HYDROGEOLOGIC ASSESSMENT OF SHALLOW GROUNDWATER FLOW SYSTEMS IN THE WALNUT FORMATION, CENTRAL TEXAS

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of
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by
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ABSTRACT

The Walnut Formation is the most clay-rich member of the limestone dominated Lower Cretaceous rocks of central Texas. Due to this clayey nature, the Walnut Formation is a natural target for landfills in this region. Shallow groundwater flow systems present within the Walnut Formation provide baseflow to streams which transect the Walnut outcrop belt in Central Texas.

Three sites within the outcrop belt of the Walnut Formation were investigated. The Walnut flow systems are geomorphically and stratigraphically controlled, and recharge zones are influenced by the geomorphic history and subsequent soil formation. Discharge zones are controlled by seasonal influences, stratigraphy, and geomorphic position.

Field observations indicated saturated zones in the near surface Walnut Formation may produce hydraulic heads above ground elevation. These saturated zones, within the weathered depth of the Walnut Formation, discharge to main streams by tributary discharge and spring flow. Conceptual models of the flow systems were constructed following field observations, hydrogeolgic testing (slug tests and pumping tests), geochemical analyses, and hydrograph analysis and interpretation.

Regionally, the Walnut flow systems relate to the condition of the underlying Paluxy Formation (a minor aquifer). Flow systems of the Walnut Formation are important from a regional perspective due to the potential of non-point source contamination to surface waters by landuse practices on the Walnut outcrop area.

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CHAPTER 1

INTRODUCTION

Purpose

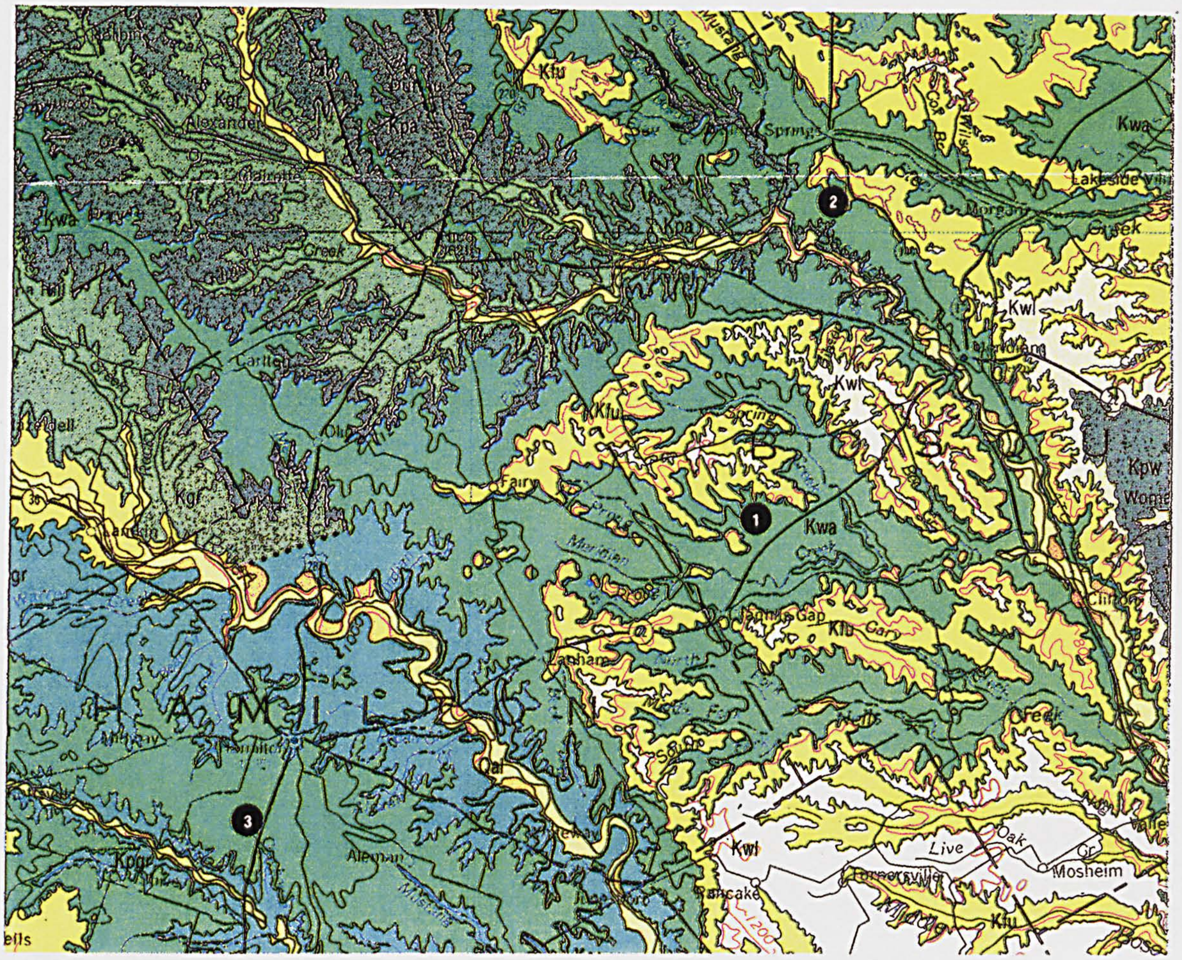
The Walnut Formation is primarily a limestone and interbedded clay and marl formation of the Lower Cretaceous outcrop belt in Texas; a section dominantly composed of limestone. Due to the clay content, the Walnut Formation often supports agricultural practices, an uncommon landuse in this section of Central Texas. The agricultural landuse and the potential for non-point source contamination makes the understanding of the shallow groundwater flow-systems extremely important. The shallow, near-surface flow-systems of the Walnut have not received much attention, but their existence and relevance is supported by the presence of baseflow in the small streams which cross the Walnut outcrop belt, by seeps in the field, and by evidence of water movement such as calcite growth and weathering profiles noted in the outcrop area. Another important aspect of the Walnut Formation is it's hydraulic connection with the underlying Paluxy Formation (Crumpler, 1989, p. vi), a minor aquifer in the State of Texas.

The clay content of the Walnut Formation, makes it a natural target for landfills amid the limestone-dominated Lower Cretaceous outcrop belt. This study describes the shallow flow systems present within the Walnut Formation, and attempts to quantify some of the aquifer parameters. Chemical analysis were conducted to delineate a base-line representation of the waters contained in the shallow flow-systems.

Location

The study area consists of three "type" sites that are included in an area which extends from near Killeen on the southern border to Walnut Springs on the northern border (fig. 1). The westward limit of the study is near Hamilton, with the eastern margin of the study area being the boundary between the Lampasas Cut Plain and the Washita Prairie, two of the subdivisions of the Grand Prairies of Texas. Structurally, the Walnut Clay lies on the stable Trinity Shelf (Lemons, 1981, p. 16), west of the Balcones Fault Zone.

The Walnut may be found in two different geomorphic locations; either divides or upper valley positions (fig. 2). The present study investigates the properties of the flow systems located in the different geomorphic positions. Because the study of the flow systems was limited to shallow depths, different facies at the near surface were not considered a dominant control on the flow system; however, stratigraphy may play a role in the formation of a water-bearing zone within the approximate thirty foot thickness studied. Site one is located approximately 6 miles northeast of Cranfills Gap, Texas. Site two is located in the town of Walnut Springs, Texas. Site three is located approximately 5 miles south of the city of Hamilton, Texas. The most common lithology which surrounds the Walnut outcrop belt is limestone. Due to the clay-like texture of the Walnut Formation in some locations, it is a natural target for landfill placement. Also, in this region of Central Texas, many creeks head on or transect the



LEGEND

Kgr - Glen Rose; Kpa- Paluxy; Kwa - Walnut;
Kfu - Upper Fredericksburg (Comanche Peak and Edwards Formations;
Kwl - Lower Washita Formation.

Figure 1. Map showing the geology and location of the three "type" sites used in this investigation. All site areas are located in the outcrop belt of the Walnut Formation. Notice at site 3 the Edwards Formation is well removed and the site is located in the Leon River Basin. Sites one and two are located in a traditional Cut Plain physiographic setting, with Edwards Limestone capping divides, slopes exposing the Comanche Peak Formation, and valleys formed on the Walnut Formation.
(Barnes, 1992, N.E. Quadrant, 1:500,000)

Walnut Formation. These streams apparently receive baseflow waters that are discharged from groundwater flow systems within the Walnut Formation.

Methods

The principle method of investigation was field reconnaissance to study outcrops of the Walnut Formation and to locate evidence of flow within the formation in the field. Site areas were chosen in different geomorphic and stratigraphic positions to evaluate the heterogeneity of aquifer parameters (fig. 2). Aquifer testing included pumping tests, slug tests, and Guelph field and laboratory permeameter testing. Water level data were collected over a period of several months, and interpretations were made based upon water level relationships and changes over the monitoring period. Chemical analyses of water samples were conducted using capillarey electrophoresis, to define a baseline water chemistry, and to observe any chemical changes in the flow regime. Several years of previous field work in and adjacent to the immediate study area aided the investigation.

Previous Works

Several works were of particular value to this investigation. One of the most helpful previous investigations was conducted by Crumpler (1989) during his study of the Paluxy Formation. He discussed the contribution of flow through the Walnut Formation and the addition of recharge to the Paluxy from the Walnut. Crumpler also mentioned the presence of several large-diameter, hand-dug wells which were completed in the Walnut Formation.

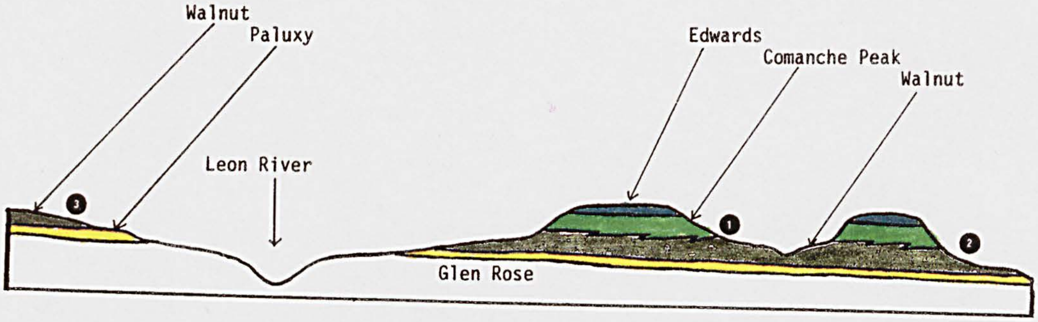


Figure 2. Diagrammatic sketch showing cross-sectional geology and land surface profile of the study area. The Cretaceous rocks dip gently to the east, and the Edwards Formation has been well removed from the region near the Leon River Basin. Site three (Hamilton) is located where the Walnut Formation is on a divide. Sites one and two are located on the Walnut Formation in a valley position below and Edwards Limestone capped scarp.

Previous works on the stratigraphy of the Walnut include Jones (1966) who discussed in detail the stratigraphy of the Walnut Formation in the study area. Moore (1961 and 1964) also detailed stratigraphic relationships of the Walnut Formation and the Fredericksburg Group. Amsbury (1988) detailed an outcrop study of the Fredericksburg Group, which included information on stratigraphy and lithologic character of the Walnut Formation in the study area.

Leach and Herbert (1982) documented shallow groundwater flow in a colluvial hillslope, a paper which greatly aided the development of the conceptual models found in the present study. Another important paper for the present study was a conceptual model developed by Rushton (1986) which dealt with vertical flow components in hillslope and alluvial aquifers.

Brotherton (1978) mapped significant colluvial sections within the Lampasas Cut Plain region of Central Texas. Identifying colluvial sections is important to the understanding of the widespread nature of these Walnut flow systems.

Other previous works utilized for this investigation are listed in Appendix I in this investigation.

Acknowledgements

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CHAPTER 2

REGIONAL DESCRIPTION OF WALNUT FORMATION OUTCROP BELT

Introduction

The stratigraphy of the Walnut Formation and the geomorphology of the study area are important to the understanding of the hydrogeology of the formation. While the flow systems found in the Walnut are normally a function of both stratigraphy and geomorphology, it is currently understood that the dominant component of flow within the formation is lateral flow through bedding planes, with fracturing, due to weathering, often aiding the groundwater flow in the formation. Using the above interpretation, geomorphic position may be more important than stratigraphy in the control of flow systems. Also, geomorphic position would appear to influence recharge and discharge sites within the flow systems.

Regional Geology of outcrop area

Stratigraphy

The Walnut Formation is a formation of the Fredericksburg Group of Central Texas. The Fredericksburg Group is a transgressive sequence, and has often been interpreted as a "pulsed" transgression (Corwin, 1982, p. 32). Fredericksburg rocks were deposited on the Trinity Shelf, a gently subsiding platform which was slowly inundated by advancing Cretaceous seas (Lemons, 1987, p. 18).

The Walnut Formation is a series of nodular limestones, thin to medium, regular-bedded limestones (often ripple-marked), and oyster beds throughout the section (Jones, 1966, p.iv, and Flatt, 1976, p. 14). The combination of lithologies are often interbedded with thin calcareous clay layers. The oyster beds are not prominent in the western portion of the study area, but are common in the central section of the study area, in Bosque, Coryell, and Hamilton Counties (Flatt, 1976, p. 16). Normally the oyster banks are "all underlain and overlain by thin beds of clays and calcareous shale (maximum six inches)", which normally do not contain the same fossil content as the oyster beds themselves (Flatt, 1976, p. 16).

Because of the weathering profile of the Walnut Formation, there are few stratigraphic sections exposed which show a considerable thickness of the formation (fig 3). While authors mention sections of black, calcareous clay (Sellards and others, 1932, p. 330), these clay beds are usually thin and the remainder of the stratigraphic section consist of thin-bedded limestones, thicker, chalky, nodular limestones, and shell aggregates (Sellards and others, 1932, p. 330).

The Walnut Formation has a varying thickness in the study area, ranging from a few feet of exposure in the western portion of the study area to 130 feet near the eastern margin of the study area. Because the marl or clay is seldom exposed without soil cover, the limestone units form most outcrops (usually small) giving the impression that the Walnut Formation is dominantly limestone (fig. 4). It is now understood that the flatter landscape common to the Walnut outcrop belt may be more a result of landscape evolution processes than of lithology (Hayward, 1991, personal communication). Ripple-marked limestone beds have been described in

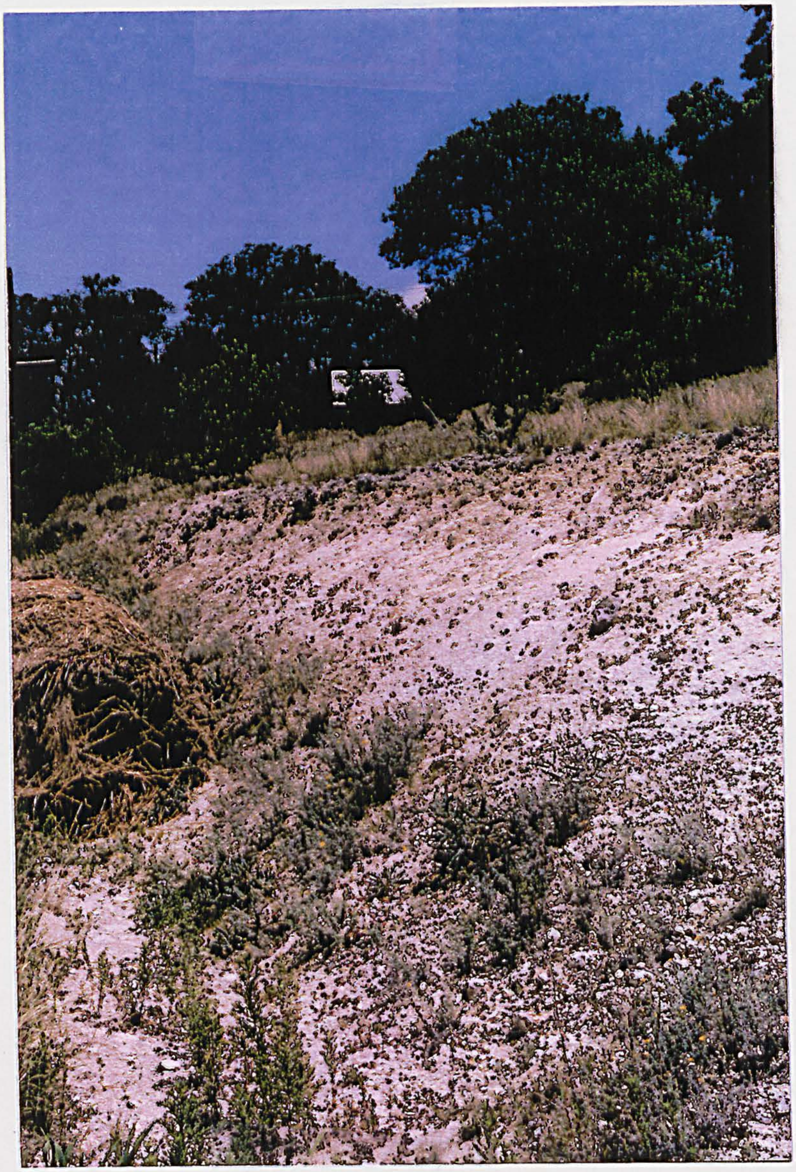


Figure 3. Photo showing typical outcrop of the Walnut Formation. The outcrop is capped and supported by an indurated limestone bed and a Gryphea shell hash bed. These indurated limestones support the topography and the less resistant nodular limestones form the outcrop lithology. The nodular limestone seen in the photo is probably the most common lithology of the Walnut Formation. These nodular limestone beds are often interbedded with thin, regular-bedded limestones, and thin calcareous clay beds.

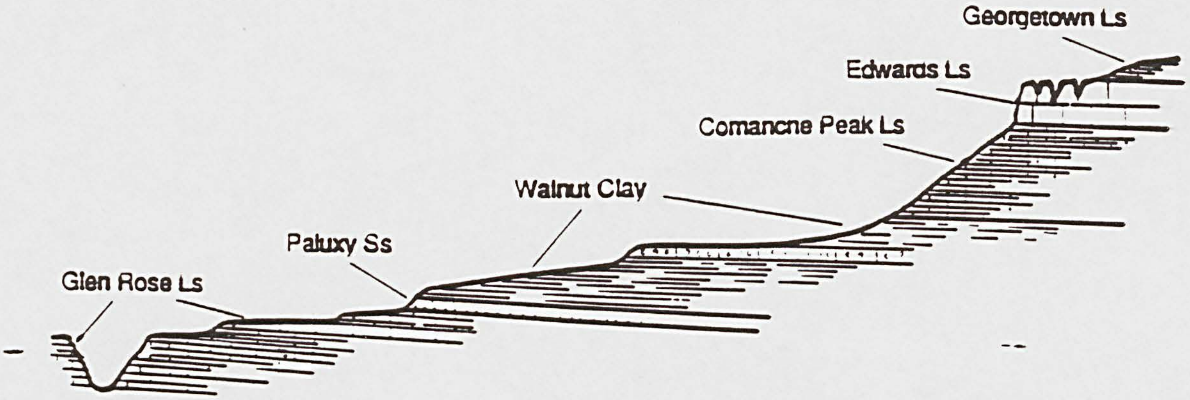


Figure 4. Index geologic section and geomorphic expression of the Cretaceous formations located in the study area. The Walnut Formation normally forms a broad valley floor beneath Edwards-capped divides.

three lower members of the Walnut Formation, the Bull Creek, the Bee Cave, and the Cedar Park (Jones 1966, pp. v-vii). The orientation of the ripple marks is predominantly NW-SE , although there may be significant variation in the orientation of ripples from outcrop to outcrop. Most of these ripple-marked limestones are indurated and probably aid the horizontal flow by creating a permeability barrier and drastically reducing flow in the vertical direction.

The Walnut Formation overlies either the Paluxy Formation, or where the Paluxy is absent, the Glen Rose Formation. In the outcrop belt, the southern extent of the Paluxy occurs in the Killeen area. The Paluxy is a fine to medium grain sandstone (Owen, 1979, p. 12), which is considered a minor aquifer within the state of Texas. In the western section of the study area, the Paluxy is thickest, and thins to the south and east. Beyond the Paluxy pinch-out to the east (fig. 1), the Walnut Formation overlies the Glen Rose Formation.

The Glen Rose Formation is a thin-to-thick-bedded limestone, and limestones are often interbedded with sandy sections. The Glen Rose Formation is not considered an aquifer within the study area. This study did not investigate Walnut Formation flow systems near the western margin of the outcrop belt due to little to no evidence of lateral flow in the Walnut Formation in this area.

The Walnut Formation has an interfingering contact with the Comanche Peak Formation in most of the study area, particularly the southern and central regions. The Comanche Peak Formation is a dominantly limestone unit of regular-bedded and nodular limestones, often interbedded with thin marl layers (Keyes, 1977, plate II). The Comanche Peak Formation is overlain by the Edwards Formation. The Edwards Formation is a 30 to 35 foot section of limestone, often biohermal in nature, overlying the Comanche Peak Formation. Present within the Edwards Formation are cherty sections which are normally associated with thick regular-bedded limestones.

Structure

Dip varies slightly across the region because subsidence and Comanchean deposition were contemporaneous. Thus, lower stratigraphic units have somewhat steeper dips than rocks in the upper portion of the section. The outcrop belt of the Walnut is a linear belt extending in a general north to south/south-west trend in Central Texas (fig. 1). The strike of the formation generally follows this trend, and the formation is a part of a gentle homocline dipping east toward the East Texas Basin. The dip increases from west to the east-southeast varying from approximately 10 to 25 feet per mile in the outcrop belt.

The fracturing seen in the outcrop of the Walnut appear to be weathering related and not due to tectonic influence. There appears to be no consistent orientation to the fractures observed on the outcrop based upon field investigation of several outcrops. The fractures are important in aiding the vertical flow dimension in the formation, and may present the only reliable vertical connection within the flow regime due to the presence of clay beds and indurated limestone beds, both of which tend to inhibit vertical flow through the formation.

Regional Geomorphology of the study area

The Walnut Formation crops out in several different geomorphic provinces. These include the Grand Prairie (fig. 5) (including the sub-province of the Lampasas Cut Plain) and the Fort Worth Prairie. The Walnut Formation typically occupies two

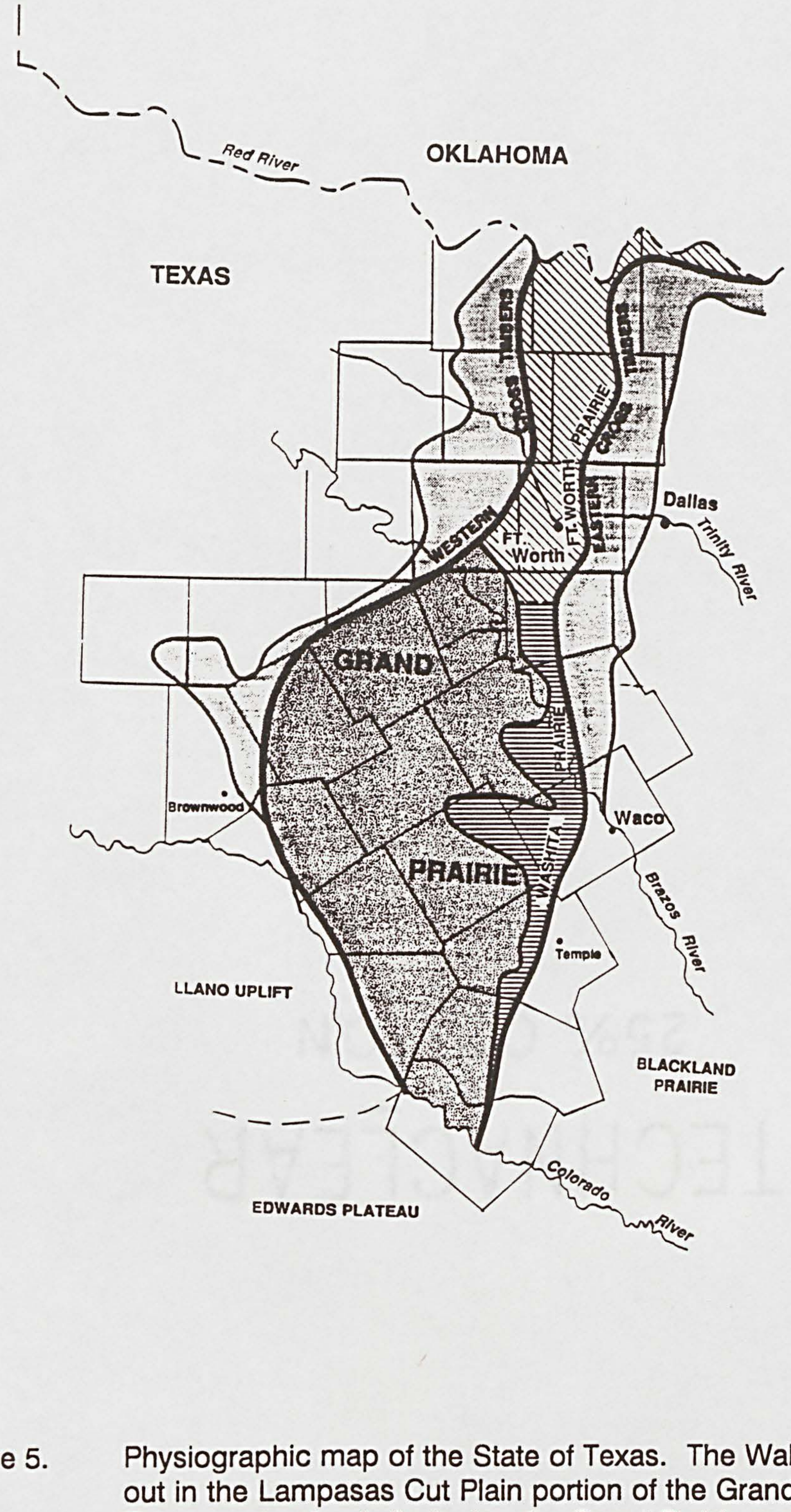


Figure 5. Physiographic map of the State of Texas. The Walnut Formation crops out in the Lampasas Cut Plain portion of the Grand Prairie of Texas. This investigation is limited to the Grand Prairie region.

major different geomorphic positions; one is a divide scenario which caps small, remnant sections of an older valley (site 3), while the other, more common position, is in a valley position which extends up to the Edwards capped divides of the Lampasas Cut Plain (sites 1 and 2) (figs. 1 and 2).

Following a period of scarp retreat (Hayward and others, 1990, p. 12), colluvial material was deposited at the base of the Edwards-capped divides, and grades out into the flatter valleys formed on the Walnut Formation. The interim slope between the Edwards and the Walnut is normally steep, and is formed on the Comanche Peak Formation, while the base of this slope is the location of colluvial deposits.

In the western portion of the study area, in the Leon River Valley (fig. 1), the Edwards Formation is well removed, and the inner valley of the Leon River often has inter-basin divides formed on the Walnut Formation. There appears to be significantly less colluvial material present where the Edwards scarps are not present.

Regional Hydrogeology

The most direct evidence of groundwater in the outcrop area is perennial baseflow in the streams which drain the landscapes (fig. 6). It was originally assumed that much of the baseflow present in the streams was from the Edwards Formation (Brotherton, 1978, p. 17); however, most of the Edwards springs which flow in the fall and winter (wet periods) are dry by late spring and summer (dry periods). When the Edwards springs are dry, baseflow continues and must be derived from elsewhere in the hydrogeologic framework such as alluvial deposits or other bedrock sources. The shallow flow systems in the Walnut Formation discharge into the streams and provide

Figure 6. Baseflow in Meridian Creek, west of Meridian, Texas. This baseflow component of Central Texas streams is the most obvious evidence of groundwater flow within the Walnut Formation. This photo was taken in the summer months when the Edwards springs have ceased flowing. The water present in the creek is discharged from the Walnut Formation, and possibly in minor amounts from alluvial sections which occur near the streams. Due to the continued flow, it is interpreted that much of the water present in the streams during baseflow conditions must be discharged from the Walnut Formation.

much of the baseflow to the streams. The town of Walnut Springs, Texas, has springs in the city park which discharge from the Walnut Formation to Steele Creek (fig. 1). Here, the presence of the springs indicates a recharge zone away from the immediate vicinity. Other lines of evidence of groundwater within the Walnut Formation are caliche profiles included in the local stratigraphy, calcite re-crystallization, and oxidized zones along fractures seen in outcrops of the Walnut Formation.

The Walnut Formation overlies the Paluxy Formation in most of the outcrop area, excluding the southern portion (fig. 1). The Paluxy is recognized as a minor aquifer in the State of Texas (as defined by the Texas Natural Recourse Conservation Commission), and represents a major component of the regional hydrogeology of the Walnut outcrop belt. In the western area of this study, the Paluxy is exposed with the Walnut in outcrop. Hydraulic head, if present in the Paluxy, is less than the head present in the Walnut Formation, indicating a downward gradient to the Paluxy from the Walnut. Further to the east in the Walnut outcrop belt, the Paluxy becomes completely saturated and eventually a confined aquifer, and the downward gradient is decreased. The confinement of the Paluxy Aquifer occurs approximately in the region between Cranfills Gap and Meridian, Texas (Crumpler, 1989, p. 28). The position of the confinement lies between sites one and two of the present study.

Crumpler's (1989) data indicatethat the piezometric surface present within the Paluxy is well below the water levels observed in the Walnut in the areas of this investigation. This interpretation indicates the overall regional gradient is downward from the Walnut Formation to the Paluxy Formation. The downward gradient between the Walnut and Paluxy Formations decreases eastward in the study area as the Paluxy Aquifer becomes confined near Meridian, Texas (Crumpler, 1989, p. 26).

CHAPTER 3

FLOW SYSTEM CHARACTERISTICS OF SITE ONE

Introduction

Site one is located approximately twelve miles southwest of Meridian, and 6 miles east of Cranfills Gap, in Bosque County, Texas (fig. 1). The geomorphic location of this site is an upper valley position, at the base of an Edwards-capped scarp. This geomorphic setting is common throughout the study area.

Geology of Site One

The geology at site one includes the Walnut, Comanche Peak, and Edwards formations, and a residual soil material remaining from the weathered, overlying Georgetown Formation (Washita Group) (fig. 7). The Paluxy Formation is not exposed in the immediate area of study, but underlies the Walnut and is probably unconfined in this area (Crumpler, 1989 p. 36).

The geomorphic evolution of the Cut Plain landscape created colluvial deposits at the base of the slopes following a period of scarp retreat (Hayward and others, 1991, personal communication). Following scarp retreat, the finer fraction of this material washed further into the valley and is represented by thick clay soils overlying the Walnut Formation (fig. 7). The colluvial deposits (fig. 8) which occur laterally along the scarp line are finer grained clay matrix with small limestone cobbles and chert cobbles. The other colluvial material present at the immediate base and on the

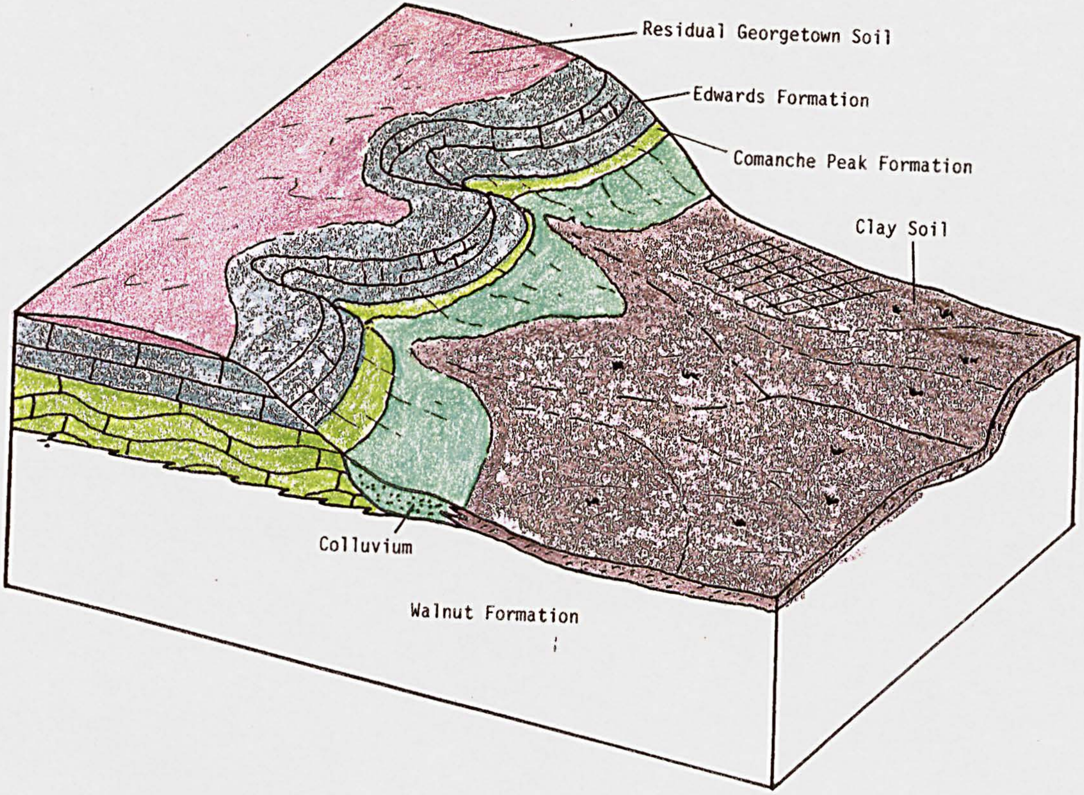


Figure 7. Diagrammatic sketch of geology present at site one. The scarp is capped by Edwards Limestone, with a soil which is the residual of the Georgetown Formation (Lower Washita Group) remaining on the top of the divide. The Comanche Peak Formation is exposed in the face of the escarpment. Colluvial material blankets the base of the slope, and represents material deposited following a period of scarp retreat that occurred during the geomorphic evolution of the Cut Plain (Hayward and others, 1990). A thick, clay soil overlies the Walnut Formation at this location, and at the base of nearly every divide in the Cut Plain.

Figure 8. Photo showing the nature of the colluvial material. This colluvial material has a high infiltration rate (compared to the neighboring soils), and represents the best potential of recharge location for the Walnut flow systems. During nearly two years of field observations, this section of the study site was never observed to hold water after significant precipitation events, even in a stock tank several feet deep constructed in this material. Notice the abundant limestone and chert fragments present in the soil column. The colluvial material at this location is over 6 feet thick, with approximately 4 feet being exposed in this cut.

slopes of the scarp is characterized by large limestone cobbles and chert cobbles with a smaller amount of finer-grained clay matrix (fig. 9). The thick clay soil material is interpreted to represent the "downdip equivalent of the colluvial material.
This interpretation is supported by drilling evidence and the presence of limestone cobbles and chert fragments present up to 6 feet in depth within the soil material. It does not appear that the soil material is derived exclusively from the underlying Walnut Formation. The Walnut Formation at this location is primarily a weathered marl.

The top of the divide at site one is capped by a soil which is formed from the weathered remnants of the Georgetown Formation. While the Georgetown is not exposed on the top of the divide, limestone fragments from the Georgetown may be seen littering the surface and form the base material from which the soil is derived.

The Edwards Formation at this locality is a buff to dark grey, thick-bedded, rudistid bioherm with cherty, regular-bedded limestone sections also present. The Edwards Formation in this general area is characterized by rudistid bioherms (Corwin, 1982, p. 35).

The Comanche Peak Formation at site one is typified by nodular, buff to tan limestones, often with interbedded marls and thin to medium, regular-bedded limestones. This formation is particularly well exposed where quarrying has taken place (fig. 9).

The Walnut Formation occurs in the subsurface at site one. Drilling indicates the presence of weathered dark grey shale with small limestone flags present over an oxidized marl unit, which overlies an indurated limestone bed (see Appendix 3). The limestone bed was not penetrated by the drilling process, but it's presence is strongly

Figure 9. Photo showing the contact of the coarser colluvial material and the Comanche Peak Formation. The colluvial material occurs as a wedge extending beyond the Edwards/Comanche Peak contact and continuing down slope, a distance of several hundred feet. Infiltration rates in this colluvial material indicate that significant recharge to the flow systems occurs in this region. The Comanche Peak Formation, as exposed in this quarry cut, may occasionally contain moist zones within it, but the entire Comanche Peak Formation was never saturated during the study period of nearly two years. Water which does infiltrate into the Comanche Peak Formation is discharged into the colluvial material by lateral migration of the water. The lateral flow is enhanced by the bedded nature of the Comanche Peak Formation.

supported by the difficult drilling encountered at this interval. The oxidized zone was encountered approximately 19 feet below the ground level. It is this oxidized zone which is the predominant water-bearing zone in the flow system. The thickness of this water bearing zone was approximately 7 feet.

The Walnut is overlain by a thick (6 to 8 foot) section of dark brown clayey soil. It is interpreted that this clay soil is the down-dip equivalent of the colluvial material and is a transported material capping the Walnut Formation. The presence of small limestone cobbles and chert fragments present in the soil material supports this interpretation (see Appendix 3).

Soil Types of Site One

Eckrant Soils

The Eckrant series soils are formed on the remnants of the Georgetown Formation which previously overlain the Edwards Formation (fig. 10). These soils are shallow and clayey, cobbley, well-drained soils common to uplands. Eckrant soils typically form over thick beds of indurated , fractured limestone (Stringer, 1980, p. 14). Permeability is 0.2 to 0.6 inches/hour (1.4 x 10^{-4} to 4.2 x 10^{-4} cm/sec) (Stringer, 1980, p. 96).

Brackett - Eckrant Soils

The Brackett - Eckrant soil association normally consists of shallow to very shallow, stony soils on hillsides. These soils are formed on the Edwards and Comanche Peak Formations in this area (fig. 10). Slope is highly variable from 8 to

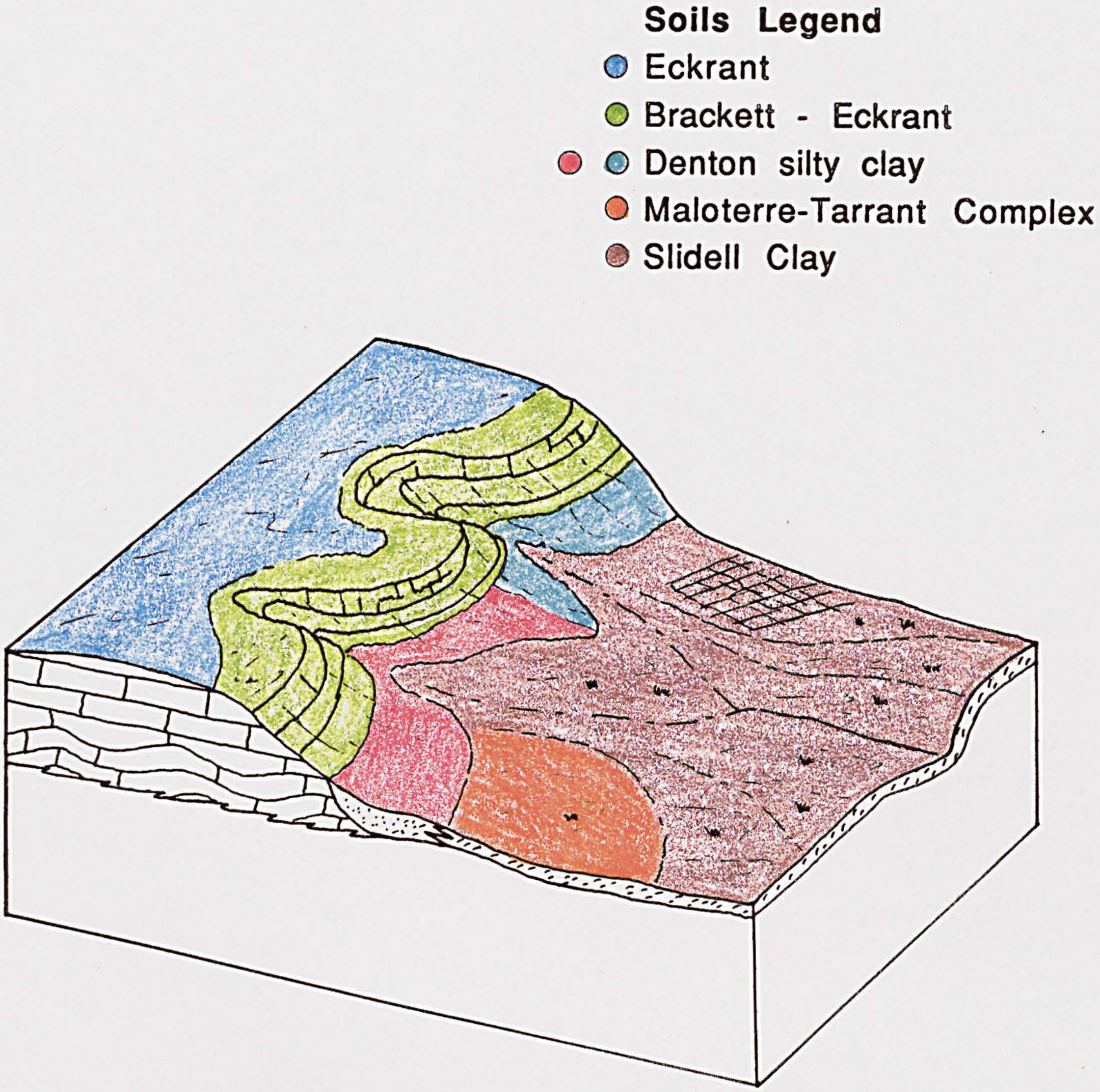


Figure 10. Diagrammatic soils sketch relating soils to geology and geomorphic position. Soils are typically formed from the underlying materials, with exception of the thick Slidell Clay soils representing a valley fill of material which was deposited at the base of the slope, downdip from the colluvial material. The Eckrant soils are probably formed from the remnants of the Georgetown Formation, and are not formed from the Edwards Formation. These clayey soils capping the uplands makes infiltration into the Edwards Formation occur at a slower rate than if the Edwards Formation was exposed on the top of the divide.

40 degrees. Exposed bedrock is commonly found within this soil association. This soil association is a loamy, calcareous clay material at the surface with abundant limestone fragments included (Stringer, 1980, p. 10). Permeability of these soils are normally 0.2 to 0.6 inches/hour (1.4×10^{-4} to 4.2×10^{-4} cm/sec) (Stringer, 1980, p. 96).

Denton Silty Clay Soils

The Denton Silty Clay soils are mapped over the colluvial deposits at the base of the slopes in site one (fig. 10). McCaleb (1985) states these soils are formed on interbedded limestones and marls (p. 8). These soils are probably better classified as Cranfill series soils which are formed on loamy, calcareous clay colluvial deposits (Stringer, 1980, p. 44). The assigned permeability rates for the Cranfill series soils are 0.6 to 2.0 inches/hour (4.2×10^{-4} to 1.4×10^{-3} cm/sec) (Stringer, 1980, p. 96). Field permeability values ranged from 2.4 x 10-4 to 1.6 x 10-2 cm/sec. (fig. 11). These ranges are typical of gravel to medium sand (Domenico and Schwartz, 1990, p. 65) or well-sorted sands and glacial outwash to gravel (Fetter, 1980, p. 75). The difference in the field permeabilities is probably related more to the intrinsic nature of the underlying colluvial material than to the soil developed on the colluvial material, as the Guelph permeameter must be inserted into the ground approximately 6 inches.

Maloterre-Tarrant Complex Soils

The Maloterre-Tarrant soils are developed on bedrock material of limestone interbedded with marls at the toe of the colluvial material. This bedrock slope is not

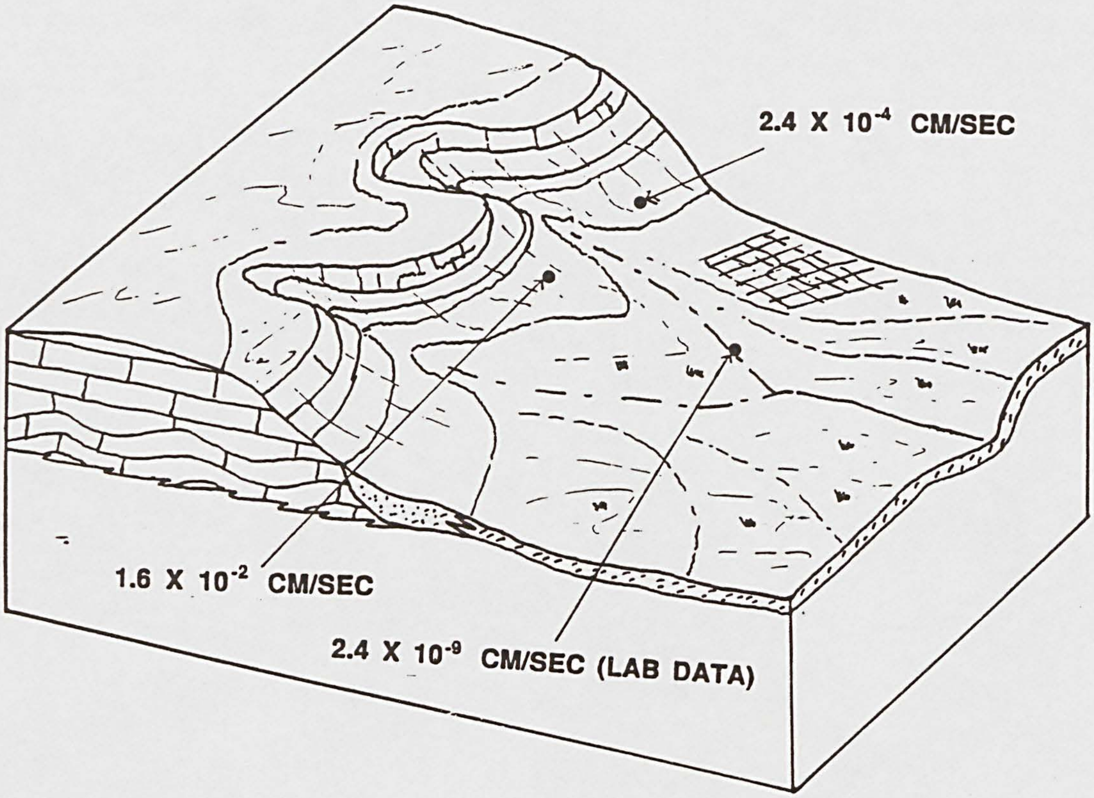


Figure 11. Diagrammatic sketch showing the study area and actual field tested permeability rates. Field testing was completed using a Guelph Permeameter and lab data. Infiltration rates shown clearly indicate the colluvial material has an excellent infiltration potential and probably represents the primary recharge zone for the flow systems at this site. The soils capping the Edwards Formation are clayey, and it is known that water is discharged from the Edwards Formation by spring flow. Also, the Comanche Peak Formation is not completely saturated during the wet period of the year. These facts, coupled with the infiltration rates shown, strongly suggest that a significant amount of water which enters the Walnut flow systems probably originates on the colluvial blanket.

covered presently by any transported material from the slope. It rises above the clay-fill located below it and extends out past the limit of the colluvial material which lies above it (fig. 10). Often this position of the slope has a well-developed caliche profile present on or near the surface. The permeability of this soil association is listed as 0.2 to 0.6 inches/hour (1.4 x 10^{-4} to 4.2 x 10^{-4} cm/sec) (Stringer, 1980, p. 96).

Slidell Clay Soils

The Slidell soils are interpreted to be a clay-fill material over an eroded and previously exposed landscape. This material is interpreted to be the down-dip "facies" of the colluvial material deposited at the base of the slopes (fig. 10). This material is extremely fine-grained and often contains small fragments of limestone and chert. There is often silty, siliceous material present (Appendix 3). Field permeability of this material was not determined specifically but is less than 10^{-6} cm/sec, which is the lower limit of the Guelph permeameter. Stringer (1980) lists the permeability as < 0.06 inches/hour (<4.2 x 10^{-5} cm/sec) (p. 97). Soil permeability determined by a flexible wall permeameter using a core sample of the clay soil material from a depth of 4 feet was 2.4 x 10^{-9} cm/sec.

The Slidell soils penetrated during drilling at site one contained chert fragments. These chert fragments likely were derived from the Edwards Formation, and indicate these soils contain transported material. It is unlikely these soils formed solely from the underlying Walnut Formation. The source of the clay material is possibly the Kiamichi Formation, which also forms the residual, clayey soil capping the Edwards divide. The Kiamichi is described as predominantly a calcareous marl (Brown, 1971, p. 19).

Data Analysis and Results for Site One

The evaluation of the flow system at site one included five monitoring wells, a weir, field infiltration data, laboratory permeameter data, slug testing, and aquifer pumping test analysis. Each of the monitoring system components is described and their analyses and results follow.

The shallow hydrogeologic system, from ground level to approximately 7 feet below the ground, was monitored by two monitoring wells. Water was encountered in a light tan, weathered marl at approximately 19 feet below ground elevation, and is considered to be the deeper, locally confined system. The confined system was monitored by three wells. The material between 7 and 19 feet below the ground surface was unsaturated during the drilling program. This zone was monitored by well BR-2 due to the completion technique used with this well (fig. 12).

Hydrograph Analysis

The hydrographs and weir flow (fig. 13) illustrates several different aspects of the hydrogeologic system at site one. Three of the wells are completed in the "deeper" flow system, while one well monitors the "shallow" soil flow system. November 28, 1992 is the first day of data collection. Two wells were installed in September of 1991. BR-1 monitors the shallow system and BR-2, 3, and 4 monitor the deeper system at the locality. Data were not collected until November due to bailing and subsequent development of the wells to insure consistent readings. Two

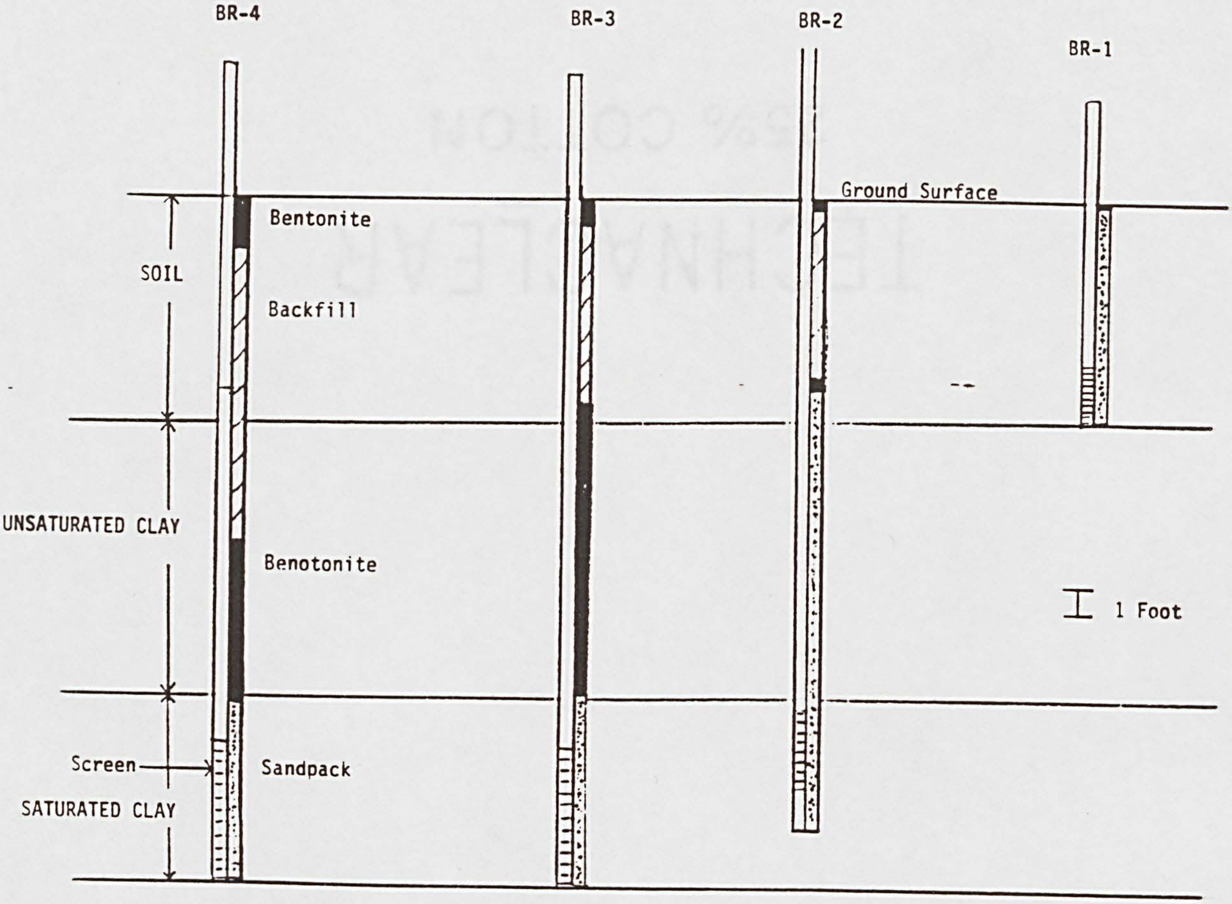


Figure 12. Completion detail of monitoring wells at site one. Of primary importance is the relationship between the three deeper wells, BR-2, BR-3, and BR-4. BR-2 is completed across the unsaturated clay zone, the hydrograph of this well correlates exactly with those of the other two deeper wells. BR-1 is completed only in the soil zone which contains water during most of the monitoring period.

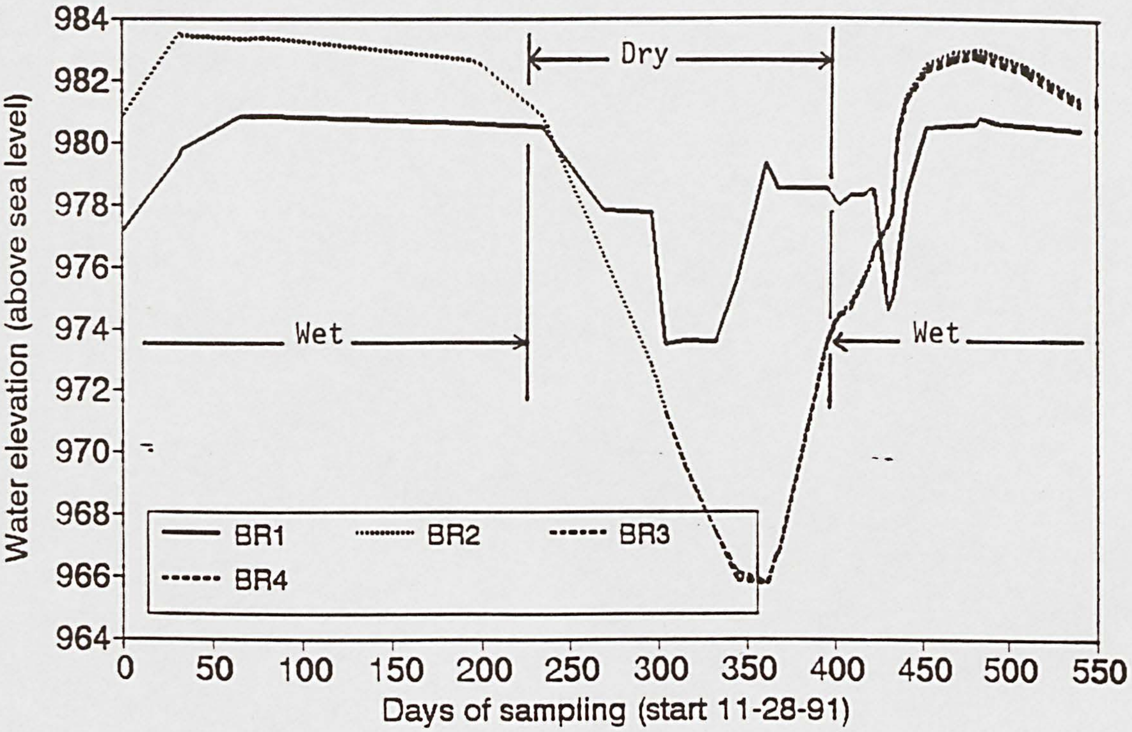


Figure 13. Hydrographs of the four monitoring wells present at site one. Note the similarity between the three deep monitoring wells (BR-2,3 and 4). Also notice the change in vertical gradient during the wet and dry periods of the year. During the wet periods of the year (such as days 400 to 475), an upward gradient exists, when head at depth is greater than the soil zone head. During the dryer (summer) periods (days 250 to 400), a downward gradient exists. Also the deep monitoring wells have a smoother hydrograph than the shallow system, and do not reflect the instantaneous influence of recharge to the system. Ground level elevation at the well field is approximately 980 feet above mean sea level.

deeper wells were added during the summer of 1992 (BR-3 and BR-4). These two wells show good correlation with the first deep well (BR-2), indicating that all three are monitoring the same deeper flow system (fig. 12). Hydrograph comparison indicates that head in BR-2 compares exactly to wells BR-3 and BR-4, even though the unsaturated zone is included in BR-2. This information indicates that the unsaturated zone does not add or remove water from the 7 foot saturated clay layer below it, and most likely behaves as a confining unit. The shallow well (BR-1) (fig. 13) shows a radically different hydrograph than do the deeper wells. This indicates separate flow systems may be present. The shallow flow system hydrograph of BR-1, shows water levels consistent with seasonal influences. The water level in the well (BR-1) is highest during the winter or wet months, and lower during the summer or dryer months. Head in the shallow zone may rise above ground elevation for brief periods following rainfall. The decline of the water levels within the shallow zone are also quite rapid.

The hydrographs for the deeper system, (BR-2, 3, and 4) show a seasonal trend with higher levels during the winter months and lower levels during the summer months (fig. 13). The head in this deeper system has risen as much as 3 to 4 feet above ground level elevation during the wet period of the year. The deeper system hydrographs also show no head decline on the rising limb of the hydrograph. This indicates direct recharge but water may be held in storage and allowed to filter slowly into the flow system at depth.

Stream flow over the weir was not monitored until the second winter season (fig. 14). Stream flow was monitored using a rectangular weir. The small stream which drains the study area (fig. 15) does not flow throughout the year but flows only

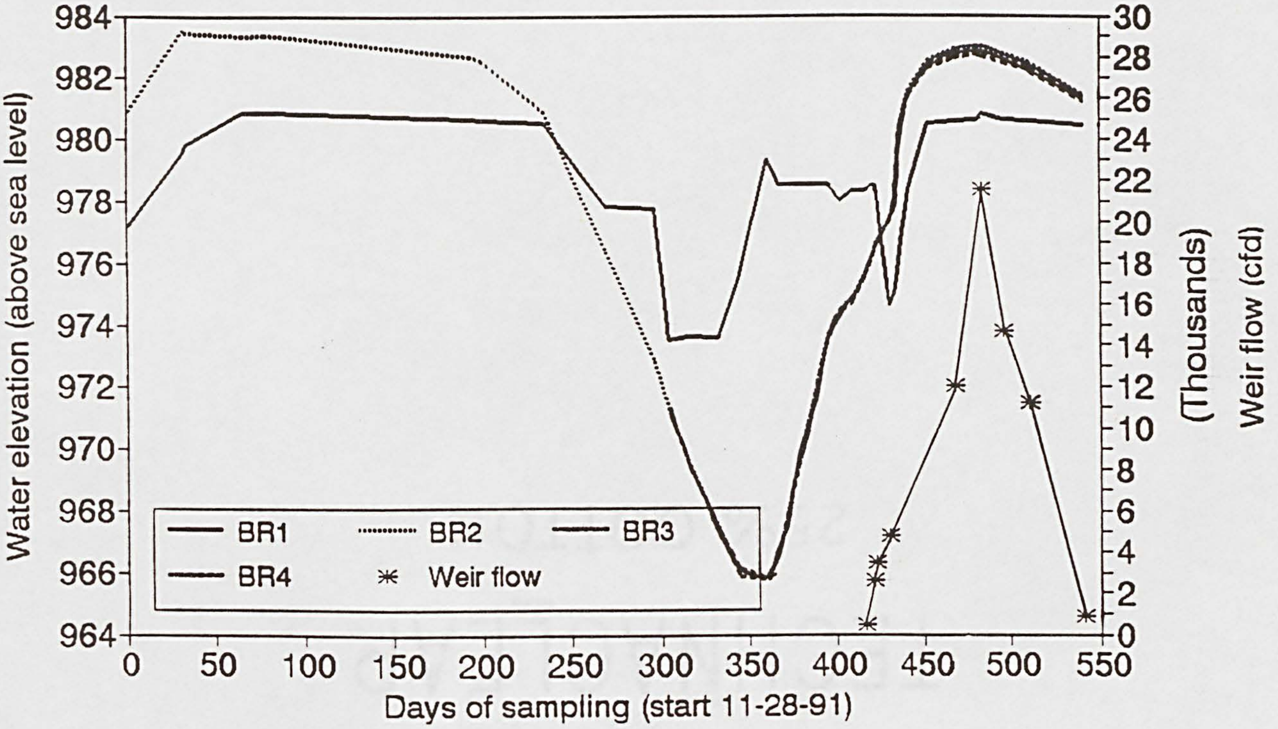


Figure 14. Hydrograph showing water levels of the monitoring wells and the stream flow (in thousands of cubic feet/day) at the study site. The weir hydrograph is rising during the rising limb of the deeper system hydrographs (represented by BR-2, 3 and 4). Water begins to flow in the creek when the water level in the confined deep portion of the flow system is approximately 976 feet above mean sea level, or approximately 4 feet below ground surface. The shallow system hydrograph is declining during this same period, then begins to rise later.

Figure 15. Photograph showing the creek flow and the weir monitoring system. The water flowing over the weir is interpreted to be discharged primarily from the deeper, confined portion of the flow system, with minor contributions from the shallow or soil portion of the flow system. This interpretation is based upon field observations of specific electrical conductivity, and from geochemical analysis of the waters from both segments of the flow system and the creek.

during the winter and early spring. In comparing the stream flow against the well hydrographs, it appears that stream flow begins when the head in the deep flow system is approximately 4 feet below ground level (fig. 14), and baseflow increases as head in the deeper flow system increases.

Results and Interpretation from hydrograph data

The deeper flow system is interpreted as being a locally confined system. This interpretation is based on drilling evidence, as well as the flow system having a head up to 3 feet above ground elevation. When the two deep wells (BR-3 and 4) were added to the monitoring system, head in the deep well already present was approximately 10 feet below ground level elevation. During drilling for the two subsequent wells, water bearing material was not encountered until a depth of 19 feet below ground level elevation. When this water bearing zone was encountered, water was present in the borehole in significant amounts. Also, there was a distinct color change in the same interval. Dark brown to grey, weathered, unsaturated clay was taken from cuttings above the 19 feet depth interval, and a light buff to light tan saturated clay was removed from the drill string once the 19 feet depth was penetrated (fig. 16).

Another line of evidence supporting a confined condition is the artesian head conditions that exist during the wet season for the deeper flow system. Head in the deeper system may be up to three feet above ground elevation, while there is no water present on the surface. Because the hydrograph for the deeper system shows no decline on the rising limb of the hydrograph (fig. 17) the rate of increase can be calculated. Predicting water levels for the deeper system is possible because of the

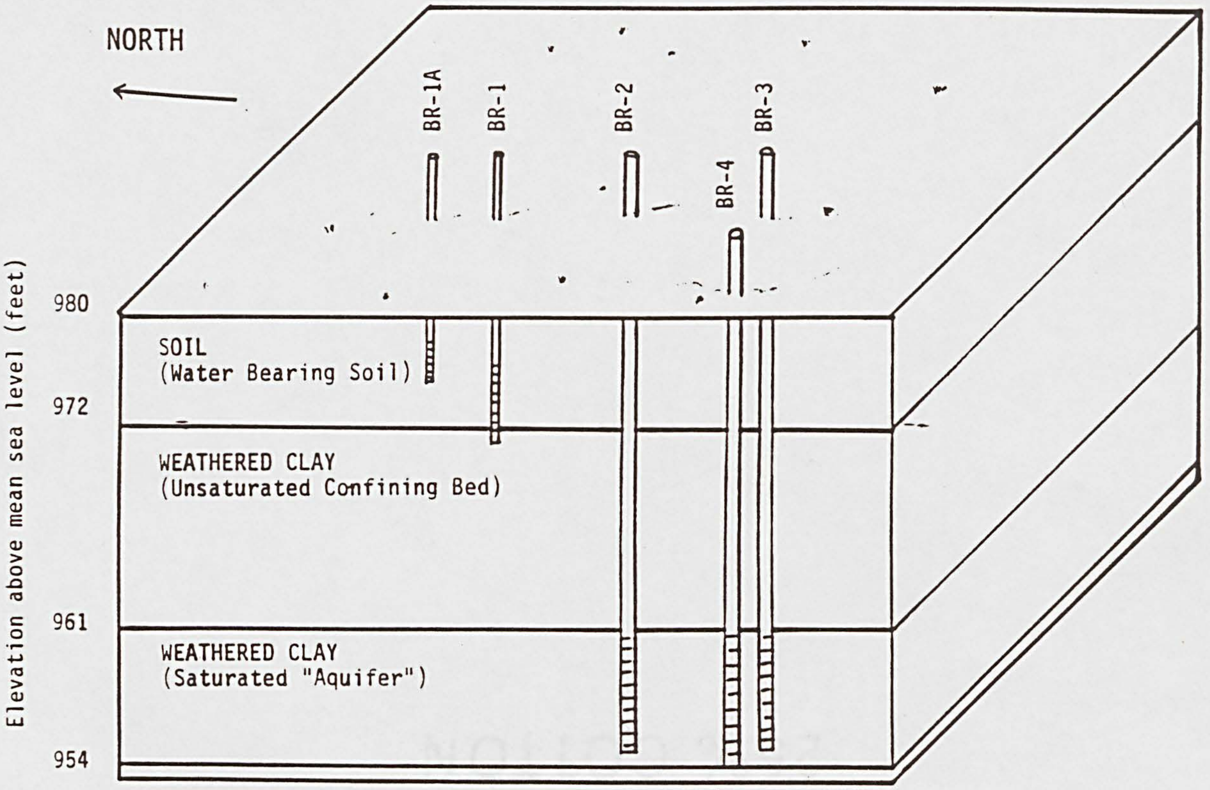


Figure 16. Figure showing the well completions and the interpreted portions of the flow system which they monitor. BR-1A was added only to verify the readings of the shallow BR-1 monitoring well. The nature of the material, and their corresponding hydrogeologic "units" are shown. The primary zone of water bearing material is located in a seven foot thick section of saturated clay that begins at 19 feet below the ground surface.

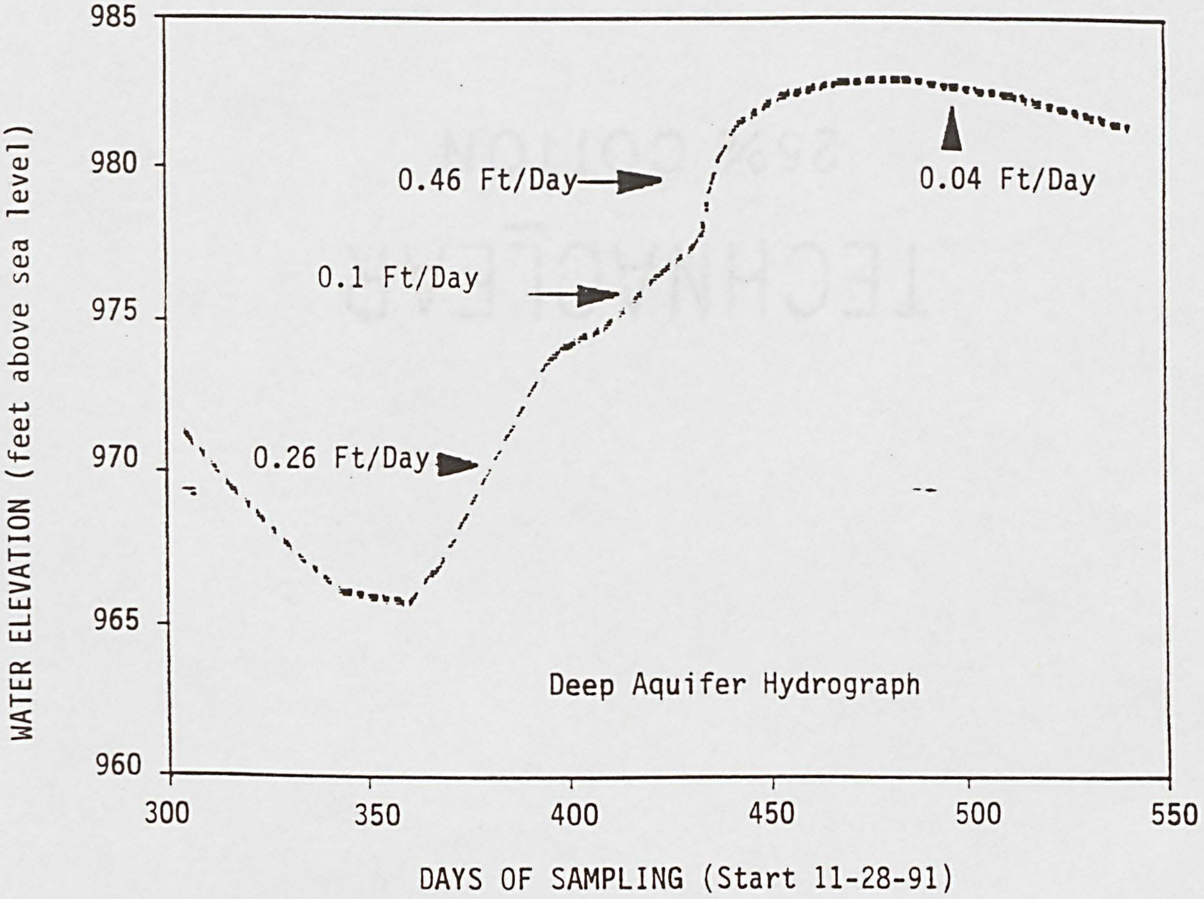


Figure 17. Section of the hydrograph from day 300 to day 550 of monitoring showing rates of rise and decline. The hydrograph is a relatively smooth curve which allows for predictions of water levels. Predicting the water level of the flow system would allow for an estimate of when the creek would begin to flow, or when water levels may be above the ground surface. This information would be useful for land use management practices such as farming or excavation work.

nature of the rising limb of this hydrograph, which does not rise and fall in direct response to recharge.

The hydrographs can also be used to compute the volume of water in storage to account for an increase or decrease in stream flow. The method is from Moore (1992). The interpretation indicates that the change in the volume of water in storage is related to the flow rate of the stream by $(V_1 - V_2) = (Q_1 - Q_2)/\text{alpha}$ (Moore, 1992, p. 393). Q represents the flow of the stream, and V represents the volume of water. The alpha factor is derived from the plot of the hydrograph over time, and represents the slope of the line of the hydrograph. Alpha is calculated by $\ln(Q_1/Q_2) / (t_2 - t_1)$, with Q being stream flow at time 1 and 2, and t being the time of stream flow (Moore, 1992, p. 392).

The total volume of water responsible for producing the baseflow is related to the alpha factor and the flow rate by $V_t = Q_t/\text{alpha}$ (Moore, 1992, p. 393), where V_t equals the volume at any time t, Q_t equals the stream flow at the same time t, and the alpha factor for the slope of the hydrograph which includes the time t.

The flow system was analyzed from day 437 to day 453, a total of 16 days. The alpha for this period of the stream hydrograph is .0038. Stream flow on day 437 was 13,760 ft^3/day, while flow on day 453 was 14,620 ft^3/day. The volume of water in storage on day 437 was calculated at 3,621,053 ft^3 (83.1 acre/feet). The volume of water in storage for day 453 was 3,847,368 ft^3 (88.3 acre/feet), with an increase of the volume of water in storage of 226,315 ft^3 (5.19 acre/feet) over the 16 day period.

Specific yield can also be calculated from these data with $V_1 - V_2 = A\ Sy$ (delta y) (Moore, 1992, p. 393), with V representing volume at time 1 and 2, A representing basin area, Sy is specific yield, and delta y represents the change in head in the hydrograph between time 1 and 2. The specific yield for the entire flow system was calculated at 14%, using the area of the basin from the colluvial material to the weir measuring point (13,707,809 ft^2 or 314 acres). This is consistent with specific yield values other authors have calculated for flow systems in the shallow weathered bedrock zone, but the value calculated for this study includes a fractured bedrock system and the colluvial material.

Statistical analysis were also conducted on the data from the flow system at site one. The STATPLAN computer program was utilized to determine statistical relationships between the shallow, deep and surface water systems. Comparison analysis indicate a poor relationship between the deep and shallow flow systems at site one (fig. 18), while the deeper monitoring wells reflected a strong relationship with one another. The statistical analysis examined trends in water level elevation only, and assumes all the variables are independant and respond to the same influences.

Aquifer Testing

Two primary methods of aquifer testing were conducted at the locality to determine the aquifer characteristics of the saturated section. Slug tests and constant rate pumping tests were conducted and evaluated to determine values for hydraulic conductivity, transmissivity and storage coefficient values of the saturated clay interval.

Data reduction used the Bouwer and Rice slug test method (Bouwer and Rice, 1976 and Bouwer, 1989). Pumping test values were reduced using the Theis type-curve method, and Jacob's approximations, as well as distance and time drawdown methods (Theis, 1935, Jacob, 1946, and Driscoll, 1986, pp. 205 - 267). All

Variable	BR-1 Water Level	BR-2 Water Level	BR-3 Water Level	BR-4 Water Level	Weir Flow (CFD)
Water Level BR-1 **Probability**	------	0.568 **1.000**	0.460 **0.991**	0.458 **0.990**	0.348 **0.641**
Water Level BR-2 **Probability**		------	1.00 **1.000**	1.00 **1.000**	0.764 **0.984**
Water Level BR-3 **Probability**			------	1.00 **1.000**	0.765 **0.984**
Water Level BR-4 **Probability**				------	0.765 **0.984**
Weir Flow (CFD) **Probability**					------

Figure 18. STATPLAN computer program correlation matrix showing the probability of relationships between the water levels of the monitoring wells and the creek flow. Of primary interest is that the weir flow in the creek is better related to the water levels of the deeper confined flow system monitored by BR-2, BR-3 and BR-4 than to the water levels measured in BR-1.

data reduced from the aquifer test analysis are included in Appendix II. Because the E.P.A. has determined the maximum hydraulic conductivity value of acceptable landfill liner material is 10^{-7} cm/sec (Albrecht and Cartwright, 1989, p. 14), all values will be reported in standard english units (ft/min) and in metric units (cm/sec). Aquifer analysis was completed by hand calculations and by various analytical groundwater computer programs. Slug tests were conducted to obtain hydraulic conductivity values for all four of the wells at the test site and to observe lateral heterogeneity. The values derived from the slug testing data reduction are shown in Table 1.

Table 1. Hydraulic conductivity values calculated by slug testing (Bouwer and Rice Method)

WELL	SLUG ADDITION	SLUG REMOVAL
BR-1	7E-06 (3.5E-06)	Not Available
BR-2	4.4E-04 (2.4E-04)	6.4E-04 (3.3E-04)
BR-3	4.3E-04 (2.2E-04)	5.1E-04 (2.6E-04)
BR-4	5E-06 (2.5E-06)	Not Available

* Units are feet/minute and (cm/sec)

Pumping test results were based on three constant rate pumping tests (for details on aquifer testing, Appendix 2). The water bearing zone in the flow system at site one is difficult to test because of only a 7 foot saturated thickness. Pumping rates were low and testing could not be conducted for extended periods of time. Values of transmissivity and storage coefficients are shown in Table 2. Also shown are the calculated hydraulic conductivities based on the transmissivity values from the pumping test and dividing by the saturated thickness.

Table 2. Transmissivity (T), storage coefficient (S), and hydraulic conductivity (K) values calculated from pumping tests.

WELL	T ft2/min	T cm2/sec	K cm/sec	Storage Coefficient	Pump Rate ft3/min
BR-2 Drawdown (Theis)	0.073	0.0371	0.0053	0.013	0.042
BR-3 Drawdown (Theis)	0.0014	0.0007	0.0001	----	0.042
BR-3 Recovery (Theis)	0.0011	0.0006	0.00008	----	0.042
BR-2 (Pumped well) Drawdown	0.0005	0.0003	0.00004	----	0.09
BR-4 Drawdown	0.049	0.0249	0.0036	0.022	0.042
AVERAGE	0.025	0.0127	0.0018	0.0175	----

K assumes thickness (b) = 7 feet; Transmissivity (T) = Hydraulic conductivity (K) x thickness (b)

Due to the short pumping time of all of the pumping tests (less than 30 minutes), Jacob's approximation could not be used for accurately defining aquifer parameters. The storage coefficient is high for a confined aquifer, but this section is thought to be only locally confined. The Moore method calculated a specific yield for the entire flow system based on total basin area (including the colluvium), resulting in a much higher value of specific yield than the pumping test approximation of storage coefficient.

Streamflow and Groundwater Interaction

Statistical analysis of the monitoring system was conducted using the computer program STATPLAN 4. Correlation between the deep system, the shallow system and stream flow indicates that there is little correlation between the deep and shallow systems, and that the stream flow is more intimately related to the head in the deeper flow system than the head in the shallow system (fig. 14). This indicates that the water present in the stream is water discharged primarily from the deeper system, with minor amounts of water discharged from the shallow soil system. The relationship between the stream and the shallow and deeper flow systems is not constant, and one system may dominate discharging to the stream at different times. The system was monitored only for baseflow, and does not include stormflow interpretations. Overall, it appears the stream is influenced more by the deeper flow system than by the shallower flow system during the baseflow cycle.

Specific electrical conductance data also support the relationship between the deep flow system and the surface water system. Electric conductivity of the deep system is normally 530 microsiemens, while the shallow system has a higher electric conductivity of 600 to 640 microsiemens. The electric conductivity of the stream baseflow is normally 520 to 535 microsiemens.

Geochemical Analysis of Water Samples

Geochemical analyses were conducted at the site to determine major cation and anion components of the different flow zones and of the stream flow. The data were analyzed by capillary electrophoresis, with the results shown in figure 19.

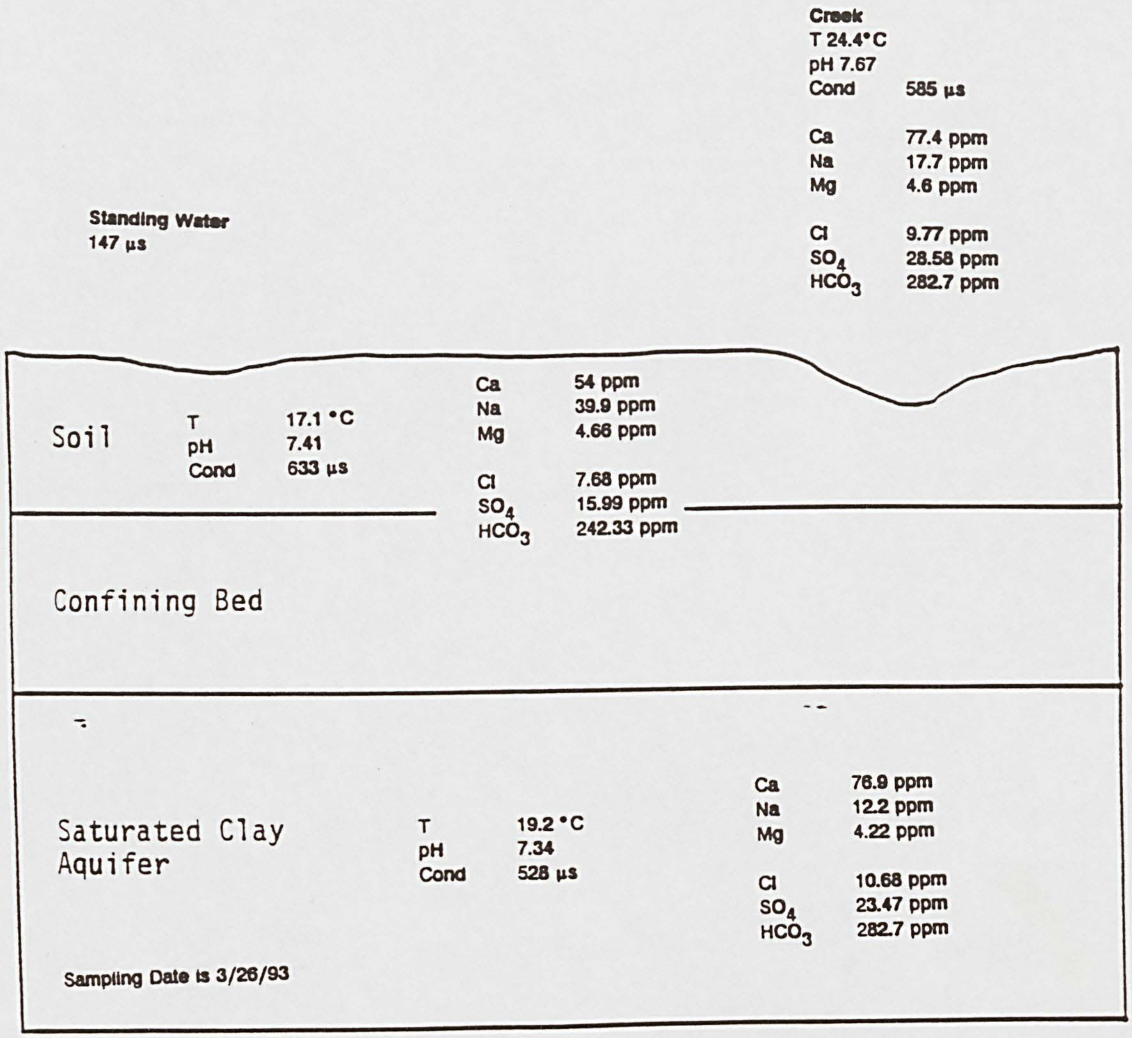


Figure 19. Diagrammatic depiction of water chemistry of the deeper, confined portion of the flow system, the shallow, unconfined soil portion of the flow system, and the water present in the creek. Conductivity of water standing in the field was included to determine if this water was discharged from the soil system or if it represented standing water from rainfall events. Due to the lower conductivity reading, it is interpreted to represent standing water remaining after a rainfall event. Notice the similarity of the geochemical nature of the water in the creek and the water from the deeper, confined portion of the flow system. While it appears minor mixing may be occurring, the water in the creek is probably discharged from the deeper flow system, as was also interpreted by the hydrograph analysis and the statistical analysis of the flow system.

The geochemical analyses indicate that the water present in the stream is more like the water in the deeper flow system than the water in the shallow (soil zone) flow system. This is best explained by the stream downcutting below an elevation of 961 feet, which is the elevation of the top of the water-bearing zone at the well field.

Water from the shallow soil system also enters the stream, but in lower volumes due to a low hydraulic conductivity and a limited gradient potential.

Conceptual model of site one

The conceptual model of the flow system at site one is shown in figure 20. The conceptual model shows that rainfall which falls on the top of the divide infiltrates through the thin soil and into the Edwards Formation. Water flows both vertically through fractures and laterally along bedding planes in the Edwards Formation. This water is then discharged from springs at the valley heads present in the Edwards Formation (fig. 21). Spring flow from the Edwards continues downslope until the water encounters the colluvial material, at which time the water infiltrates into the colluvial material (fig. 21).

Water which is not discharged as spring flow in the Edwards, continues downward and eventually infiltrates into the Comanche Peak Formation. Flow occurs primarily along vertical fractures and does not saturate the entire section of the Comanche Peak. Water is discharged from the Comanche Peak laterally along bedding planes into the colluvial material.

Due to the high infiltration rate of the colluvial material, it is interpreted as being the major pathway into the flow system. This material is in the vadose zone, and the

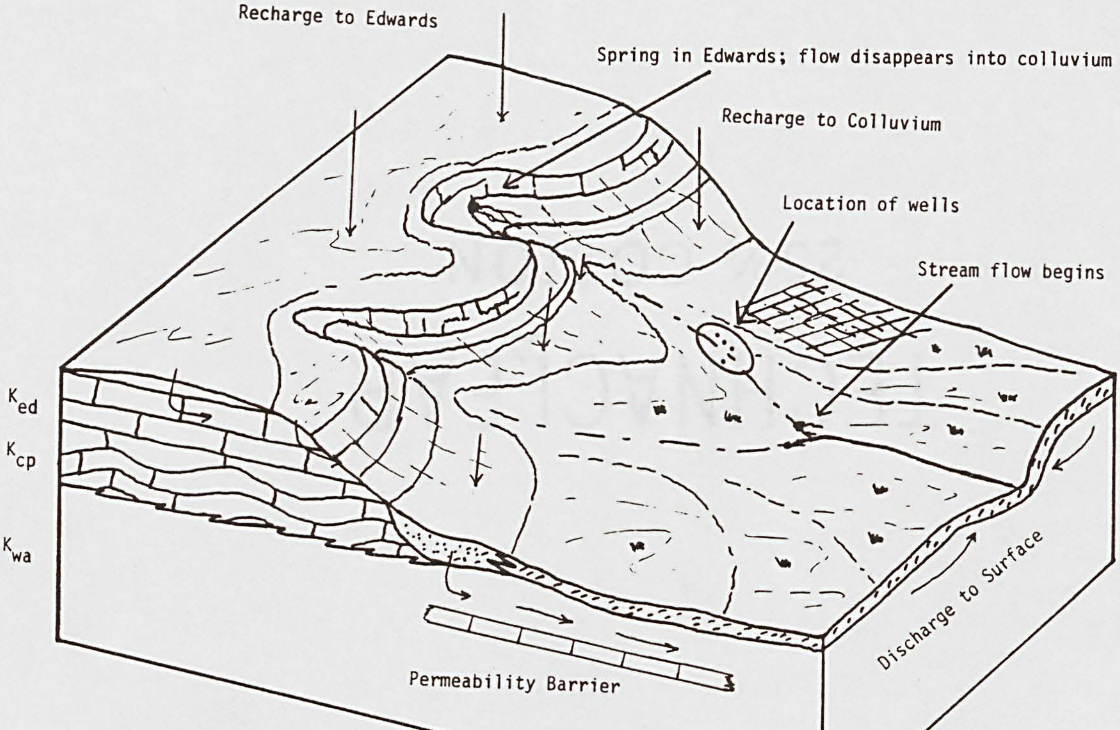


Figure 20. Conceptual model of the flow system present at site one.

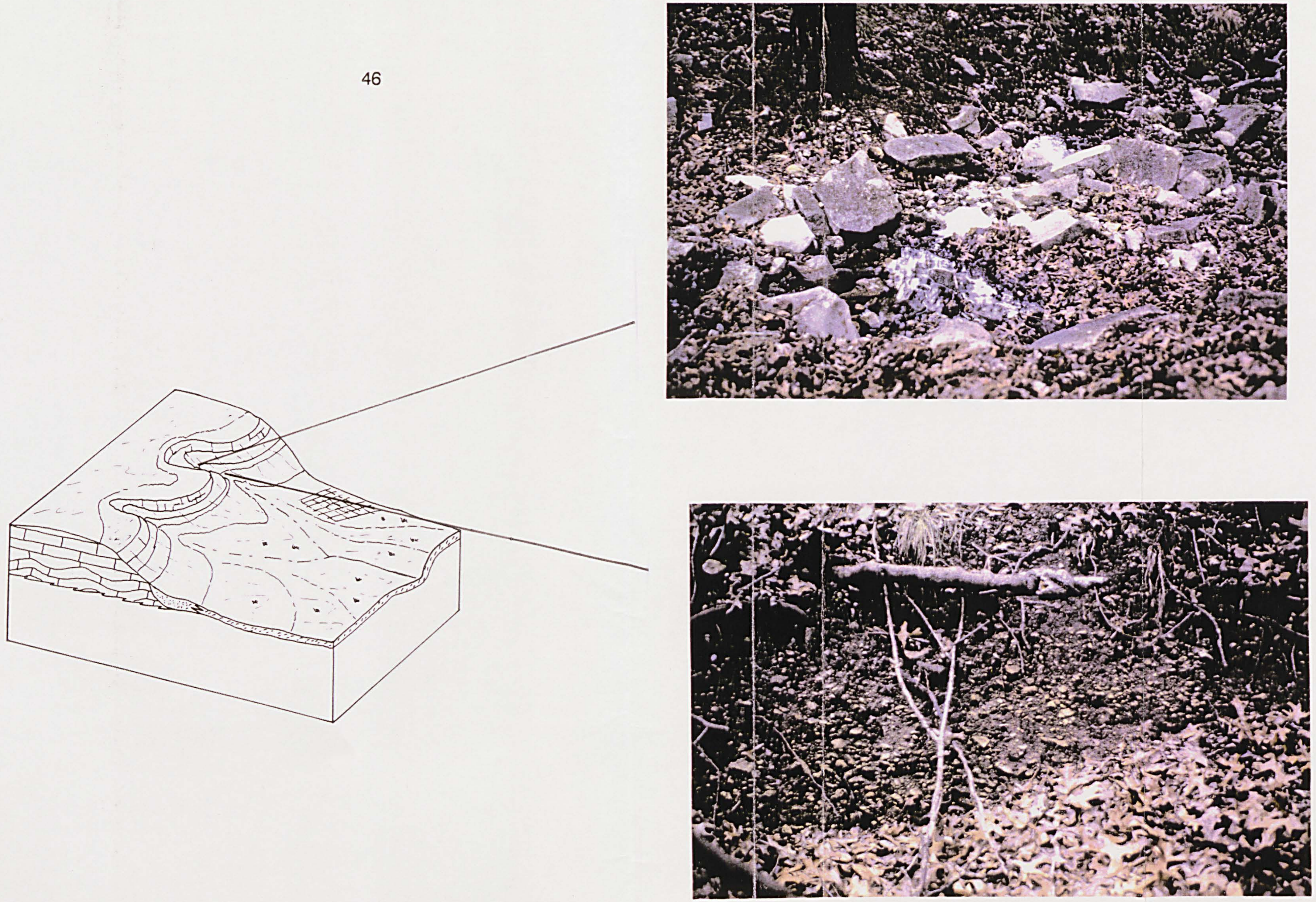


Figure 21. Photos showing spring flow from the Edwards Formation and where the flow disappears into the colluvium which extends up into the valley.

limestone cobbles present within the colluvium exhibit signs of dissolutioning. Hydraulic properties of the stony soils in the vadose zone are poorly understood; however, a good discussion is given by Bouwer and Rice (1984).

Water from the colluvial material enters the deeper flow system along fractures in the weathered bedrock underlying the colluvium. Water continues to travel both vertically and horizontally, until a permeability barrier is encountered. When the vertical flow potential is reduced by the presence of a permeability barrier such as an indurated limestone bed, horizontal flow dominates. Rainfall which lands directly on the colluvial material recharges the system and travels through the colluvial material to depth until horizontal flow begins.

Some of the rainfall which occurs on the thick, clay soils of the Slidell soils recharges the shallow system, but much of the rainfall flows quickly overland into the stream and is discharged as storm flow. Water from the colluvial material may also enter the shallow groundwater flow system, which may account for the artesian condition encountered in the well monitoring the shallow flow system.

The above-ground head levels of the deeper flow system are explained by water being held in storage in the colluvial material at an elevation well above the ground level elevation at the well sites. The potentiometric surface is then determined by the height of water present in the colluvial material (fig. 22). During the dry season, water levels in the colluvial material drop, decreasing the head in the deeper flow system. During the monitoring period, the entire 7 foot thickness of the deeper flow system was continually saturated (fig. 23). This indicates that water may be held in storage upgradient of the well field in the colluvial blanket, and slowly migrates from the recharge zone, through the well field, to the discharge point.

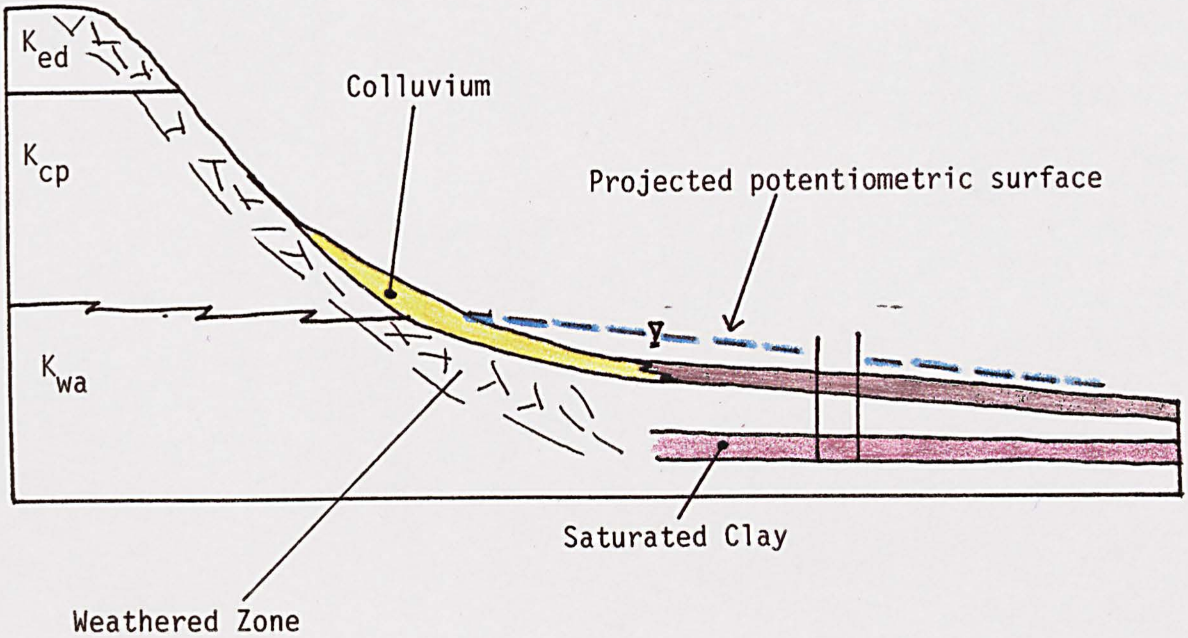


Figure 22. Conceptual diagram showing the relationship between the gradient present at the well field at site one and the position of the potentiometric surface at the colluvial blanket at the base of the slope. Based upon the groundwater gradient, the gradient present at the well field intercepts the slope area approximately half way up the colluvial slope. This supports the interpretation that the colluvium is the recharge zone for the system, and water is held in storage in the colluvial material until it can be slowly filtered through the flow system present in the Walnut Formation.

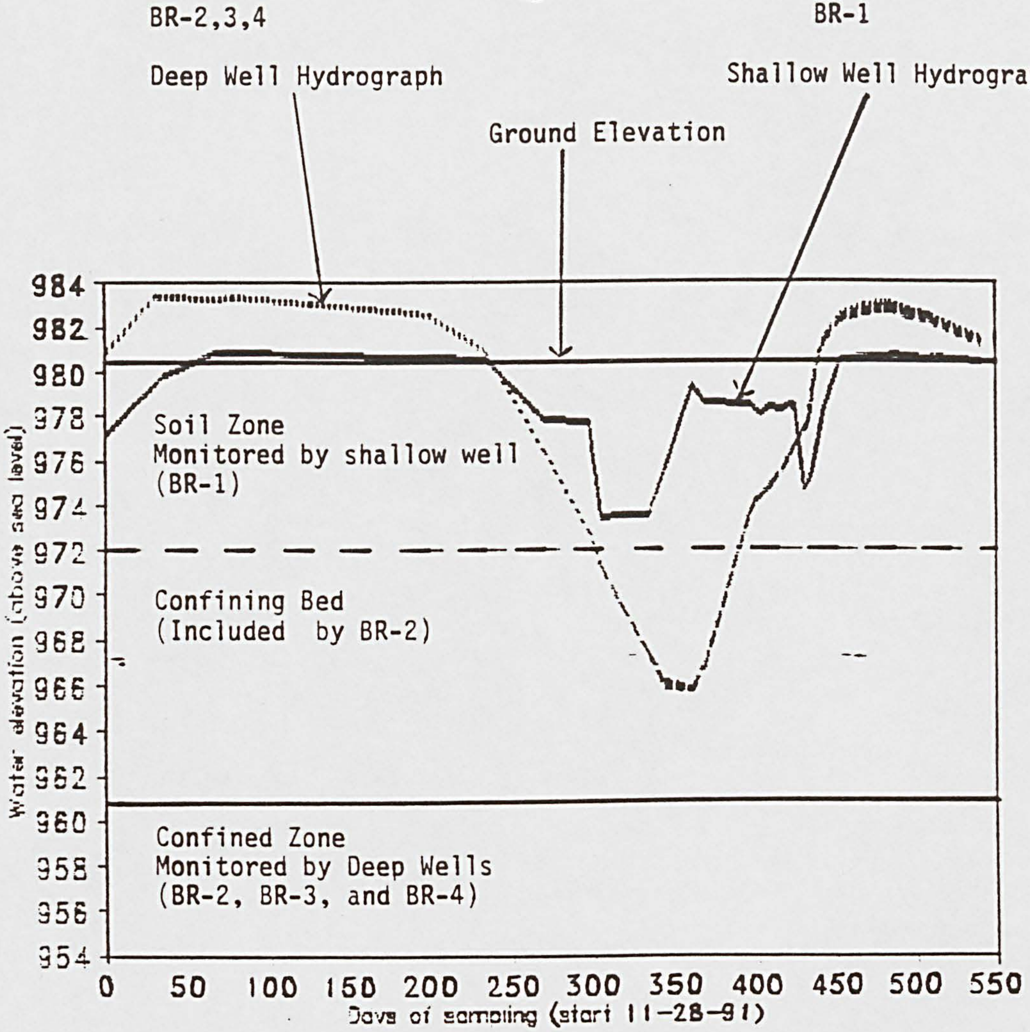


Figure 23. Well hydrograph and well completion information. This figure illustrates the well monitoring zones and the water levels present in the wells. The deeper portion of the flow system remained artesian during the entire 550 days of monitoring. The hydrograph for the deeper saturated section is a relatively smooth curve, indicating that during the drying periods of the year, water is still being released from storage in the colluvial material and passing through the saturated zone at depth. This figure also illustrates that during the wet periods of the year, the head in the deeper system is higher than the head in the shallow system, meaning an upwards gradient, while in the dryer periods of the year a downward gradient is present in the area of the well field. The saturation condition of the deeper marl unit is subject to change during different climatic conditions such as drought.

Somewhat similar flow systems have been described in alluvial material and colluvial material (Leach and Herbert, 1982, and Rushton, 1986). These works aided in the formation of the conceptual model for site one.

Summary of the site one flow system

Site one in interpreted as having at least two distinct sections within the flow system; a shallow soil section and a deeper, locally confined flow component. While aquifer methods were utilized to determine flow system characteristics, the area is not viewed as a classic aquifer setting with aquifer and confining beds, but rather a flow system from recharge to discharge incorporating the geomorphic evolution of the landscape, soils, and weathering to develop the conceptual model.

Of primary importance at this locality is the strong relationship between groundwater and surface water. Also, the hydraulic conductivity of the material at depth is not suitable for landfill liner material as it exists in-situ. Extremely variable head with artesian conditions above ground level indicate a discharge point for the flow system that is important to understand prior to any intrusive land use. This setting is repeated over much of the outcrop belt of the Walnut Formation in Central Texas.

Utilizing the present conceptual model would indicate that stream water quality may be directly related to land use on the colluvial slope area. This has significant implications with respect to non-point source contamination from land-use practices.

CHAPTER 4

FLOW SYSTEM CHARACTERISTICS OF SITE TWO

Introduction

The second site investigated is the region surrounding and including the town of Walnut Springs, Bosque County, Texas (fig. 1). The setting here is similar to site one, with the exception of water discharging from the Walnut Formation as spring flow. The springs in this locality have been incorporated into a park setting (fig. 24).

Geologic setting of site two

The geologic setting of site two includes the Walnut, Comanche Peak, and Edwards formations. The Paluxy Formation is not exposed in the immediate area of study, and is probably a confined aquifer in this area (Crumpler, 1989 p. 26). The geomorphic evolution of this landscape created colluvial deposits at the base of the slopes following a period of scarp retreat, as discussed for site one. The amount of colluvial cover appears to be considerably larger than was present at site one.

The Edwards Formation is the uppermost stratigraphic unit exposed in the immediate study area. The Edwards Formation at this locality is a buff to dark grey, thick-bedded limestone with cherty sections present. The Edwards is exposed at the crest of the escarpment (fig. 25). There is a thin soil capping the Edwards Formation.

Figure 24. Photos showing the park setting and the spring present at the park in Walnut Springs, Texas. The gazebo covers a large spring pool which is constructed in the Walnut Formation and supplies water to a wading pool located downhill from the gazebo. The spring studied is located in the foreground of the upper picture at the base of the tree in the center of the photo. This spring occurs at the contact between a saturated marl unit and a fractured oyster bed. The fractured limestone directly overlies the marl unit, and occasionally flow may been seen coming from the fractures of the limestone immediately following a period of rainfall,but the flow lasts only a few days.

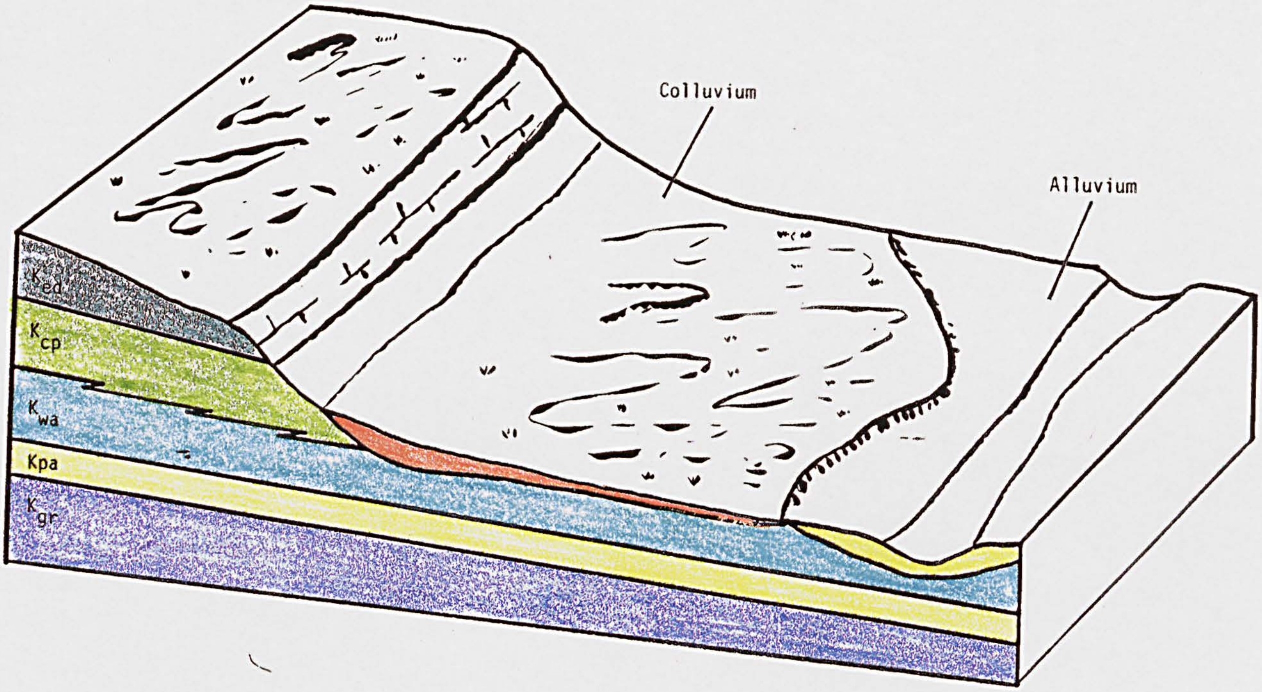


Figure 25. Figure showing the geologic setting of site two of this study. The divide is capped by the Edwards Formation. The Comanche Peak Formation is exposed in the slope of the hill, and the valley floor is the location of the Walnut Formation.

The Comanche Peak Formation at site two is identified by nodular, buff to tan colored limestones, often with interbedded marls and thin to medium, regular bedded limestones.

The Walnut Formation occurs at the surface and in the sub-surface at site two (fig. 25). Minor outcrops of the Walnut Formation appear in the area of Walnut Springs. A *Gryphea* bed caps the divide in the immediate vicinity of the park in downtown Walnut Springs where the springs occur. The Walnut is overlain by a thick section of dark brown clayey soil near the base of the Edwards scarp. This clay fill is interpreted to be the down-dip equivalent of the colluvial material. Away from the base of the scarp, the soils appear to thin and become more stony. The landuse is varied between crop, grazing, and residential uses. Also located on this slope is a cemetery and sewage treatment facility.

Soils of Site Two

Eckrant Soils

Eckrant soils cap the divide south of the town of Walnut Springs. These soils consist of shallow to very shallow, clayey and cobbley, well drained soils (Stringer, 1980, p. 46) (fig. 26). These soils appear shallow to non-existent on the divide, and are formed from the Edwards Formation. These soils are probably not formed from a residual material remaining from the Kiamichi Formation (Lower Washita Group). With a general lack of soil capping the divide, water either infiltrates into fractures of the Edwards Formation, or rapidly runs-off and onto the side of the slope. Infiltration rates for Eckrant soils are approximately 0.2 to 0.6 in/hr (Stringer, 1980, p. 96).

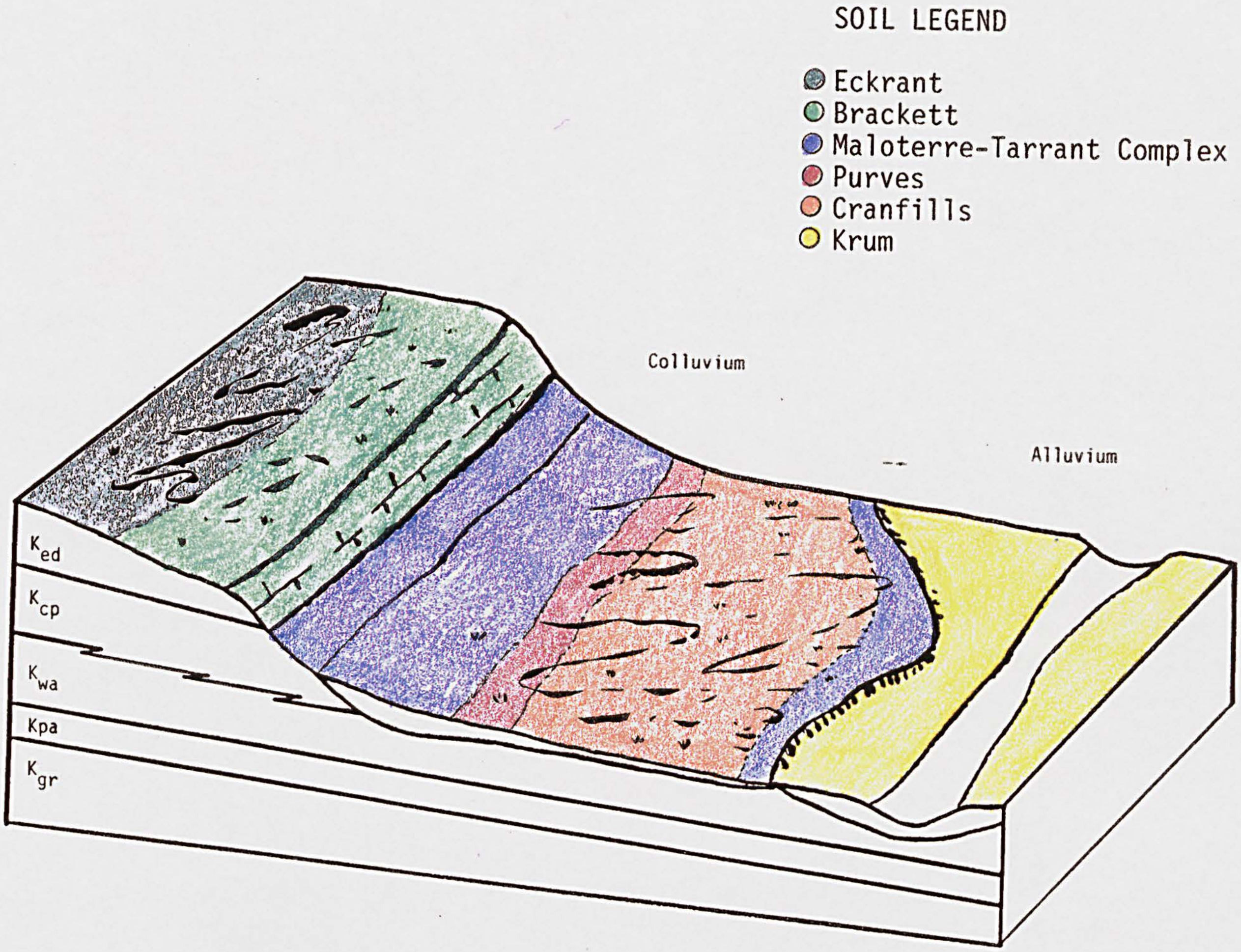


Figure 26. Diagrammatic sketch showing the soils relationship to the geomorphic and geologic positions. The colluvial material found at the base of the slope and the upper portion of the valley has the highest intrinsic permeability of the surrounding materials. The lower portion of the slope is actually outcrop of a *Gryphea* bed.

Brackett Soils

Brackett series soils form primarily on the crest of the Edwards divide, and consist of shallow, well-drained upland soils. These soils typically form from soft limestone which is interbedded with harder limestones and marl (Stringer, 1980, p. 44). These soils are not commonly found on the divide. Listed infiltration rates for the Brackett series soils are 0.2 to 0.6 in/hr (Stringer, 1980, p. 96).

Maloterre-Tarrant Complex Soils

These soils form over hard limestone, and their distribution correlates with outcrops of the Comanche Peak Formation in the study area (fig. 26). These soils are shallow, extremely well-drained soils. The Maloterre fraction of the complex is normally a gravelly loam, while the Tarrant fraction is slightly more clay-rich (Stringer, 1980, p. 48 and 54). These soils form from the limestones and marls common to the Comanche Peak Formation in the study area. Infiltration rates of these soils are 0.2 to 0.6 in/hr (Stringer, 1980, p. 96). There is also a thin band of these soils which formed on the *Gryphea* bed immediately upslope from the springs located in the park (fig. 26). The *Gryphea* bed has almost no soil to a very thin soil veneer present in the park area. Because of disturbances to the natural setting, it is difficult to tell how much of the park setting may be fill material.

Purves Soils

Purves soils are a clay to gravelly-clay soil which form at the break in slope of the divide (fig. 26). These soils are shallow, well-drained soils formed over interbedded limestones and marls (Stringer, 1980, p. 50). This soil probably represents transported material from the slope wash occurring on the Comanche Peak Formation, and is finer, more clayey material than present in the Maloterre-Tarrant Complex Soils. Infiltration rates of this soil are 0.2 to 0.6 in/hr (Stringer, 1980, p. 96).

Cranfills Soils

Cranfills soils form from loamy, calcareous colluvial material and are normally found at the base of slopes on a convex upland surface (Stringer, 1980, p. 44). These soils form from the colluvial material deposited at the base of the slopes following scarp retreat during the evolution of the Lampasas Cut Plain landscape as discussed in Hayward and others (1990). The infiltration rate of these soils is quite high, up to 2.0 in/hr, and measurements of similar materials located at site one indicate a vertical hydraulic conductivity of 22.7 in/hr. It is this high infiltration rate which indicates these soil areas are the most likely recharge area for this flow system. The Cranfills soils cover a large upland surface extending from near the base of the slope to the city park in Walnut Springs.

Krum Clay Soils

The Krum series soils are deep, well-drained soils formed from alluvial and terrace deposits which are typically unconsolidated clayey, calcareous material in the study area (Stringer, 1980, p. 48). The soils are located downslope from Walnut Springs and are limited to the stream valley area (fig. 26). It is possible that infiltration through these soils provide baseflow to Steele Creek, but these soil do not appear to aid in the development of the Walnut Formation flow systems in the immediate vicinity of the spring area.

Data Analysis and Results

Groundwater discharge from the springs in the city park at Walnut Springs was not monitored other than visually. Flow increased during the winter periods and spring flow diminished through the spring and summer months. For the entire study period, some spring flow was present. Water from the Walnut Formation is used in the park for aesthetic purposes and for a water fountain/wading pool in the park itself. The creek which transects the park in Walnut Springs, Texas (Steele Creek) also maintained flow on a continual basis, and did not go dry during the study period.

Geochemical Analysis Results and Interpretations

Geochemical analyses of the water at the spring studied at site two indicate that the water is chemically similar to the water at site one. One minor difference is the amount of nitrate in the water located at Walnut Springs. This is probably contamination from residences located in the immediate area or from agricultural practices on the colluvial recharge area of the flow system. Results of the Geochemical analyses are shown in Table 3.

Based on the geochemical information, it is unlikely that the water from Walnut Springs is from the Paluxy Formation because the calcium levels are higher than those normally associated with the Paluxy, and sodium levels are significantly lower than Paluxy waters as reported in Nordstrom (1982, p. 45).

Table 3.Geochemical results of Walnut Springs.

CATIONS	**CONCENTRATION IN PPM**
Calcium	104.7
Sodium	25.5
Magnesium	2.8
ANIONS	
Bicarbonate	255.79
Chloride	51.0
Sulfate	65.3
Nitrate	104.6

PPM = parts per million or mg/l

Conceptual Model for site two

The conceptual model for site two is similar to site one with a few minor exceptions. No springs were observed in the Edwards Formation on this divide. The colluvial blanket at the base of the slopes is the primary recharge area as indicated by the high infiltration rate and nature of the material of the colluvial deposits. The colluvial deposits are extensive in this area and comprise almost the entire upland surface to Steele Creek (fig. 27). Infiltrating water percolates downward until a permeability barrier is encountered. In this area, permeability barriers may be clay , marl, indurated *Gryphea* beds. All lithologies are visible in the small outcrop at the springs in the city park. The continued spring flow in the park is attributed to two primary causes: 1) the increased amount of colluvial material which stores a larger volume of water than at site one, and 2) decreased downward gradient between the

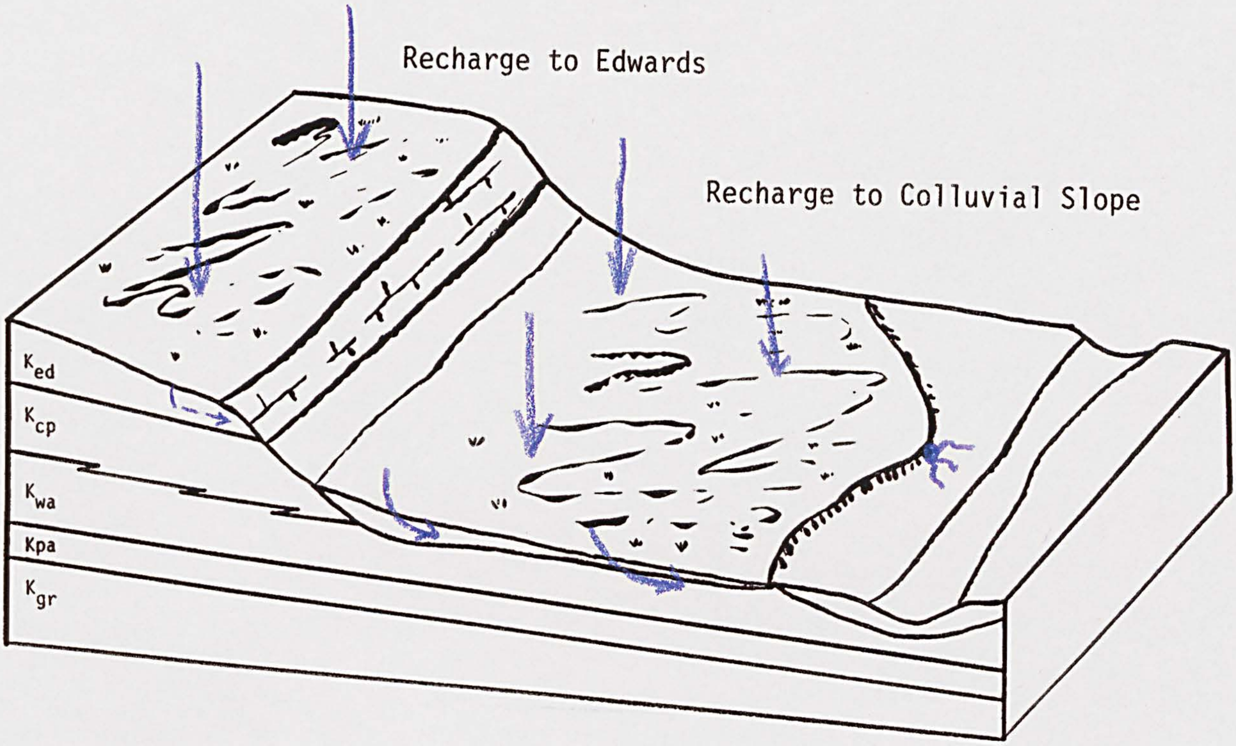


Figure 27. Conceptual diagram of the flow system at site two. Water infiltrates into the flow system primarily from the colluvial blanket (Cranfill soils), and through the fractures of the Gryphea bed at the lower portion of the slope. No spring flow was ever observed emanating from the Edwards, although staining along some of the bedding planes indicates some flow may occur at this location. Water infiltrates into the colluvium and then migrates laterally until encountering a permeability barrier. Spring flow occurs at Walnut Springs perennially. Sustained spring flow in this area is likely due to the condition of the underlying Paluxy Formation. The Paluxy at this location is a confined aquifer, and the downward gradient between the Walnut and the Paluxy is reduced drastically. The head in the Paluxy is not above the level of the spring (Crumpler, 1989, p. 28), but the decreased downward gradient facilitates prolonged lateral flow to the spring. Because the spring is located topographically higher than the alluvial material, it is believed the alluvium does not contribute to the spring flow at this site.

Walnut and Paluxy formations contributes to increased lateral flow within the Walnut Formation.

Summary of Site Two Flow System

The flow system present at site two is similar to that described at site one with two major differences; the downward gradient to the Paluxy is decreased, and there is an increased amount of colluvial material present on the upper portion of the valley floor. Because of the decreased vertical gradient to the Paluxy, there is greater potential for horizontal flow within the Walnut flow system. When the horizontal flow potential is coupled with an increased amount of colluvial cover serving as the recharge point, prolonged discharge at the spring is enhanced. During the course of this investigation, there was always dishcarge present at the springs in the city park of Walnut Springs, Texas.

CHAPTER 5

FLOW SYSTEM CHARACTERISTICS OF SITE THREE

Introduction

Site three is located approximately 3 miles south of the Hamilton City Airport in Hamilton County, Texas (fig. 1). The Walnut Formation is exposed in this region along a divide which extends from north of Hamilton to near the city of Killeen, Texas. The geomorphic location of this site is a divide between Leon River Drainage and Cow House Creek, a major tributary to the Leon River. The surface lithology of the Walnut Formation in this area is dominantly limestone, as opposed to interbedded limestone and calcareous clay in site one.

Geologic Setting of Site Three

The geologic setting of site three indicates this portion of Central Texas may represent a landscape older than that of the previous two areas. Dissection of the major streams has extended into the Lower Trinity Group, with streams flowing on the Glen Rose and Twin Mountains Formations (fig. 1). The uppermost formation present in this area is the Walnut Formation (fig. 28). From field evidence obtained by drilling and outcrop study in the immediate area of the well field, the dominant lithology present is limestone with occasional thin-bedded calcareous clay layers. The nature of the limestone ranges from thin regular-bedded limestones to *Gryphea* beds, while the most common limestone lithology has a nodular-bedded character.

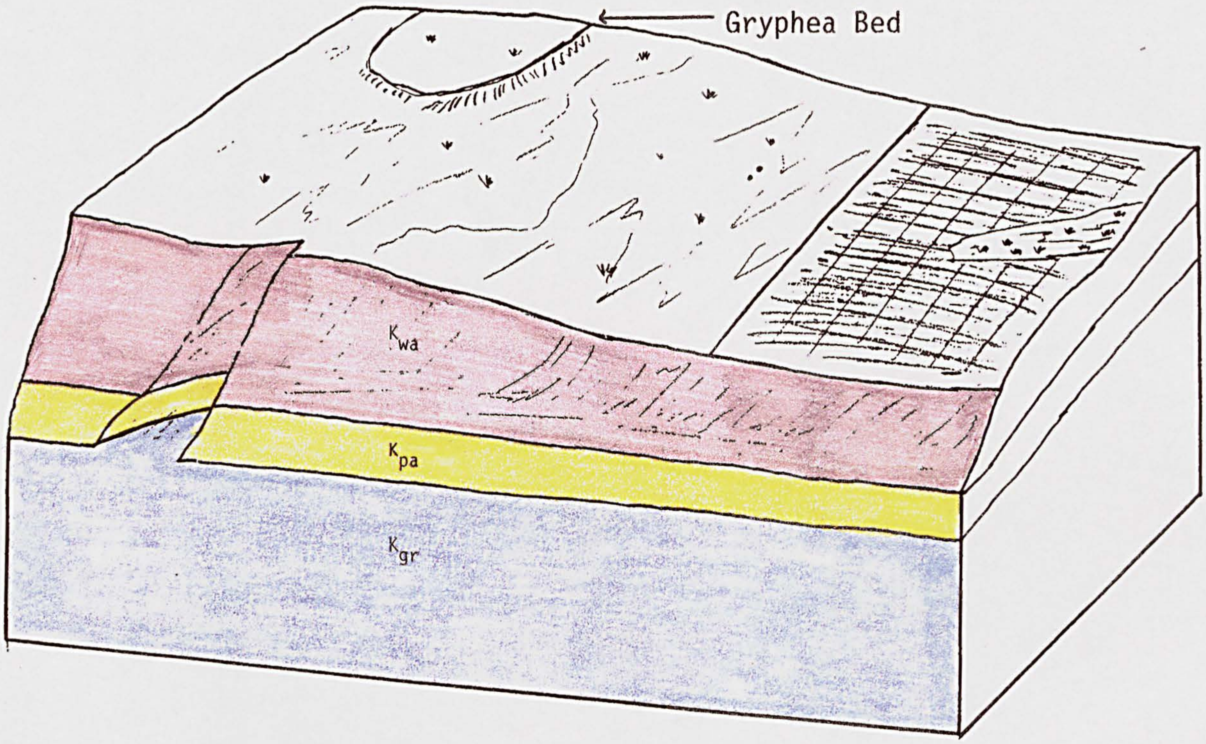


Figure 28. Diagrammatic sketch of geology and geomorphology of site three. The divide surface exposes the Walnut Formation. The Paluxy Formation and the Glen Rose Formation are exposed to the south of the study site. The Paluxy Formation is in the subsurface at the well field, and the small knoll is capped by an indurated Gryphea bed that is approximately 1 foot thick.

The interval drilled was a nodular limestone. From drilling information and logging of cuttings, the upper 5 to 7 feet of the limestone was considerably more fractured than the limestone material below 7 feet. There was no obvious color change of material indicating a change from a more weathered to a less weathered zone in the 15 feet penetrated.

The Paluxy Formation immediate underlies the Walnut at this location. The Paluxy Formation is thicker at this locality than at either site one or two. Because the Paluxy is considered unconfined at this locality, the gradient for the regional flow system is downward from the Walnut Formation to the Paluxy Formation. The Paluxy Formation at this location is exposed to the west in the outcrop belt of the Paluxy, and to the east in the Leon River valley. Because of the nature of the Paluxy exposure, the Paluxy here represents an unconfined portion of the aquifer. The downward gradient between the Walnut and the Paluxy is greater here than at the other two locations of this study.

Soils of Site Three

Soils of site three were mapped using field copies of soil maps obtained from the Soil Conservation Service located in Hamilton, Texas. The published soil survey was not available at the time this study was ongoing. The geomorphic relationships of the soils may be seen in figure 29.

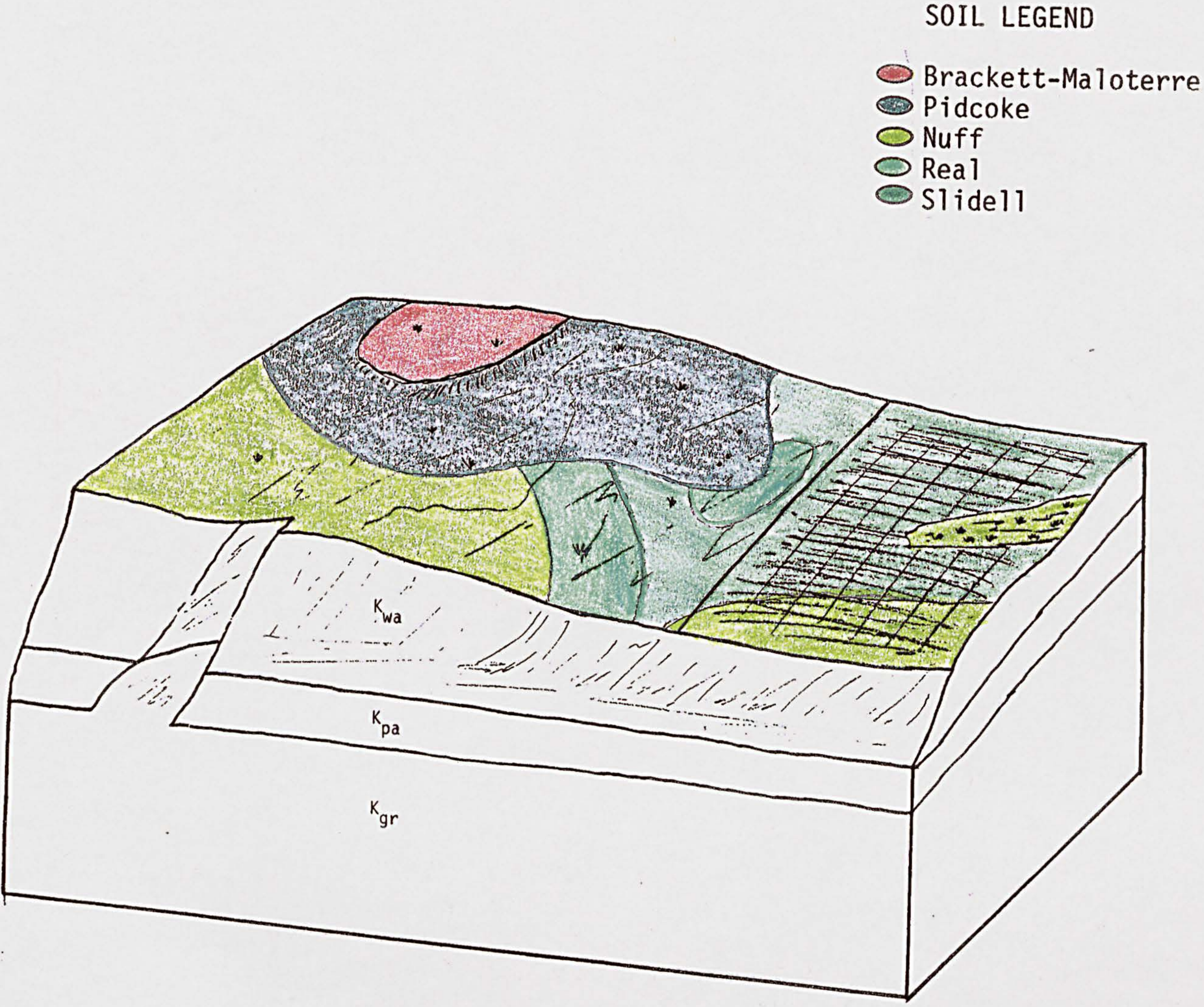


Figure 29. Diagrammatic sketch of soils relationship at site three. The figure shows the relationship among soils, geology and geomorphic position at the study site. While the soil relationship appears complex, the knoll and surrounding hillslope have soils less than six inches thick. The Slidell soil is located in the flatter portion of the valley, although there is little relief in the Walnut outcrop belt on this, the western margin, of the outcrop belt. High infiltration rates of soils tested near the wells (Pidcoke gravelly clay loam) indicated a potential for recharge to occur on the knoll, the hillslope near the top, and along the sides of the knoll.

Brackett-Maloterre Complex (2-12% slope)

Brackett series soils normally develop on interbedded limestones, marls, and shales. Brackett soils are typically deep, well-drained, loamy upland soils (McCaleb, 1985, p. 57). Infiltration rates are 0.6 to 2.0 in/hr.

Maloterre soils consist of very shallow, well-drained loamy upland soils normally formed on limestone. The soils in the immediate vicinity of the wells at site three are very shallow soils (less than 3 inches). The soils on the top of the small divide (fig. 29) are extremely shallow to non-existent.

Pidcoke Gravelly Clay Loam (1-3% slope)

Pidcoke series soils consist of shallow, well-drained, loamy soils formed from marly marine sediments with indurated limestones and abundant fossil fragments (McCaleb, 1985, p. 68) (fig. 29). Depth may be up to 13 inches; however, in the vicinity of the wells at site three only 3 inches of soil was present. Infiltration rates of these soils was measured by utilizing a Guelph Field Permeameter and results were 3.0 in/hr.

Nuff Silty Clay Loam (2-6% slope)

Nuff silty clay loam soils are deep soils normally found on the sides of low ridges and stream divides (fig. 29). These soil are formed primarily on limestone and marls. The soil often contains large "stones" or rock fragments which cover the ground surface. Permeability is moderately slow (0.2 to 0.6 in/hr), and the available water capacity is high (McCaleb, 1985, p. 24).

Real Gravelly Clay Loam (1-3% slope)

Real soils are typically well-drained soils with moderate permeability. Real soils are often associated with rock outcrops, and the soils normally form over weakly to strongly cemented, interbedded limestones (fig. 29) (McCaleb, 1985, p. 26). Permeability rates are 0.6 to 2.0 in/hr (McCaleb, 1985, p. 119). In site three the topography is gentle and the Real series is found on less steep slopes than elsewhere in Central Texas.

Slidell Silty Clay (1-3% slope)

The Slidell Silty Clay is a deep, gently sloping soil in valley fill areas along drainage ways (McCaleb, 1985, p. 27) (fig. 29). Permeability is very low (<0.06 in/hr) and is below the limit for the Guelph Permeameter in the field. During dry periods, cracks form in the soil (McCaleb, 1985, p. 24) which provide passageways for water to infiltrate by macropore flow.

Data Analysis for Site Three

Hydrograph Analysis

Two wells were placed on the side of the divide, within the direct recharge zone of the hillslope, with limestone at the surface and near surface (fig. 30). One piezometer was drilled to a depth of 6 feet, while the other was drilled to a depth of 14 feet. The shallow piezometer monitors the zone from 1 to 5 feet below the ground surface, while the deeper piezometer monitors the zone from 4 to 14 feet below the ground surface. Thus, the monitoring wells share a common one foot zone from 4 to 5 feet below ground level (fig. 31).

Figure 30. Photos showing the geologic setting at site three. The upper photo shows the flat landscape with the Walnut Formation cropping out, and capping the hill. Thickness of this outcrop is 12 feet. Lower photo shows nature of limestone material capping the small hill. Notice the fractured nature of the limestone material.

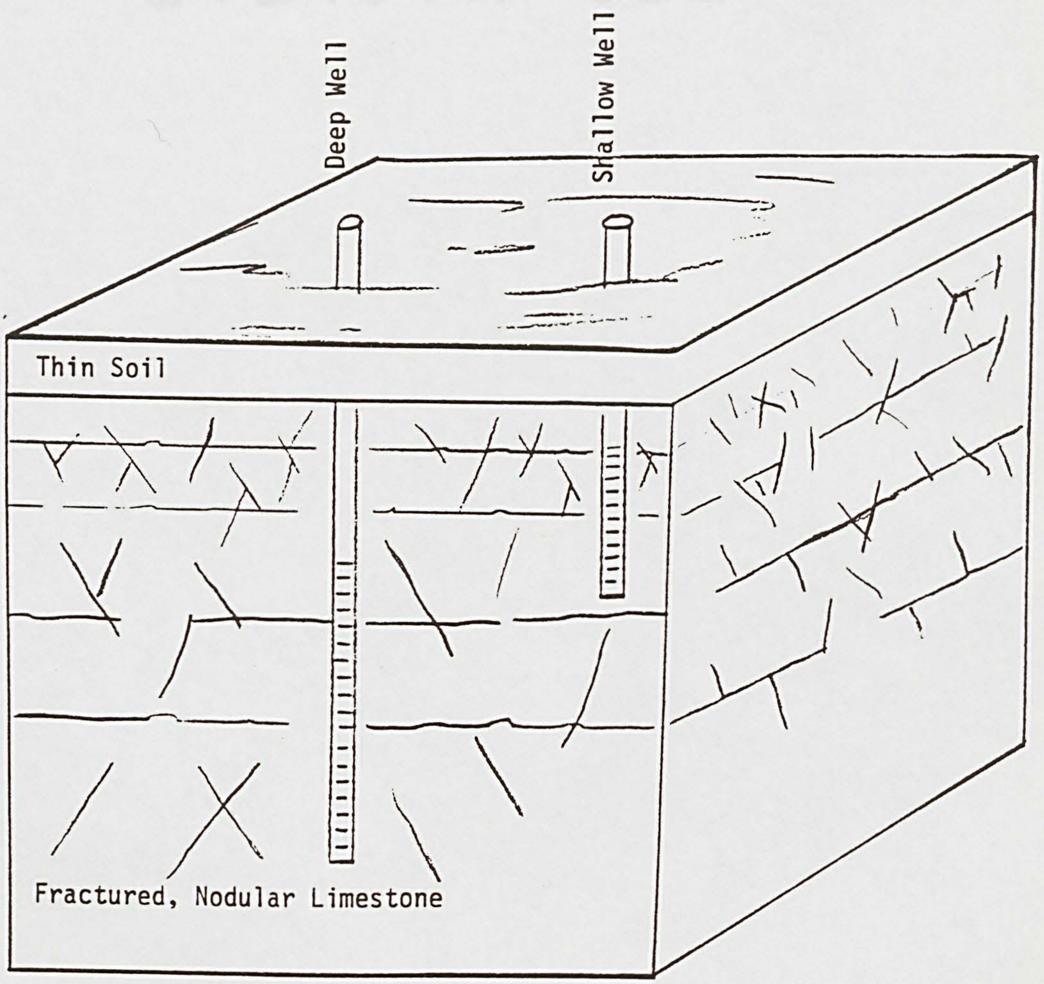


Figure 31. Diagrammatic sketch showing the well monitoring zones. Both wells were completed in a nodular limestone material which appears to have very little matrix porosity. It is interpreted that most of the groundwater present at this location migrates via fractures and bedding planes present in the limestone. The wells share a common 1 foot zone at the base of the screen of the shallow well and the top of the screen of the deeper well.

Water was present at approximately 4 to 5 feet below ground during the drilling of these wells, and water levels were monitored. Both wells reacted similarly to recharge events (fig. 32). No stream flow was present in the immediate vicinity to make definite conclusions about the relationship between the ground and surface waters. However, some small streams were located flowing on the Walnut Formation, indicating that in some areas, a groundwater/surface water relationship may exist.

Interpretation of the hydrograph data (fig. 32) indicates the water level elevation recorded in both wells is nearly identical. This strongly indicates that the wells monitor an unconfined aquifer and that the monitoring wells are along equipotential lines of the flow system, with groundwater flow being downhill (downgradient) (fig. 33).

Electrical conductivity of the groundwater at site three rise as groundwater levels fall (fig. 32). This indicates that the water in storage reacts with the limestone. The shallow well has slightly lower conductivity than the deeper well during the beginning of the hydrograph, but the conductivity values converge near the end of the hydrograph. Because recharge (rainfall) has not occurred during the time at the end of the hydrograph, fresh water is no longer being added to the flow system, and the water becomes similar with respect to electrical conductivity.

Permeameter Analysis

A Guelph permeameter was also used in an attempt to characterize the saturated hydraulic conductivity of the soils in the immediate vicinity of the wells at this locality. Results of the permeameter testing produced values of 4.17×10^{-3} ft/min or 2.12×10^{-3} cm/sec.

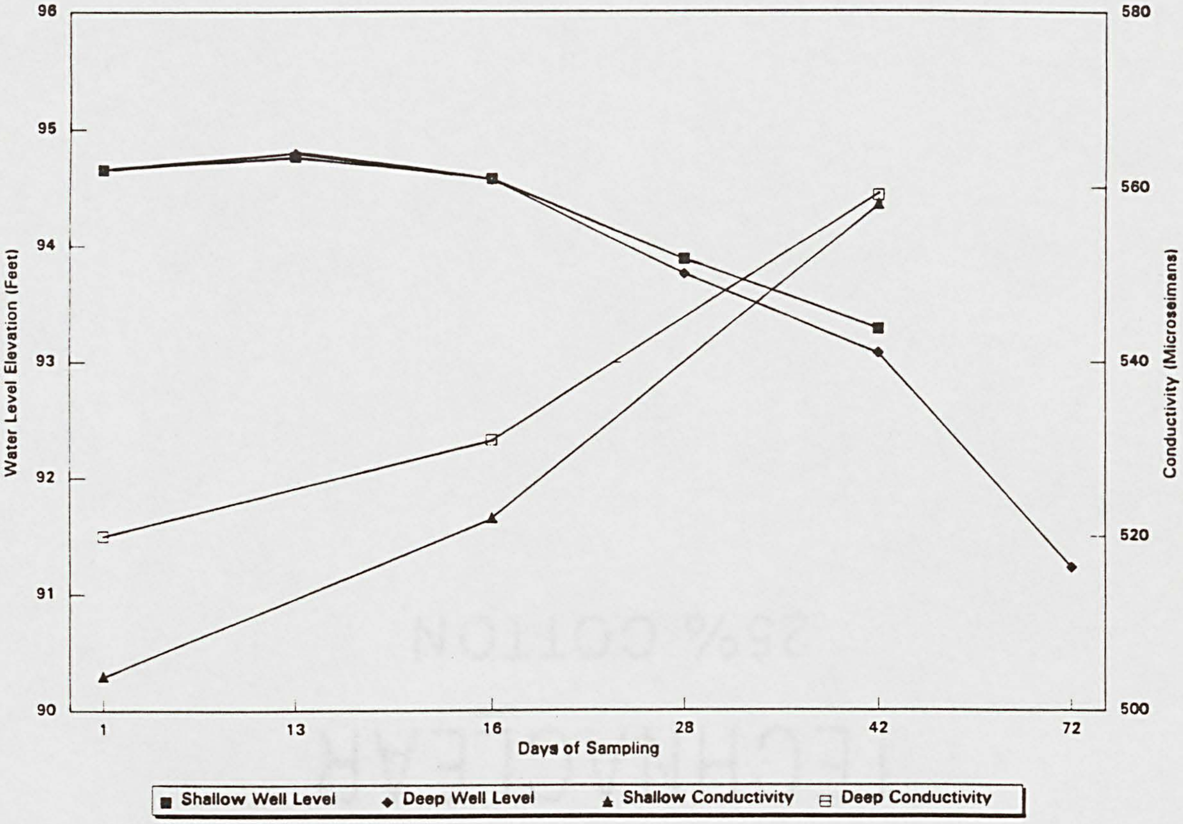


Figure 32. Hydrograph showing water levels and electrical conductivity of the two monitoring wells present at site three. Conductivity values indicate the deeper well has higher electrical conductivity values than the shallow well. As water levels decline, electrical conductivity increases in both wells. The conductivity also becomes more homogeneous in the system over time. Rainfall occurred on the eighth day of monitoring, and both wells showed a slight increase in water levels on the tenth day. No recharge was monitored during the remainder of the monitoring period.

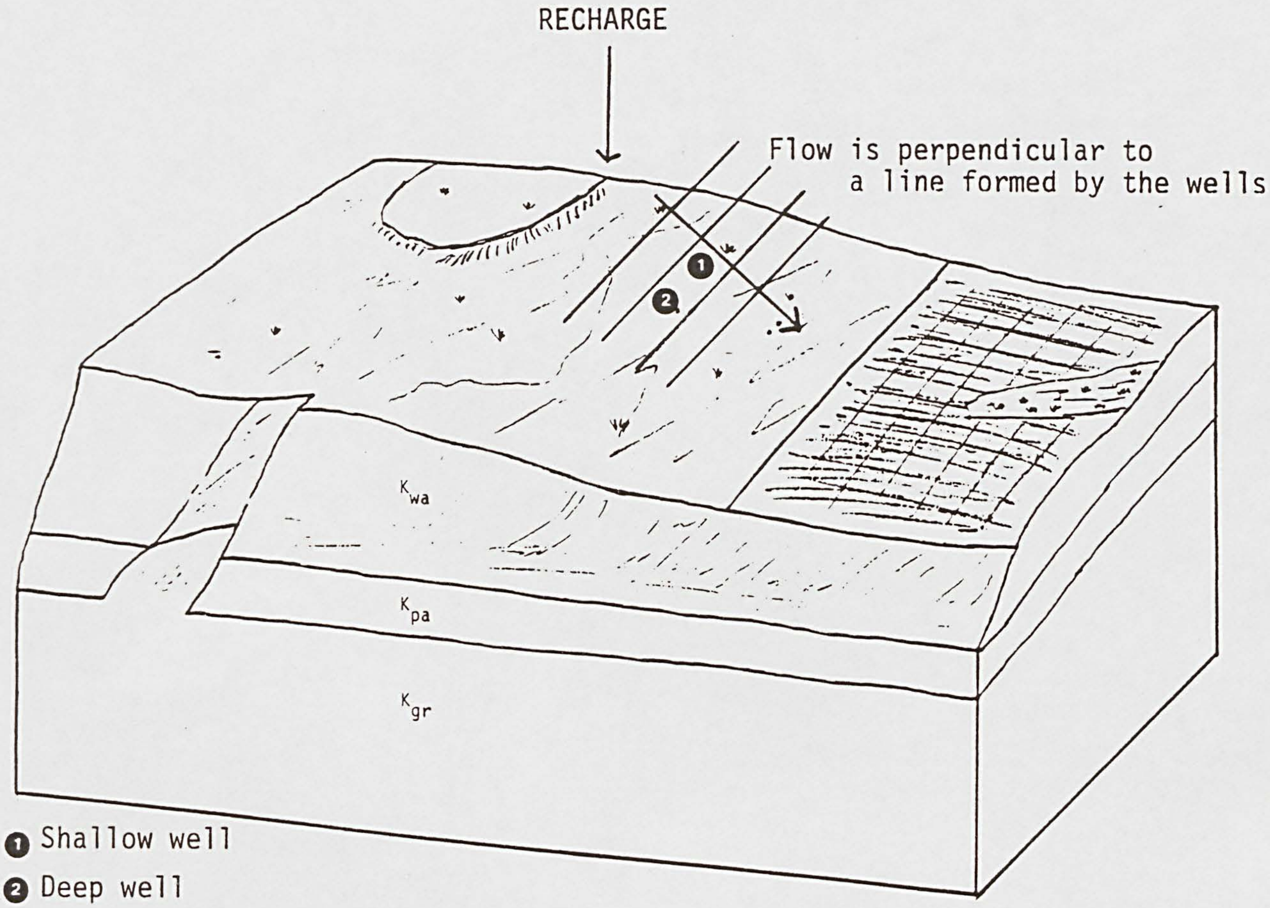


Figure 33. Conceptual diagram of well placement and groundwater flow direction. Because the water levels in the two monitoring wells are essentially the same during the entire monitoring period, the two wells are place along equipotential lines of the flow system. This would indicate that recharge occurs near the top of the hill (and along the entire hillslope), and water moves perpendicular to a line formed by the two monitoring wells.

Aquifer Testing Analysis

Slug tests and a pumping test were conducted at the study site to obtain hydrogeologic characteristics within the immediate area. The deeper piezometer was designated as the pumping well, and drawdown was monitored in both the pumped well and the shallower observation well. Results of the aquifer testing are shown in Table 4. Data reduction and further discussion is included in Appendix 2.

Table 4. Aquifer Testing Results at Site Three

Method of Analysis	Transmissivity (ft2/min)	Storage Coefficient
Theis Pump Well Drawdown	.017	----
Theis Observation Well Drawdown	.027	.00077
Theis Pumped Well Recovery	.0091	----
Time-drawdown Observation Well	.013	.0026
Bouwer and Rice Slug Test (Deep well)	Hydraulic Conductivity K = .00004 (ft/min)	----
Average	**0.017**	**0.0013**

The flow system is composed of fractured and nodular limestones. Groundwater flow occurs along the fractures and bedding planes. The storage coefficient is low for an unconfined aquifer; however, the water in storage is primarily in the fractures, with little matrix porosity in the limestone. This storage coefficient is probably representative of the system present at site three.

Data Interpretation and Results for Site Three

Interpretation of the hydrograph data for site three indicate that both wells monitor the same water bearing zone (due to similar head), although the wells are completed at different depths. The aquifer at this site is considered to be unconfined based on the field observations made during the drilling program. The matrix of the limestone material recovered during coring appeared dry. This indicates that most of the flow at site three probably occurs in fractures and along bedding planes. Indurated limestone beds may act as vertical barriers and enhance lateral flow within the formation.

The thin soils that cap the divide at site three have a relatively high hydraulic conductivity and allow sufficient water to infiltrate to depth and saturate the limestone lithology of the Walnut Formation. Sufficient recharge occurs during the fall and winter months, and the system begins to "dry out" in the late spring and into summer, as illustrated by the declining limb of the hydrograph during the spring months (fig. 32).

The Paluxy Formation, which underlies the Walnut Formation at this locality, is also an unconfined aquifer. While partial saturation may occur, the Paluxy Formation is exposed to the west of the study site and also to the east of the study site in the Leon River Basin. With groundwater flowing through the Paluxy from recharge to discharge points in a relatively short distance, it is unlikely that artesian conditions within the Paluxy can develop in this area.

Because the Paluxy is not artesian in this area, the overall groundwater gradient is downward from the Walnut to the Paluxy. Although most of the groundwater movement in the Walnut Formation at this locality is downward, permeability barriers such as indurated limestone beds and marl beds divert flow laterally. The lateral movement of the groundwater may continue within the Walnut until it intercepts a fracture or other means of downward migration, at which time downward movement would again occur. This type of groundwater motion may explain the lack of correlation between the Walnut flow systems and surface water in the immediate vicinity.

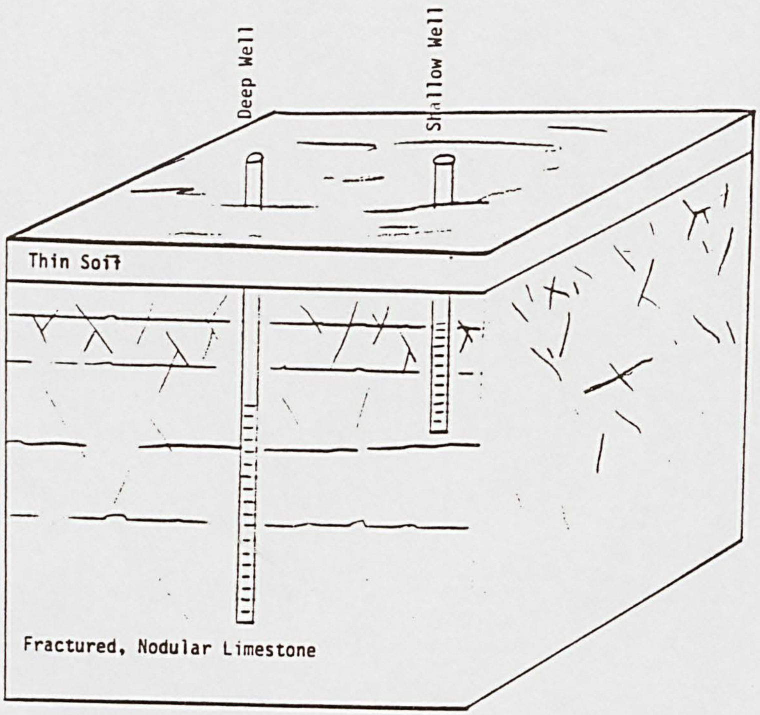
Statistical analysis of the water levels and the electrical conductivity values show a direct correlation, as supported by the hydrograph data. Statistical correlation of the values may be seen in figure 34.

Geochemical Analysis Results and Interpretations

Geochemical analysis of the water from both wells present at site three indicate that the waters are similar in chemical composition, indicating that the wells monitor a single groundwater flow zone, and support the conclusion of an unconfined flow system present at this location. Geochemical results can be seen in figure 35.

VARIABLE	Shallow Well Water Level	Deep Well Water Level	Conductivity Shallow	Conductivity Deep
Shallow Well Water Level	------	1.00	-0.961	-0.975
Probability		**1.000**	**0.821**	**0.857**
Deep Well Water Level		------	-0.960	-0.974
Probability			**0.820**	**0.856**
Conductivity Shallow			------	0.998
Probability				**0.964**
Conductivity Deep				------
Probability				

Figure 34. STATPLAN correlation matrix of water levels and conductivity values at site three. The matrix indicates perfect correlation between water levels of the two wells, and strong correlation between the electric conductivity values measured at the monitoring wells. Also of importance is the inverse relationship between electric conductivity and the water levels of the monitoring wells. As water levels decrease, conductivity increases.



Shallow Well

T	16.4°C
pH	7.20
Cond	522 µs
Ca	58.9 ppm
Na	6.7 ppm
Mg	4.42 ppm
Cl	19.01 ppm
SO_4	27.5 ppm
HCO_3	228.86 ppm

Deep Well

T	17.4 °C
pH	7.09
Cond	531 µs
Ca	60.9 ppm
Na	7.3 ppm
Mg	1.55 ppm
Cl	13.34 ppm
SO_4	22.95 ppm
HCO_3	296.17 ppm

Sample Date is 3/29/93

Figure 35. Figure showing the geochemical relationships at site three. Of primary interest is the deeper water contains slightly higher concentrations of cations and bicarbonate, and a higher conductivity (Figure 32). This indicates the waters present deeper in the flow system have achieved more water/rock interaction. Temperature is also higher at depth in the flow system, and the pH is slightly more acidic than in the shallow portion of the flow system.

Conceptual model of Site Three

Site three is located on the side of a small hill south of Hamilton, Texas. This hill is large enough to be a groundwater divide for a shallow flow system within the Walnut Formation. Essentially all of the water found within the flow system recharges in the immediate vicinity of the hilltop and the surrounding hillslope areas (fig. 36). The geology of this area is predominantly limestone, with minor amounts of marl. This flow-system begins with infiltration through the very sparse soils that cap the hilltop. Water moves both laterally and vertically (downward) through the bedding planes and along fractures within the limestone lithologies. Due to the downward gradient from the Walnut to the Paluxy Formation, water moves primarily downward, with lateral movement occurring when water intercepts a permeability barrier. This water movement also explains the poor correlation with surface waters in the immediate area of the wells.

Summary of Site Three Flow System

The flow system at site three is unconfined with groundwater flow occurring primarily along bedding surfaces and fractures in the nodular limestone material. Recharge appears to occur at the top of the hill and probably downslope past the location of the wells. This groundwater is strongly influenced by a steep downward gradient to the unconfined Paluxy Formation, and the water table does not appear to intersect the ground surface in the immediate vicinity, creating a situation where it is difficult to determine the relationship between groundwater and surface water.

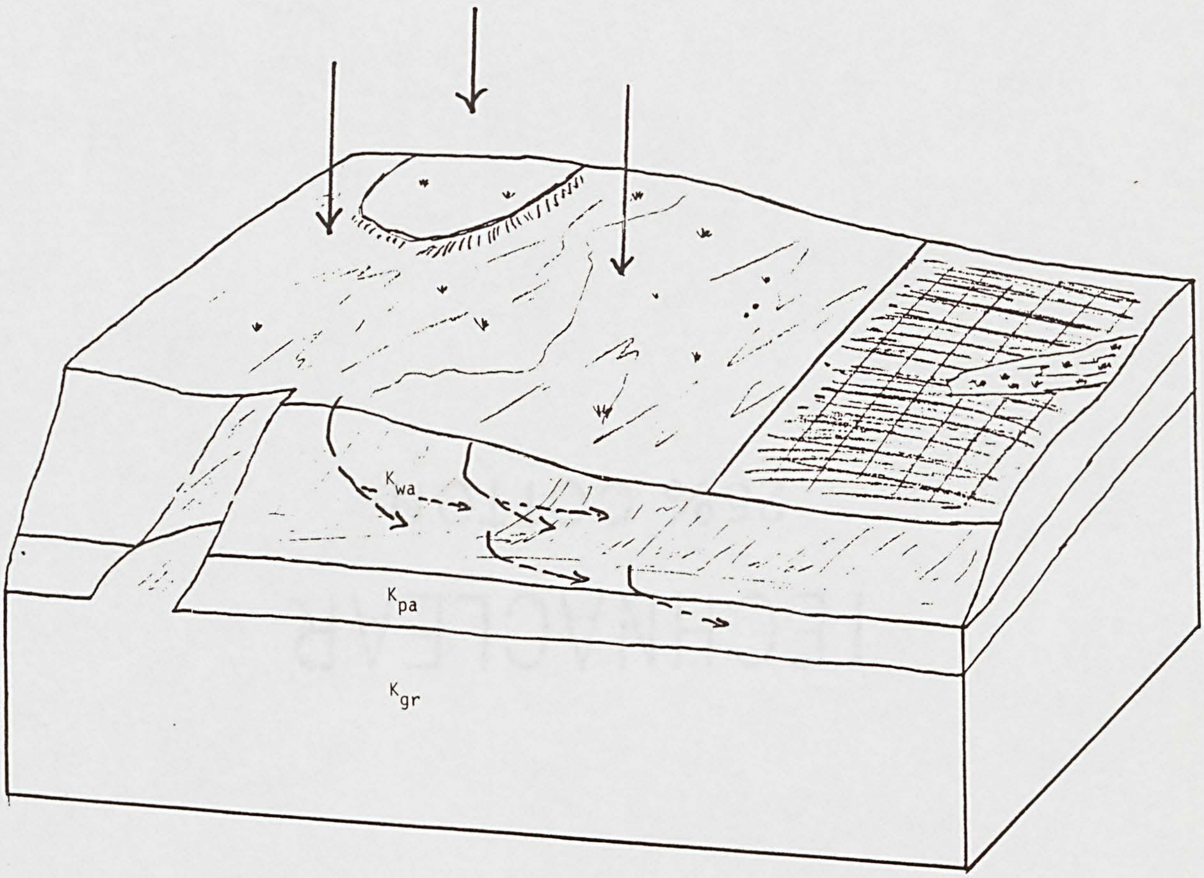


Figure 36. Conceptual diagram of the flow system at site three. Infiltration occurs on the surface of the divide and water migrates into the limestone present in the shallow subsurface. Flow in the limestone is primarily along fractures and bedding planes in the Walnut Formation limestones. Because the underlying Paluxy Formation is unconfined in this area, there is a strong downward gradient between the Walnut and Paluxy formations. This may account for the difficulty in determining a relationship between surface waters and groundwater in the immediate area of the monitoring wells. While lateral flow occurs in the Walnut, it would appear the greatest potential is downward toward the Paluxy Formation.

CHAPTER 6

INTERPRETATION OF REGIONAL WALNUT FORMATION FLOW SYSTEMS

Introduction

Based on information gathered from the flow systems present in the Walnut Formation at the three sites discussed, it is possible to extrapolate the information to a regional perspective. The primary evidence of groundwater in the Walnut Formation is baseflow in streams which transect the Walnut outcrop belt. It is not implied that all of the water in the streams during baseflow periods is discharged from the Walnut Formation; however, some or much of the water in the streams during baseflow periods apparently discharges from shallow flow systems within the Walnut Formation.

Other potential sources of water present in the streams during baseflow periods include discharges from the Edwards Formation and a contribution from alluvial sections bordering the streams. It has been observed that the Edwards Formation contributes water only during the late fall, winter, and early spring periods of the year in most locations. It is also possible, as seen a locality one, that water discharged from the Edwards springs travels through a flow system in the Walnut Formation prior to reaching the stream, giving the water a "dual" flow-system history.

Because the flow zones observed in the Walnut during this investigation were in either limestone or a carbonate clay, it would appear that the carbonate material forms the saturated zones within the Walnut Formation. It is also possible that the flow zone at site one is influenced by the surface water, with increased hydraulic conductivity being present in the near stream zone due to increased solutioning of the carbonate material in that area. This idea was discussed in detail by LeGrand and Stringfield (1977, p. 1289). Gburek and Urban (1990) also noted that fracture density may increase in the near stream zone due to weathering and groundwater flow, increasing permeability. However; the flow systems at sites two and three were not associated with a near stream zone, and the limestone material may have an enhanced permeability because of dissolutioning by infiltrating waters from rainfall events. Site one is located in the near stream zone of an ephemeral stream.

The conceptual model of the regional flow system is shown in figure 37. The entire conceptual model is actually made up of several smaller "pieces" which are the three flow-systems as described in this work (fig. 38). At any one location, there may be a combination of the conceptual models from sites one, two and three, or the location may be almost an exact match of one of the conceptual models presented in this work. A spatial relationship also appears to exist, with "site three" areas located at the toe of Edwards capped slopes, and "site one" areas present in the re-entrant valleys (fig. 39).

One of the major factors controlling the regional flow-systems in the Walnut appears to be underlying Paluxy Aquifer. To the west (in the area of site three), the Paluxy Aquifer is exposed on the up-dip and down-dip side of the outcrop. It is unlikely that the Paluxy exists as a confined aquifer in this position. The Walnut flow-systems in this area have a downward gradient to the Paluxy Formation, and lateral flow in the Walnut Formation is enhanced by locally continuous indurated limestone beds. The correlation between surface water and the water present in the Walnut is difficult, if not impossible, to determine. In some localities it appears that

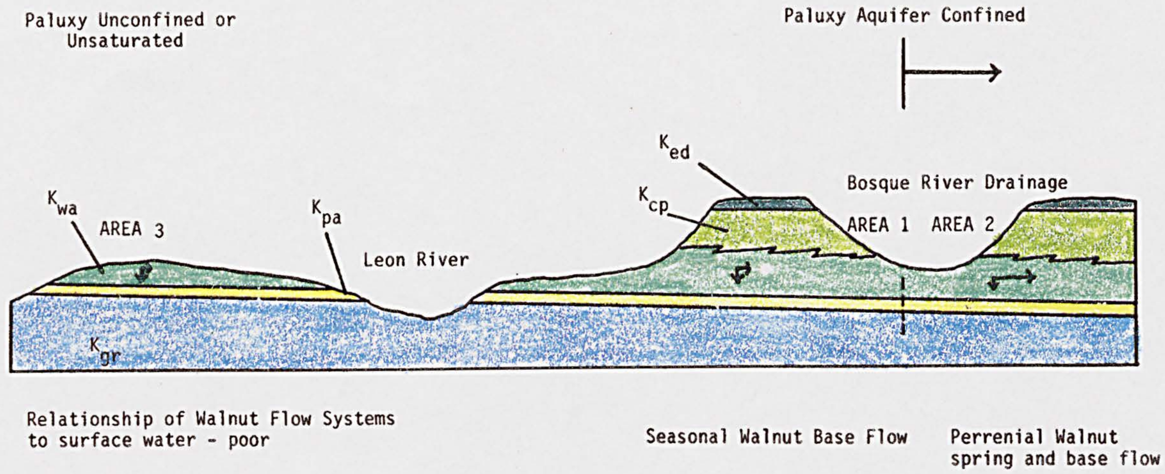


Figure 37. Diagrammatic sketch of the regional flow system of the Walnut Formation in the outcrop belt. On the western margin, the gradient between the Paluxy and the Walnut Formations is greatest, and water moves primarily downward into the Paluxy due to the difference in hydraulic head potential. Eastward in the outcrop belt, the Paluxy Aquifer eventually saturates and becomes confined. As this confinement occurs, lateral flow in the Walnut Formation increases. Site two of this study is west of the confinement of the Paluxy, and the Walnut flow system contains water for the entire year; however, the water from the Walnut is not discharged to surface waters in the higher geomorphic positions. It does continue to discharge to the surface waters in the lower geomorphic positions as witnessed by continued baseflow of these streams. On the far eastern margin of the Walnut outcrop belt, near Walnut Springs, the downward gradient is much less, and lateral flow in the Walnut continues year-long because the water is held in storage in the Walnut longer, and water does not migrate into the Paluxy Formation as quickly as in the western portions of the outcrop belt.

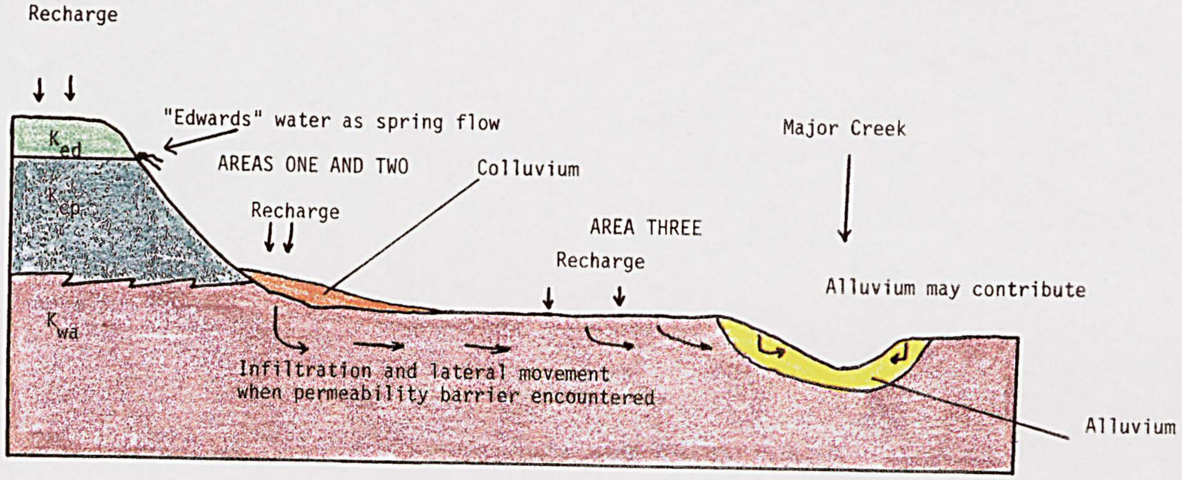


Figure 38. Diagrammatic conceptual diagram of the relationship of the flow systems of this study. The upper geomorphic positions behave as sites one and two of this study. The valley of the streams would behave like site three of this study, and water would continue to discharge to the streams. As the dryer period of the year progresses, water in storage in the upper geomorphic positions is depleted, creating a flatter gradient, and surface water flow diminishes, but does not cease in a normal climatic year. The wetter period of the year recharges both the lower and upper valley positions of the flow system, and stream flow migrates up to higher geomorphic positions in response. It is this interaction among these individual "pieces" of the flow system that constitute the entire flow system of the near-surface Walnut Formation.

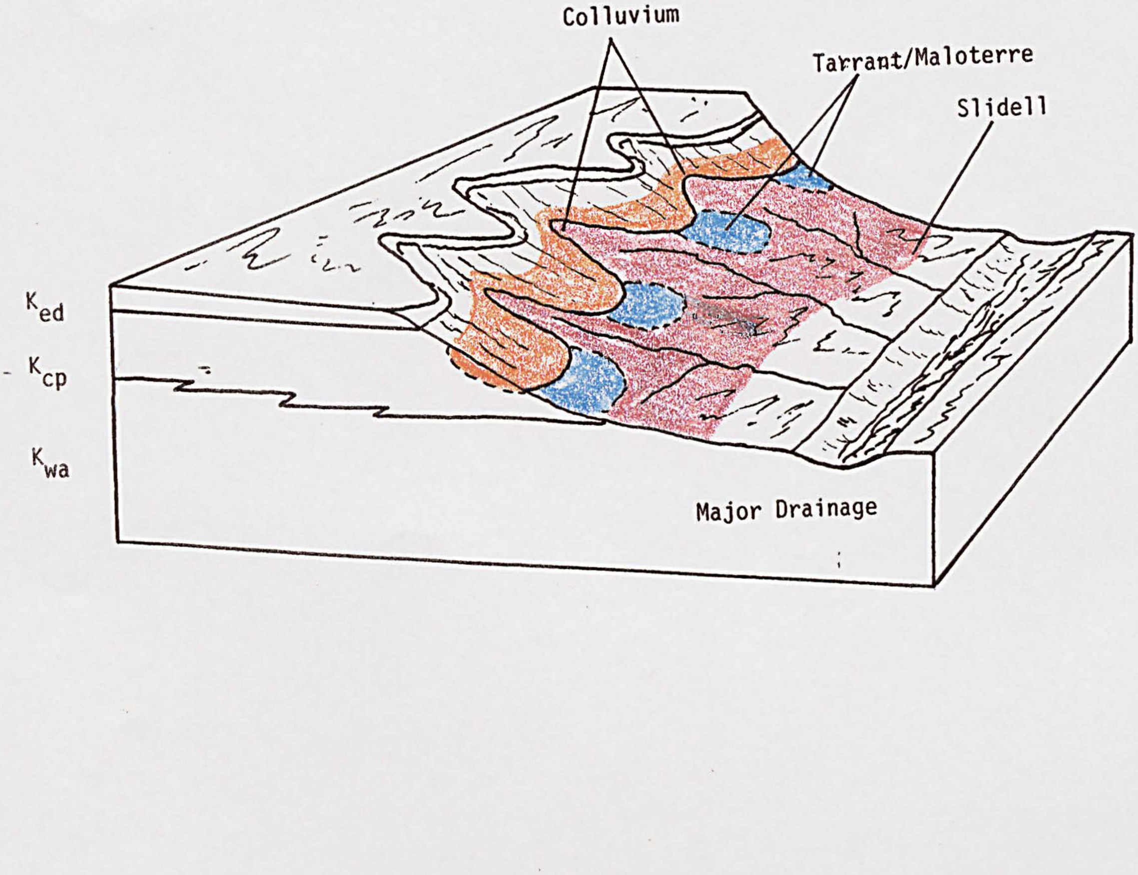


Figure 39. Diagrammatic block sketch showing the spatial relationship between site one (and two) and site three flow systems. The toe of the slopes typically have Tarrant/Maloterre soils (site three), where water would directly infiltrate through the bedrock material. The Slidell soils are located in the re-entrant valleys with colluvial material blanketing the base of the Edwards-capped scarps (site one and two), with the colluvial material representing the primary recharge location.

water is discharged to the creeks from the Walnut, while a few miles away at the same time, in approximately the same geomorphic position, the creeks remain dry. This suggests that stratigraphic variations play a significant role in Walnut flow-systems and their relationship to creeks in this area.

Further east, near Cranfills Gap, Texas, the Paluxy up-dip outcrop is well to the west, and the Paluxy is found from 80 to 120 feet below the ground elevation of the Walnut outcrop. The Paluxy Aquifer here is probably still unconfined, although the confinement point occurs just to the east of this area (Crumpler, 1989, p. 26). From this information it appears that the Paluxy Aquifer is completely saturated. Due to the saturation of the Paluxy Formation, the downward gradient from the Walnut to the Paluxy may not be as great as in the western portion of the cross-section. Due to this possible reduction in downward gradient, more water in the Walnut may migrate laterally. Stratigraphic variables such as indurated limestone beds and clay beds may also aid the lateral flow of water as in the western portion of the study area.

Because of the decreased downward gradient in the eastern portion of the study area, water is continually supplied to streams that cross the Walnut outcrop belt during a normal year of precipitation. During wetter periods of the year, discharge may occur farther up the slopes (higher geomorphic position) as seen at site one of this study. When water is depleted from storage in the upper geomorphic positions, the lower geomorphic positions (systems much like the Hamilton site) continue to discharge water to the creeks. It is possible the alluvial stretches along the creeks also supply some of the water however, that was not investigated in this study.

In the extreme eastern portion of the study area near Walnut Springs, Texas, the Walnut flow systems are still influenced by the condition of the Paluxy Aquifer. In this region, the downward gradient to the Paluxy from the Walnut is the lowest gradient of the three sites discussed in this work, based on information from Crumpler (1989). The decreased downward gradient allows more lateral flow to occur, thus creating springs which flow, or at least seep, during the entire year. The primary differences between sites one and two of this study are 1) slightly different lithologies and 2) downward gradient to the Paluxy Formation. It is most likely a combination of the two differences that create different flow system characteristics among the three flow systems discussed.

It is likely that the creeks transecting the Walnut Formation in Central Texas receive baseflow water from basin-wide Walnut flow systems which are a compilation of the three flow systems discussed in this thesis. Closer to the Edwards-capped divides, flow systems such as those discussed near Cranfills Gap or Walnut Springs (sites one and two) are common. Further away from these flow systems, where the Walnut Formation crops out closer to the streams, or at the toes of the slopes where the colluvial material is thinner, flow systems such as that discussed at site three are most common (figs. 38 and 39). These flow systems are not separate entities, but are connected at a larger, regional scale as well.

CHAPTER 7

CONCLUSIONS

The purpose of this investigation was to provide information about groundwater flow systems that are located in the Walnut Formation of Central Texas. Information was also presented on hydrogeologic parameters of the Walnut Formation for use in construction and land-use planning. The current investigation also indicates a strong relationship between groundwater found in the Walnut Formation and the surface waters located in Central Texas streams. The conclusions of this investigation include:

1 The Walnut Formation contains flow systems which provide water to Central Texas streams.

2 Specific locations within the Walnut flow systems may have hydraulic heads above ground surface elevations during wetter months of the year.

3 Hydraulic conductivities of the Walnut Formation in some locations are greater than those allowed for in-situ landfill liners.

4 Colluvial blankets at the base of the Edwards-capped divides of Central Texas appear to be recharge zones for the Walnut flow systems (sites one and two).

5 Recharge may occur through thin soils which cover the limestone outcrop of the Walnut Formation (site three).

6 Potentially hazardous landuse practices in the recharge zones of the flow systems may endanger the surface water quality by introducing material from the recharge zones to the creeks via flow systems present in the Walnut Formation. A very similar situation is discussed by Azimi-Zonooz and Duffy (1993, p.972 - 981) in which creek salinity is increasing due to increased water

moving through a flow system in the Mancos Shale in Utah; a situation similar to the Walnut flow systems described in this work.

7 Baseline geochemistry data now exists for Walnut groundwater; these are by no means definitive geochemical studies, but they do allow for discrimination between Paluxy water and Walnut water.

CHAPTER 8

RECOMMENDATIONS

This investigation was intended to provide insight into a previously undescribed, potential source for baseflow in central Texas streams. A broad reconnaissance cannot possibly begin to describe all of the subtleties that may exist in these Walnut flow systems. Further, and more detailed investigations are necessary to better understand these flow systems. Items to be considered include the following:

- The Walnut Formation and the underlying Paluxy Formation maintain a complex hydrogeologic relationship in the Central Texas area, further study of this relationship is warranted to better determine the hydrogeologic relationship of the two formations.
- Highly detailed studies of flow systems in the Walnut Formation should follow this initial investigation to better determine the geomorphic, geologic, and hydrogeologic relationships of the Walnut Formation flow systems.

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APPENDIX ONE

Previous Works

Year	Author(s)	Importance to this study
1901	Hill	Described Cretaceous deposits in Central Texas; Description of Comanchean Series remains unchanged.
1935	Theis	Detailed method of aquifer analysis for deriving transmissivity and storage coefficient values for pumping tests, implementation of type curve solution used in AQTESOLV computer program
1946	Jacob	Detailed aquifer analysis for deriving transmissivity and storage coefficient values following pumping test
1959	Lozo, F.E. (ed.)	Described lithologic and stratigraphic character of the Edwards Formation in the study area
1960	Atlee	Broad reconnaissance of Paluxy Formation; Study dealt with facies and lithologies
1963	Frost	Discussed Edwards Formation of Central Texas; Established regional facies variations.
1966	Jones	Regional study of Walnut Formation; identified five members of the Walnut Formation.
1969	Lewand	Interpreted geomorphic evolution of Leon River System
1969	Moore	Described the geologic complexities within the Lampasas Cut Plain, Callahan Divide, and the Edwards Plateau
1971	Brown	Discussed lithologies and stratigraphy of Washita Group of Central Texas
1973	Epps	Described the history of the Brazos River. Discussed in depth the base level changes to this trunk stream of the smaller Central Texas streams of interest to this study
1976	Bouwer and Rice	Discussed methodology for determination of hydraulic conductivity from slug testing.
1976	Flatt	Discussed Oyster Banks in Walnut Formation; discussed constituents of oyster beds in detail
1977	Bishop	Detailed surface water flow in the Bosque River Basin, discussed physical characteristics of the drainage system
1977	LeGrand and Stringfield	Discussed development and distribution of permeability in carbonate aquifers

1977	Keyes	Discussed stratigraphy and lithologies of Comanche Peak Formation
1977	Mikel	Discussed geomorphology of Lampasas Cut Plain in Central Texas; attempted to estimate time necessary for landscape formation; provided insight on formation of landscape which controls the flow systems of the present study; studied the formation of caliche and discussed water movement in caliche formation.
1979	Owen	Study looked at the regional stratigraphy of the Paluxy Formation in Central Texas.
1982	Corwin	Discussed Fredericksburg stratigraphy of Central Texas; detailed discussions of Walnut lithologies
1982	Leach and Herbert	Discussed genesis of flow systems in colluvial hillslopes
1986	Rushton	Discussion of alluvial aquifers, provided insight on water movement for site one of this study
1987	Alexander, Black, and Brightman	Discussed the role of low permeability rocks in terms of a regional flow perspective
1987	Lemons	Described the structural evolution of the Lower Cretaceous Trinity Shelf which influenced the deposition of Lower Cretaceous sediments including the Walnut Formation and the Fredericksburg Group
1988	Brown	Described two types of basins and related their formation to the Cut Plain evolution
1989	Albrecht and Cartwright	Study presented information on hydraulic conductivities of compacted layers, included discussion of water movement within clay material
1990	Gburek and Urban	Discussed weathering and fracturing in a near stream zone resulting in enhanced permeability in the stream area
1990	Hayward, Allen and Amsbury	Detailed discussion of landscape evolution of Lampasas Cut Plain; explained geomorphic positions and landscape and land use of the study area for this investigation.
1992	Moore	Study provided information on relationships between surface and groundwater; detailed hydrograph analysis methods.

APPENDIX 2

Aquifer Test Results

AQUIFER TEST RESULTS FOR SITE ONE

Purpose

The determination of the following aquifer characteristics; transmissivity, hydraulic conductivity and storage coefficient (T, K, and S), was necessary to better understand the mechanics of the flow systems present. Testing was also performed to determine hydraulic conductivity values to compare to the United States Environmental Protection Agency (U.S.E.P.A.) recommended minimum hydraulic conductivity of 10^{-7} cm/sec for in-situ landfill liners. In-situ testing of the Walnut Formation is seldom performed.

AQUIFER TESTING

Pumping Test Number One

The initial pumping test conducted at site one was performed when only one deep well (BR-2) and the shallow well (BR-1) were present. The purpose of this pumping test was to determine transmissivity from the recovery of the pumped well (BR-2) and to observe if the shallow well (BR-1) could be influenced by the pumping of the deeper well (BR-2).

A constant rate pumping test was performed with a pumping rate of 0.032 ft^3/min. The total pumping time was 120 minutes. Drawdown in the shallow observation well (BR-1) was monitored by hand with an electronic water tape. Drawdown was not monitored in the pumped well (BR-2).

Results of Pumping Test One

No drawdown occurred in the shallow observation well (BR-1). The only aquifer parameter calculated from this constant rate pumping test was transmissivity from the recovery of the pumped well (BR-2). The Theis recovery calculation by the AQTESOLV computer program is shown in figure 40.

Conclusions from Pumping Test One

The initial pumping test provided several pieces of necessary information. It inidcated the water present in the shallow well was separated from the water in the deeper system by an effective confining layer, and that the deeper water bearing zone was, at least, locally confined. Also it was determined that sufficient water was

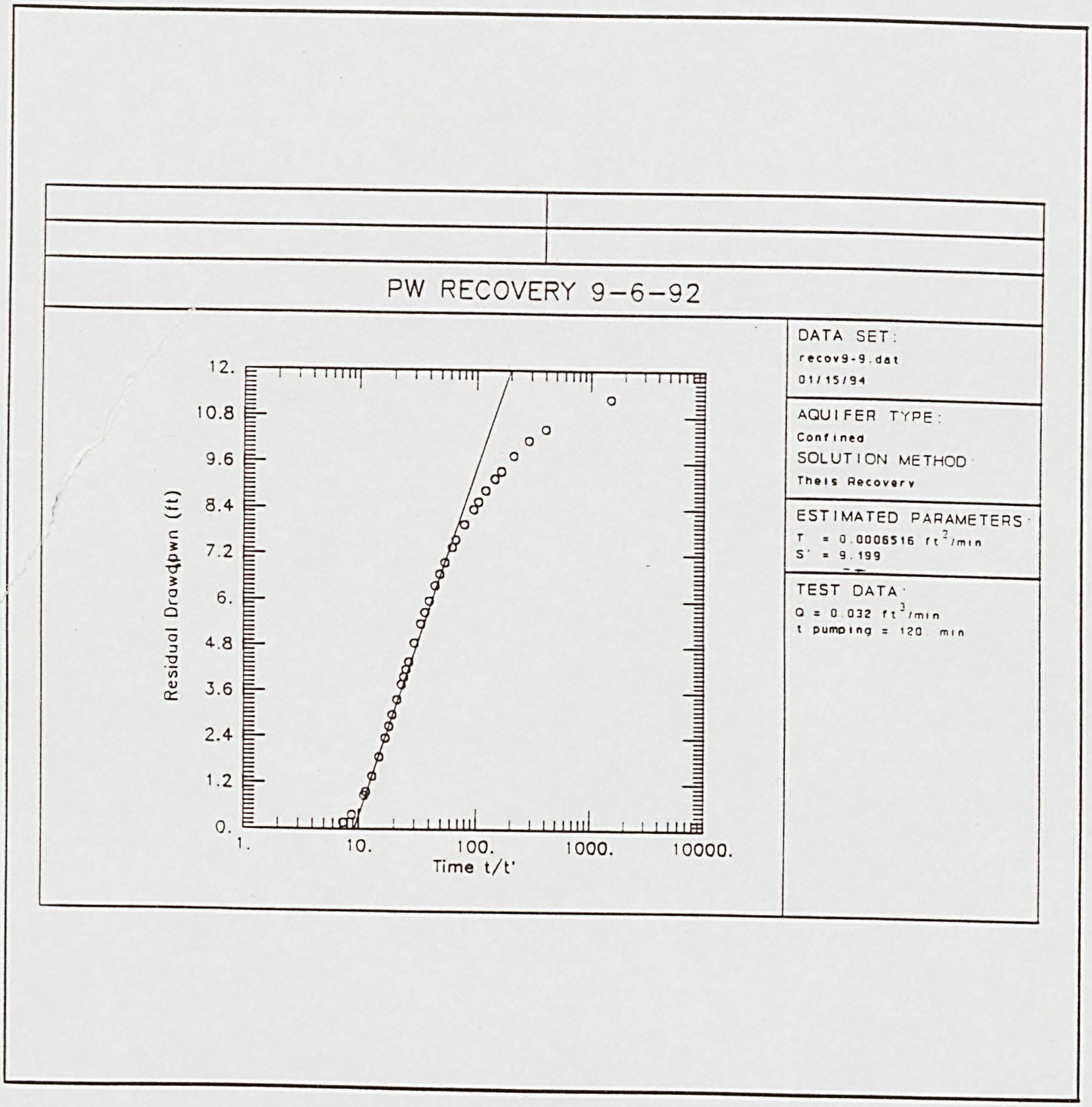


Figure 40. Calculation of transmissivity based upon recovery of BR-1. The pumping rate was 0.032 cubic feet per minute. The transmissivity based on the Theis recovery method is 6.5E^{-4} ft^2/min.

present in the deeper system to install more wells for the purpose of a constant rate pumping test of the lower water bearing zone.

Pumping Test Number Two

A second pumping test was performed on 2-11-93. The water levels at this time were significantly higher than when pumping test one was conducted. It was anticipated that the higher water levels would provide a substantial pumping period and allow for significant drawdown to occur.

A pumping rate of 0.09 ft^3/min was selected. The pump well for this test was BR-3, with the other three wells (two deep wells and the shallow well) utilized as observation wells. Drawdown in BR-2 and BR-3 was monitored with a HERMIT datalogger and pressure transducers placed in the wells. BR-4 and BR-1 drawdowns were monitored by hand with an electronic water tape. Water levels in BR-2 and BR-3 were checked periodically with an electronic water tape to validate the datalogger measurements.

This test was unsuccessful because the pumping rate was too great. It was obvious that the pump well would soon be pumped dry and the test was terminated after 10 minutes. The only data recovered were the drawdown values of the pumped well. The value of transmissivity from the pump well drawdown is shown in figure 41. After the test was terminated, all equipment was left in place and the aquifer was allowed to recover to pre-test water levels.

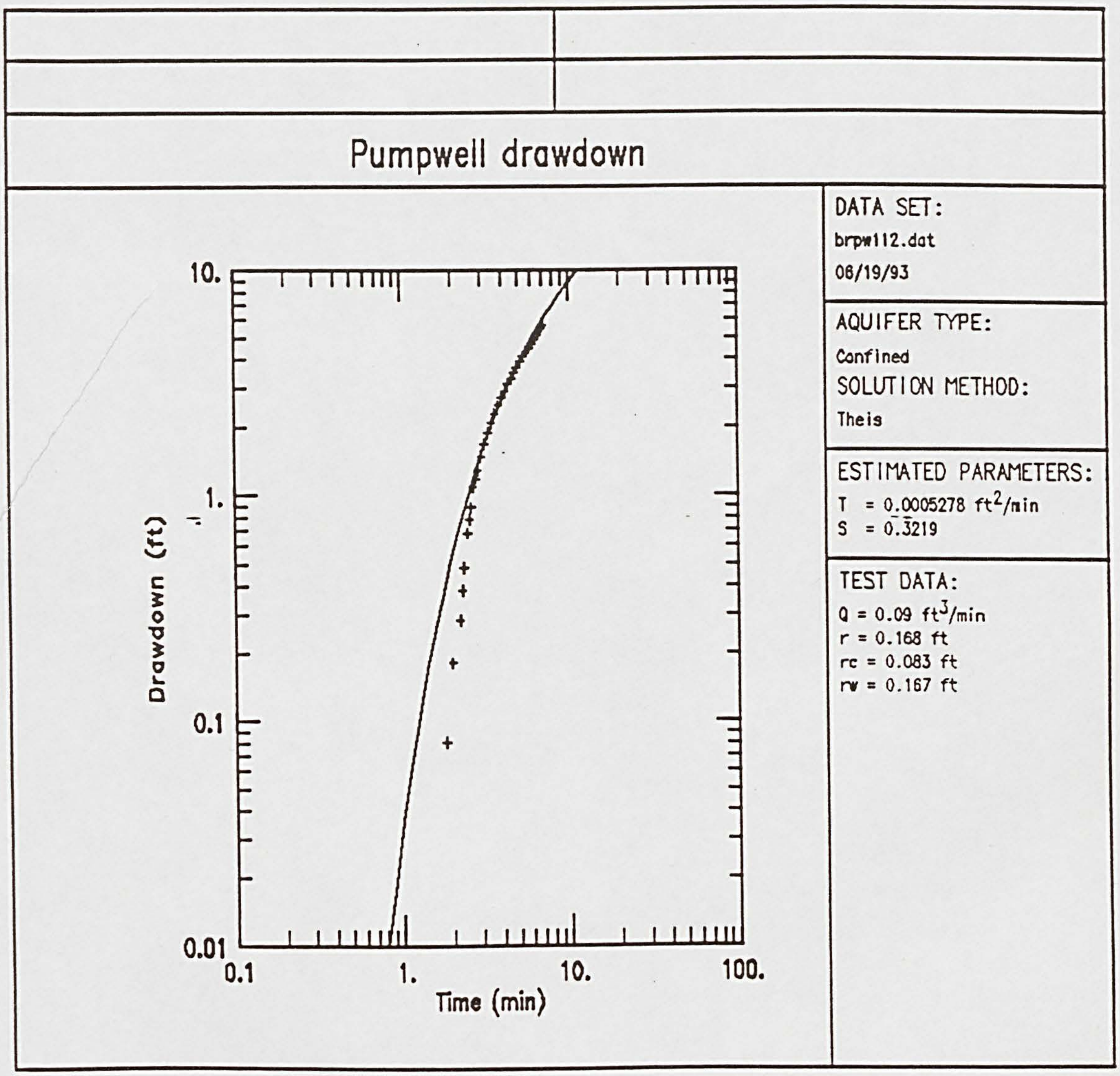


Figure 41. AQTESOLV data plot for drawdown in the pump well by the Theis method from second pumping test. The pumping rate for this test was 0.09 cubic feet per minute; however, this rate was too great for continued pumping. The transmissivity based upon pump well recovery is 5.3E^{-4} ft^2/min.

Pumping Test Number Three

The conditions of the third pumping test were the same as for test #2, with BR-3 being the pump well, and the other three wells monitored for drawdown. The pumping rate was reduced from test #2 to 0.042 ft^3/min.

Pumping began and the flow rate was monitored to insure a constant pumping rate was maintained. The initial data indicated minor fluctuations in the pumping rate. Drawdown was recorded in the three monitor wells by either a pressure transducer linked to a HERMIT datalogger, or by an electronic water level indicator.

The pumping test was terminated after 30 minutes of pumping due to mechanical failure of the pump. Transmissivity and storage coefficient values were calculated using the Theis method for the pump well and the observation wells. Jacob time-drawdown calculations were performed on the observation well data. All data reduction was performed by using AQTESOLV for the Theis method, and by a BASIC program named WELLTEST.BAS for the time-drawdown data. Printouts of the data results are shown in figures 42 - 45.

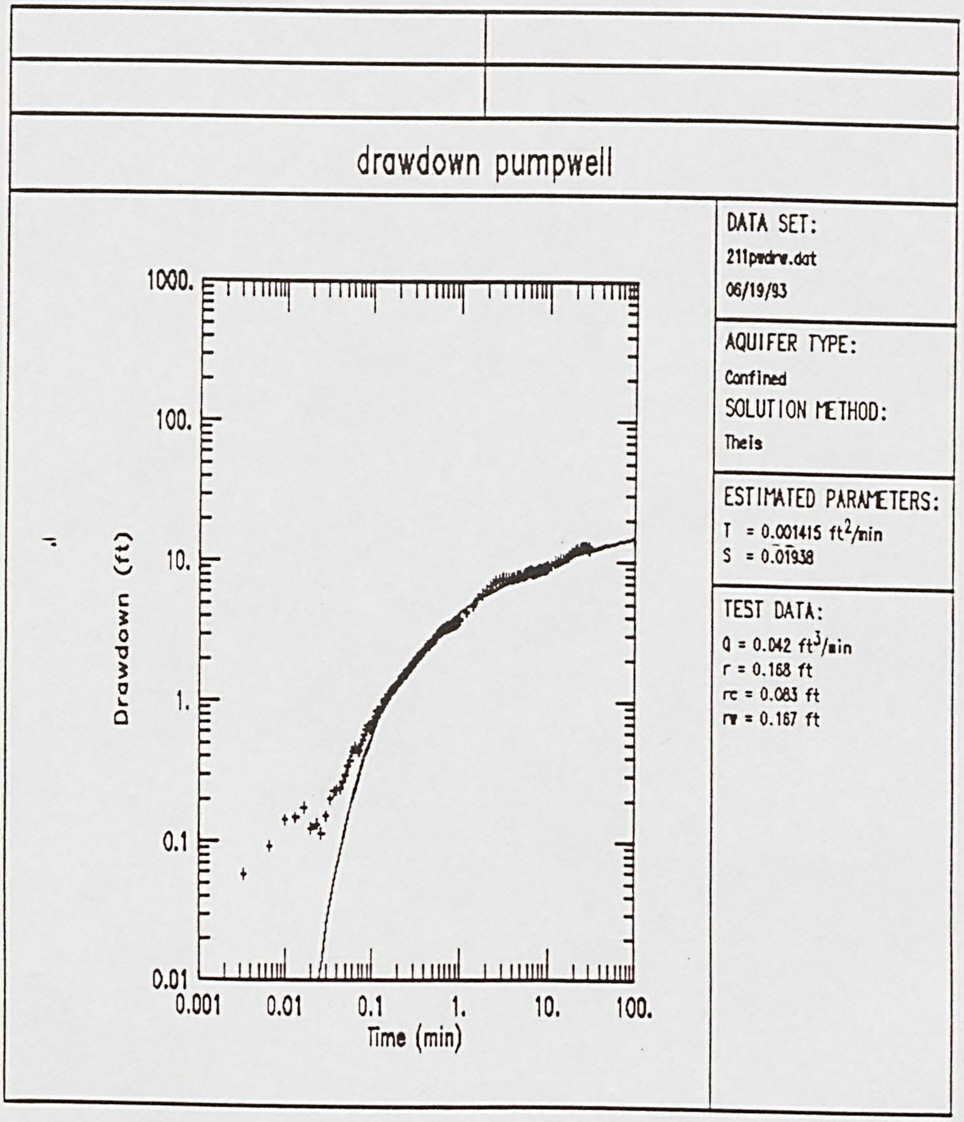


Figure 42. AQTESOLV data plot for Theis method for pumped well drawdown for the third pumping test. The pumping rate for this test was 0.042 cubic feet per minute. The calculated transmissivity was 1.4E^{-3} ft^2/min. The data plot shows a deviation near the early part of the test with rate maintenance difficulty and well storage problems. Later data fit the curve well.

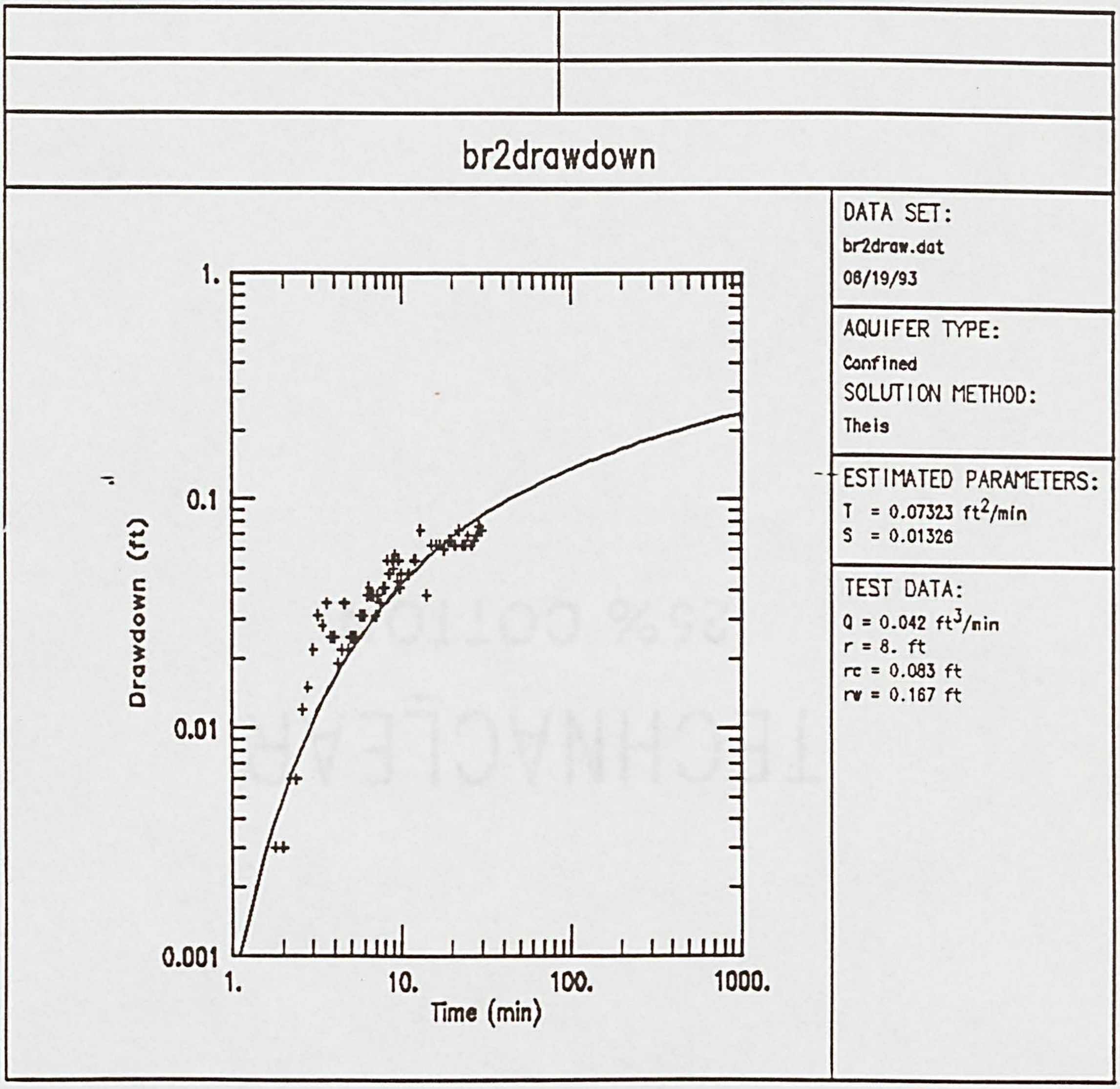
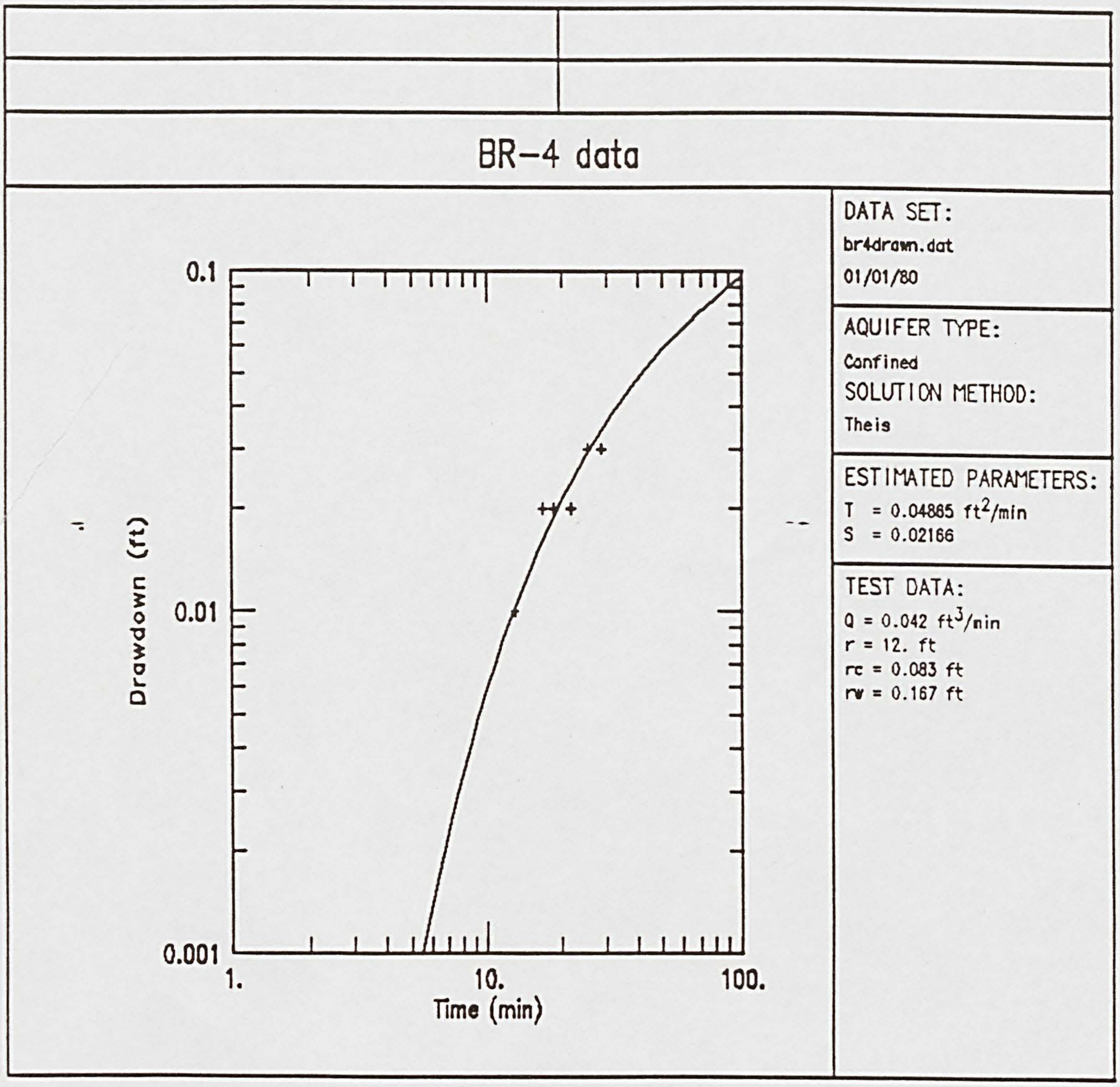


Figure 43. AQTESOLV data plot for Theis method for BR-2 drawdown for the third pumping test. The pumping rate for this test was 0.042 cubic feet per minute. The calculated transmissivity was 7.3E^{-2} ft^2/min. Data plot shows scatter of data and sensitivity of lower hydraulic conductivity material to fluctuations in the pumping rate. Curve is fit to the lower portion of the bulk of the data.



BR-4 data

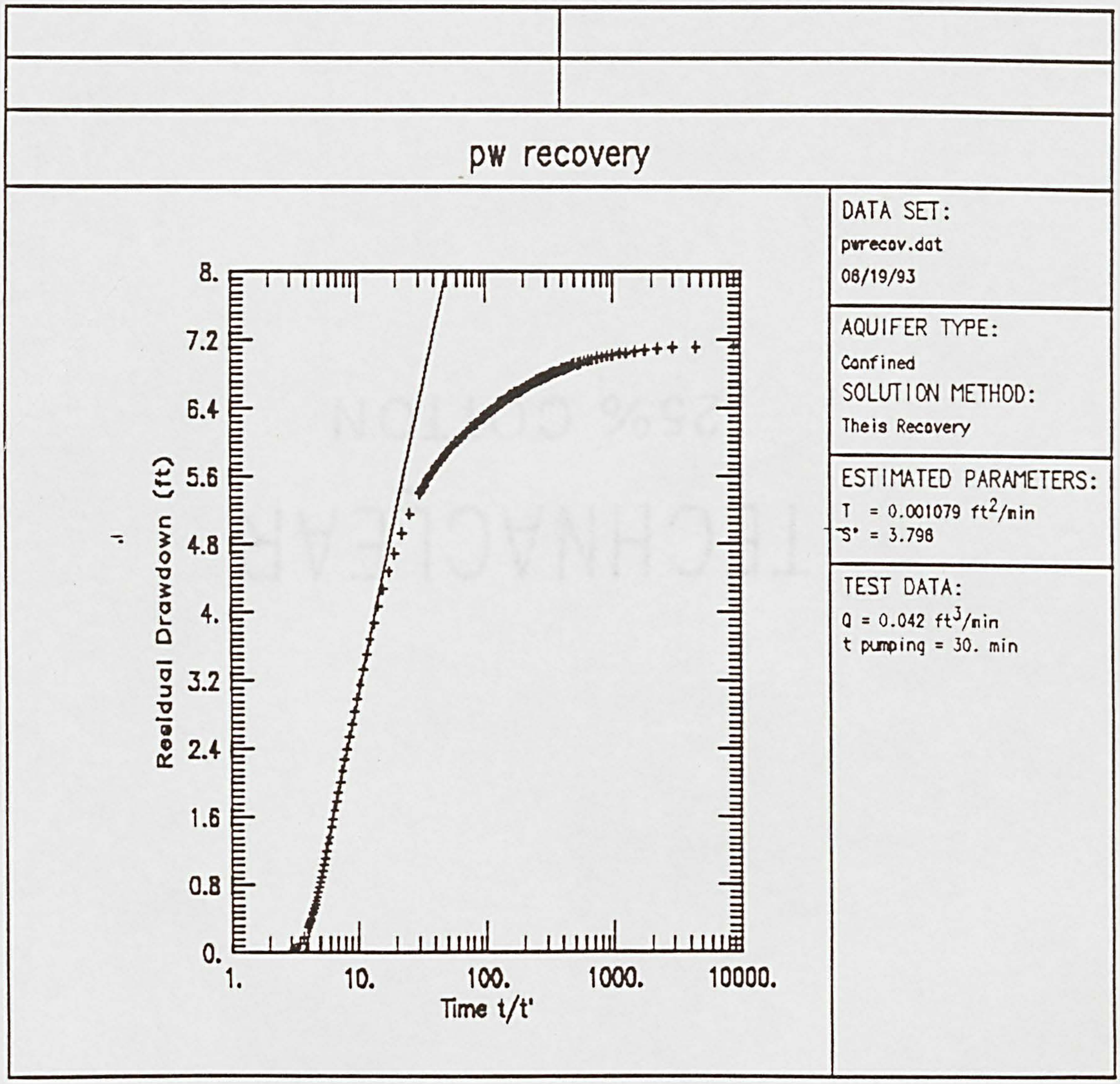
DATA SET:
br4drawn.dat
01/01/80

AQUIFER TYPE:
Confined
SOLUTION METHOD:
Theis

ESTIMATED PARAMETERS:
T = 0.04865 ft^2/min
S = 0.02166

TEST DATA:
Q = 0.042 ft^3/min
r = 12. ft
rc = 0.083 ft
rw = 0.167 ft

Figure 44. AQTESOLV data plot for Theis method for BR-4 drawdown for the third pumping test. The pumping rate for this test was 0.042 cubic feet per minute. The calculated transmissivity was 4.9E^{-2} ft^2/min. This well was not monitored with a pressure transducer during the test. Drawdown did not occur until approximately 10 minutes into the test. Because drawdown was monitored by hand, minor water level changes were difficult to measure.



pw recovery

DATA SET:
pwrecov.dat
08/19/93

AQUIFER TYPE:
Confined

SOLUTION METHOD:
Theis Recovery

ESTIMATED PARAMETERS:
T = 0.001079 ft^2/min
S' = 3.798

TEST DATA:
Q = 0.042 ft^3/min
t pumping = 30. min

Figure 45. AQTESOLV data plot and Theis recovery calculation for the pump well BR-3) from the third pumping test. The calculated transmissivity is $1.1E^{-3}$ ft^2/min.

Results of Pumping Test Three

The three wells located in the saturated clay all responded to the pumping of well BR-3. The well located in the shallow clay soil zone, well BR-1, did not respond to pumping. This result was expected from the previous pumping test conducted at this location.

Conclusions of Pumping Test Three

The lack of response in the shallow well supports the locally confined condition of the deeper saturated clay interval, and indicates little hydraulic communication occurs between the two water bearing zones. The pumping rate of test three was sufficient to have allowed pumping for an extended period of time. The test was terminated due to mechanical failures; however, the flow system appeared able to withstand a much longer pumping period.

The amount of hydraulic head varied drastically from test one to test three. The confined system was near the lower portion of the hydrograph when the initial pumping test was conducted. During test three, the system was near the peak of the hydrograph. This indicates that longer pumping times and greater pumping rates are attainable during periods of higher hydraulic head in the lower saturated clay. The recovery of the deeper saturated clay was significantly quicker under the higher hydraulic head conditions that during the lower hydraulic head conditions. This may also be due to gradient changes within the system.

Limitations of pumping tests in this setting made aquifer parameter determination increasingly difficult. Pumping rates were low, and the aquifer was a thin zone of permeable material. While pumping of this saturated clay section was performed, it should be considered only moderately successful. The aquifer parameters defined from the pumping tests probably fall within a full order of magnitude error, due to the short pumping time period.

It appears after reduction of the data collected during the aquifer testing, recovery test and slug testing are better suited for reasonable analysis of lower hydraulic conductivity units such as the saturated clay at site one.

PARAMETERS DERIVED FROM AQUIFER TESTS

Transmissivity

Based on the data reduction of the available pumping tests, the transmissivity values range from 6.6×10^{-4} ft^2/min to 9.4×10^{-2} ft^2/min. The average of all data for transmissivity was 1.3×10^{-2} ft^2/min. This average is a logarithmic mean value, as discussed in Freeze and Cherry (1979, p. 31).

Storage Coefficient

Storage values of the saturated clay range from 7.7×10^{-3} to 2.2×10^{-2}. The logarithmic mean of the storage values was 1.1×10^{-2}. A storage coefficient within this order of magnitude is normally indicative of an unconfined aquifer (Fetter, 1980, p. 97). After evaluation of the pumping test data, it is suggested that the storage value may actually represent the saturated clay material, and the system is only locally confined in the vicinity of the pumped well. It is also likely, and the preferred interpretation, that the pumping tests were not conducted for a sufficient period of time to fully stress the aquifer and make determination of a reliable storage coefficient possible.

Boundary Conditions

No boundary conditions were evident during the duration of the pumping tests. It is possible that boundary conditions may be encountered if a longer-term pumping test would be conducted and the cone of depression was considerably larger that the cone of depression that formed during the short-term pumping tests.

Heterogeneity and Anisotropy

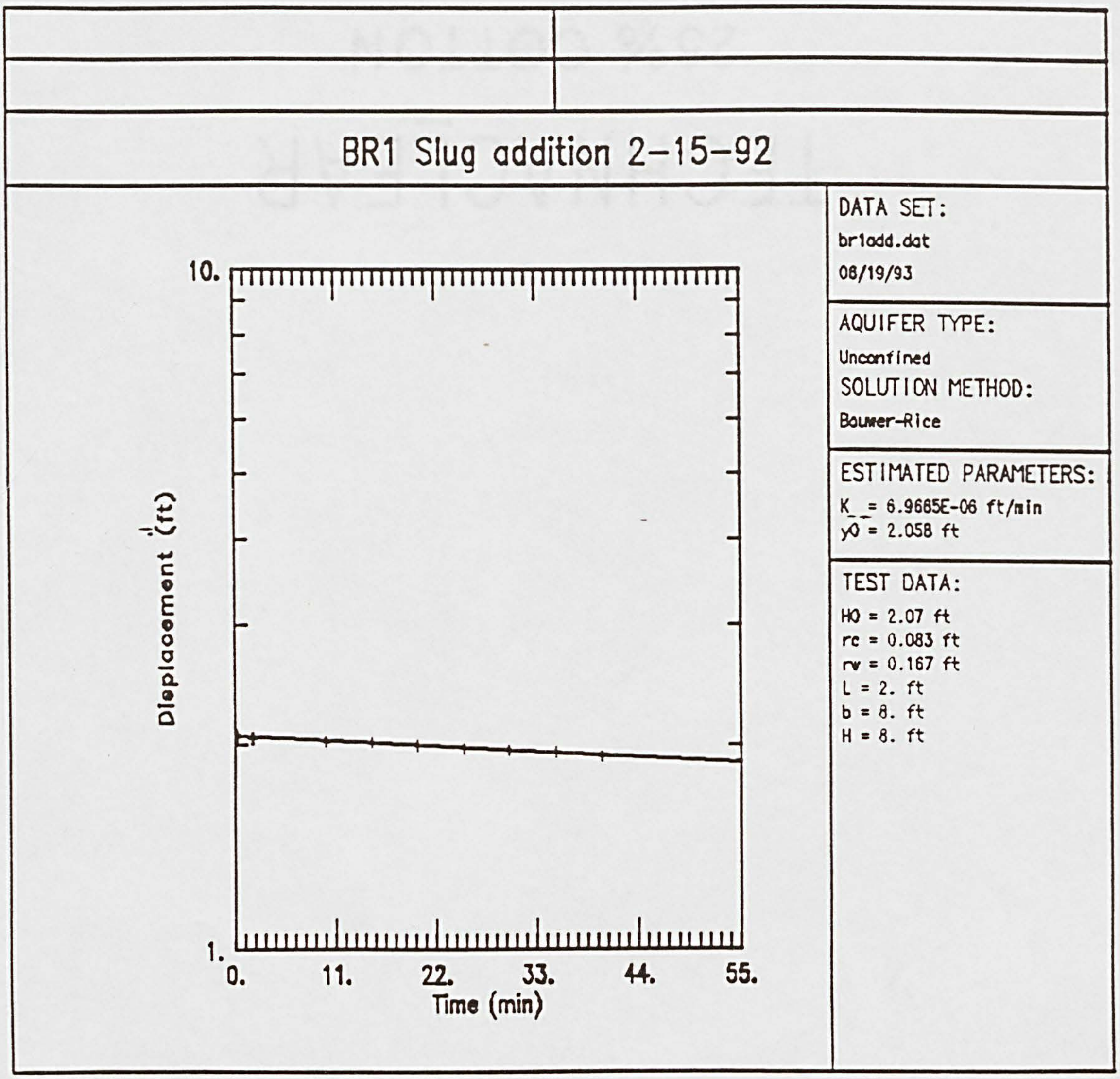
The evidence of heterogeneity in the flow system is difficult to determine because of scale dependency. At the larger scale, all drilling evidence shows that similar geologic materials were encountered at similar depths of all wells. The water bearing clay was encountered at the same drilling depth in all three of the wells penetrating that layer.

Transmissivity values calculated for BR-4 vary from values calculated for BR-2. This may indicate anisotropic conditions existing for water flowing at right angles to the pump well, or it may indicate a lack of development in well BR-4. It is interpreted that the system is best represented by a homogeneous, anisotropic condition, but heterogeneity probably exists at a smaller-than-field scale and more on a laboratory scale.

Hydraulic Conductivity

Slug testing was performed on the wells at various times of the year. Due to the range of values and the changes in hydraulic conductivity for the same wells, it was determined that slug tests be performed at similar times in all wells, and as close to the time as the pumping test as possible to insure comparison of similar conditions. Slug tests were performed within one week as the pumping test, or at a time when similar water level conditions existed to attempt to obtain similar conditions. Well BR-4 did not respond well to the slug testing. The well casing was crimped and prevented insertion of a slug. When a smaller slug was utilized, the well responded poorly, possibly due to poor well development. The value of hydraulic conductivity obtained from well BR-4 may not be an actual representation of the characteristics of the water-bearing clay material in the immediate vicinity of that well.

Slug test data from wells BR-1, BR-2, BR-3, and BR-4 were reduced using AQTESOLV and the Bower and Rice solution. The Bower and Rice method was selected due to other authors showing it to be the most conservative and consistent method in the efforts (Welby, 1992, p. 119 and Campbell and others, 1990, p. 9). The log mean average slug test value for hydraulic conductivity of the saturated clay material was 5.15 x 10^{-4} ft/min (2.6 x 10^{-4} cm/sec). Slug test data indicated the hydraulic conductivity of the shallow zone monitored by BR-1 has a K value of 6.9 x 10^{-6} ft/min (3.5 x 10^{-6} cm/sec). The calculated transmissivity from the slug test values, for the deeper saturated clay (assuming a thickness of 7 feet) is 1.82 x 10^{-3}; an order of magnitude lower than the transmissivity value calculated from the pumping test analysis. AQTESOLV data plots for the slug testing are shown on figures 46 - 51.



DATA SET:
br1add.dat
08/19/93

AQUIFER TYPE:
Unconfined
SOLUTION METHOD:
Bouwer-Rice

ESTIMATED PARAMETERS:
K = 6.9665E-06 ft/min
y0 = 2.058 ft

TEST DATA:
H0 = 2.07 ft
rc = 0.083 ft
rw = 0.167 ft
L = 2. ft
b = 8. ft
H = 8. ft

Figure 46. AQTESOLV data plot for the Bouwer and Rice method for slug addition in BR-1. The calculated hydraulic conductivity is 6.96E^{-6} ft/min.

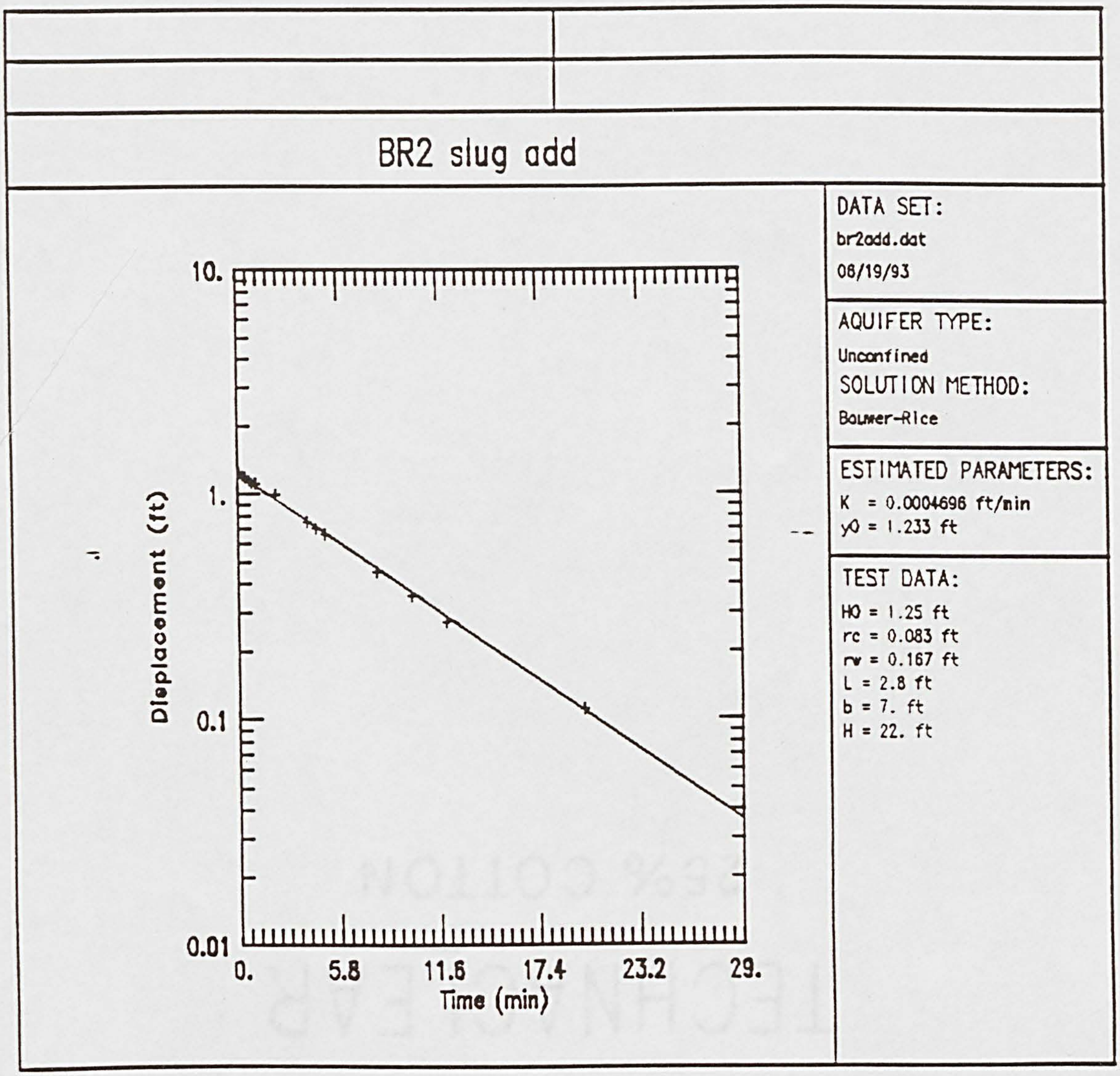
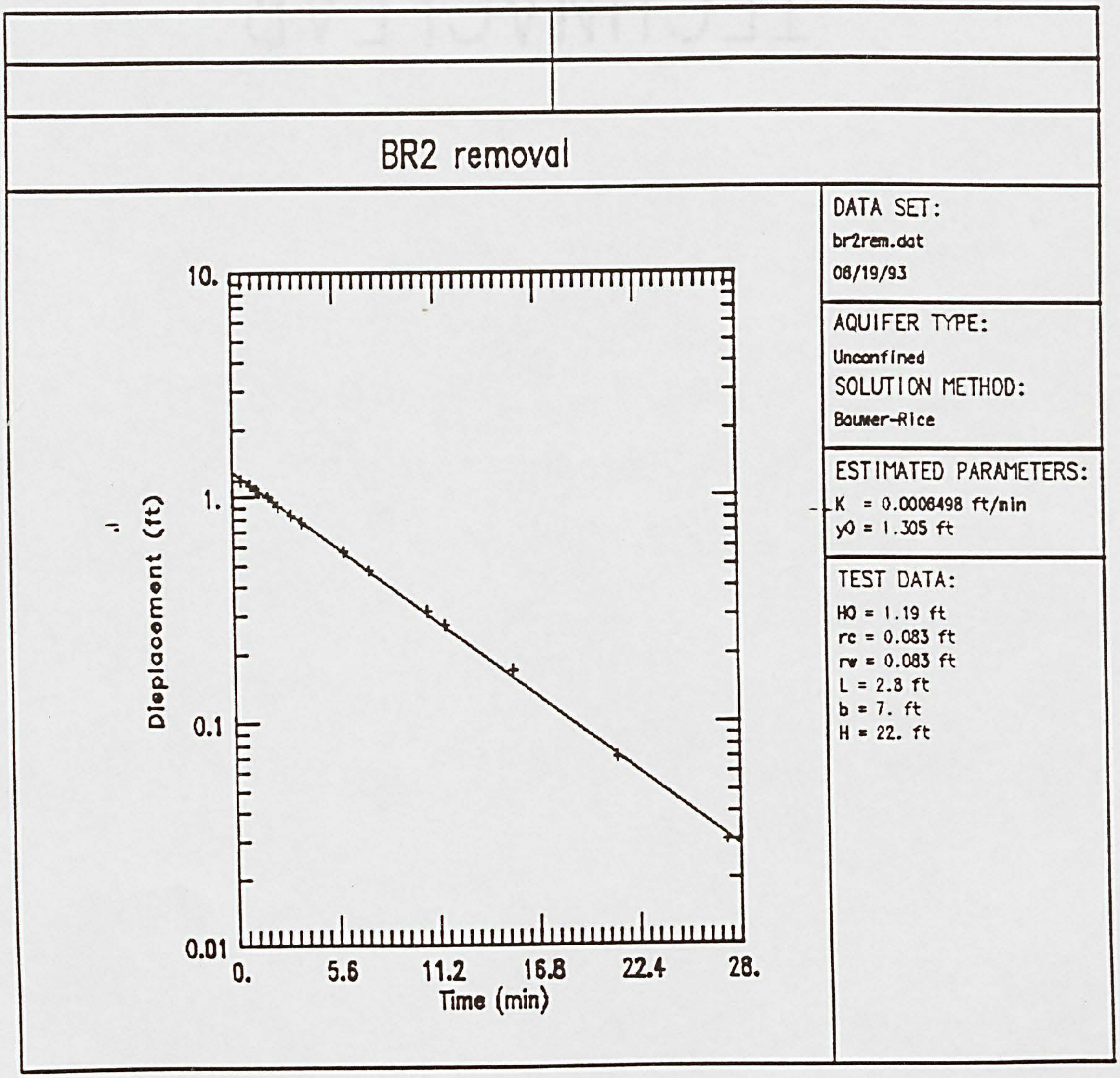


Figure 47. AQTESOLV data plot for the Bouwer and Rice method for slug addition in BR-2. The calculated hydraulic conductivity is 4.7E^{-4} ft/min.



BR2 removal

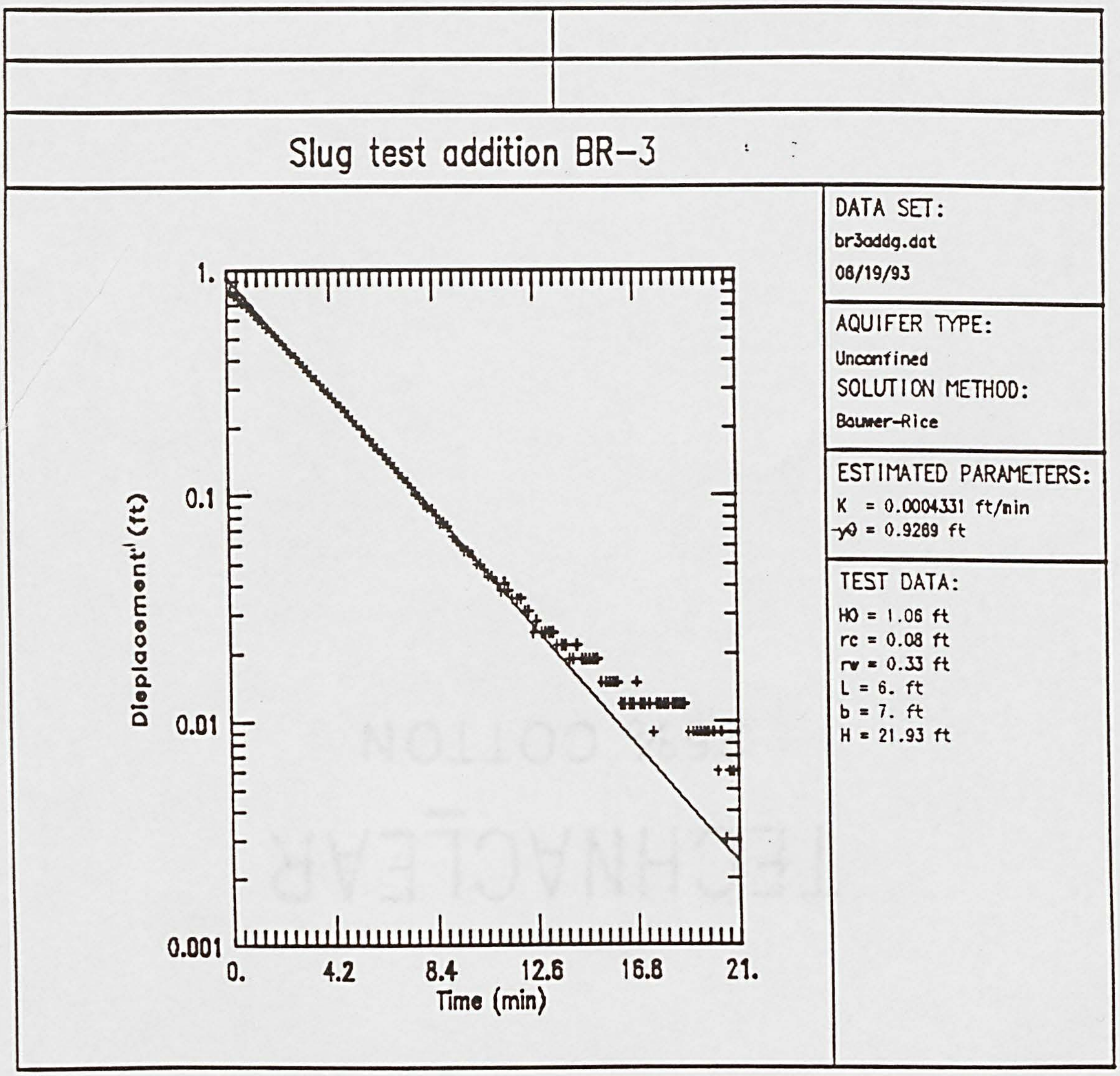
DATA SET:
br2rem.dat
08/19/93

AQUIFER TYPE:
Unconfined
SOLUTION METHOD:
Bouwer-Rice

ESTIMATED PARAMETERS:
K = 0.0006498 ft/min
y0 = 1.305 ft

TEST DATA:
H0 = 1.19 ft
rc = 0.083 ft
rw = 0.083 ft
L = 2.8 ft
b = 7. ft
H = 22. ft

Figure 48. AQTESOLV data plot for the Bouwer and Rice method for slug removal in BR-2. The calculated hydraulic conductivity is 6.5E^{-4} ft/min.



Slug test addition BR-3

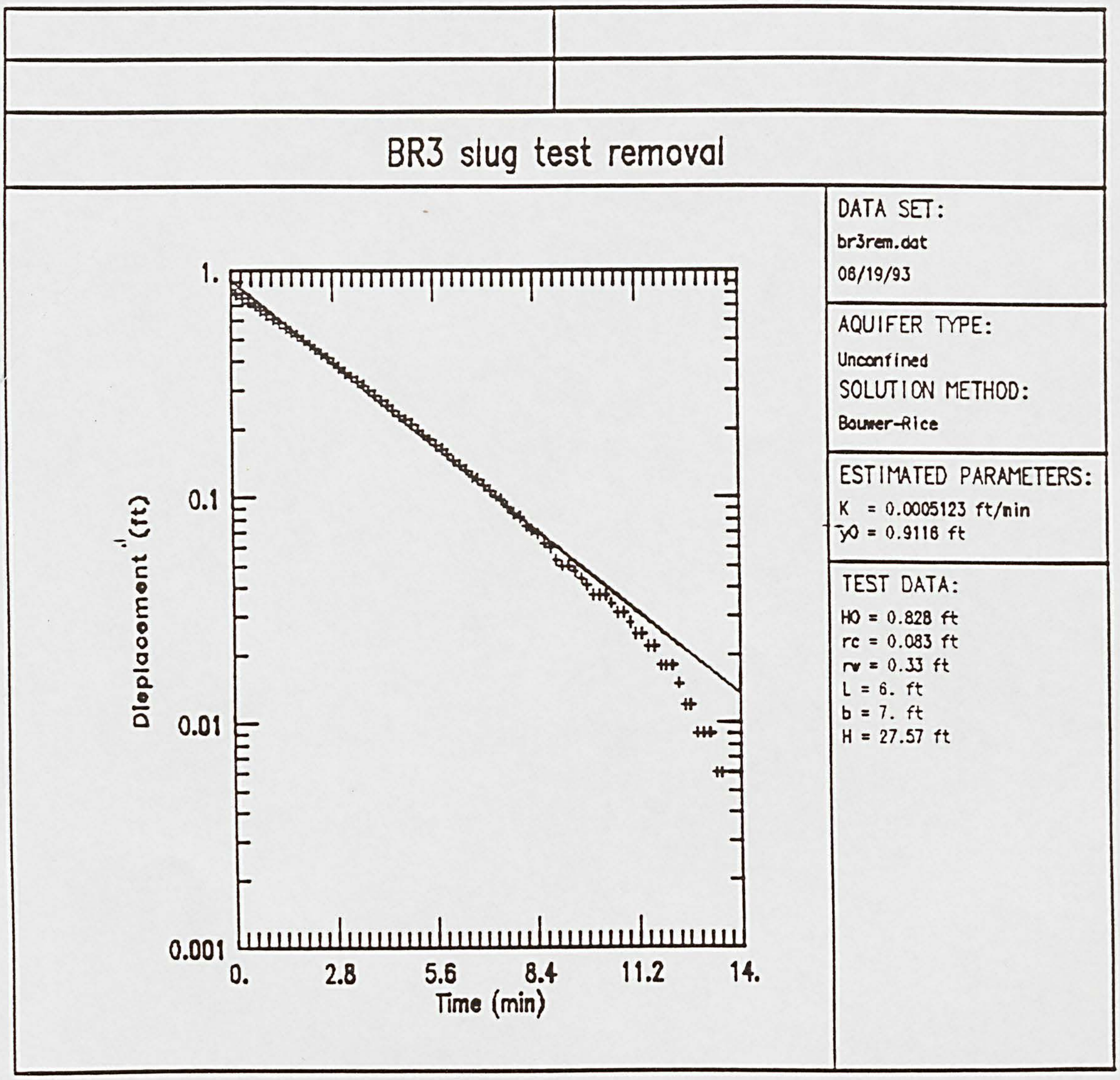
DATA SET:
br3addg.dat
08/19/93

AQUIFER TYPE:
Unconfined
SOLUTION METHOD:
Bouwer-Rice

ESTIMATED PARAMETERS:
K = 0.0004331 ft/min
y0 = 0.9269 ft

TEST DATA:
H0 = 1.06 ft
rc = 0.08 ft
rw = 0.33 ft
L = 6. ft
b = 7. ft
H = 21.93 ft

Figure 49. AQTESOLV data plot for the Bouwer and Rice method for slug addition in BR-3. The calculated hydraulic conductivity is 4.3E^{-4} ft/min.



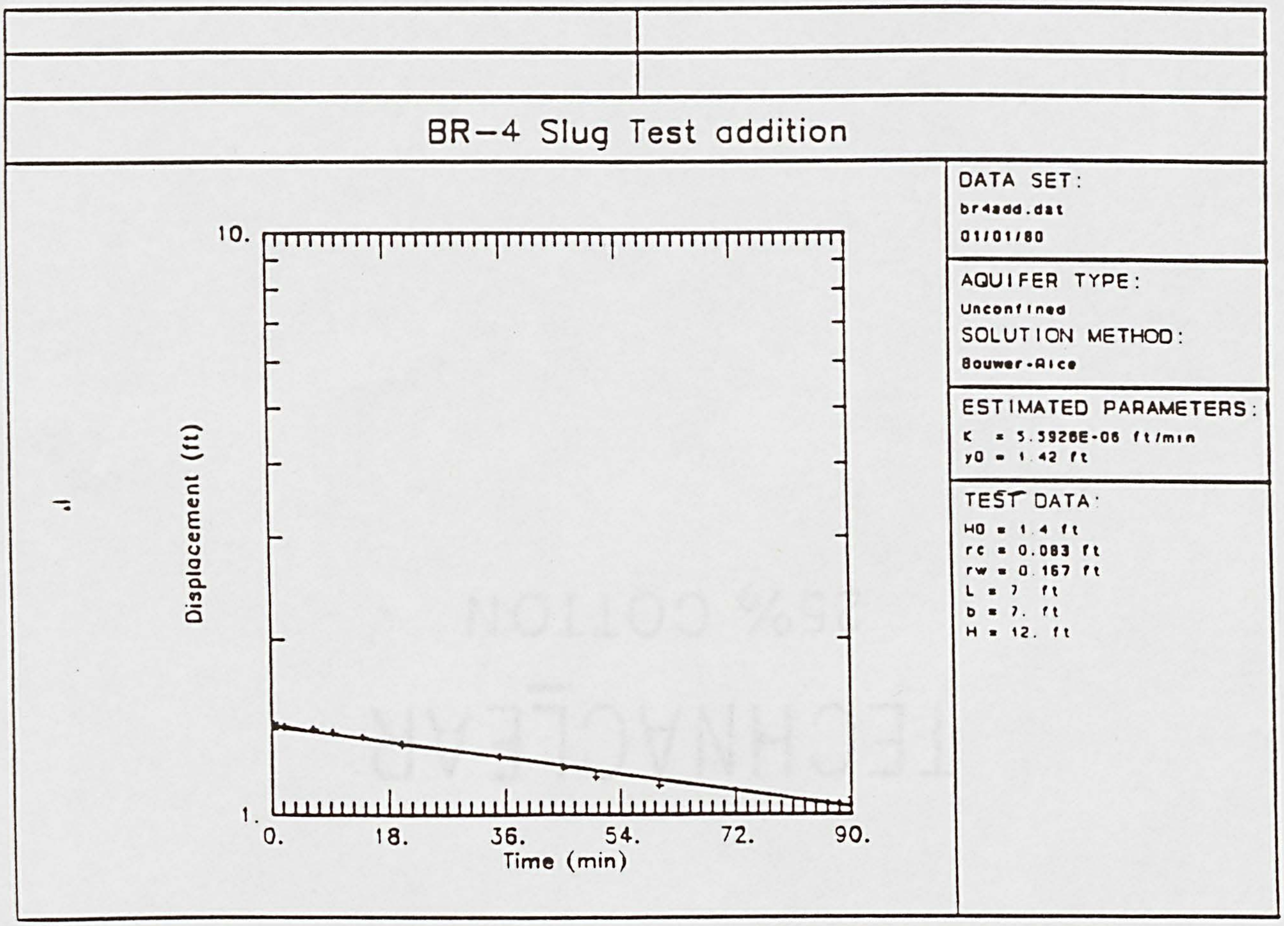
DATA SET:
br3rem.dat
06/19/93

AQUIFER TYPE:
Unconfined
SOLUTION METHOD:
Bouwer-Rice

ESTIMATED PARAMETERS:
K = 0.0005123 ft/min
y0 = 0.9116 ft

TEST DATA:
H0 = 0.828 ft
rc = 0.083 ft
rw = 0.33 ft
L = 6. ft
b = 7. ft
H = 27.57 ft

Figure 50. AQTESOLV data plot for the Bouwer and Rice method for slug removal in BR-3. The calculated hydraulic conductivity is 5.1E^{-4} ft/min.



BR-4 Slug Test addition

DATA SET:
br4add.dat
01/01/80

AQUIFER TYPE:
Unconfined
SOLUTION METHOD:
Bouwer-Rice

ESTIMATED PARAMETERS:
K = 5.5926E-06 ft/min
y0 = 1.42 ft

TEST DATA:
H0 = 1.4 ft
rc = 0.083 ft
rw = 0.167 ft
L = 7 ft
b = 7. ft
H = 12. ft

Figure 51. AQTESOLV data plot for the Bouwer and Rice method for slug addition in BR-4. The calculated hydraulic conductivity is $5.6E^{-6}$ ft/min. The lower hydraulic conductivity in this well is believed to be a development problem with this particular well not being extensively pumped, and continual silting of the screen on this well.

Permeameter Testing

A flexible wall permeameter lab test was performed on a Shelby tube sample taken from BR-1 (depth = 4.5 feet). The reported value of vertical hydraulic conductivity was 2.4 x 10^{-9} cm/sec (4.7 x 10^{-9} ft/min). This indicates a Kh is three orders of magnitude higher than Kv when compared to the slug test values for this well.

A field permeameter test using a Guelph field permeameter was also conducted on the Slidell Clay (representing the surface of the zone monitored by BR-1). The test was not valid because the lowest detectable value of hydraulic conductivity of the Guelph is 10^{-6} cm/sec. The test indicates that the vertical hydraulic conductivity is lower than 10^{-6} cm/sec for that unit. This suggests that direct infiltration into the soil at the well field is very slow, and that vertical movement into the underlying saturated clay layer is minimal.

AQUIFER TEST RESULTS FOR SITE THREE

Purpose

The determination of the following aquifer characteristics was performed at the Hamilton site by using a constant rate pumping test and by slug testing. Values of transmissivity, hydraulic conductivity and storage coefficient (T, K, and S), were necessary to better understand the mechanics of the flow system present. Testing was also performed to determine hydraulic conductivity values to compare to the U.S.E.P.A.. recommended minimum hydraulic conductivity of 10^{-7} cm/sec for in-situ permeability for landfill liners.

AQUIFER TESTING

Constant Rate Pumping Test

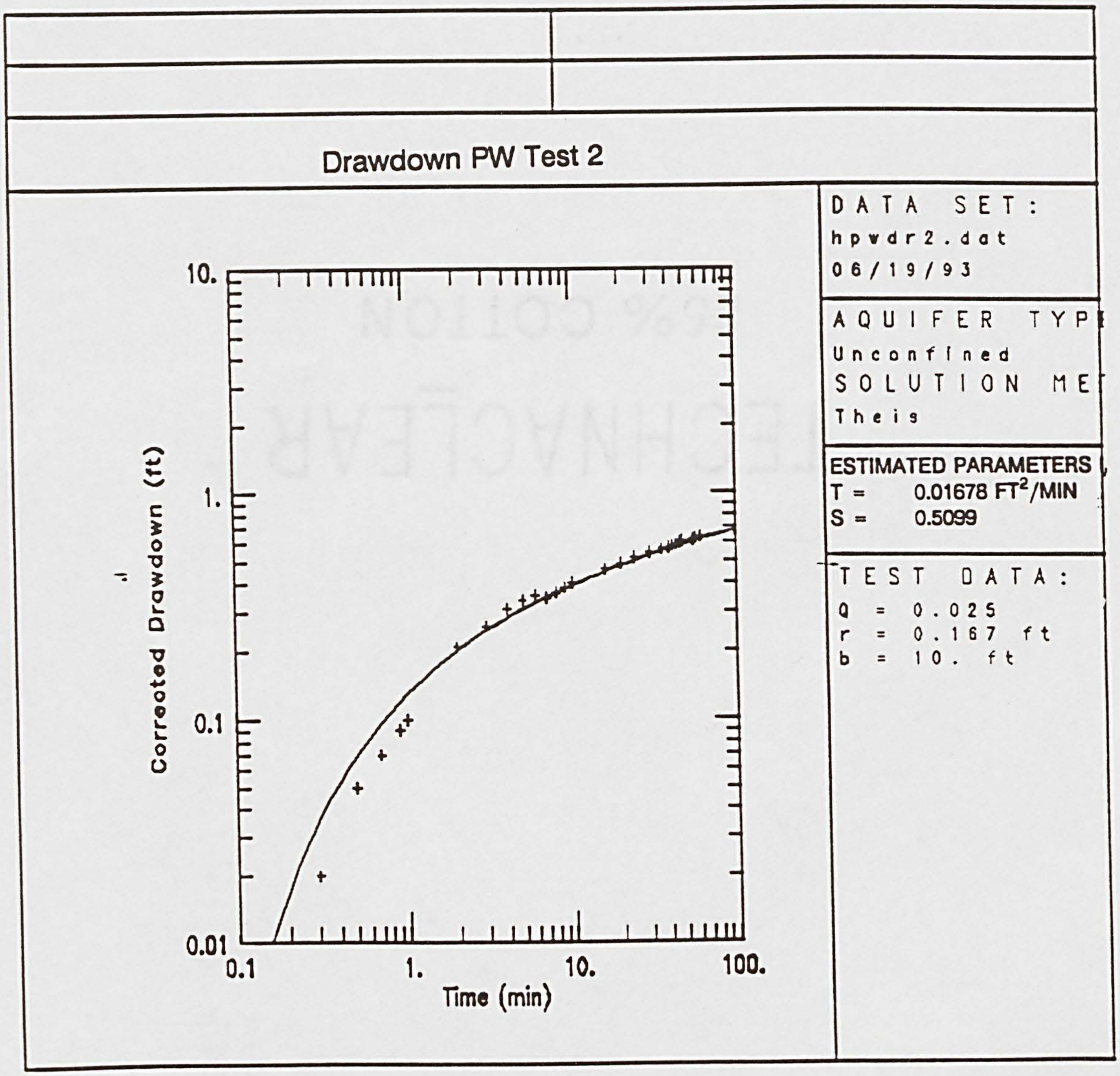
A constant rate pumping test was performed to obtain values of T and S. The pumping rate was 0.025 ft^3/min. The deeper well was used as the pump well and the shallow well was used for a monitoring well. The total pumping time was 62 minutes. Drawdown and recovery was monitored using a Hermit datalogger and pressure transducers in both wells.

Pumping Test Results

During the 62 minute pumping period, drawdown was monitored in the observation well. When pumping stopped, recovery of the deeper pumped well was also monitored; however, little recovery occurred in the observation well during the recovery period.

Interpretation from Pumping Test Data

The average transmissivity value calculated for drawdown in both wells and recovery in the deep well was 1.8×10^{-2} ft^2/min (2.7×10^{-1} cm^2/sec). The storage coefficient calculated was 1.5×10^{-3}. Methods used include the Theis drawdown and recovery method of the AQTESOLV computer program and a time-drawdown calculation for the observation well using WELLTEST.BAS. AQTESOLV data results are shown in figures 52 - 54.



Drawdown PW Test 2

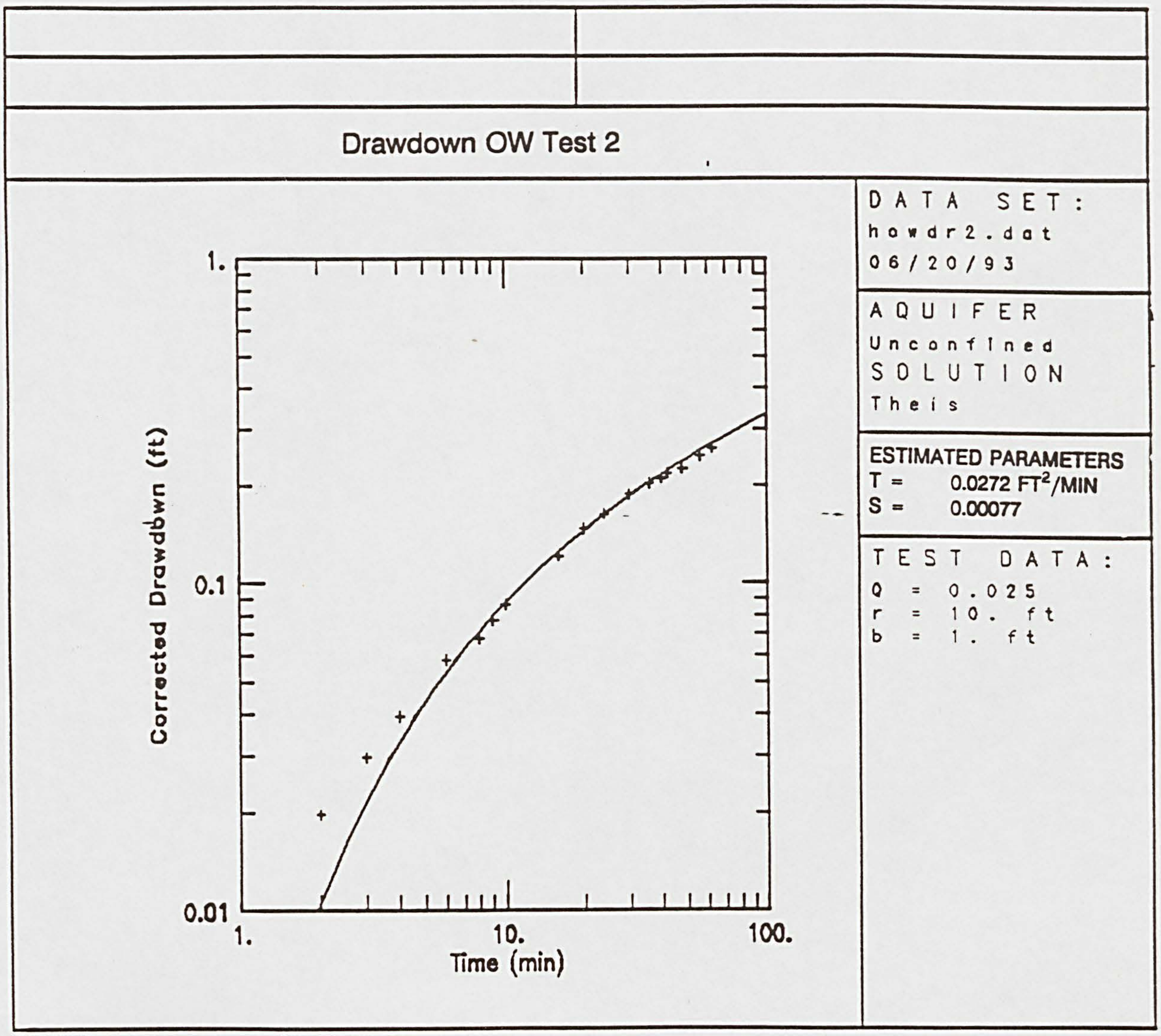
DATA SET:
hpwdr2.dat
06/19/93

AQUIFER TYP
Unconfined
SOLUTION ME
Theis

ESTIMATED PARAMETERS
T = 0.01678 FT^2/MIN
S = 0.5099

TEST DATA:
Q = 0.025
r = 0.167 ft
b = 10. ft

Figure 52. AQTESOLV data plot calculation for drawdown in the pump well. The pumping rate for this test was 0.025 cubic feet per minute. The transmissivity value calculated was 1.7E^{-2} ft^2/min.



Drawdown OW Test 2

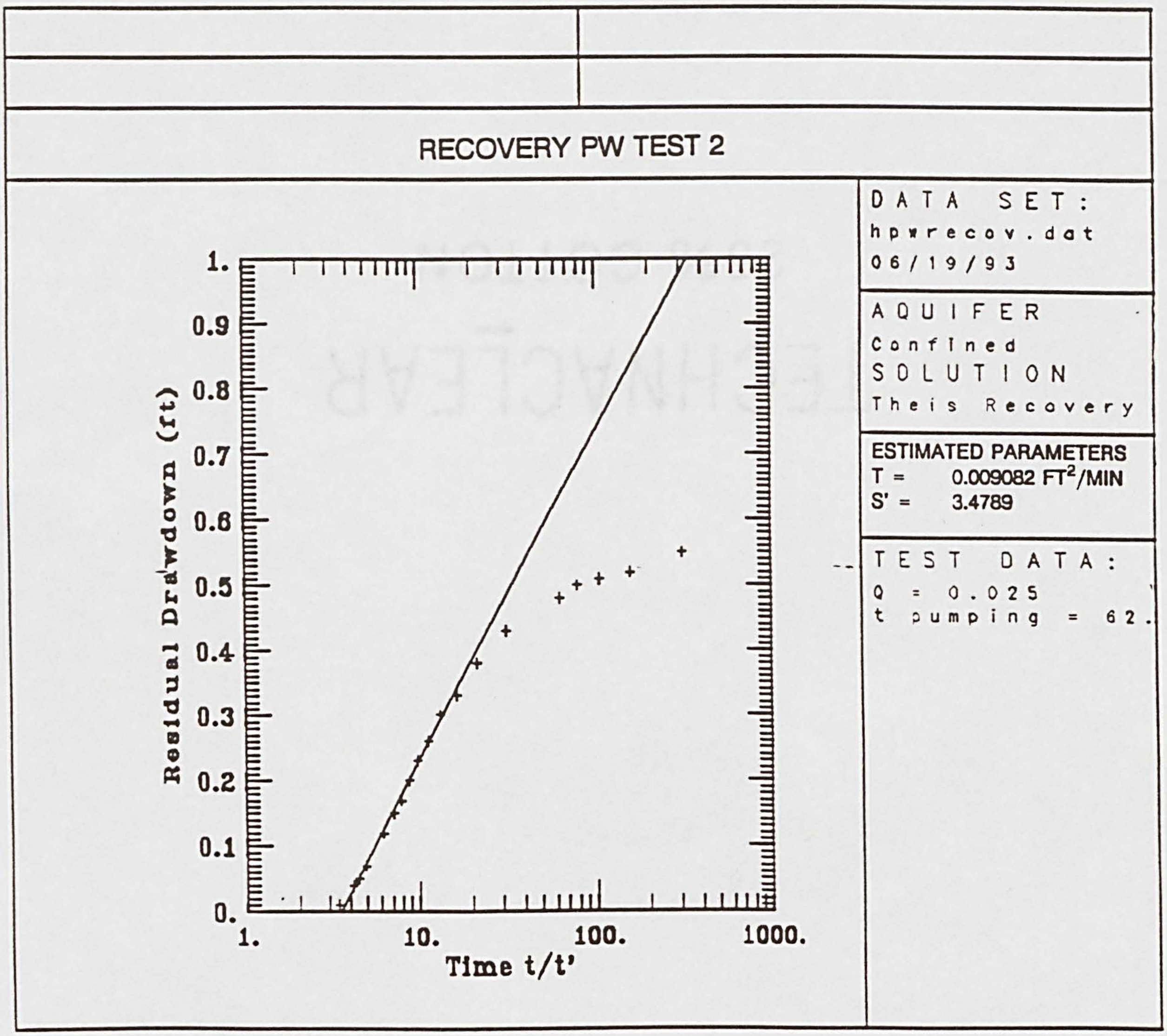
DATA SET:
howdr2.dat
06/20/93

AQUIFER
Unconfined
SOLUTION
Theis

ESTIMATED PARAMETERS
T = 0.0272 FT^2/MIN
S = 0.00077

TEST DATA:
Q = 0.025
r = 10. ft
b = 1. ft

Figure 53. AQTESOLV data plot for Theis calculation of drawdown in the shallow observation well. Transmissivity from this data was 2.7E^{-2} ft^2/min. The storage coefficient was 7.7E^{-4}. The storage coefficient is low for an unconfined aquifer; however, it is interpreted that the primary storage occurs in fractures and bedding planes with little matrix porosity in the limestone material.



RECOVERY PW TEST 2

DATA SET:
hpwrecov.dat
06/19/93

AQUIFER
Confined
SOLUTION
Theis Recovery

ESTIMATED PARAMETERS
T = 0.009082 FT^2/MIN
S' = 3.4789

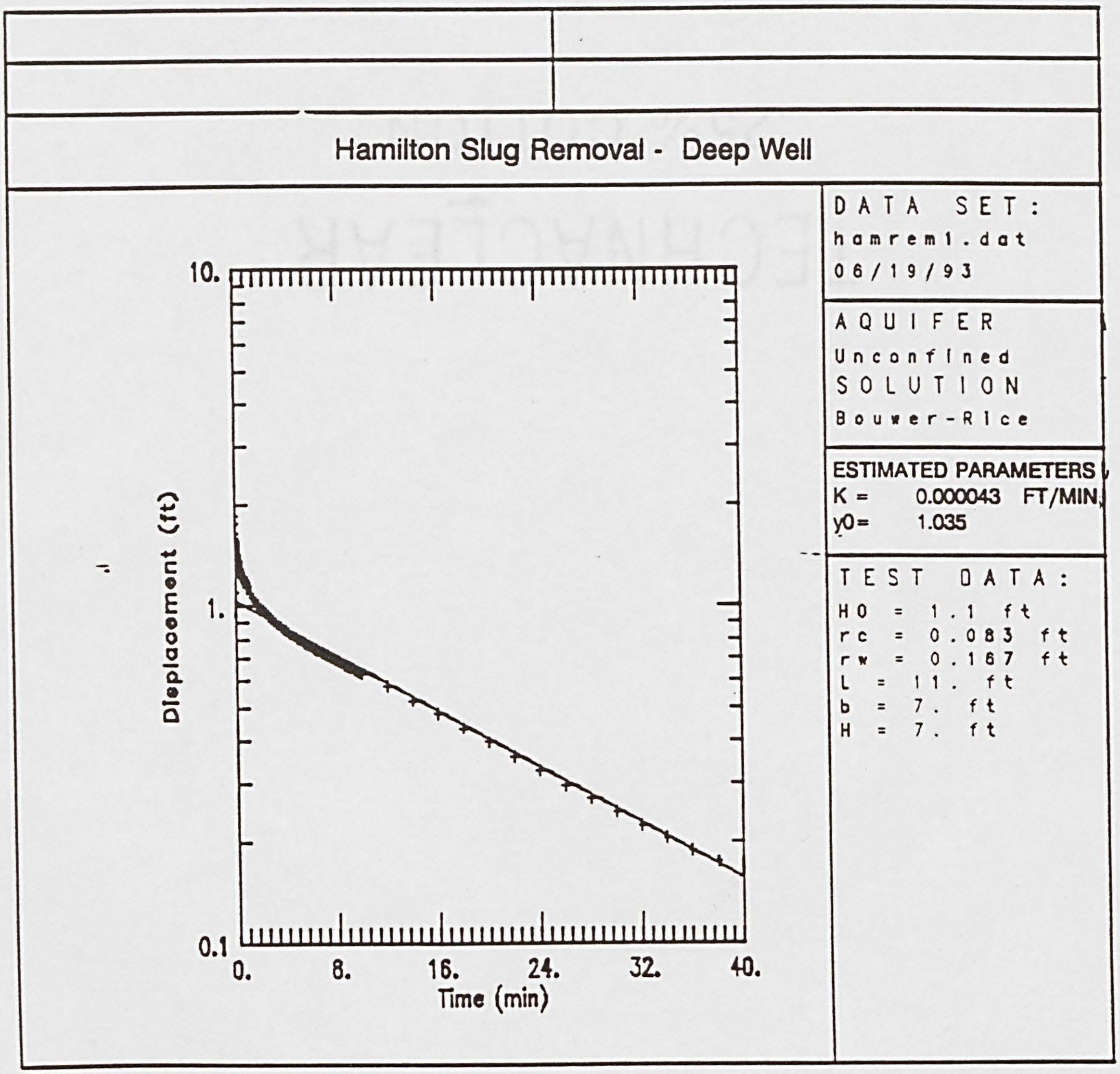
TEST DATA:
Q = 0.025
t pumping = 62.

Figure 54. AQTESOLV data plot for pump well recovery at site three. Drawdown dropped off considerably near the end of the test. This is interpreted to indicate difficulty for the aquifer to release water from storage within the fractures and bedding planes of the material. The day following the pumping test, the water level was nearly the same as the day of the pumping test, indicating that recovery in this system require longer periods of time. The calculated transmissivity from this curve match is $9.1E^{-3}$ ft^2/min. No storage coefficient is available from recovery data.

Slug Test

Static water levels dropped in elevation between the pumping test and the slug testing at site three. An insufficient amount of water was present in the shallow well to perform a slug test.

A pressure transducer with the Hermit datalogger was used to monitor water level changes in the deep well while a PVC slug was removed from the well. The results are shown in figure 55.



Hamilton Slug Removal - Deep Well

DATA SET:
hamrem1.dat
06/19/93

AQUIFER
Unconfined
SOLUTION
Bouwer-Rice

ESTIMATED PARAMETERS
K = 0.000043 FT/MIN
y0 = 1.035

TEST DATA:
H0 = 1.1 ft
rc = 0.083 ft
rw = 0.167 ft
L = 11. ft
b = 7. ft
H = 7. ft

Figure 55. AQTESOLV data plot for slug removal in the deeper well using the Bouwer and Rice method. The hydraulic conductivity is 4.3E^{-5} ft/min based on this curve match. Early data probably represents water released from the sandpack material and is not used in determination of the hydraulic conductivity value.

RESULTS OF AQUIFER TESTING

Transmissivity

The transmissivity value average of the constant rate pumping test was 1.8 x 10^{-2} ft^2/min (2.7 x 10^{-1} cm^2/sec). Drawdown in the pumped well after 62 minutes of pumping was 0.65 feet, indicating that the well could withstand considerable pumping at the utilized rate, or be subjected to another test at a much higher pumping rate provided water levels were similar.

Storage Coefficient

The flow system is composed of fractured limestones and nodular limestones. Flow is interpreted as occurring along the fractures and bedding planes within the formation. The storage value of the flow system averaged 1.5 x 10^{-3}, which is small for an unconfined system; however, because water is held in storage primarily in fractures, with very little matrix porosity of the limestone itself, this storage value is considered representative of the system present. The range of storage values was 7.7 x 10^{-4} to 2.6 x 10^{-3}, falling within 1/2 order of magnitude. These values are reasonable for the flow system storage coefficient.

Hydraulic Conductivity-Slug Testing

The one slug test was conducted at a lower water level than the pumping test. The K value computed by Bower and Rice method using AQTESOLV was 4.3 x 10^{-5} ft/min (2.2 x 10^{-5} cm/sec) which is lower than expected when compared to the transmissivity calculated by the pumping test, and assuming a 15' saturated thickness. This may indicate that the most transmissive zone lies above the level tested by the slug test, but was included in the pumping test due to higher water levels. It is interpreted that hydraulic conductivity decreases with depth and there exists a zone of higher hydraulic conductivity in the shallow subsurface that was not saturated during the slug testing procedure. A decreasing K with depth has been noted as a common phenomenon in near-surface carbonate aquifers (Gburek and Urban, 1990, p. 880 and LeGrand and Stringfield, 1977, p. 1286).

Other Field Testing

Guelph permeameter testing was conducted to evaluate the infiltration ability of the soils immediately overlying the water bearing materials. The test results indicate the saturated hydraulic conductivity of the soil in the immediate vicinity of the well field is 2.5 x 10^{-2} ft/min (2.12 x 10^{-3} cm/sec).

APPENDIX 3

Boring logs and well construction diagrams for Site One and Site Three

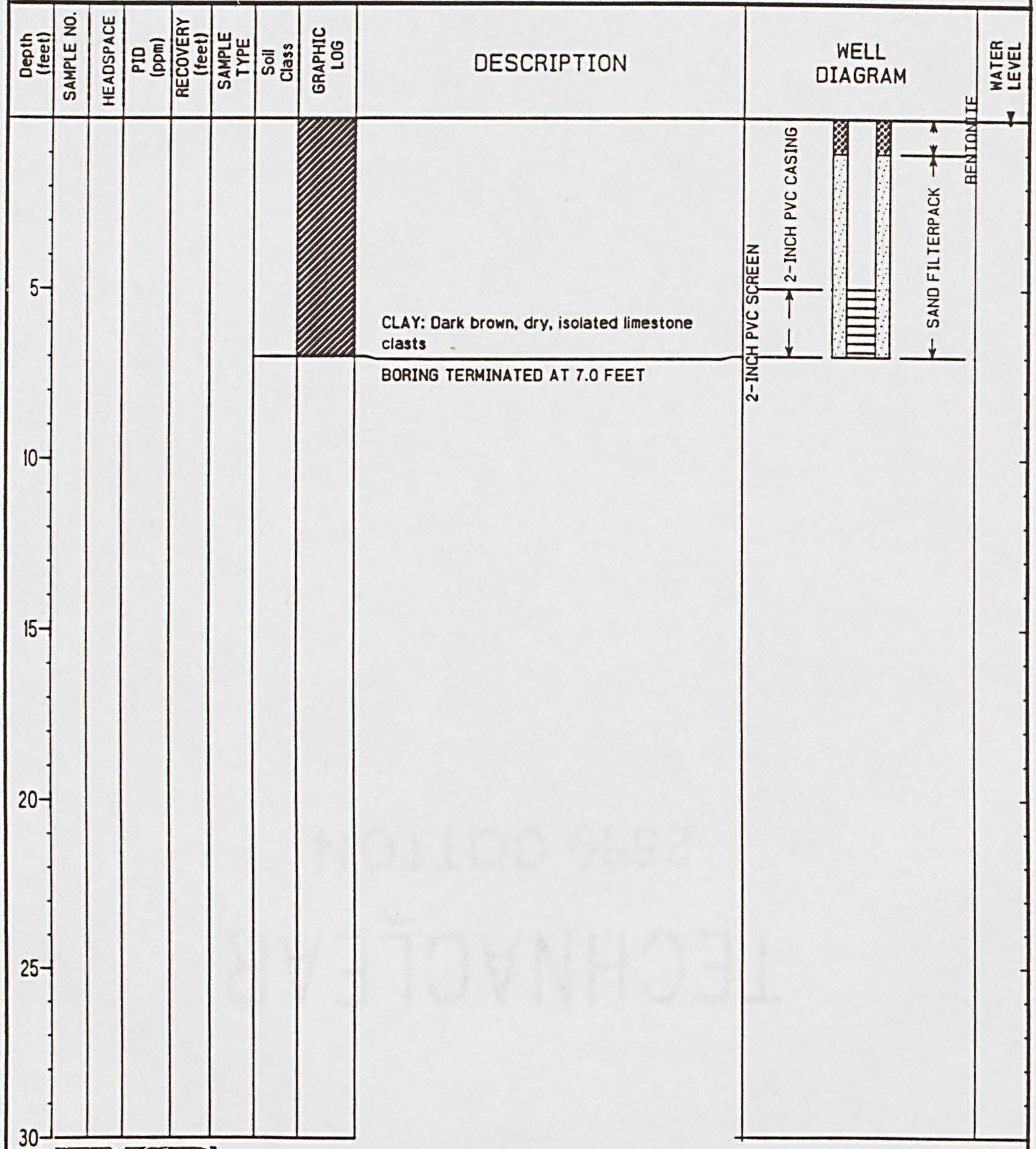
BORING LOG FOR BR-1

Depth feet	Description
0	Surface, dark brown soil, clay/marl rich, 1 - 4 mm. limestone fragments.
1	Dark clay/marl, organic rich material, moist but not saturated.
3	Dark brown clay/marl soil with silica (chert) and other silica less than 1 mm.
6	Clay/marl color reddish-brown on surface of core, red not present in core slice, dark brown clay/marl soil, roots.
7	Soil color change to light brown, clay/marl -rich with slightly more siliceous material than above. Hole terminated in light brown clay/marl with silica and chert fragments.

LITHOLOGIC LOG BR-1

Client :
Project Name : FECKLEY THESIS
Project Location : BEALL RANCH, CRANFILLS GAP, TEXAS
Project Number :
Geologist : DLF
Drilled By : BAYLOR GEOLOGY

Date Drilled : MARCH 2, 1994
Method : SOLID STEM AUGER/SHELBY TUBE
Top of Casing Elevation : 0
Ground Surface Elevation :
X-Coordinate :
Y-Coordinate :
Total Depth : 7



CLAY: Dark brown, dry, isolated limestone clasts

BORING TERMINATED AT 7.0 FEET

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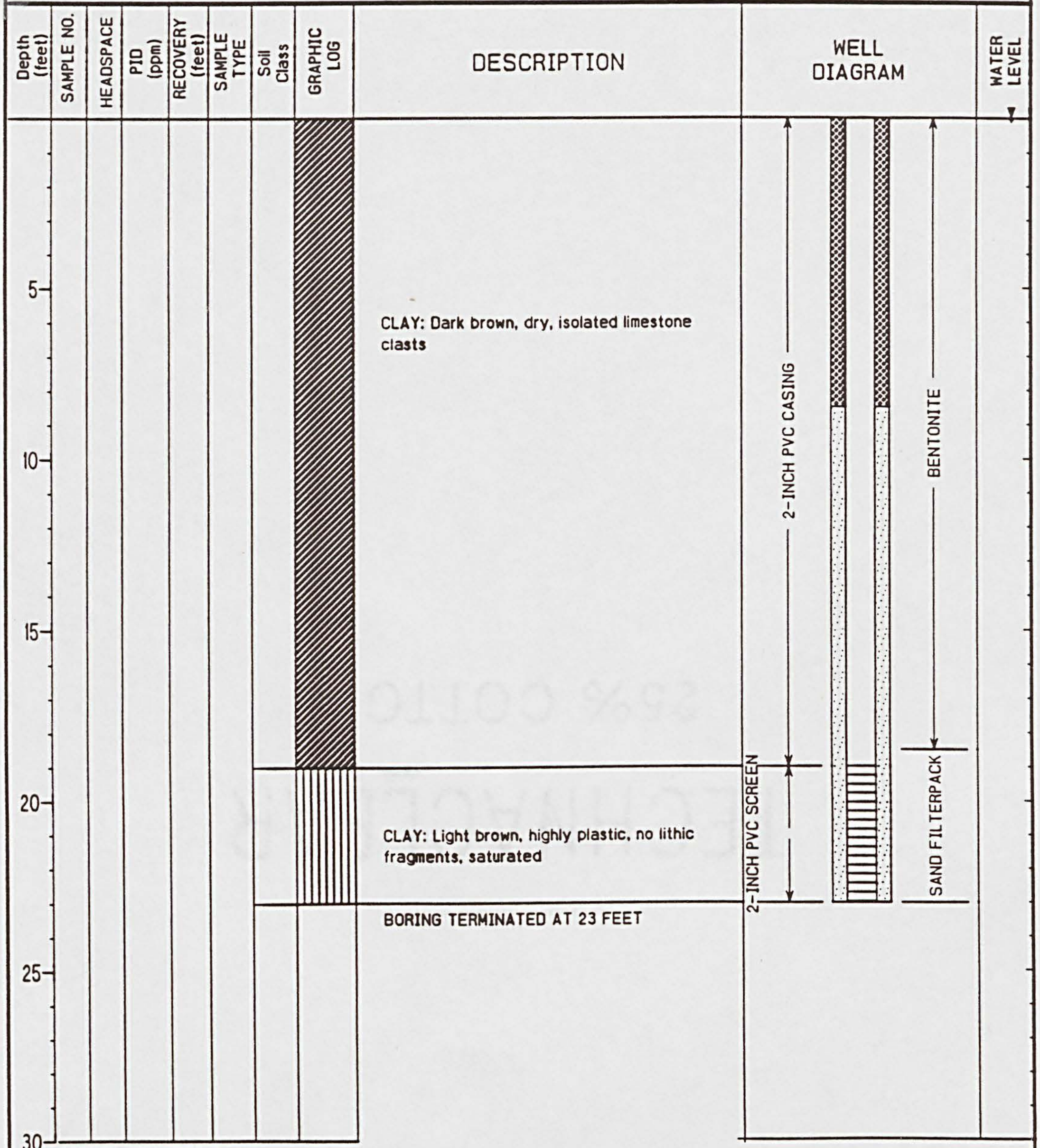
BORING LOG FOR BR-2

Depth feet	Description
0	Surface, dark brown clay/marl rich soil with limestone fragments 2 - 4 mm. Moist, not saturated. Organic material present, roots. Small silica fragments (possibly chert) present in clay/marl material.
5	Dark brown clay/marl soil, low silt, lighter brown than above. Limestone fragments smaller in size than above.
9	Medium brown soil, moist, few lithic grains, very little siliceous material.
11	Light brown clay/marl, abundant small limestone fragments, siliceous material more abundant than 9 foot interval.
13	Clay/marl soil with low moisture content, abundant small limestone fragments.
15	Light brown clay/marl with streaks of darker clay/marl material, Cretaceous marine fossils present, abundant limestone fragments.
19	Water rises to surface, material is light brown to buff colored shale/marl with plastic properties, must be pulled from auger flight. Limestone fragments and silt content very low to not present.
23	Hole terminated in marl material described above. Material is completely saturated.

LITHOLOGIC LOG BR-2

Client :
Project Name : FECKLEY THESIS
Project Location : BEALL RANCH, CRANFILLS GAP, TEXAS
Project Number :
Geologist : DLF
Drilled By : BAYLOR GEOLOGY

Date Drilled :
Method : SOLID STEM AUGER/SHELBY TUBE
Top of Casing Elevation : 0
Ground Surface Elevation :
X-Coordinate :
Y-Coordinate :
Total Depth : 26



CLAY: Dark brown, dry, isolated limestone clasts

CLAY: Light brown, highly plastic, no lithic fragments, saturated

BORING TERMINATED AT 23 FEET

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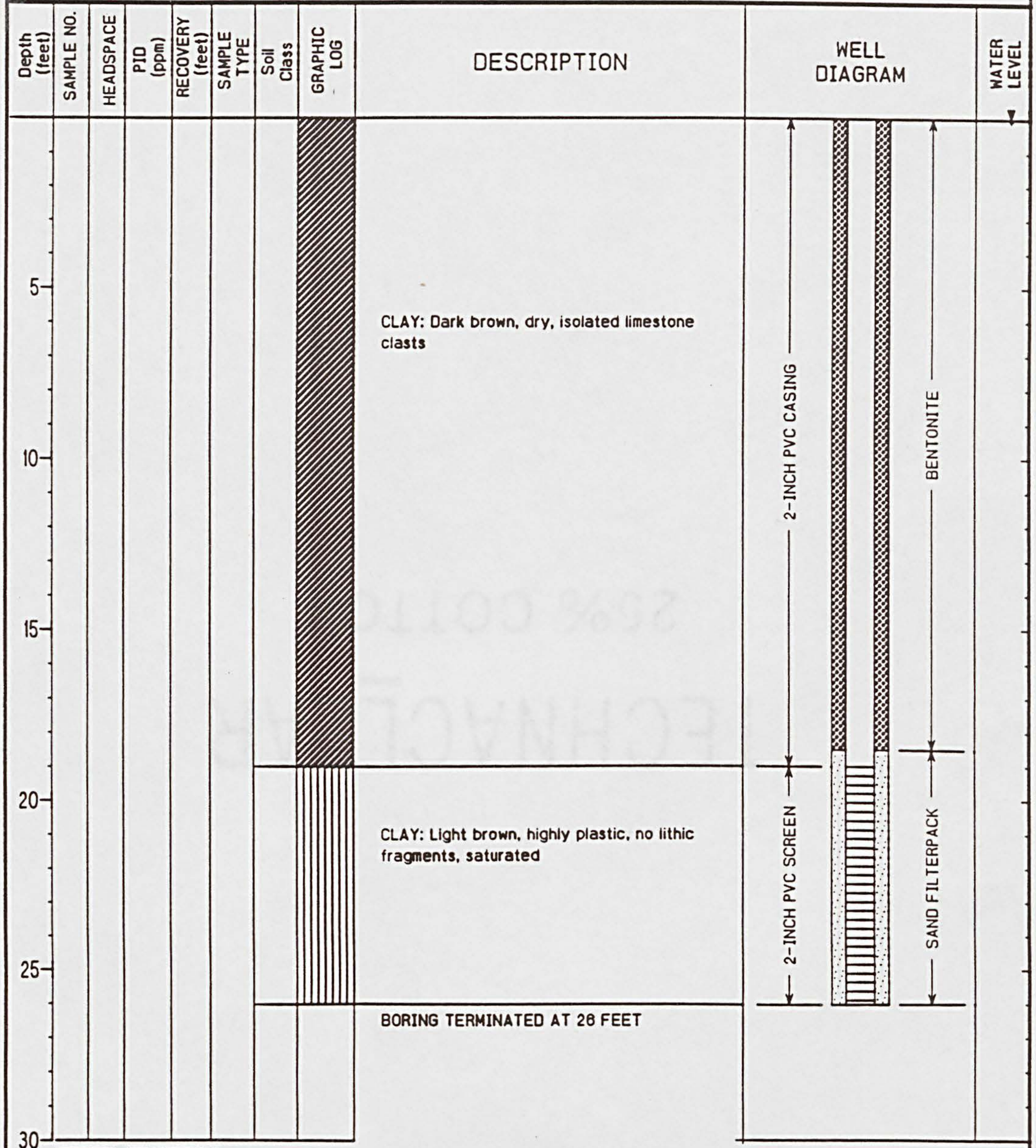
BORING LOG FOR BR-3

Depth feet	Description
0	Surface, dark brown clay/marl with siliceous silt and limestone fragments, abundant organic material
6	Brown to grey clay/marl with siliceous silt and limestone fragments.
12	Light brown clay/marl with Gryphea fossils, abundant limestone fragments, may be thin limestone flag.
15	Light brown to buff clay/marl material, low moisture content.
19	Water rises to surface, no cuttings.
26	Hole terminated in light brown to buff clay/marl with plastic properties, material must be manually removed from auger flight. Material is completely saturated. Boring cannot be advanced due to competent material at base of boring.

LITHOLOGIC LOG BR-3

Client :
Project Name : FECKLEY THESIS
Project Location : BEALL RANCH, CRANFILLS GAP, TEXAS
Project Number :
Geologist : DLF
Drilled By : BAYLOR GEOLOGY

Date Drilled :
Method : SOLID STEM AUGER/SHELBY TUBE
Top of Casing Elevation : 0
Ground Surface Elevation :
X-Coordinate :
Y-Coordinate :
Total Depth : 26



CLAY: Dark brown, dry, isolated limestone clasts

CLAY: Light brown, highly plastic, no lithic fragments, saturated

BORING TERMINATED AT 26 FEET

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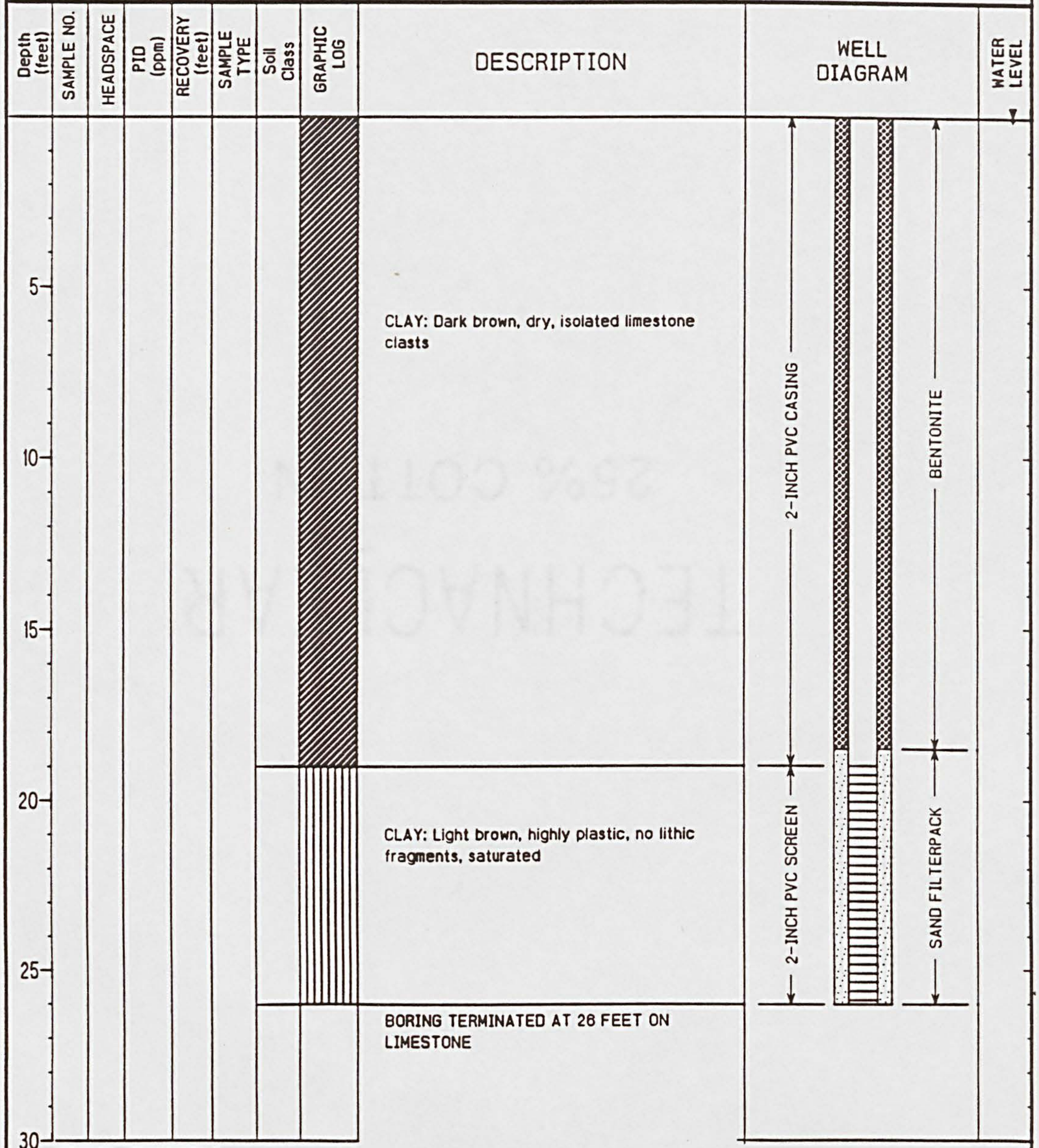
BORING LOG FOR BR-4

Depth feet	Description
0	Surface, dark brown clay/marl material with limestone fragments and siliceous material. Abundant organic material.
6	Medium brown to grey clay/marl with small limestone fragments and siliceous material (chert?).
12	Thin limestone flag with Gryphea fossils in cuttings.
12.5	Light brown to buff clay/marl with abundant limestone fragments, siliceous material not present.
17	Thin limestone flag
17.5	Same as 12.5 interval.
19	Water rises to surface, no cuttings
26	Hole terminated in light brown to buff clay/marl with plastic properties. Material must be manually removed from auger flight. Material has no limestone fragments and is completely saturated. Boring terminates on competent material (interpreted to be limestone).

LITHOLOGIC LOG BR-4

Client :
Project Name : FECKLEY THESIS
Project Location : BEALL RANCH, CRANFILLS GAP, TEXAS
Project Number :
Geologist : DLF
Drilled By : BAYLOR GEOLOGY

Date Drilled :
Method : SOLID STEM AUGER/SHELBY TUBE
Top of Casing Elevation : 0
Ground Surface Elevation :
X-Coordinate :
Y-Coordinate :
Total Depth : 26



CLAY: Dark brown, dry, isolated limestone clasts

CLAY: Light brown, highly plastic, no lithic fragments, saturated

BORING TERMINATED AT 26 FEET ON LIMESTONE

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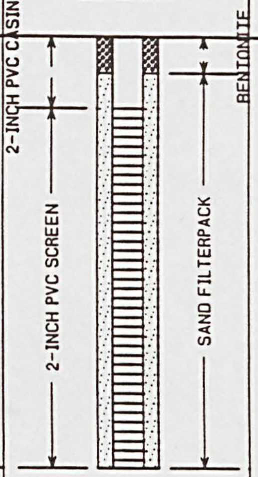
BORING LOGS FOR HAMILTON SITE

The entire thickness of the material encountered at Site Two (Hamilton) consisted of indurated, nodular limestone with minor shale (marl) partings. An occasional indurated bed that would produce fossiliferous cuttings was encountered, and these beds were interpreted to be *Gryphea* beds; however, these beds were thin and exact placement in the boring depths was not possible.

LITHOLOGIC LOG HAM-1

Client :	**Date Drilled :** MARCH 2, 1994
Project Name : FECKLEY THESIS	**Method :** MUD ROTARY
Project Location : HANSON RANCH, HAMILTON, TEXAS	**Top of Casing Elevation :** 0
Project Number :	**Ground Surface Elevation :**
Geologist : DLF	**X-Coordinate :**
Drilled By : BAYLOR GEOLOGY	**Y-Coordinate :**
	Total Depth : 6

Depth (feet)	SAMPLE NO.	HEADSPACE	PID (ppm)	RECOVERY (feet)	SAMPLE TYPE	Soil Class	GRAPHIC LOG	DESCRIPTION	WELL DIAGRAM	WATER LEVEL
5								LIMESTONE: Tan to buff colored, nodular with thin regular-bedded section, thin (<1') clay/marl seams		▼
								BORING TERMINATED AT 6.0 FEET		
10										
15										

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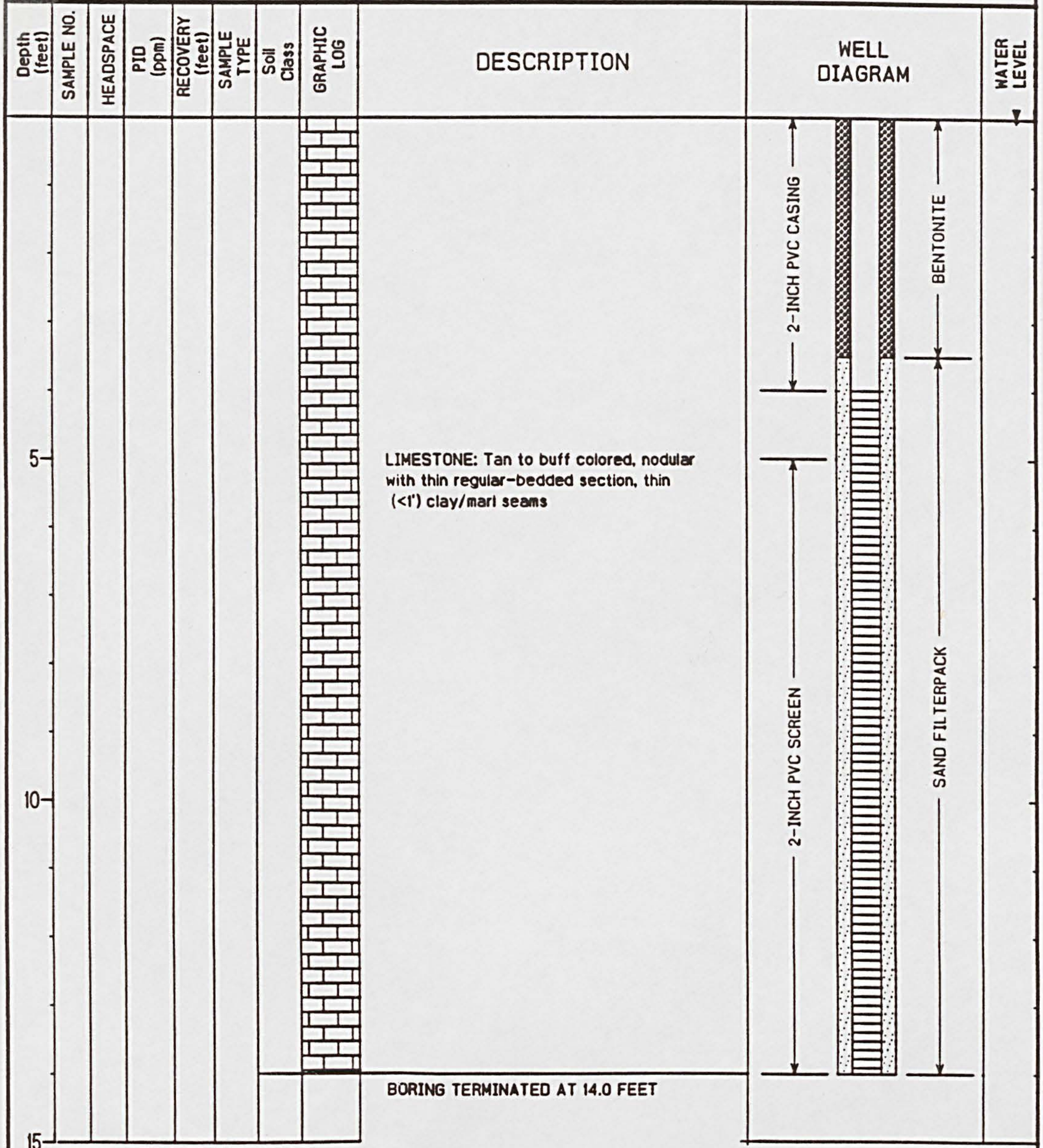
LITHOLOGIC LOG HAM-2

Client :
Project Name : FECKLEY THESIS
Project Location : HANSON RANCH, HAMILTON, TEXAS
Project Number :
Geologist : DLF
Drilled By : BAYLOR GEOLOGY

Date Drilled : MARCH 2, 1994
Method : MUD ROTARY
Top of Casing Elevation : 0
Ground Surface Elevation :
X-Coordinate :
Y-Coordinate :
Total Depth : 14



LIMESTONE: Tan to buff colored, nodular with thin regular-bedded section, thin (<1') clay/marl seams

BORING TERMINATED AT 14.0 FEET

APPENDIX FOUR

Water level data for hydrograph generation

Beall Ranch Data

Day	BR-1	BR-2	BR-3	BR-4
1	977.16	980.91		
32	979.54	983.49		
34	979.79	983.41		
66	980.87	983.3		
78	980.84	983.34		
127	980.76	983.06		
193	980.65	982.65		
200	980.61	982.52		
235	980.52	980.9		
270	977.83	976.32		
297	977.74	972.77		
305	973.46	971.26	971.24	971.26
316	973.58	969.56	969.54	969.54
333	973.53	967.41	967.36	967.35
344	975.46	966	966.1	965.88
361	979.32	965.76	965.76	965.76
366	978.73	966.7	966.66	966.62
367	978.64	966.75	966.72	966.69
368	978.52	966.77	966.74	966.72
395	978.5	973.67	973.61	973.55
396	978.43	973.74	973.68	973.61
397	978.36	973.89	973.83	973.76
398	978.29	974.05	973.99	973.91
399	978.19	974.19	974.14	974.08
400	978.13	974.23	974.17	974.14
403	977.98	974.48	974.42	974.38
409	978.31	974.86	974.81	974.68
416	978.28	975.63	975.58	975.51
421	978.49	976.29	976.26	976.17
423	978.47	976.62	976.58	976.53
430	974.57	977.63	977.31	977.23
433	975.01	977.78	977.74	977.69
435	975.73	979.43	979.38	979.31
437	976.37	980.39	980.32	980.24
442	978.32	981.53	981.41	981.32
453	980.48	982.52	982.38	982.25
468	980.58	982.9	982.74	982.6
481	980.6	983.01	982.86	982.72
484	980.82	982.98	982.82	982.67
496	980.59	982.73	982.58	982.45
510	980.56	982.48	982.34	982.21
511	980.57	982.44	982.3	982.16
541	980.45	981.41	981.33	981.21

Hamilton Site Data

Day of total	Day	Date	Shallow	Shallow Cond.	Deep	Deep Cond.
468	1	3-9-93	94.65	504	94.65	520
481	13	3-22	94.76		94.79	
484	16	3-25	94.57	522	94.56	531
496	28	4-9	93.88		93.75	
510	42	4-23	93.28	558	93.07	559
540	72	5-23			91.23	

FLEXIBLE WALL PERMEABILITY TEST

Slidell Clay.

PROJECT NAME LOCATION: Walnut Clay Groundwater Assessment PROJECT NO.: —
SAMPLE DESCRIPTION: DK Gr. Brown/ Clay (CH) PI: ____ PL: ____ LL: ____ -200: ____
BORING DEPTH: 4.5-5.0 ' TECHNICIAN: R.D /WM PERMEAMETER NO.: 1 PANEL NO.: 1/2/3
SAMPLE HEIGHT: (I) 1.5/(F) 1.55 In. SAMPLE DIAMETER: 2.75/2.80 in. SAMPLE AREA: (A) 38.32 cm²
WET WEIGHT OF SAMPLE, INITIAL: 301.4 gms FINAL 307.6 gms.
INITIAL WET DENSITY: 128.9 pcf INITIAL DRY DENSITY: 110.3 pcf
(e) VOID RATIO: 0.54 SATURATION, INITIAL: 85 % FINAL: 97 % $e = \left(\frac{SG\gamma_w}{UDW}\right) - 1$ $s = \frac{SG\ (mc\ \%)}{e}$
(i) HYDRAULIC GRADIENT: h/L 92.3 AVERAGE CONFINING PRESSURE: 7.5 PSI

INITIAL MOISTURE 16.9 % FINAL MOISTURE 17.3 % SAMPLE TYPE: ____
WW 354.9 DW 311.4 WW 361.1 DW 311.4 Total Time =
DW 311.4 TW 53.5 DW 311.4 TW 53.5 287 hrs
TARE 43.5 252.9 TARE H /49.7 257.9

DATE	TIME	TEST PRESSURES (psi)				INFLOW (cc)	OUTFLOW (cc)	ΔQ		Δt (sec)	HYDRAULIC CONDUCTIVITY K=QL/hAt (cm./sec)
		σ₀	Δσ₃	IN (h)	OUT			IN	OUT		
2/5	10:00A	10.0p	60	55	50	0.0p	20.0p	—	—		
2/5	11:30A	9.5p				3.6p	18.3p	3.6	1.7		
2/5	11:30A	10.0p		reset		0.0p	20.0p	—	—		
2/5	2:35p	9.6p				0.9p	20.3p	1.2	0		
2/5	2:35p	10.0p		reset		0.00	20.00	—	—		
2/6	7:30A	8.4p				1.5p	20.5p	2.0	0		
2/6	7:30A	10.0p		resett		0.0p	20.0p	—	—		
2/7	7:30A	9.7				1.0	19.8	1.0	0.2		
2/7	7:30A	10.0p		Reset		0.0p	20.0p	—	—		
2/10	7:30A	9.9p				1.8p	19.3p	1.8	.7		
2/10	7:30A	10.0p		reset		0.0p	20.0p	—	—		
2/11	7:30A	10.0p				0.6p	19.7p	.6	.3		
2/11	7:30A	10.0p		resett		0.0p	20.0p	—	—		
2/12	[illegible]	10.0				0.6	19.7	.6	.3		
2/12	[illegible]	10.0		Reset		0.0	20.0	—	—		
2/13	5:30A	10.2p				0.5p	19.7p	.5	.3		
2/13	5:30A	10.0p		resett		0.0p	20.0p	—	—		
2/14	10:15A	10.0				0.6	19.6	0.6	0.4	103,500	1.3 X 10-9
2/14	10:15A	10.0		Reset		0.0	20.0	—	—		
2/15	9:20A	10.0				0.5	19.3	0.5	0.3	83,100	1.3 x 10-9
2/15	9:20A	10.0		Reset		0.0	20.0				
2/16	2:45p	10.0p				0.6p	19.6p	.6	.4	105,900	1.3 x 10-9
2/16	2:45p	10.0p		reset		0.0p	20.0p	—	—		
2/17	9:00A	10.0				0.5	19.4	.5	.6	63,900	2.4 x 10-9
	terminate test										

NOTES: A = 38.32 H = 351.7 1.3 x 10-9 cm/sec. = 2.5 x 10-9 ft/min X ≈ 8 x 10-4
2.4 x 10-9 cm/sec = 4.7 x 10-9 ft/min

L = 3.81

GP FIELD DATA SHEET

Slidell clay.

SECTION 2: STANDARDIZED PROCEDURE FOR PERMEAMETER READINGS AND CALCULATIONS

Date 2-2-93 Investigator Feney / Scheerhorn

Reservoir Constants: (See label on Permeamter)

Combined Reservoirs	X	34.93	cm²
Inner Reservoir	Y	2.22	cm²

☐ ☒ CHECK RESERVOIR USED

Depth of Well Hole 29.53cm

Note: In standardized procedure the radius of the well hole is always 3.0 cm

@ well 6

1st Set of Readings with height of water in well (H_1) set at 5 cm

READING NUMBER	TIME	TIME INTERVAL (MIN)	WATER LEVEL IN RESERVOIR, (CM)	WATER LEVEL CHANGE, (CM)	RATE OF WATER LEVEL CHANGE, R_1, (CM/MIN)
1		1.00	2.7		
2		2	2.7	0	
3		3	2.7	0	
4		4	2.7	0	
5		5	2.7	0	
6		6	2.7	0	
7		7	2.7	0	
8		8	5.5	—	TO 10cm head
		9	5.6	.1	
		10	5.6	0	
		11	5.6	3	
		12	5.6	0	
		13	5.7	.1	
		14	5.7	0	
		15	5.7	0	

2nd Set of Readings with height of water in well (H_2) set at 10 cm

READING NUMBER	TIME	TIME INTERVAL (MIN)	WATER LEVEL IN RESERVOIR, (CM)	WATER LEVEL CHANGE, (CM)	RATE OF WATER LEVEL CHANGE, R_2, (CM/MIN)
		16	5.7	0	
		17	5.7		
		18	5.7	0	
		19	5.7	0	
20cm head		20	11.2	X	
		21	11.2	0	
		22	11.2		
		23			
		24			
		25			

CALCULATIONS

$\bar{R}$, the steady state rate of flow, is achieved when R is the same in three consecutive time intervals.

For the 1st Set of Readings $\bar{R}_1$ = (0)/60 = 0 cm/sec
(R_1)

For the 2nd Set of Readings $\bar{R}_2$ = (____)/60 = ____ cm/sec
(R_2)

K_{fs} = [(.0041)(____)(____)] - [(.0054)(____)(0)] = ____ cm/s

FIELD SATURATED HYDRAULIC CONDUCTIVITY; RESERVOIR CONSTANT; $\bar{R}_2$-STEADY STATE RATE OF FLOW; RESERVOIR CONSTANT; $\bar{R}_1$-STEADY STATE RATE OF FLOW

ϕ_m = [(.0572)(____)(____)] - [(.0237)(____)(____)] = ____ cm²/

MATRIC FLUX POTENTIAL; RESERVOIR CONSTANT; $\bar{R}_1$ STEADY STATE RATE OF FLOW; RESERVOIR CONSTANT; $\bar{R}_2$ STEADY STATE RATE OF FLOW

α = (____)/(____) = ____ cm^{-1}

ALPHA PARAMETER; K_{fs}; ϕ_m

Δθ = (____) - (____) = ____ cm³/cm³

DELTA THETA; θ_{fs}, FIELD SATURATED WATER CONTENT OF SOIL, IN CM³/CM³; θ_i, AMBIENT WATER CONTENT OF SOIL, IN CM³/CM³

ESTIMATED	☐	CHECK ONE
MEASURED	☐	

S = $\sqrt{2}$(____)(____) = ____ cm $sec^{-1/2}$

SORPTIVITY; Δθ; ϕ_m

GP FIELD DATA SHEET

SECTION 2: STANDARDIZED PROCEDURE FOR PERMEAMETER READINGS AND CALCULATIONS

11.75 in

Date 3-2-93 Investigator Feeney / Scheuhorn

Reservoir Constants: (See label on Permeamter)

Combined Reservoirs	X 34.93	cm²	☐
Inner Reservoir	Y 2.22	cm²	☐

CHECK RESERVOIR USED

Depth of Well Hole 29.845 cm.

Note: In standardized procedure the radius of the well hole is always 3.0 cm

1st Set of Readings with height of water in well (H_1) set at 5 cm

READING NUMBER	TIME	TIME INTERVAL (MIN)	WATER LEVEL IN RESERVOIR, (CM)	WATER LEVEL CHANGE, (CM)	RATE OF WATER LEVEL CHANGE, R_1, (CM/MIN)
1		1:00	8.4	—	
2		2:00	8.4	—	
3		3:00	9.5	1.1	
4		4:00	11.3	1.8	
5		5:00	12.3	1.0	
6		6:00	14.2	1.9	
7		7:00	15.8	1.6	
8		8:00	16.5	.7	
9		9:00	18.0	1.5	
10		10:00	19.4	1.4	
11		11:00	20.6	1.2	
12		12:00	22.3	1.7	
13		13:00	23.5	1.2	
14		14:00	24.7	1.2	
15		15:00	26.7	2.0	

2nd Set of Readings with height of water in well (H_2) set at 10 cm

READING NUMBER	TIME	TIME INTERVAL (MIN)	WATER LEVEL IN RESERVOIR, (CM)	WATER LEVEL CHANGE, (CM)	RATE OF WATER LEVEL CHANGE, R_2, (CM/MIN)
1		16:00	8.3		
2		17:00	8.4	.1	
3		18:00	14.8	0	
4		19:00	14.8	0	
5		20:00	14.8	0	
6		21:00	15.1	.3	
7		22:00	15.1	0	
8		23:00	15.4	.3	
9		24:00	18.5	3.1	
10		25:00	21.9	3.4	
11		26:00	25.2	3.3	
12		27:00	28.2	3.0	
13		28:00	31.3	3.1	
14		29:00	34.7	3.4	
15		30:00	38.0	3.3	

CALCULATIONS

$\bar{R}$, the steady state rate of flow, is achieved when R is the same in three consecutive time intervals.

4.7×10^{-4} R1

For the 1st Set of Readings $\bar{R}_1$ = (1.46 R_1) / 60 = .02433 cm/sec

For the 2nd Set of Readings $\bar{R}_2$ = (3.23 R_2) / 60 = .05383 cm/sec

K_{fs} FIELD SATURATED HYDRAULIC CONDUCTIVITY = [(.0041)(2.22 RESERVOIR CONSTANT)(.0583 $\bar{R}_2$ - STEADY STATE RATE OF FLOW)] - [(.0054)(2.22 RESERVOIR CONSTANT)(.02433 $\bar{R}_1$ - STEADY STATE RATE OF FLOW)] = 2.4×10^{-4} cm/s

.00053 .00029 .00024

ϕ_m MATRIC FLUX POTENTIAL = [(.0572)(2.22 RESERVOIR CONSTANT)(.02433 $\bar{R}_1$ STEADY STATE RATE OF FLOW)] - [(.0237)(2.22 RESERVOIR CONSTANT)(.0583 $\bar{R}_2$ STEADY STATE RATE OF FLOW)] = 1.83×10^{-5} cm²/s

.003086 .003D673 .0000183

α ALPHA PARAMETER = (2.4×10^{-4} K_{fs}) / (1.83×10^{-5} ϕ_m) = 4.392×10^{-9} cm⁻¹

Δθ DELTA THETA = (______ θ_{fs}, FIELD SATURATED WATER CONTENT OF SOIL, IN CM³/CM³) - (______ θ_i, AMBIENT WATER CONTENT OF SOIL, IN CM³/CM³) = ______ cm³/cm³

ESTIMATED	☐	CHECK ONE
MEASURED	☐	

S SORPTIVITY = $\sqrt{2(\_\_\_\_\_)(\_\_\_\_\_)}$ (Δθ) (ϕ_m) = ______ cm sec$^{-1/2}$

Colluvial Soil

GP FIELD DATA SHEET

SECTION 2: STANDARDIZED PROCEDURE FOR PERMEAMETER READINGS AND CALCULATIONS

Date 2-6-93 Investigator Fecklew

Reservoir Constants: (See label on Permeamter)

Combined Reservoirs X 34.93 cm²	☐	CHECK RESERVOIR USED
Inner Reservoir Y 2.22 cm²	☒	

Depth of Well Hole ________

Note: In standardized procedure the radius of the well hole is always 3.0 cm

1st Set of Readings with height of water in well (H_1) set at 5 cm

READING NUMBER	TIME	TIME INTERVAL (MIN)	WATER LEVEL IN RESERVOIR, (CM)	WATER LEVEL CHANGE, (CM)	RATE OF WATER LEVEL CHANGE, R_1, (CM/MIN)
1		1:00	27.0	Y	
2		2:00	26.3		
3		3:00	25.2		
4		4:00	25.2		
5		5:00	25.2		
6		6:00	27.5	2.3	
7		7:00	30.2	2.7	
8		8:00	33.1	2.9	
9		9:00	35.7	2.6	
10		10:00	38.8	3.1	
11		11:00	41.8	3.0	
12		12:00	44.4	2.6	
13		13:00	48.4	4.0	
14		14:00	51.6	3.2	
15		15:00	54.2	2.6	

2nd Set of Readings with height of water in well (H_2) set at 10 cm

READING NUMBER	TIME	TIME INTERVAL (MIN)	WATER LEVEL IN RESERVOIR, (CM)	WATER LEVEL CHANGE, (CM)	RATE OF WATER LEVEL CHANGE, R_2, (CM/MIN)
16		16:00	33.6	X	
17		17:00	33.5	X	
18		18:00	33.5	X	
19		19:00	33.5	X	
20		20:00	38.7	5.2	
21		21:00	44.7	6.0	
22		22:00	50.0	5.3	
23		23:00	55.3	5.3	
24		24:00	60.3	6.0	
25		25:00	66.0	5.7	
26		26:00	35.9		
27		27:00			
28		28:00			
29		29:00			
30		30:00			

CALCULATIONS

$\bar{R}$, the steady state rate of flow, is achieved when R is the same in three consecutive time intervals.

For the 1st Set of Readings $\bar{R}_1$ = (2.9 [R_1])/60 = 2.9 cm/sec

For the 2nd Set of Readings $\bar{R}_2$ = (5.6 [R_2])/60 = 5.6 cm/sec

K_{fs} = [(.0041)(2.22 [RESERVOIR CONSTANT])(5.6 [$\bar{R}_2$ - STEADY STATE RATE OF FLOW])] - [(.0054)(2.22 [RESERVOIR CONSTANT])(2.9 [$\bar{R}_1$ - STEADY STATE RATE OF FLOW])] = .0162 / 1x10⁻² cm/s

FIELD SATURATED HYDRAULIC CONDUCTIVITY

.0509712 .0347652

ϕ_m = [(.0572)(____ [RESERVOIR CONSTANT])(____ [$\bar{R}_1$ STEADY STATE RATE OF FLOW])] - [(.0237)(____ [RESERVOIR CONSTANT])(____ [$\bar{R}_2$ STEADY STATE RATE OF FLOW])] = ____ cm²/

MATRIC FLUX POTENTIAL

α = (____ [K_{fs}])/(____ [ϕ_m]) = ____ cm⁻¹

ALPHA PARAMETER

Δθ = (____ [θ_{fs}, FIELD SATURATED WATER CONTENT OF SOIL, IN CM³/CM³]) - (____ [θ_i, AMBIENT WATER CONTENT OF SOIL, IN CM³/CM³]) = ____ cm³/cm³

DELTA THETA

ESTIMATED	☐	CHECK ONE
MEASURED	☐	

S = $\sqrt{2}$(____ [Δθ])(____ [ϕ_m]) = ____ cm sec $^{1/2}$

SORPTIVITY

Colluvine Soil