structure to augment the deep wells. Since the infiltration gallery is not very deep in the earth, these devices may provide more applicable information regarding the flow processes through it.

In the future, rain gages must be located on site. This would provide much more accurate values of rainfall amounts and increase the number of events that could be analyzed. This may greatly increase the strength of the relationship between groundwater rise and rainfall depth.

It is also suggested that in the future detailed sub surface investigations be conducted at each well location within each test site. Although this may increase costs, without this information the analysis of groundwater behavior is greatly hindered.

The Lisse effect is still a relatively unknown phenomenon that could only be speculated on in this research. It is suggested that either specialized equipment, such as sensitive pressure gages, be employed at the test sites to try to identify this effect or that laboratory analysis be completed to visualize the mechanisms that cause the unique response patterns.

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