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The Case of Canoe Brook Wells in Glacial Sand and Gravel, Livingston, New Jersey : Establishing the Hydraulic Signs of Well Contamination Risk Using Topography

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MONTCLAIR STATE UNIVERSITY

THE CASE OF CANOE BROOK WELLS IN GLACIAL SAND AND GRAVEL, LIVINGSTON, NEW JERSEY:

Establishing the Hydraulic Signs of Well Contamination Risk using Topography

by

Brian Frank

A Master's Thesis Submitted to the Faculty of

Montclair State University

In Partial Fulfillment of the Requirements

For the Degree of

Master of Science

August 2012

School/College: College of Science and Mathematics

Department: Earth and Environmental Studies

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College Dean: Robert S. Prezant, Ph.D.

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ABSTRACT

When little groundwater level data is available, the potential energy gradients reflected in the topography, assumed to be saturated to the surface, can be used to estimate the directions and relative rates of groundwater flow (flow systems). Darcy's law conveniently relates groundwater water levels to the rate of groundwater flow. Tòth (1963) related topography to groundwater flow systems. Flow systems can transport surface contamination, if present, to wells. The topography and likely contamination point source surface locations were used to create and contrast the flow systems impacting two wells in order to assess contamination risk. The two wells, Canoe Brook well no. 1 (CB-1) and Canoe Brook no. 3 (CB-3) are in the East Orange Water Reserve (EOWR). Only well CB-3 has high chloride ion concentrations. Both wells are completed in the EOWR's sand and gravel aquifer, which is overlain by low permeability clay-rich till and underlain by a fractured bedrock aquifer (Towaco and Preakness Basalt Formations). The distribution of groundwater flow (flow systems), well capture zones and recharge zones were characterized using MODFLOW. Features of the topography, geology, flow systems, capture zones and recharge zones which might relate to contamination risk for each well were compared. The Canoe Brook well field was conceptualized as a 10,667 ft. by 8,888 ft. by 400 ft. deep drainage basin- with the Livingston half-basin on Canoe Brook's west bank and the Millburn-South Mountain half-basin on its east bank. Maximum elevations in the Millburn-South Mountain half-basin were double those in the Livingston half-basin. The domain's three layers were represented using hydraulic conductivities typical for silty clay, sandy gravel and fractured bedrock, respectively. Consistent with Tòth s (1963) findings, high magnitude

relief generated deeper surface-influenced groundwater flow (local flow systems). Well CB-3 was in high relief topography with low overall basin slope. The local flow systems were the dominant flow systems at CB-3. More relief features and lower basin slope meant more recharge starting points on the surface area, which caused more drainage over a wider area. There was no deep groundwater flow at CB-3. Well capture zones show the recharge starting points and flow path of the majority of the groundwater supplying a well. The well CB-3 capture zone directly received bulk transport from scattered recharges resulting in a capture zone with less integrity. Many recharges are overlain by roads. In addition, chloride dispersion downward could occur most easily into the CB-3 capture zone based on its shallow subsurface position, long length and flat shape. Simulated aquifer recharge was occurring directly above CB-3; chloride could disperse into the well itself. Geology also predisposed well CB-3 to contamination. The protective clay-rich till layer at CB-3 was the thinnest. The hydraulic and geological features of the well CB-1 were opposite to CB-3. Topographically, the basin slope was high and relief was low. The groundwater flow at CB-1 was marked by a deep intermediate flow system. The CB-1 capture zone had no recharges under roads. Its structure was deep, squat and fast flowing. No aquifer recharge occurred above the well. The protective clay layer at CB-1 was the thickest. In light of Tòth's topography-flow system relationships and Darcy's law, the results of the simulation predict the long term impact of the development over regional recharges. With the loss of regional recharges, regional flow systems are replaced by local flow systems. High relief areas become more strongly influenced by surface-associated local flow systems. As a result, with regional development, high relief areas may become more prone to contamination from the surface.

The Case of the Canoe Brook Wells in Glacial Sand and Gravel, Livingston NJ

Establishing the Hydraulic Signs of Well Contamination Risk using Topography

A THESIS

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by

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1.0 Introduction

A declining water level in a well is a concern because it reflects a decline in potential energy relative to a saturated surface topography. Water will flow from points of high potential energy on the surface to the point of low potential energy in the well bringing surface contamination. Declining water level will reduce the drawdown, the distance between the un-pumped and pumped water level, which results in lower well yields, or lower production (Uhl and Associates, Inc. 2003). If the water level decline exposes the well screen to air, the screen may become biologically fouled, further reducing well productivity and water quality. Declining well water level is a truly negative sign.

In 1907 flowing artesian conditions existed in the EOWR's Canoe Brook well field in Livingston, NJ (Figure 1, EOWR Regional Map). Static water levels were 10 to 20 feet above ground surface. By 1925, static water levels declined 30 to 40 feet below ground surface (Uhl and Associates, Inc. 2007). Appendix A shows historic water levels. Water quality as measured by hardness, total dissolved solids (TDS) and chloride began to deteriorate starting in the 1950's. Between 2003 and 2007 chloride concentrations increased as much as 50% in well CB-3 (Appendix B).

Chloride contamination of wells is considered irreversible and a cause for permanent shut-down (Strumm 2004). Chloride contamination of surface water and groundwater is a growing problem. Increasing chloride ion concentrations have been linked to urbanization, which accelerated after World War II (Kelly 2008). Chloride concentrations in urban surface water and groundwater commonly increases about 1.5

mg/l per year and 55% of this chloride is retained in the soil (Kelly 2008). Chloride contamination of production wells renders them non-potable with concentrations greater than 250 mg/l, the secondary maximum contaminant level (SMCL). Chloride contamination of surface and groundwater not only affects humans, it is lethal to some aquatic organisms (Evans et al. 2001). Sub-critical levels decrease biodiversity, facilitate invasive species colonization, increase water density inhibiting spring mixing, act synergistically with other contaminants, change water temperatures and levels and interfere with the nitrogen cycle (Kelly 2008).

Ninety one percent of all chloride in freshwater comes from road salt (Kelly 2008). In northeast Illinois, road departments administer 20 tons of NaCl/lane-mile-season (Panno et al. 2002). According to Panno et al. (2002) high chloride concentrations can be found in surface and groundwater near roads. Chloride concentrations in urban water bodies in southeast New York State are commonly 3,000 mg/l (Kelly 2008). A more detailed picture of the source(s) of the contamination is not possible without a sense of the direction and rates of groundwater flow (the flow systems) relative to the potential point source locations. Flow systems in the Canoe Brook well field had not been characterized in prior studies. The goal of this project was to characterize the groundwater flow patterns to better understand the source of chloride contamination.

1.1 Background

Historically, water levels in the EOWR have been declining since its inception 100 years ago (Appendix A). Well efficiency, measured as the yield in gallons per minute (gpm) per foot of drawdown, was steadily declining. Deteriorating hydraulic conditions correlated with other negative changes. Water quality was deteriorating; chloride, other inorganics and total dissolved solids were increasing in wells. Two hydrogeological studies were conducted. In 1976, Geraghty and Miller, Inc. produced "Ground-water Conditions, City of East Orange Water Reserve, August, 1976" (Uhl and Associates 2007). Uhl and Associates, Inc. produced "Phase I Hydrogeological Study, 2003, East Orange Water Reserve, Livingston, Millburn and Florham Park, NJ" and "2007 Hydrogeologic Study Update Program, City of East Orange Reserve Well Fields".

1.2 Findings from Prior Studies

Prime recharge areas have been developed and roads, potential chloride point sources, have been constructed in the Canoe Brook well field. Development occurred within the EOWR and in the Canoe Brook watershed on the boundaries of the EOWR. Three roads, South Orange Avenue, Hobart Gap Road and John F. Kennedy Parkway, were constructed through the Canoe Brook well field. Construction on the largest, a four lane county highway, John F. Kennedy Parkway, began in 1963. Outside the reserve, from 1955 to 1970 development spread in elevated areas, prime recharge zones, from the southeast to the east and finally the northern boundaries of the reserve. Historic recharge zones (Appendix C) overlap "urbanized" areas (Appendix D).

This development correlates with water level declines in and around the EOWR (Appendix A). Consultants wells logs (Figure 2), show the groundwater level decline in the four Canoe Brook (CB) wells CB-1, CB-2, CB-3 and CB-4. Water levels declined below the confining till layer in all wells but CB-1. Despite New Jerseys increasingly wet climate (Rutgers Climate Lab 2010), water levels in wells CB-2, CB-3 and CB-4 remain below the confining layer. Along with the decreasing well productivity, water quality has steadily deteriorated as chloride concentrations in all Canoe Brook wells have been increasing (Appendix B).

The chloride concentrations increased in all wells. In CB-3 it increased 50%, to 143 mg/l, between 2005 and 2009. The concentration in the least affected well, CB-1, was 75.5 mg/l. The United States Environmental Protection Agency's secondary maximum contaminant level (SMCL) for chloride concentrations in drinking water is 250 mg/l (EPA 2011). The SMCL indicates that there is no health risk but that taste, odor or appearance will make the water unappealing for consumption (EPA 2011).

When the EOWR was dedicated in 1906 all chloride concentrations were sharply lower, 6 mg/l in all wells. Now surface water in the reserve also has problems with high chloride concentrations. Chloride concentrations of 7,000 mg/l have been reported in the Canoe Brook (Uhl and Associates 2009). Flow systems in EOWR were unexamined. Prior studies call for more research on 1) the chloride contamination risks faced by individual wells, 2) the changing state of recharge in the EOWR and 3) Taylor Lake's role in recharge (Geraghty & Miller 1976; Uhl and Associates 2007). Prior studies clearly document that development strangled the EOWR in a semicircle, severely on the northern and less so on the eastern boundaries. Development occurred within the reserve itself. Roads had been constructed in the reserve itself. Declining hydraulic head (hydraulic head equals elevation head plus pressure head) and increasing chloride correlate with the development.

1.3 Study Purpose and Objectives

The primary purpose of this project was to infer the chloride contamination risks of the highest chloride well (CB-3) and the lowest chloride well (CB-1) by contrasting their hydraulic environments, i.e., their flow systems. Flow systems are driven by hydraulic gradients, which are determined from water levels. In this case, multiple observation wells with detailed water level data were not available. But, topographic elevations of the surface and thus the elevation gradients were known. A secondary purpose was to demonstrate the importance of geomorphologic data for deriving hydraulic behavior and inferring the long term environmental impact of regional development.

There were eight subordinate objectives. These were to analyze and compare CB-1 versus CB-3 in terms of: 1) well chloride concentrations for the year 2007, 2) the geomorphology of the basin in three dimensions, 3) the geography of road point sources, 4) geological differences, 5) flow systems, 6) well capture zones, 7) recharge and 8) correlate these findings.

The tools available were Tòths (1963) study to classify the geomorphology based on the parameters of basin slope and local relief and the USGS application , MODFLOW, loaded with site-specific geomorphologic and geologic data to simulate groundwater flow systems, capture zones and recharge.

1.4 General Assumptions

Assumptions were made regarding chloride sources and mechanisms of chloride transport to wells. Chloride was assumed to be transported to wells from the surface by two possible mechanisms. The faster mechanism was the purely hydraulic bulk transport, when chloride is carried in bulk with the groundwater flow, from a recharge to a well.

A secondary (and slower) mechanism of transport was assumed to be some combination of dispersion and bulk transport. Dispersion is the mechanical mixing of chloride into groundwater (Mackay et al. 2011). For example, rather than bulk- transport from the surface, chloride could disperse from the surface into groundwater flowing in a well capture zone. Dispersion into a capture zone could be facilitated by local flow systems not in the capture zone. In other words, chloride might disperse from one flow system to another to be transported to a well.

The ease by which surface chloride could be mechanically mixed into a sub-surface flow system was assumed to increase the nearer the chloride source was to it. Road locations were the assumed point sources for chloride since road deicer is the source of 91% of the chloride in freshwater (Kelly 2008).

2.0 Description of Study Area

The site is covered by woodlands in the east and wetlands in the south and west. There are four EOWR well fields. The Braidburn and Dickenson wells are in the Passaic River flood plain. The Slough Brook wells are in the Slough Brook catchment area. The well field of interest, the Canoe Brook (CB) wells (Figure 3, Consultants Site Map), are in the Canoe Brook catchment area (Appendix D). The two wells of interest, CB-1 and CB-3, are completed in sand and gravel. The climate is temperate. Average yearly precipitation in New Jersey has been increasing for 100 years and is currently 48.58 inches (Rutgers Climate Lab 2010, Appendix E).

2.1 Topography

The well field is remarkable for its hills, terraces and intervening areas of variably saturated and often flooded areas; it is lush woodland, a seemingly pristine island surrounded by roads and busy suburbs. Elevations along the northern boundary undulate between 240 fasl and 260 fasl. Its southern boundary is 190 fasl in the southwest approaching the Canoe Brook reservoir but elevations rise to 260 at the reserve's boundary in the southeast. Elevations in the east continue to rise sharply to 400 fasl one thousand feet outside the reserves boundary. The domain's average elevation is 215 fasl. In the central basin, elevations undulate between 200 fasl and 220 fasl.

The Canoe Brook traverses the domain diagonally forming two half-basins, the Livingston half-basin on the west and the Millburn-South Mountain half-basin on the east. It flows from the northeast (water level elevation 260 fasl) to the south central (water level elevation 200 fasl), ultimately discharging into the Passaic River outside the reserve (USDA 2011). West of the Canoe Brook, in the Livingston half-basin, the slope trends vary from southwest to southeast. East of the Canoe Brook, Second Watchung Mountain's Triassic bedrock dictates a western and southwestern dip and drainage pattern. The Canoe Brook, exhibits the same southwest trending drainage pattern (USGS 2010). Other water bodies include Taylor Lake, a dilation of the Canoe Brook, and Butler Pond in the Millburn-South Mountain half-basin. In the southwest, just outside the EOWR boundaries lay the Canoe Brook Reservoirs #1 and #2.

2.2 Geology

The surficial geology consists of unconsolidated sediments of Quaternary glacial origin (Qr, Rahway till) and more recent Holocene alluvial deposit (Qal and Qaf). Along the Canoe Brook the sediment is alluvium (Qal)- stream-deposited silt, sand, gravel and cobbles (USGS 2010) in the lower reaches. Along the upper reaches it is sorted Qaf (alluvial fan deposits of pebbles, cobbles, gravel, sand and minor silt). Moving away from the Canoe Brook, east or west, the sediment is glacial till (Qr), an unsorted and non-stratified mix of clay, silt, sand, gravel, cobbles and boulders (Neuendorf 2005) and morainic deposits which are the same composition as Rahway till (Qr) but differ by their morphology. Glacial till (Qr) is capable of confining an aquifer when its clay composition is sufficiently high. A Mesozoic paleo-valley underlies the unconsolidated Quaternary sediment (USGS 2010). It is bedrock typical of the Newark Basin (basalt, shale and meta-sandstone) and an unconformity (Michalski 1997). The bedrock rises in the east as Second Watchung Mountain (Preakness Basalt). The EOWR's sand and gravel is a buried valley aquifer (Geraghty & Miller 1976; Uhl and Associates 2007).

The geology is heterogeneous (Figure 4) and the confining layer is not uniformly thick. Figure 4 shows the surficial geology and USGS borehole locations. Figure 5 profiles the sediment strata in the two USGS boreholes circled in Figure 4 demonstrating how the impervious layer thickness varies dramatically. Near well CB-1 (borehole #394), the confining (impervious) layer is 63 ft. thick. Upstream along the Canoe Brook, near Well CB-3 (borehole #402), the confining layer is just one foot thick. And a perched water table aquifer (boulders, sand and gravel) 70 ft. thick overlies the thin impervious layer, while a perched water table aquifer only 20 ft. thick overlies 63 ft. of clay in borehole #394. The aquifer at borehole #402, near CB-3, is much more vulnerable since the till confining layer is 1/63rd the thickness of the till confining layer at #394 and it is overlain by a potentially contaminated perched water table aquifer which is 3.5 times thicker. The perched water table aquifers in both cases would leak to the underlying confined aquifer, although at different leakage rates; it would be much slower at #394, due the thicker confining layer and likely higher pressure head in the underlying confined aquifer.

2.3 Hydrogeology

There are three fundamental water-bearing strata in the reserve: 1) the clay-rich till on top, 2) the sand and gravel in the middle, and 3) the fractured bedrock on the bottom. The most productive aquifer is the sand and gravel, followed by the fractured bedrock, followed by the clayey till.

The sand and gravel aquifer is semi-confined from above and below, sorted and stratified, between 20 ft. and 40 ft. thick in the Canoe Brook and has a porosity of 15%. The geology (grain size, roundness and packing) determines the permeability; large grains, roundness and loose packing create large, connected pores which allows more groundwater flow. Estimates for the hydraulic conductivity (K) for sand and gravel aquifers range from 100 ft./d (Bair 1992) to 2,834 ft./d (Freeze et al. 1979). Sand and gravel aquifers are considered highly productive.

In fractured bedrock aquifers water enters though the vertical joints on the surface but ultimately flows primarily in horizontal major bedding plain partings. This bedrock aquifer is part of the Towaco and Preakness Basalt Formations, which ranges in thickness from 11,480 ft. to 11,810 ft. and is semi-confined from above. Most groundwater flows in the uppermost bedrock (Michalski 1997). Fractured meta-sandstone, shale and basalt aquifers generally have a porosity of about 15% (Freeze et al. 1979; Bair 1992; Deolankar 2011) and hydraulic conductivities range from 5 ft./d (Bair 1992) to 283 ft./d (Freeze et al. 1979). Fractured bedrock aquifers are considered moderately productive.

In the confining till layer, groundwater tends to prefer vertical rather than horizontal flow paths (Freeze et al. 1979). The till layer thickness generally ranges from 15 ft. to 80 ft. (but there are thin spots as seen in USGS borehole #402). The consultants well logs, Figure 2, shows that the till confining layer is thickest at well CB-1 (84 ft. thick) and thinnest at CB-3 (31 ft. thick).

The sand and gravel aquifer is a deltaic fan deposit (USGS 2010). Thus in Figure 2 it is narrowest downhill at CB-1 and widest uphill at CB-3, like a funnel. This might maximize pressure head as groundwater is squeezed into the narrow end at CB-1.

The degree of sorting and the composition of clay versus silt also vary. The standard porosity of clay-rich sediments is 30%. The hydraulic conductivities of clay and till range from 0.0001 ft./d (Freeze et al. 1979; Schilling 2006) to 0.11 ft./d (Bair 1992). Due to its high clay content the till has low permeability is considered to be a confining layer for the aquifer at the Canoe Brook wells.

Groundwater is replenished by recharge. The amount of recharge received is affected by numerous factors including soil type, vegetation and climate. Problems arise in comparing recharge rates given that many methods for estimating recharge exist and it is not always clear how an estimate was derived (Freeze et al. 1979). Examples of recharge estimates from areas similar to the EOWR in terms geology and climate come from New Jersey, New York and Connecticut and range from 5.80 x 10^{-4} ft./d to 7.30 x 10^{-3} ft./d (Council of Governments 2011; Findley 2010; NJGS 2005).

3.0 Methods

The problem was analyzed in theory and site data was simplified and software-automated. The theory of flow systems was examined using the work of Tòth (1963). The site data was simplified in the conceptual model. The conceptual model was translated into MODFLOW settings and automated as the flow model in MODFLOW.

3.1 Theoretical Flow Systems

Geomorphology dictates the quality and quantity of groundwater flow. Again assuming Darcy's law held, Tòth (1963) related geomorphology to flow systems analytically and defined three classes of flow systems; local, intermediate and regional. The theory assumes a small drainage basin is symmetrical and the porous media is isotropic and homogeneous. The intensity, direction, length and depth of flow lines (flow systems), are represented in a two-dimensional flow net, controlled by two parameters 1) topographic relief and 2) basin slope (Tòth 1963).

3.1.1 Topographic Relief Intensifies Local Flow Systems

Increasing topographic relief increases the number and depth of local flow systems (Appendix F). Local flow systems (and local flow lines) are comparatively short and shallow. Their recharge and discharge points are more numerous. Intermediate and regional flow systems are long and deep. Their recharge and discharge points are more widely spaced on the surface, thus more sparse. Local flow systems have adjacent recharge and discharge zones which are not at the highest and lowest basin elevations, respectively. Intermediate and regional flow lines and systems bypass deep to local flow systems. Regional flow systems flow from the basin's maximum elevation to its minimum elevation.

Relief generates local flow systems at the expense of intermediate/regional flow systems. The higher the relief magnitude, the deeper the local flow systems penetrate. This permits less space for the longer, deeper intermediate/regional flow systems to pass below. Tòth (1963) used sine waves to represent topographic relief. Increasing the amplitude (magnitude of relief) of the sinusoids increased the depth of local flow lines and thickness of aquifer influenced by the local flow systems. When local flow lines penetrated deeply due to higher local relief and gradients, intermediate/regional flow decreased because some intermediate/regional flow lines discharged in the deepened sine troughs. Therefore increased relief magnitude correlated with increased flow from local flow systems which correlated with decreased flow from regional/intermediate flow systems.

3.1.2 Decreasing Basin Slope Intensifies Local Flow Systems

A negative correlation exists between basin slope and local relief; lowering the basin slope increases the prominence of local relief, which deepens local flow systems. The opposite is also true. Increasing basin slope dampens relief's effect, decreasing local flow system depth/thickness and increasing regional/intermediate flow systems thickness in the deep part of the porous media. For example, Tòth (1963) demonstrated that local flow lines penetrate to 3,400 feet below ground surface (fbgs) when the slope is 0.02 (Appendix F). If the slope is increased to 0.05, the deepest local flow lines shallow to 2,700 fbgs and intermediate/regional flow systems spread (thicken) to fill the void. Intermediate flow lines spread upward to 3,000 fbgs from 5,000 fbgs in Tòths illustration and regional flow lines (black) spread deeper, to 10,000 fbgs from 8,500 fbgs (Appendix G). The net effect is that the local flow systems thin and intermediate-regional flow systems take up a greater thickness of the porous media when basin slope is increased.

To summarize the theory, high basin slope and high local relief are in a sense antithetical in their impacts on groundwater flow distribution. High basin slope is related to increased deep groundwater flow and long flow paths (intermediate/regional flow systems). Increasing magnitude in local relief is associated with increased shallow groundwater flow and shorter flow paths (local flow systems). They are negatively correlated; increased groundwater flow in the upper porous media means decreased groundwater flow in the lower porous media, and vice versa. Increasing the sine amplitude increases the magnitude of relief, which increases recharge from local relief points. This increases the depth of local flow systems (the thickness of their share of the porous media) in the upper porous media. When basin slope increases, the intensity of recharge from distant intermediate/regional flow system recharges increases. Intermediate/regional flow systems spread upward and downward (thicken) in the bottom half of the porous media. The consequences are significant depending upon whether a) local flow systems or b) intermediate/regional flow systems supply a given well and whether surface contamination is present at a) nearby local relief maxima or b) distant regional elevation maxima (i.e. basin elevation maxima). Tòth only considered the impact of relief of constant frequency. In this domain, the frequency of relief features increases in the more terraced areas near CB-3. This translates to more relief points, more local recharges, more local flow systems and a larger recharging surface area. Contamination risk will increase because the probability that a recharge will underlie a contamination point source will increase.

3.2 The Conceptual Model

The conceptual model generalized the geologic features in the domain to make the problem practical for software simulation. The Canoe Brook well field is defined as a 10,667 ft. by 8,888 ft. area within the 2,300 acre EOWR. The domain thickness is 400 ft. (0 to 400 fasl). There are three model strata, top to bottom they are: 1) clay to sandy silt, 2) sand and gravel and 3) fractured bedrock. The three layers are represented in the model using hydraulic conductivities (K) typical of till (5 ft./d), sand/gravel (250 ft./d) and fractured bedrock (30 ft./d), respectively.

For mass balancing purposes, the groundwater flow is simplified as flow in and out through only the top surface. The sides and bottom are defined as no-flow boundaries. Flow in will occur through recharge areas. Flow out should occur through the primary surface discharge feature (the Canoe Brook) and the four wells. No-flow boundaries coincide with real geomorphologic features in the domain, groundwater divides. These are, 1) a high-elevation hummocky ridge forming the northern boundary, 2) a NW dipping Mesozoic bedrock layer (Preakness Basalt) forms the eastern boundary, 3) the western boundary of Canoe Brook is the eastern boundary of Slough Brook watershed, 4) the marshy approaches of Canoe Brook Reservoir #1 in the south and 5) the bedrock forming the x-y plane at elevation zero feet above sea level which ranges between 200 and 400 feet below ground surface (fbgs). The no-flow sides and the bottom and represented with hydraulic conductivity (K) set to zero.

Potential differences drive groundwater flow velocity and direction in accord with Darcy's law. Therefore it was required that the model be saturated with water to elevations defined by the topography. Constant hydraulic head values were set equal to the topographic surface elevations.

In MODFLOW Darcy's law is combined with the continuity equation to arrive at the flow equations. These assume that 1) flow is saturated and steady state, 2) conditions are isotropic and homogenous, 3) water's density is constant and 4) all sediment grains are fixed. Taylor's approximation allows the derivatives in Laplace to be represented with the finite difference equation and automated in MODFLOW to get estimates of hydraulic head, flow rates and flow directions at each cell in the model.

3.3 The Flow Model

3.3.1 Simulation Purpose

Groundwater simulation is a convenient, qualitative and quantitative analytical tool. Simulations can be done without water level data. Repeated site visits are not required. It is inexpensive and environmentally safe because no drilling is required. It facilitates the integration of site data. The process is flexible. Different scenarios can be tested. Rates of flow and hydraulic head can be quantified at any location in the subsurface and flow systems can be visualized. Discharge and recharge can be quantified.

The results can be interpreted for their impact in terms of contamination (Anderson et al. 2002).

3.3.2 MODFLOW Settings

The conceptual model was translated within MODFLOW using its settings and applied with the pre/post processor GMS 6.5. The domain was represented with a grid having dimensions 24 rows wide by 20 columns long by 10 layers deep. The result was a domain with 4,800 cells. The till confining layer was represented by model layers one through three with K equal to 5 ft./d. The sand and gravel aquifer layer was represented by model layers four through six with K equal to 250 ft./d. The fractured bedrock layer was represented with model layers seven through nine with K equal to 30 ft./d. No-flow boundaries were represented by layer 10 and all the outermost boundary cells with K equal to zero.

Flow into and out of the model was through the constant head configuration defined by the surface elevations (the topography). There was also flow out via well discharge. Well specifications (Appendix I), i.e. depths and pumping rates, for all four wells were based on consultants reports (Uhl and Associates 2007). Horizontal and vertical anisotropy were assumed. MODPATH forward tracking was used to simulate flow systems. Well capture zones and recharge zones are simulated using reverse tracking. MODPATH accounts only for bulk transport not dispersion, diffusion or chemical reactions.

3.3.3 Verification

Simulated flow systems and simulated recharge both verify the model. In a realistic simulation groundwater discharges to locations of actual discharge, a stream, or lake (Tòth 1963). Simulated flow lines in Figure 6 (High Slope Generates Deep, Long Flow Systems), shows high slope causes discharge to locations which match the site map locations for the Canoe Brook in Figure 3, the consultants site map. A long regional flow line also flows toward Canoe Brook Reservoir #1. Simulated aquifer recharge zones (Figure 7) also reflect the recharge zones in prior studies (Appendix C).

3.3.4 Model Calibration/Water Budget

The model is manually calibrated to recharge (Aquaveo 2011). In the MODFLOW water budget (Appendix J), inflow minus outflow is -159,099 ft^3/d. This is the volumetric rate of recharge required to maintain full saturation with well pumps on. Dividing this volumetric recharge rate by the domain surface area of 70,400,000 ft^2, the equivalent recharge rate (ft./d) is 2.26×10^{-3} ft./d. This is consistent with a range of recharge estimates for the region (5.8×10^{-4} ft./d to 7.3×10^{-3} ft./d) (Council of Governments 2011) making the model calibrated to recharge.

4.0 Results

4.1 Geomorphology Dictates Flow System Character

Well CB-1, CB3 and Taylor Lake are impacted by flow systems which reflect the local geomorphology; where overall slope is high and surface variability (relief) is low, intermediate/regional flow systems, deep groundwater flow and sparse recharges result. Where overall slope is low and relief is high, local flow systems, shallow groundwater flow and frequent recharges result. To illustrate this, the domain was divided into seven geomorphological subsets, "geomorphs". Each had a characteristic slope, relief and slope trend. Using Tòth's example, slope was defined as the total elevation change in a given vertical cross-section and calculated as the rise over run from the low elevation end to the high elevation end. Relief was defined as the presence of non-linear changes in elevation (akin to a sinusoidal pattern) and identified by irregular elevation contour line spacing. This is interpreted geomorphologically as hummocks and terraces. Depth was equal to the thickness of the shallow or low elevation end of the vertical cross-section. Slopes ranged from 0.0035 in the western basin to 0.0718 in the eastern basin. High slope correlated with low relief. The number of identifiable relief features (hummocks/terraces) ranged from zero in the high sloped geomorphs to three in low sloped geomorphs. High sloped Geomorph #7 which borders CB-1 and strongly influences that well has zero relief features. Low sloped Geomorph #2, where CB-3 resides, has three terraces. Figure 8 (Geomorphs) shows the domain divided into geomorphs based upon their unique geomorphologic features (overall slope vs. relief).

The high sloped areas send groundwater flowing long distances. In Figure 6 (High Basin Slope Generates Deep, Long Flow Systems), Geomorph #1 (slope = 0.014) sent groundwater flowing long distances. It generated regional and intermediate flow lines which undercut neighboring geomorphs. The flow direction was south and southeast as dictated by the trend in elevation contours. Some long flow lines discharge in the Canoe Brook, others flow south towards the Canoe Brook Reservoir #1 (at the southern boundary) and to Well CB-2. The long flow paths can have a positive impact if the Geomorph #1; the long flow path could help maintain pressure head in well CB-2 and supplement the water supply to help dilute chloride. But the impact could be negative if the surface of Geomorph #1 is contaminated; the long flow lines could also transport chloride to well CB-2, the Canoe Brook and Reservoir #1.

4.1.1 High Slopes/Deep Flow Systems Impact CB-1

Well CB-1 borders high sloped/low relief topography which strongly influences its hydraulics. CB-1 has a deeper water supply and is supplied by sparse and distant recharge zones. East of CB-1, Second Watchung Mountain dips west causing high slope (slope=0.01) along line F-F', seen in Figure 8 (Geomorphs) in plan view. As a result, intermediate flow systems penetrate deeply near CB-1. In Figure 9, deep intermediate flow lines are shown in side view dominating 30% of the total porous media thickness (2/3's of lower half of the porous media). At CB-3 the intermediate flow lines form a thin band which appears to laminate the base of a thick complex of local flow systems. Intermediate groundwater flow must mix with the overlying local flow groundwater flow. At CB-1, intermediate flow lines are separated from local flow lines by intervening stagnant zones.

The intermediate flow lines which discharge under well CB-1 have their recharges uphill of John F. Kennedy Parkway. Chloride-laden runoff from the highway can't flow uphill to these recharges. Several local flow lines recharge uphill of John F. Kennedy Parkway. They flow upward and discharge under the highway. This upward flow would inhibit the downward dispersion of chloride into the deeper flow system which supplies CB-1. Pressure head (and hydraulic head) is high at CB-1; blue contour lines of hydraulic head jut out above the ground surface in Figure 9.

Local flow lines at CB-1 are well-separated from the underlying intermediate flow lines; there is less potential for the mixing of local and intermediate flow systems. Even the local flow lines at CB-1 behave differently than those at CB-3. They are less penetrating than those in relief of higher magnitude; at CB-1 they only occupy the upper 42% of the total porous media thickness.

4.1.2 High Relief/Shallow Flow Systems Impact CB-3

In contrast to CB-1, CB-3 is impacted by high relief and low sloped geomorphology. In Figure 8 (Geomorphs) CB-3 resides in terrain with low overall slope (slope = 0.0053) yet high relief (three sets of elevation contours = three terraces). The result hydrogeologically is intense, penetrating groundwater flow in the upper porous media. The greater frequency of relief, more terraces, etc. produces more recharge start points covering a wider surface area.

In addition, there is no deep groundwater flow to dilute the increased recharge from the local surface. In Figure 10 (Shallow Flow Systems Impact CB-3, Side View, Line B-B') high relief results in four recharging surfaces; three of these recharge zones can be attributed to local flow systems (green) and one recharge zone is attributed to a shallow intermediate flow systems (blue). Well CB-3 is supplied by intense surface-associated local flow lines which occupy the upper 58% of the total porous media thickness. If local flow lines are close to shallow intermediate flow lines, the potential for chloride to disperse from local flow systems to the intermediate flow system will increase. The risk of contamination is high since John F. Kennedy Parkway follows the same path as line B-B'. No deep groundwater flow system exists to dilute the surface-associated groundwater supply; the bottom 42% of the porous material is stagnant.

4.1.3 High Relief Causes Recharge from Taylor Lake

Taylor Lake is a potential point source for CB-1. High relief in the Taylor Lake lakebed generates local flow systems and therefore recharge to the aquifer as shown in Figure 11 (Taylor Lake High Relief, Plan View with Line E-E'). Taylor Lake is shaded blue and bounded by John F. Kennedy Parkway in the north and therefore a potential chloride point source. Most groundwater is flowing north towards well CB-2 from a sinusoid in the southern lakebed. Groundwater flowing northward along line E-E' is also visible in side view (Figure 12 Taylor Lake High Relief, Side View, Line E-E'). The large amplitude relief feature (a hummock) in the southern lakebed of Taylor Lake is clearly recharging the aquifer. There is 100,251 ft^3/d of groundwater flowing downward into the underlying aquifer. In total, a groundwater exchange between Taylor Lake's and the aquifer occurs (Figure 13, Taylor Lake Flow Budget).

These flow systems were characterized by forward tracking, a non-statistical process, where MODFLOW maps a given recharge starting point to a discharge endpoint. Reverse tracking, in contrast, is a statistically-based routine for simulating capture zones and recharge zones. It maps a discharge endpoint to its highest probability recharge starting point, i.e., the surface location from where most of the groundwater is flowing (Aquaveo 2011). It was used to show that the southern lakebed is recharging the aquifer. A recharge (green) zone marked "R" for relief-driven, lies in the southern end of the lake in Figure 7. Reverse tracking is also used to simulate capture zones also.

4.2 Well Capture Zones and Signs of Risk

Unlike CB-1, the CB-3 capture zone structure and subsurface orientation indicate that it is most susceptible to chloride contamination from the surface. The capture zone features which can be inferred to relate to contamination vulnerability relative to point source locations include 1) the location of recharges and 2) the structure and subsurface orientation of the capture zone volume. Bulk transport to wells occurs quickly through recharges. Dispersion will occur more slowly and its rate will depend upon the structure and subsurface orientation of the capture zone volume.

4.2.1 CB-3 Capture Zone Recharges under Roads

The CB-3 capture zone has many recharge start points, in clusters, over a large area. Like a vessel with many holes, the capture zone lacks integrity. This is due to the integration of both local and intermediate flow systems into the CB-3 capture zone. Note that the upper surface of the CB-3 capture zone near the well is 76 fbgs (Figure 15). This is also the depth of the local flow system parallel to line B-B' near the well (Figure 10). The CB-1 capture zone, in contrast, is derived from only intermediate flow lines; the local flow systems have been factored out of that capture zone.

Unfortunately for CB-3, some recharges directly underlie or are downhill of John F. Kennedy Parkway, South Orange Avenue and Hobart Gap Road. As a result, chloride-laden runoff from precipitation can 1) flow directly into recharges, essentially drains, under the roadway or 2) wash into recharges downhill of the road. Therefore CB-3 provides the best opportunity for chloride to be transported in bulk with the groundwater flow along the hydraulic gradient to the well. Figure 14 (Capture Zone Projections on the Surface) shows the CB-3 and CB-1 capture zones projected on the surface (plan view) to illustrate their surface area and relationship to roads. Recharge start points are red. Discharge endpoints (blue) are in the well. Figure 15 (CB-3 Capture Zone Transection) shows the CB-3 capture zone transected (a longitudinal cross-section). Recharge start points span 5,000 ft. in three clusters, reflecting the three terraces present. John F. Kennedy Parkway is black. South Orange Avenue is yellow. Hobart Gap Road can be seen in plan view crossing overlying the northern most and highest elevation recharge start point. In contrast to CB-3, the CB-1 capture zone recharge start points are consolidated in a smaller area and uphill of John F. Kennedy Parkway. Figure 16 (CB-1 Capture Zone Transection) shows the more discreet organization of the CB-1 capture zone recharges. There is only one recharge start point cluster.

4.2.2 A Vulnerable Shallow Flowing Volume: The CB-3 Capture Zone

The structure and subsurface orientation of the CB-3 capture zone, relative to CB-1, makes it more susceptible to chloride contamination via the dispersion of chloride. Figure 17 illustrates the differences in their structures and subsurface positions. Dispersion could participate in contamination in two ways. Anywhere along the capture zones course, chloride could slowly disperse downward from the surface to the capture zone without the facilitation of any flow system. Or worse, dispersion might be facilitated by flow systems if chloride is dispersed from one flow system to another to end up in a capture zone, which will transport it to a well. Figure 17 (Capture Zone Structures and Subsurface Orientations in 3-D) shows the two capture zones in three dimensions. The

CB-3 capture is can be described as shallower, flatter, longer and greater in surface area. The risk that it would catch downward dispersing chloride from the surface must be greater. The CB-1 capture zone is deep, small and stout, which minimizes its surface area and thus minimizes its risk of exposure to dispersing chloride from the surface. The center of mass of the CB-3 capture zone is shallower than that of the CB-1 capture zone. The center mass of the capture zone volume was estimated using the mean particle depth calculated from the MODFOW particle elevations data sets for each capture zone. The mean particle depth was 88 fbgs for CB-3 and 94 fbgs for CB-1.

There is more roadway footage crossing the CB-3 capture zone than the CB-1 capture zone, note the surface projections of the two capture zones (Figure 14). Using the Adobe measuring tool, there was 3,553 ft. of John F. Kennedy Parkway and 641 ft. of South Orange Avenue traversing the CB-3 capture zones projection on the surface. The CB-1 capture zone surface projection was traversed by 334 ft. of John F. Kennedy Parkway.

The shallower, flatter, and longer CB-3 capture zone should catch more dispersing chloride than CB-1. Once chloride begins to disperse though saturated surface sediment, it will have a shorter distance to go before it reaches the CB-3 capture zone. The depth to the upper surface of the capture zone was also shallower for CB-3 than for CB-1. The depth (fbgs) to the upper surface of the CB-3 capture zone was 76 ft. (Figure 15, CB-3 Capture Zone Transection). The depth to the upper surface (fbgs) for most of the CB-1 capture zone was 98 ft. (Figure 16, CB-1 Capture Zone Transection).

The dispersion of chloride into the CB-3 capture zone would be easier than for the CB-1 capture zone due to high pressure head in CB-1 inferred from the simulation. The higher slopes and gradients result in the CB-1 capture zones faster groundwater flow. Faster flow means larger volumes of groundwater. Larger volumes mean higher pressure head. Higher pressure head would deflect downward dispersing chloride. For CB-3, the fastest transport occurs along a 5,111 ft. path (measured in the horizontal), which transports to the well in 1,048 days, equaling a 4.9 ft./d flow velocity. For CB-1, the fastest transport which occurs along an 888 ft. path (measured in the horizontal). It is 87 days, which equals a 10.2 ft./d flow velocity. The CB-1 capture zone has flow velocities more than twice as fast as CB-3 implying higher energy, which implies higher hydraulic head. As a result, along line F-F' at CB-1 (Figure 9), the hydraulic head contour lines (hydraulic head is the sum of elevation head and pressure head) are above the ground surface.

4.3 Aquifer Recharge above CB-3 Well Head

Recharge zones which mirror the locations of high relief points directly overlie the CB-3 wellhead. No recharge overlies the CB-1 wellhead. In Figure 7 (Simulated Aquifer Recharge Zones), green areas denoting recharge due to relief points, marked "R" for relief-driven, cover the well CB-3 location. The recharges above well CB-3 are not part of the CB-3 capture zone, nevertheless they are a dispersion risk since these flow systems may facilitate the mixing of chloride into the subsurface. Recharge near wells increases the contamination risk (Peckenham 2011).

5.0 Conclusion

Topography drives groundwater flow therefore Well CB-3 is at greater risk than well CB-1 due to its topography. Well CB-3 is in high relief terrain while CB-1 is in high sloped terrain. High magnitude relief and high basin slope have opposite hydraulic impacts on the distribution of groundwater flow. Points of relief generate recharge and local flow systems with short, surface-associated flow paths; this risk if the local recharging surface is contaminated. High basin slope generates the long and deep flow paths associated with recharge points at the distant, high elevation boundaries of the drainage basin. These regional flow systems, with their distant recharges, and long, high volume flow paths are an important water source to help dilute contaminants. They can increase pressure head to inhibit the influx of contaminated local flow systems. Using MODFLOW it was possible to estimate these differences in groundwater flow volume and direction by assuming all sediment is saturated to the topographic surface elevations and the volume of groundwater flow is directly proportional to potential energy differences on the surface (Darcy's law).

High relief topography produces surface-associated groundwater flow transmitted by local flow systems. The higher the magnitude of relief, the deeper the surface-associated groundwater flow penetrates. High basin slope, i.e. large changes in elevation over long horizontal distances, produces groundwater flow associated with the deep part of the aquifer described by Tòth (1963) as intermediate/regional flow systems. High magnitude relief, numerous relief points and low slope influence well CB-3 (highest chloride concentration) to produce its surface-associated groundwater supply. In contrast, high overall slope, less frequent and lower relief influences well CB-1 (lowest chloride concentration). These result in a groundwater supply associated with the deep aquifer for well CB-1. Differences in the source of water and hydraulic behavior impacting these wells concern us because chloride point sources (roads) exist at specific locations on the topographic surface.

Based upon MODFLOW, the low basin slope and high local relief terrain of CB-3 puts it at greater risk than CB-1 for both bulk transport and dispersion of chloride. Bulk transport occurs when chloride-laden surface water drains through capture zone recharges and flows to the well. Driven by potential energy, it is fast and can transport large quantities of chloride. MODFLOW shows the implications of low basin slope and high local relief; the CB-3 capture zone has less integrity. Recharges become scattered over a large surface area. In this case many recharges underlie or are downhill of John F. Kennedy Parkway, South Orange Avenue or Hobart Gap Road. In contrast, the well CB-1 capture zone has recharges consolidated in a small area uphill of John F. Kennedy Parkway and thus not in the path of runoff.

It can be inferred that the slower process of dispersion, which can mechanically mix chloride into flowing groundwater or wells, would occur more readily with CB-3 than CB-1. The CB-3 capture zone is a shallower, flatter and longer structure relative to CB-1; more likely to catch downward dispersing chloride. The surface projection of the CB-3 capture zone is traversed by 4,194 ft. of road as compared to 334 ft. for CB-1. Dispersion into the CB-3 should be less inhibited by fluid pressure since flow rates of are half that of CB-1. Additionally, simulated recharge zones indicate CB-3 is at risk. Aquifer recharge is occurring directly above well CB-3 itself. Geological factors favor faster dispersion to CB-3. The impervious layer is much thinner at CB-3 than at CB-1; it is one third (1:3) as thick at the well. Near CB-3 the impervious layer is only one sixtieth (1:60) as thick as it is near CB-1 according to USGS well logs.

CB-3's surface-associated groundwater supply is due the incorporation of local flow systems into its capture zone, where deep local flow systems mix with shallow intermediate flow systems and result in a capture zone with less integrity.

Tòth (1963) illustrated the relationship of surface-associated groundwater and local flow systems versus the depth-associated groundwater and regional flow systems, distant recharge zones and long flow paths. A negative correlation between local and regional flow systems can be inferred from Tòths work. Reduced regional flow system intensity means more intense and deeper local flow systems; it implies that the loss of distant regional recharge may have insidious effects. The vulnerability to contamination of high local relief areas such as near CB-3 may be compounded by the paving over of distant regional recharges in the high elevation areas of the watershed as this would reduce the saturation level i.e., the elevation head, there. The hydraulic effect should ultimately be equivalent to turning off the regional flow system and deepening local flow systems similar to Tòth's case of decreasing basin slope. Development over the slower recharge and weaker and shallower regional flow systems of the Livingston half-basin likely intensified the penetration of surface-associated local groundwater flow systems in the high relief, low-sloped areas which impact CB-3. The final blow to water quality came when roads were constructed precisely at the locations of the intensifying local recharges supplying well CB-3.

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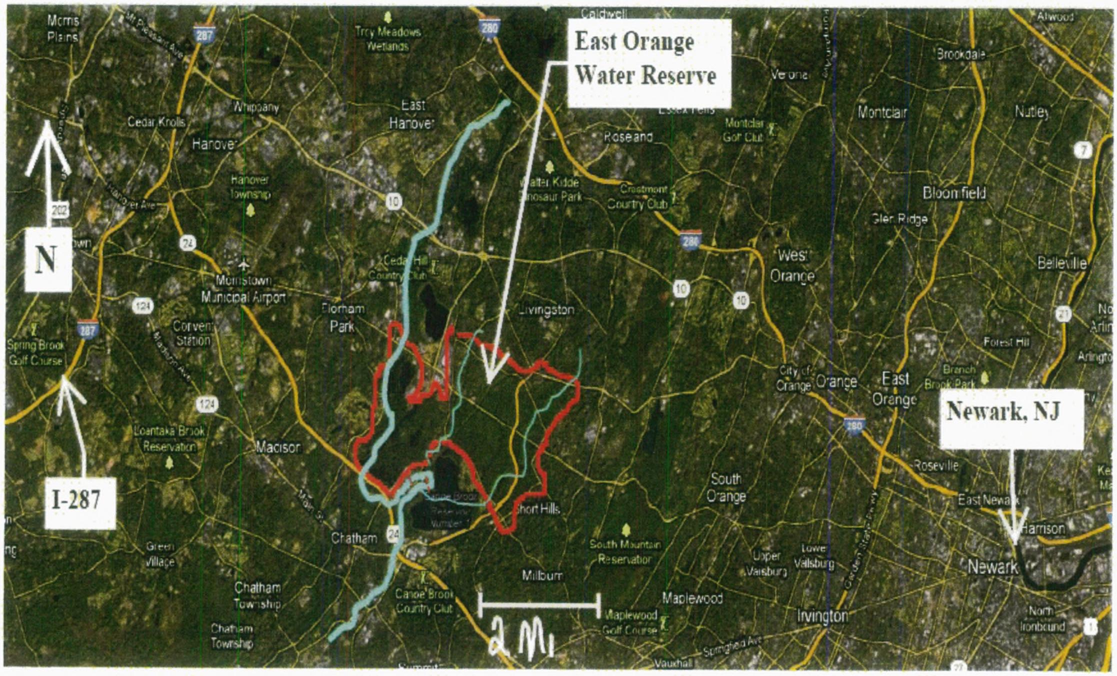


Figure 1. EOWR Regional Map. The East Orange Water Reserve (EOWR), red bounded area, is 10 miles west of Newark, New Jersey in the Newark basin (bounded by I-287 in the west). Aqua lines, west to east, are the Passaic River (thick line), Slough Brook and Canoe Brook, respectively. The Canoe Brook Basin is really two half-basins, the Livingston half-basin on the northwest side of the Canoe Brook and the Millburn-South Mountain half- basin on the opposite bank of the Canoe Brook.

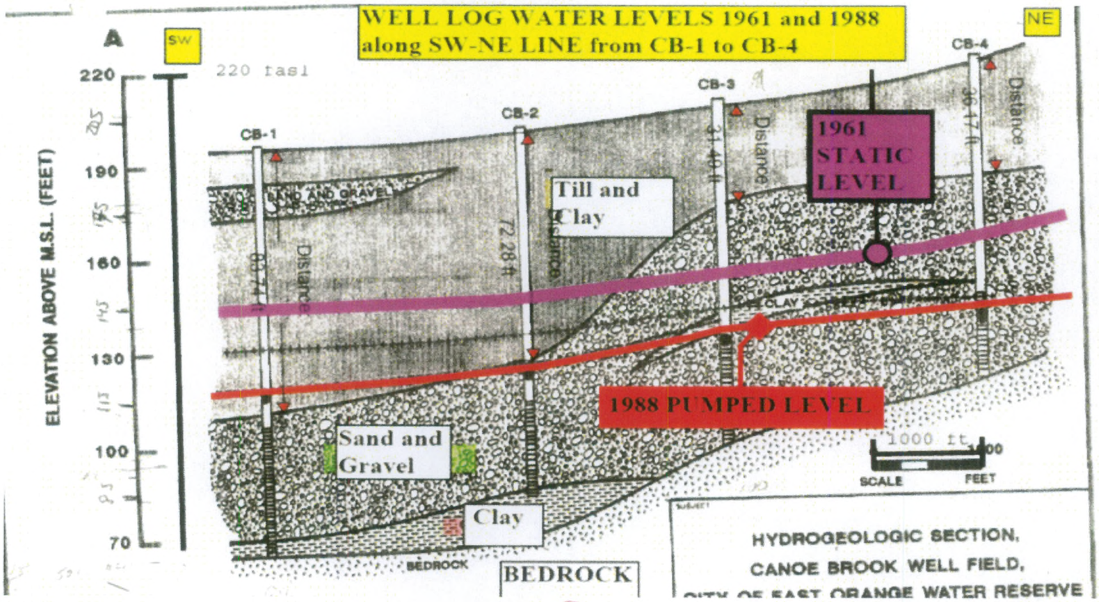


Figure 2. Consultants Well Log. Water levels have dropped below the confining layer. Even in 1961 CB-3 was below its confining layer. CB-1 is still under artesian conditions. The overlying till is thickest at CB-1 (83.74 ft thick) and CB-3 has the thinnest at CB-3, (31.49 ft thick) but the aquifer thickness at CB-1 thinner than at CB-3. The three hydrostratigraphic layers, till, sand plus gravel and bedrock are labeled.

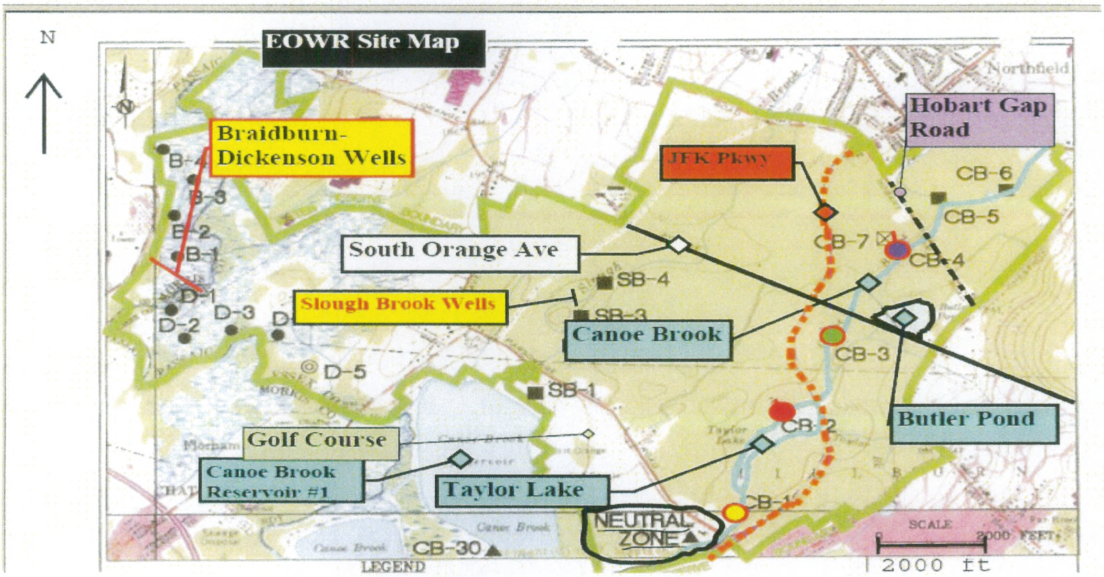


Figure 3. Consultants Site Map. The Canoe Brook wells CB-1, CB-2, CB-3 and CB-4 are along the west bank of the Canoe Brook. A USGS observation well, the Neutral Zone Well (black triangle in circle), is south of CB-1. The Roads South Orange Avenue, John F. Kennedy (JFK) Pkwy and Hobart Gap Road are labeled. Green (east) denotes woodland. The blue-white pattern in the west is wetlands.

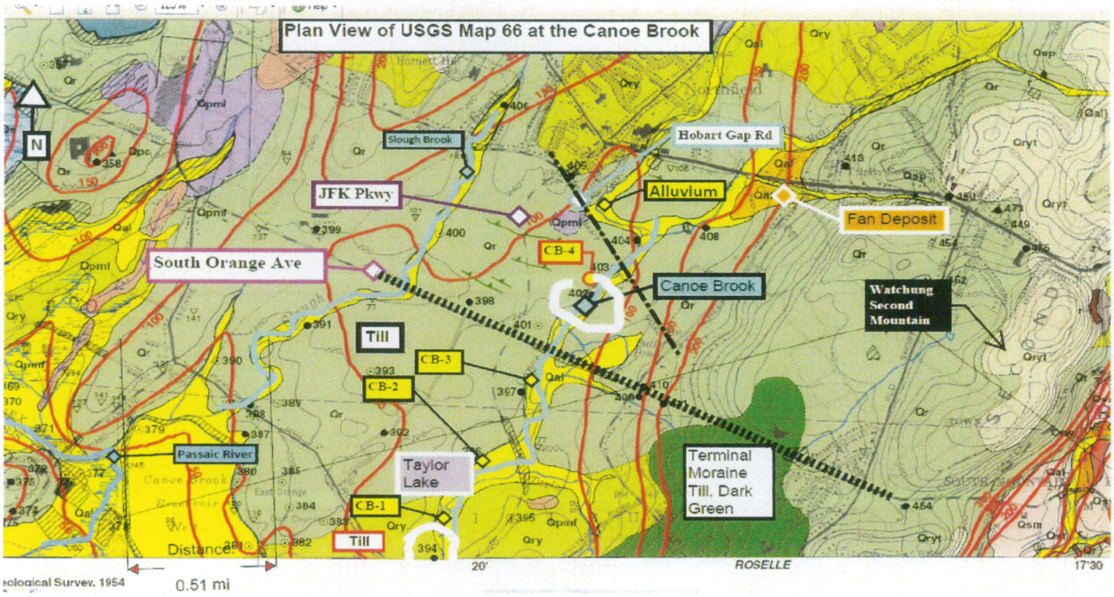
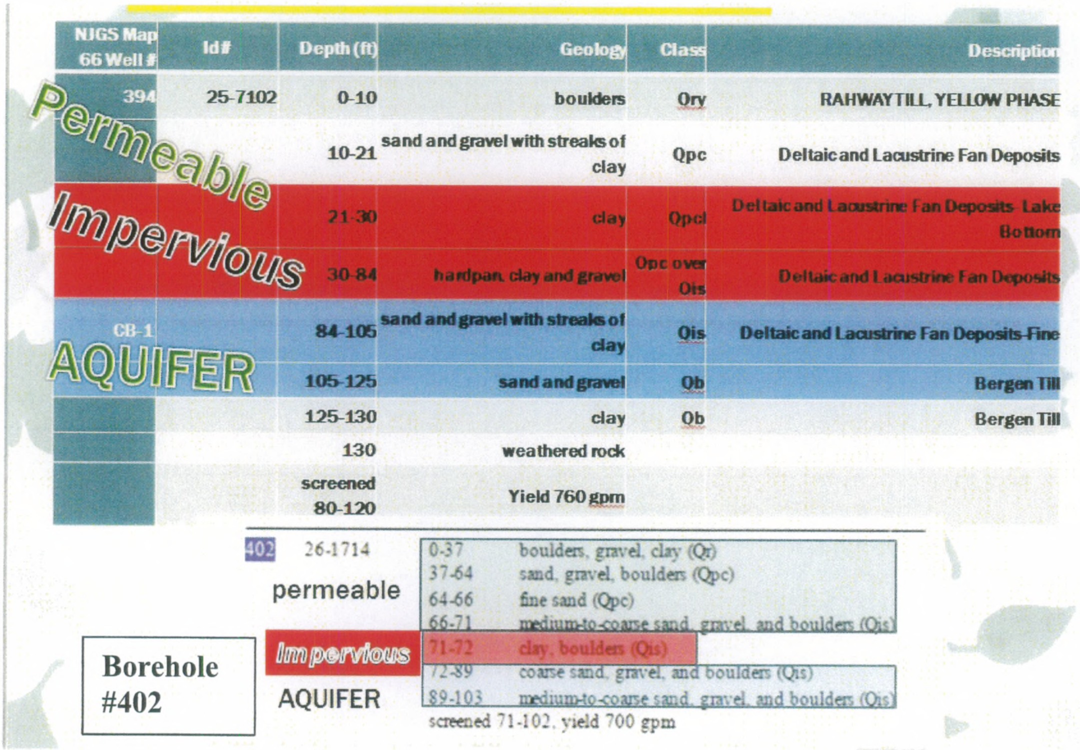


Figure 4. Surficial Geology, NJGS Map 66. The surface of the Canoe Brook well field is Quaternary till (fine grained). Along the Canoe Brook are cobble and boulder-rich alluvium and fan deposits. USGS boreholes are white-circled. Borehole #402 is uphill and near CB-3. Borehole #394 is near CB-1. Figure 5 shows differences in the confining layer thickness at these two borehole locations.



NJGS Map 66 Well #	Id#	Depth (ft)	Geology	Class	Descriptio
394	25-7102	0-10	boulders	Qry	RAHWAY TILL, YELLOW PHASE
		10-21	sand and gravel with streaks of clay	Qpc	Deltaic and Lacustrine Fan Deposits
		21-30	clay	Qpcl	Deltaic and Lacustrine Fan Deposits- Lake Bottom
		30-84	hardpan, clay and gravel	Qpc over Qis	Deltaic and Lacustrine Fan Deposits
CB-1		84-105	sand and gravel with streaks of clay	Qis	Deltaic and Lacustrine Fan Deposits-Fine
		105-125	sand and gravel	Qb	Bergen Till
		125-130	clay	Qb	Bergen Till
		130	weathered rock		
		screened 80-120	Yield 760 gpm		

402	26-1714	0-37	boulders, gravel, clay (Qr)
		37-64	sand, gravel, boulders (Qpc)
		64-66	fine sand (Qpc)
		66-71	medium-to-coarse sand, gravel, and boulders (Qis)
		71-72	clay, boulders (Qis)
		72-89	coarse sand, gravel, and boulders (Qis)
		89-103	medium-to-coarse sand, gravel, and boulders (Qis)

screened 71-102, yield 700 gpm

Figure 5. Two USGS Borehole Logs (#394 and #402). Borehole #394 is near CB-1. There are 63 feet of relatively impervious clay and hardpan (red). . Borehole #402 near CB-3 has just one foot of clay (pale red). The blue colored layers are permeable.

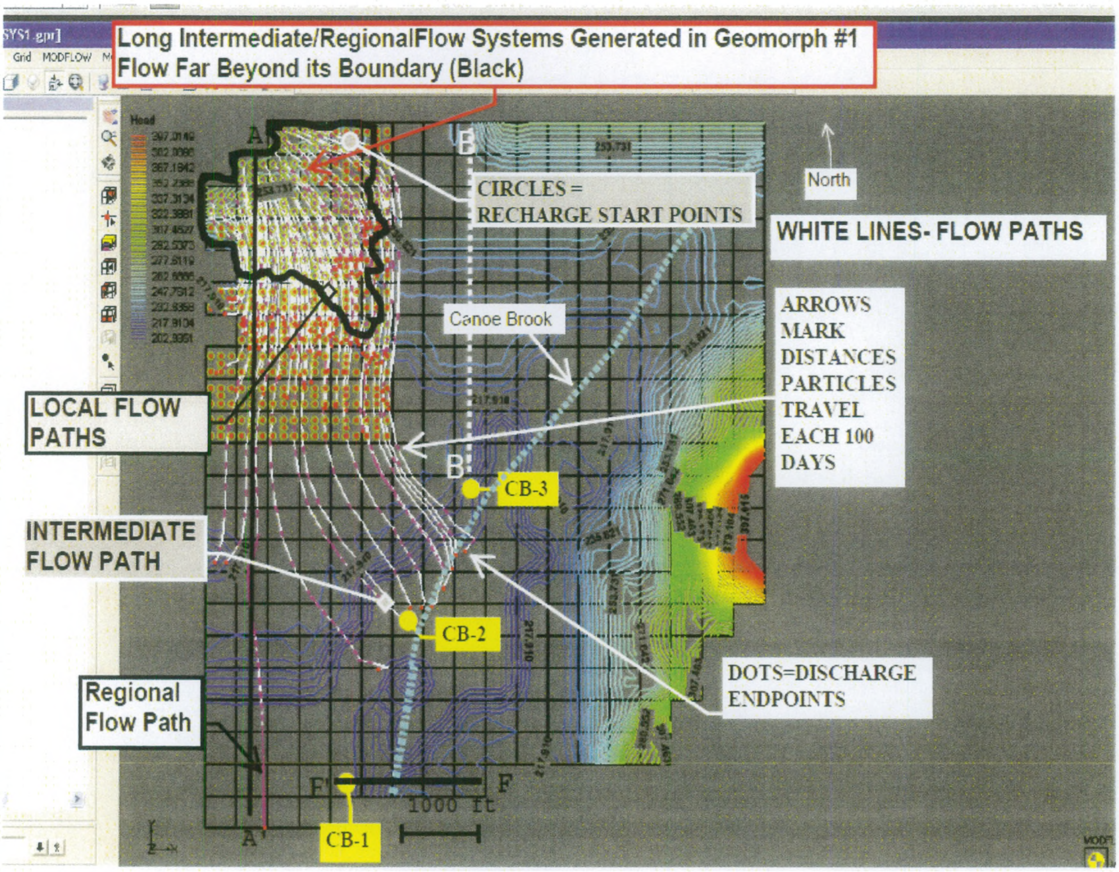


Figure 6. High Slope Generates Deep, Long Flow Systems. The high sloped topography at Geomorph #1 (black bounded area) sends long intermediate and regional flow lines under neighboring geomorphs to discharge at the Canoe Brook , CB-2 and toward s Canoe Brook Reservoir #1 south of the EOWR.

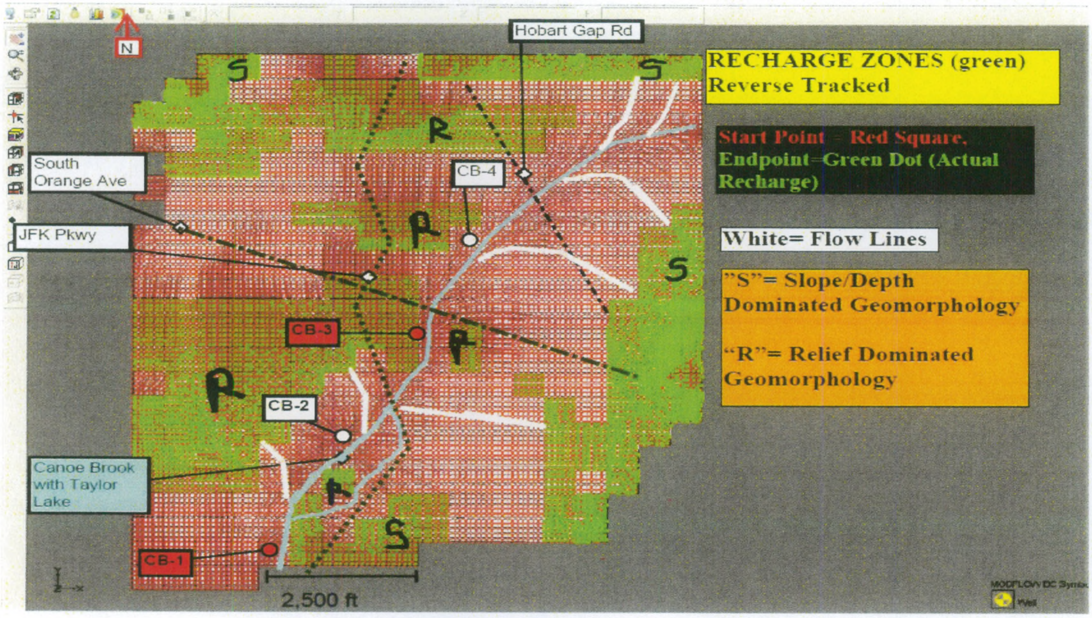


Figure 7. Simulated Aquifer Recharge. "R" denotes relief-driven recharge. "S" denotes slope-driven. Greener color means more intense recharge. " S" zones are recharging faster than "R" zones. The recharge zones reflect slope and relief in the topography. Flow lines are white but too numerous to be discerned. Some have been thickened in white to show how they converge on the Canoe Brook. Recharge occurs atop CB-3. Taylor Lake is recharging. All roads traverse recharge zones.

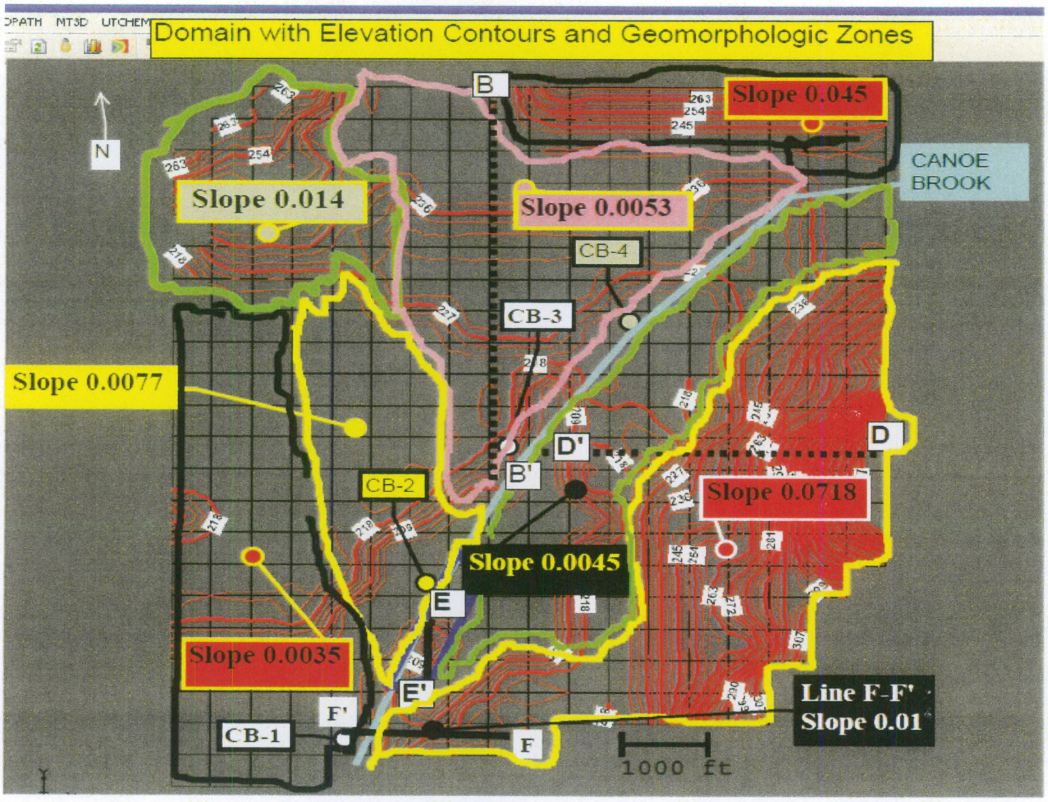


Figure 8. Geomorphs. The seven zones ("Geomorphs") are based on slope and relief differences. Geomorph #1 (slope=0.014), Geomorph #3 (slope=0.045) and Geomorph #7 (slope=0.0718) are high slope, deeper at one end with few relief features. Geomorph #7 is high sloped along line F-F' towards CB-1. Geomorph #2 (slope=0.0053), Geomorph #4 (slope=0.0035), Geomorph #5 (slope= 0.0077) and Geomorph #6 (slope= 0.0045) are lower slope, shallower with high relief (terraces/hummocks).

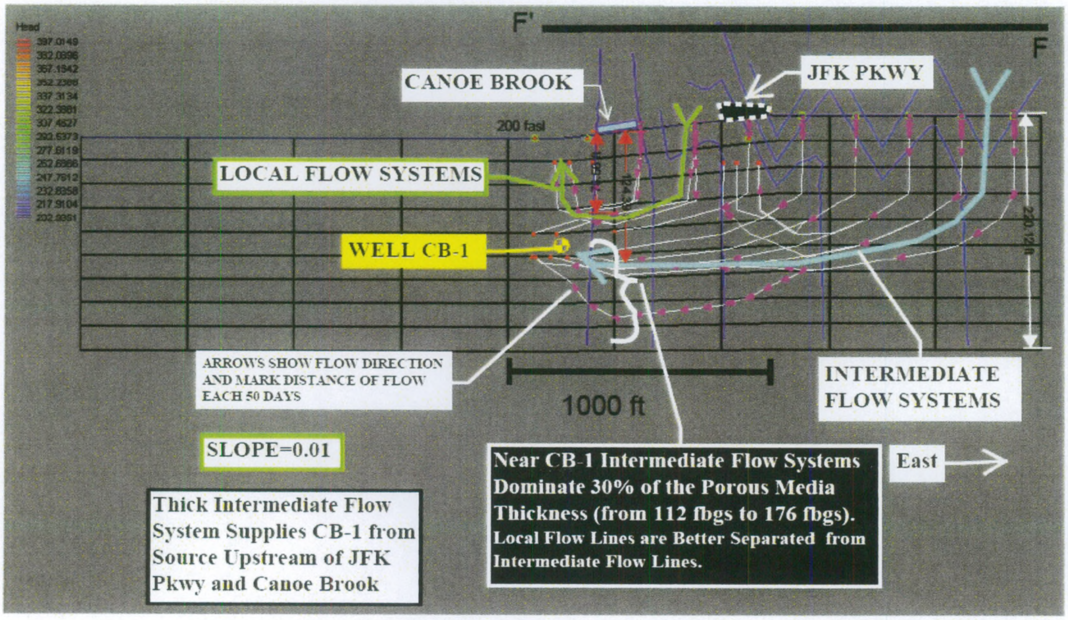
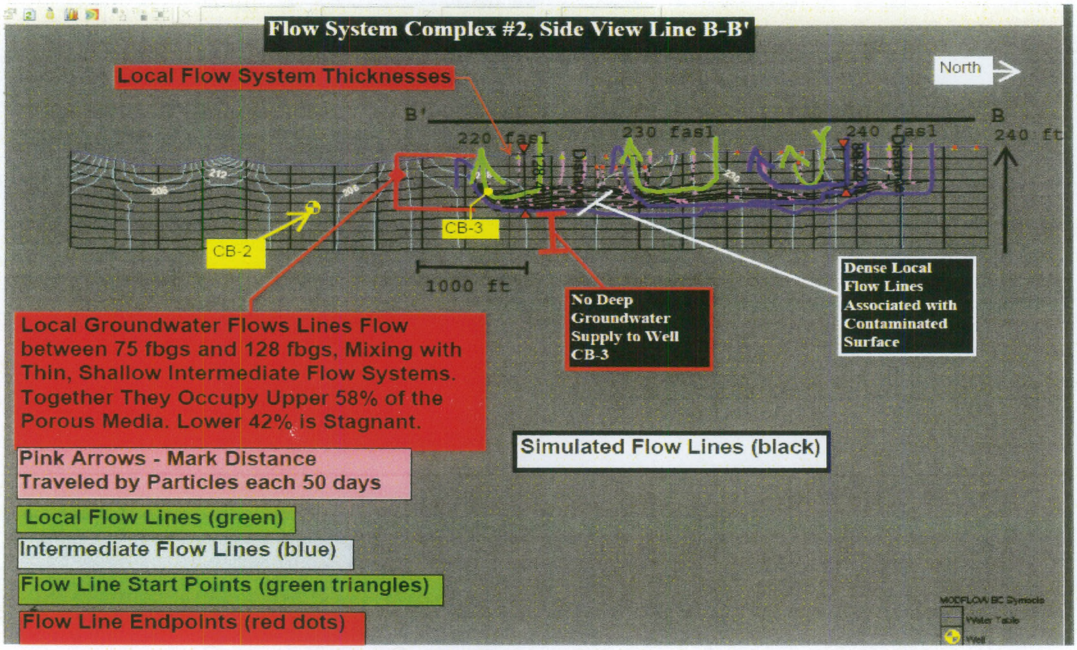


Figure 9. Deep Flow Systems Impact CB-1, Side View, Line F-F'. Well CB-1 is amid intense intermediate flow systems (aqua) which dominate 30% of the total porous media, from 112 fbgs to 176 fbgs. Local flow systems (green) near CB-1 only penetrate to a maximum depth of 88 fbgs (42% of the upper porous media thickness). Intervening stagnant areas separate local flow lines from intermediate flow lines unlike at CB-3. The slope is high (0.01) Relief is low. Recharges of the deep flow system are uphill of John F. Kennedy Parkway. Runoff from the highway can't flow uphill to enter recharges.



Flow System Complex #2, Side View Line B-B'

Local Flow System Thicknesses

Local Groundwater Flows Lines Flow between 75 fbgs and 128 fbgs, Mixing with Thin, Shallow Intermediate Flow Systems. Together They Occupy Upper 58% of the Porous Media. Lower 42% is Stagnant.

No Deep Groundwater Supply to Well CB-3

Dense Local Flow Lines Associated with Contaminated Surface

Simulated Flow Lines (black)

Pink Arrows - Mark Distance Traveled by Particles each 50 days

Local Flow Lines (green)

Intermediate Flow Lines (blue)

Flow Line Start Points (green triangles)

Flow Line Endpoints (red dots)

Figure 10. Shallow Flow Systems Impact CB-3, Side View, Line B-B'. Well CB-3 is amid intense surface-influenced local flow systems (highlighted green) which mix with a shallow intermediate flow system (highlighted blue). The Slope is low (0.0053) and the relief is high (four terraces). Recharges are overlain by John F. Kennedy Parkway (same location as line B-B'). The mixed flow systems occupy the upper 58% of the porous media. There is no deep groundwater flow system to dilute or replace the surface-associated groundwater supply. The intermediate flow system has its recharge zone on the upper terrace.

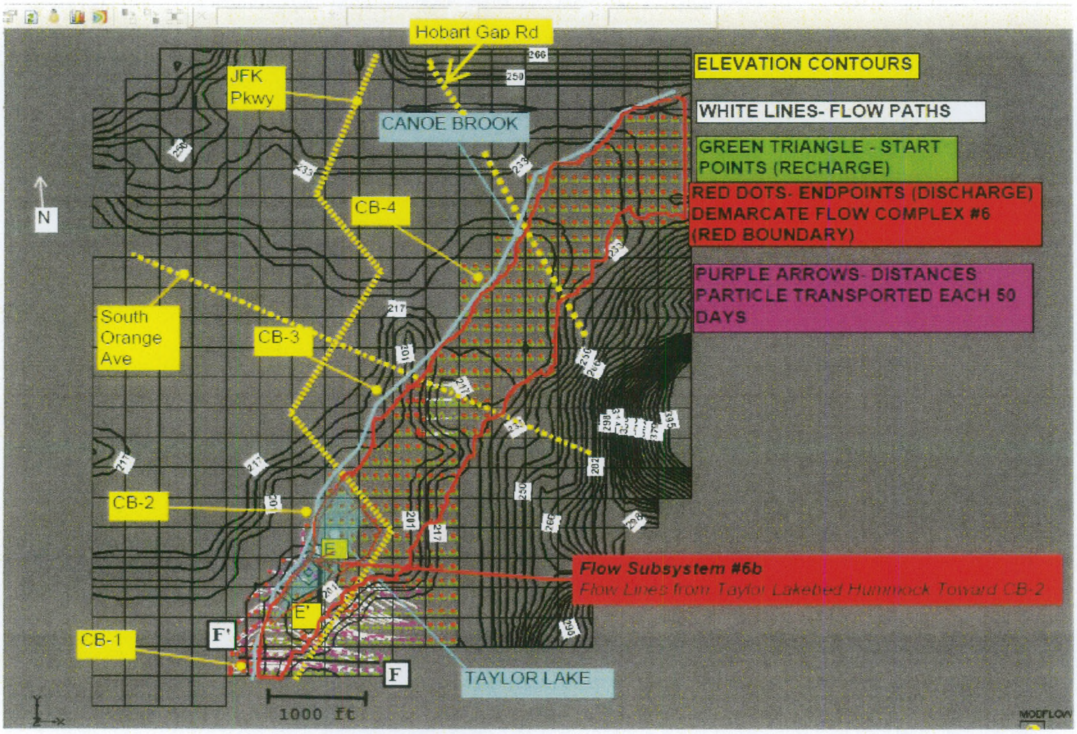


Figure 11. Taylor Lake High Relief, Plan View with Line E-E. Elevation contours show a sinusoidal relief point in southern Taylor Lake (shaded blue). Groundwater flows north from it along line E-E, away from CB-1 and towards CB-2. Taylor Lake, bounded by roads, is a potential chloride point source. Line E-E' is shown in side view in Figure 12.

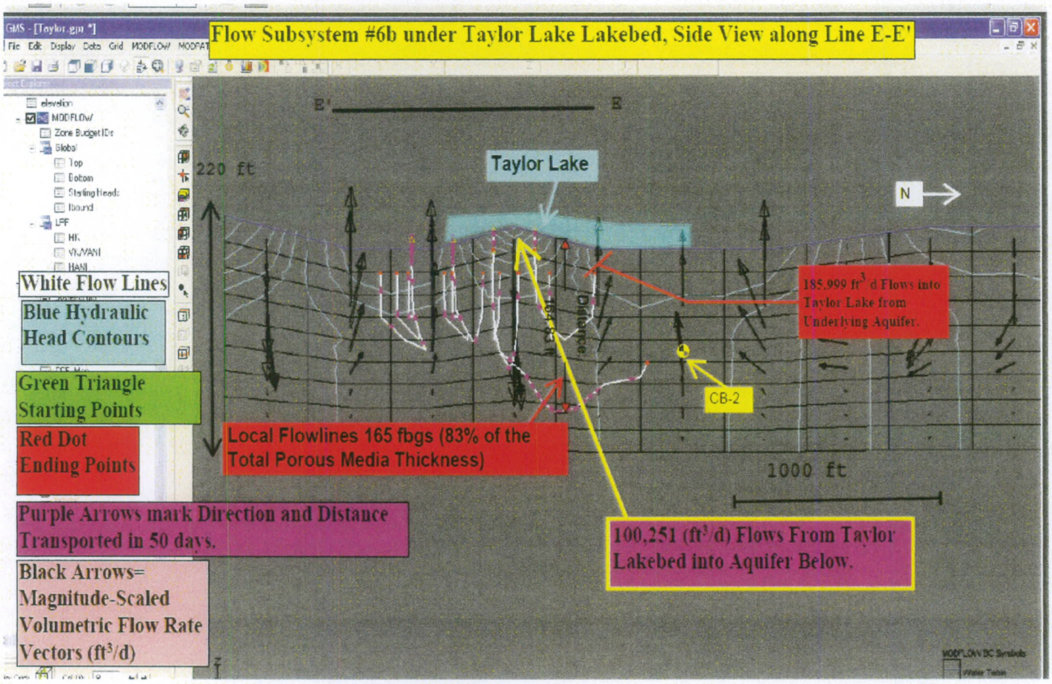
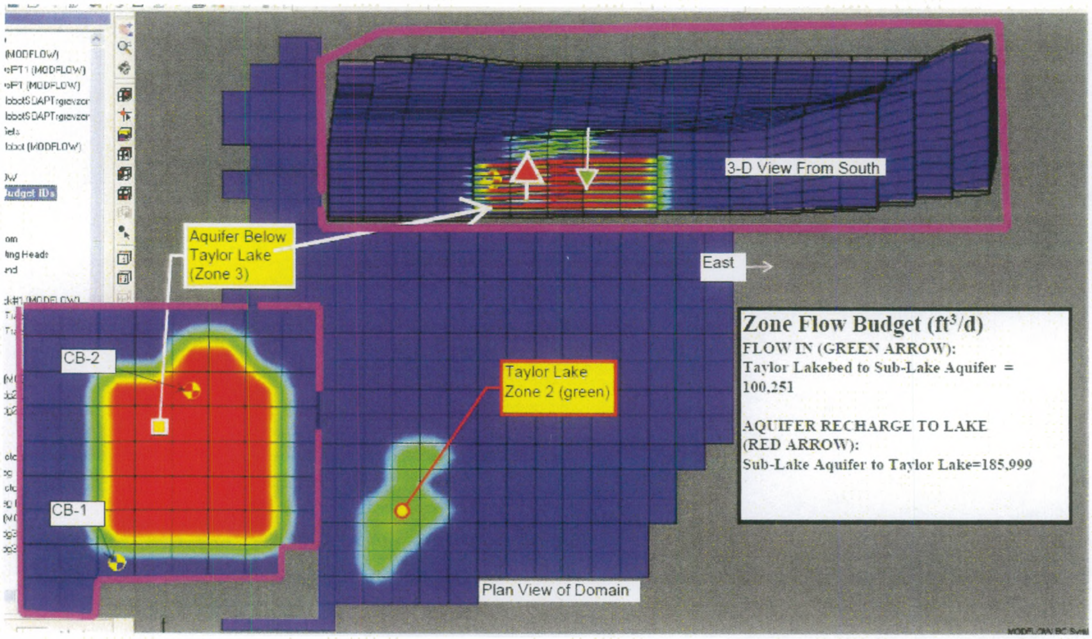


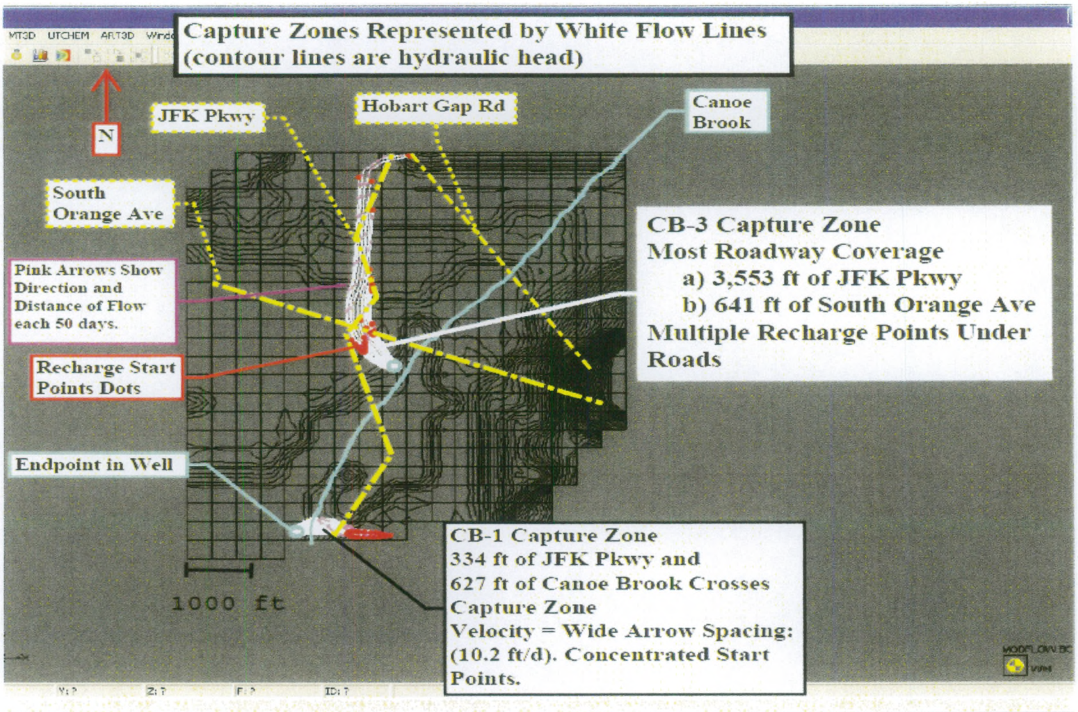
Figure 12. Taylor Lake High Relief, Side View, Line E-E'. A large amplitude relief feature (a hummock) occurs in the southern lakebed. Recharge occurs over the hummock. A deeply penetrating local flow line flows towards CB-2. Not along line E-E', CB-1 is 1,500 ft south by southwest of the crest of the relief point, not in the recharges path of flow.



Zone Flow Budget (ft^3/d)
FLOW IN (GREEN ARROW):
Taylor Lakebed to Sub-Lake Aquifer =
100,251

AQUIFER RECHARGE TO LAKE
(RED ARROW):
Sub-Lake Aquifer to Taylor Lake=185,999

Figure 13. Taylor Lake Flow Budget. Southern Taylor Lake recharges the aquifer with 100,251 ft^3/d of groundwater. It flows into the underlying Zone 3 aquifer parcel (2,220 ft by 2220 ft by 131 ft) . In total, there is an exchange of groundwater between Taylor Lake lakebed (Zone 2) and the aquifer beneath it (Zone 3). Ultimately a net 85,748 ft^3/d flows into Taylor Lake as baseflow from the aquifer.



Capture Zones Represented by White Flow Lines (contour lines are hydraulic head)

CB-3 Capture Zone
Most Roadway Coverage
a) 3,553 ft of JFK Pkwy
b) 641 ft of South Orange Ave
Multiple Recharge Points Under Roads

CB-1 Capture Zone
334 ft of JFK Pkwy and
627 ft of Canoe Brook Crosses Capture Zone
Velocity = Wide Arrow Spacing: (10.2 ft/d). Concentrated Start Points.

Figure 14. Capture Zone Projections on Surface. For CB-3, recharges undelie roads and more road crosses its capture zone. Many CB-3 capture zone recharges are downhill of roads. The CB-3 capture zone surface projection, measured with Adobe measuring tool, underlies 3,553 ft of John F. Kennedy Parkway, 641 ft of South Orange Avenue and a short span of Hobart Gap Rd (highest evevation point). The CB-1 capture zone recharges are uphill of the 334 ft of John F. Kennedy Parkway which crosses capture zone. None underlie roads.

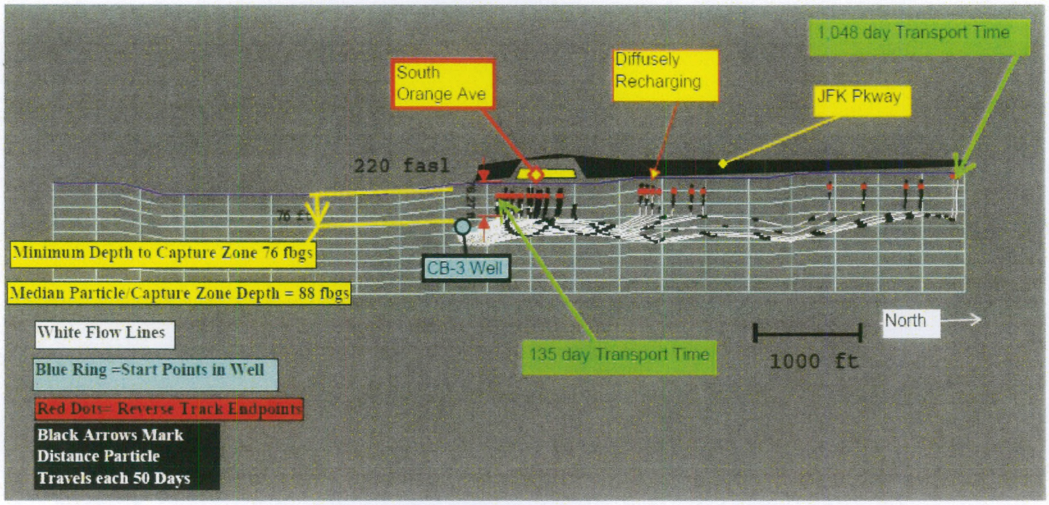


Figure 15. CB-3 Capture Zone Transection. The longitudinal cross-section shows recharges under roads and capture zone shallowness. Recharges are clustered at high elevation points on three terraces. This lack of a discreet recharge zone results in the capture zone having less integrity. The center of mass for the volume is 88 fbgs, the most shallow of all capture zone volumes. The near CB-3 the capture zones upper surface is 76 ft below ground surface (fbgs), the shallowest capture zone.

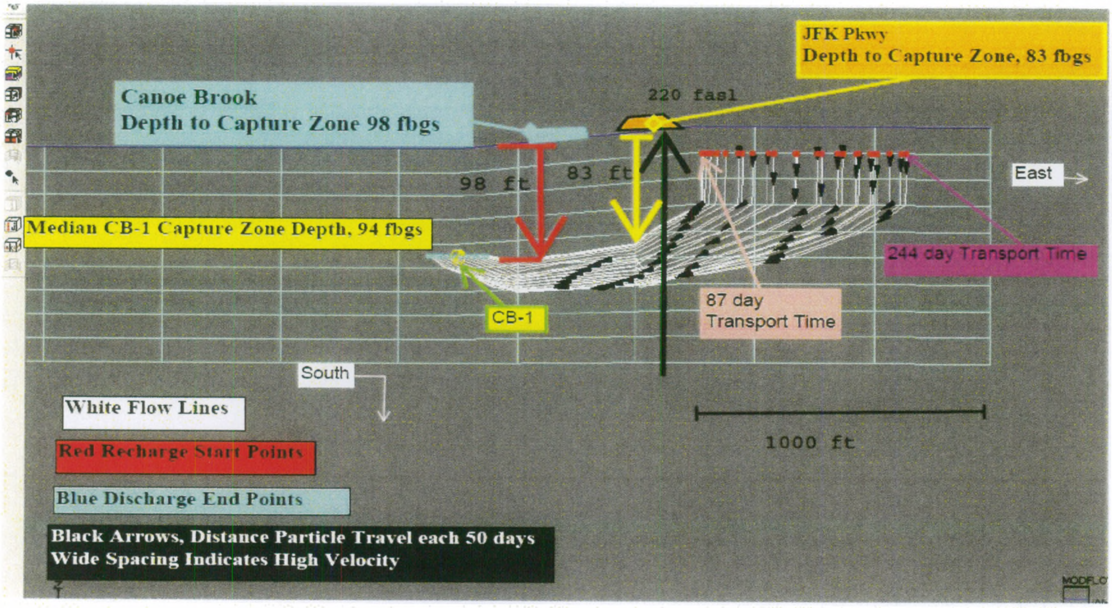


Figure 16. CB-1 Capture Zone East-West Transection. Recharge locations and the capture zone structure are less vulnerable than for CB-3. Roads are downhill of recharges. Recharges are consolidated in one zone. The capture zone is deeper. The center of mass for the capture zone volume occurs 94 fbgs. John F Kennedy (JFK) Pkwy is 83 ft above the capture zone. The average capture zone velocity is higher, 10.2 ft/d versus 4.9 ft/ for CB-3 so it likely experiences greater fluid pressure. The average depth to the upper surface (fbgs) for the CB-1 capture zone was 98 fbgs.

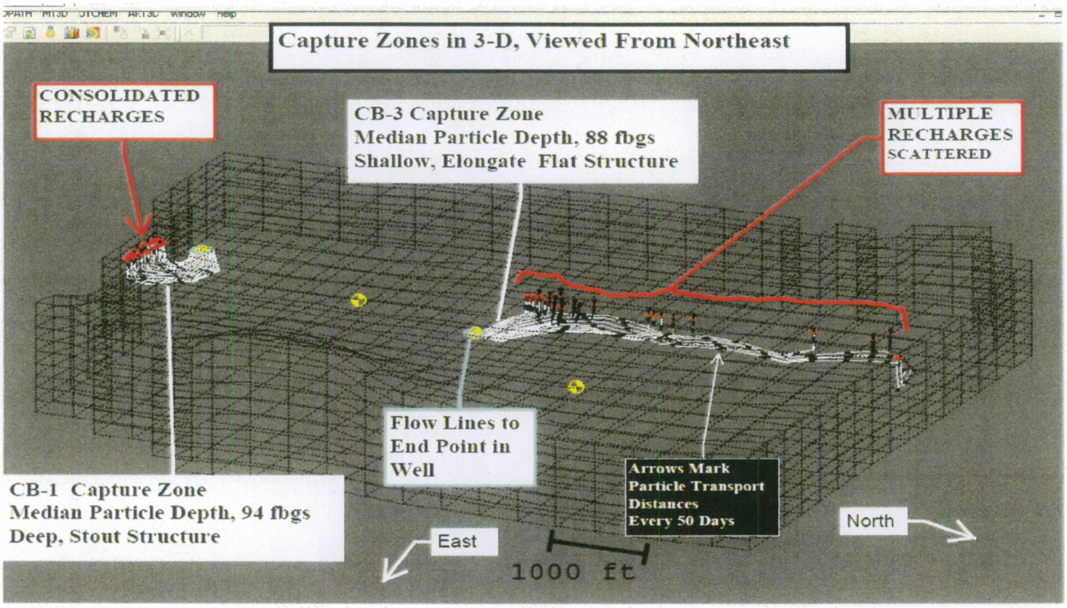
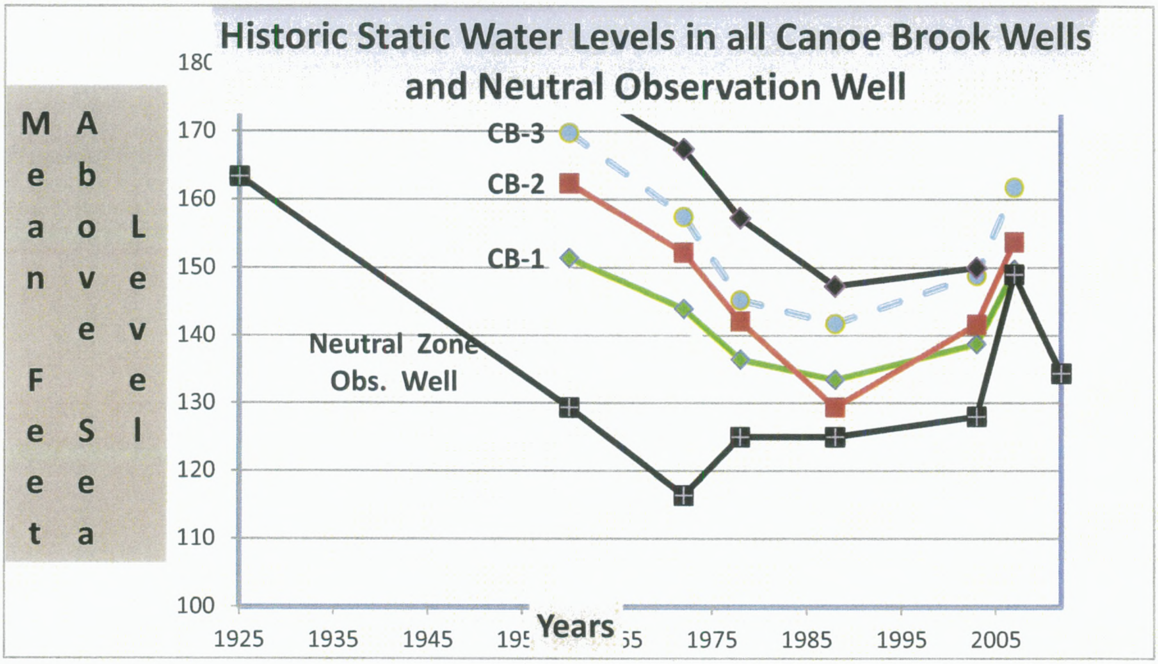


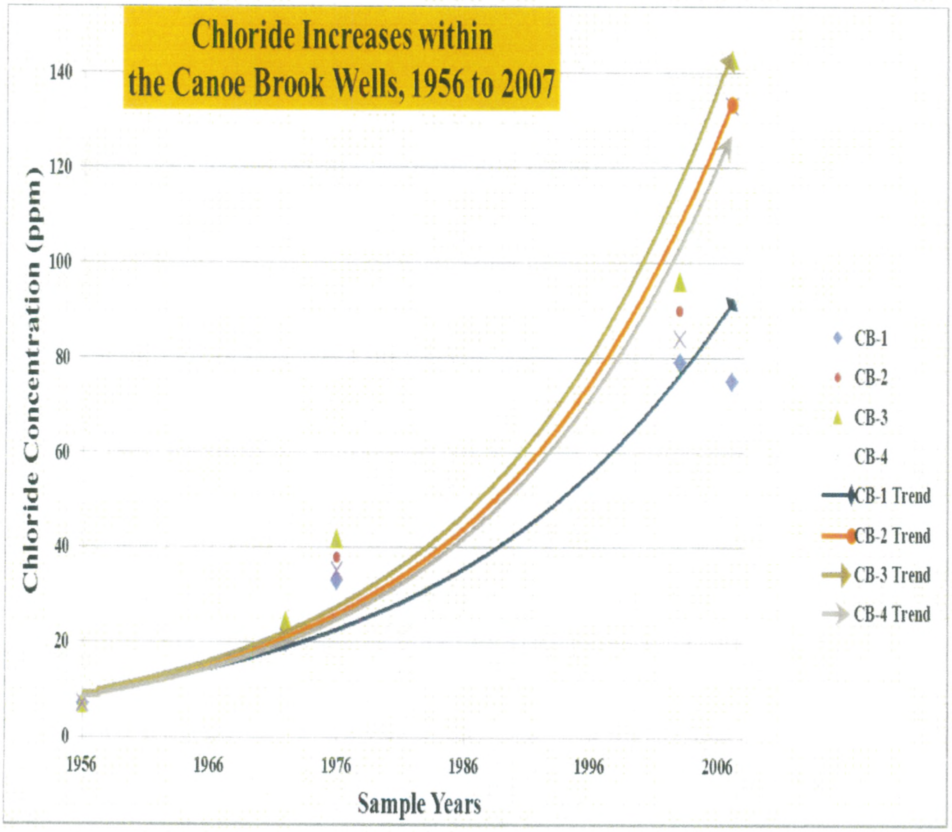
Figure 17. Capture Zone Structures and Subsurface Orientations in 3-D. The CB-3 capture size, shape and orientation are more prone to contamination from the surface. Relative to CB-1, CB-3 is large, shallow and flat , which maximizes the surface area, increasing the risk it will catch downward dispersing chloride from the surface. The CB-1 capture zone is deep and stout which minimizes the surface area and minimizes the ease of chloride entry via disersion of from the surface.

Appendix A



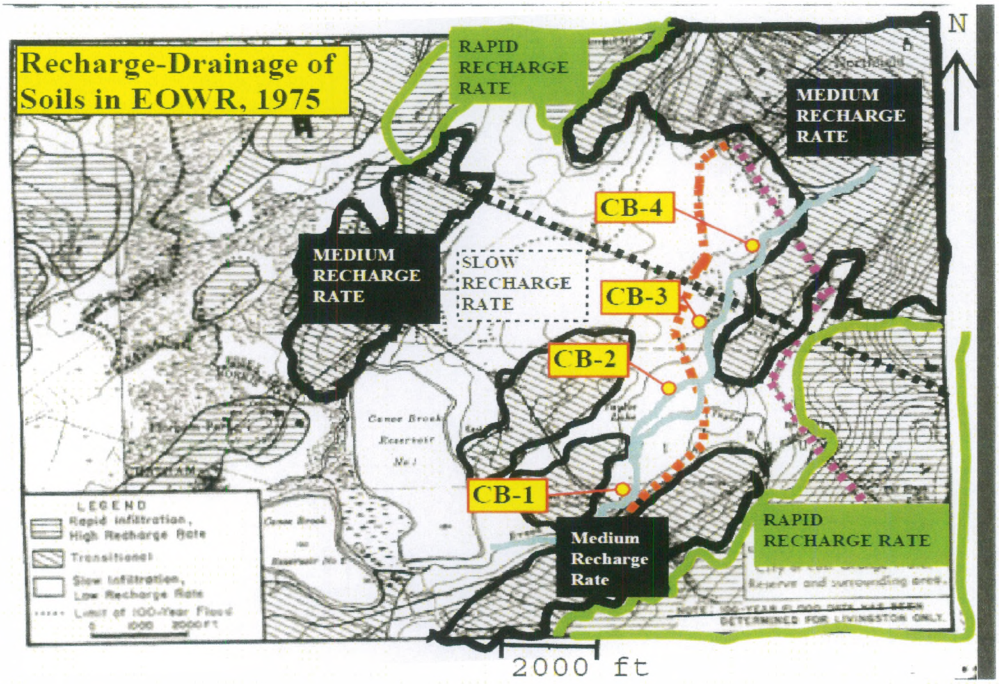
Canoe Brook Well Water Level Decline and Recovery. Water levels declined from 1961 to 1975. By roughly 1986 non-pumping water levels in Canoe Brook wells began to recover.

Appendix B



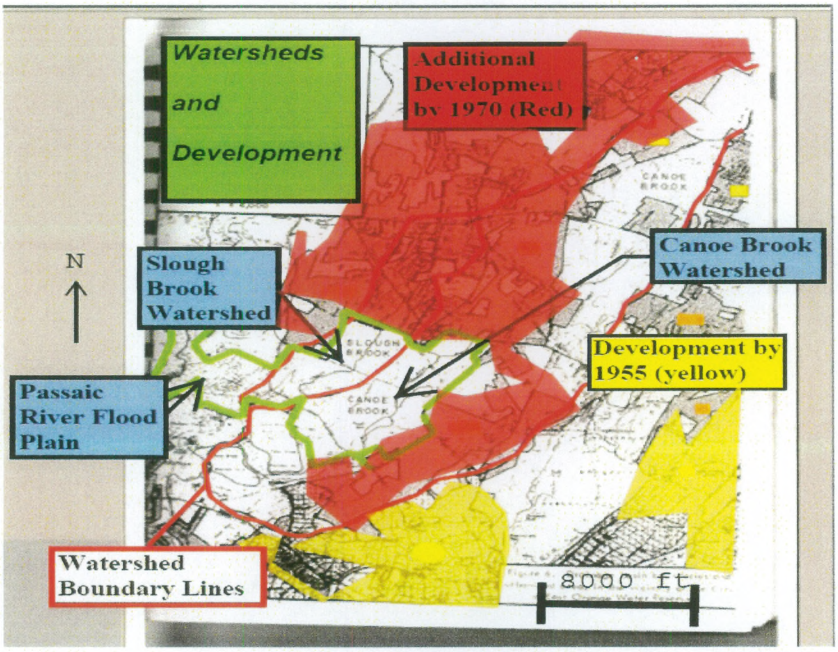
Chloride in the Canoe Brook Wells, 1956-2007. The highest concentrations and fastest rising chloride are in CB-3, followed by CB-2, followed by CB-4 and finally CB-1.

Appendix C



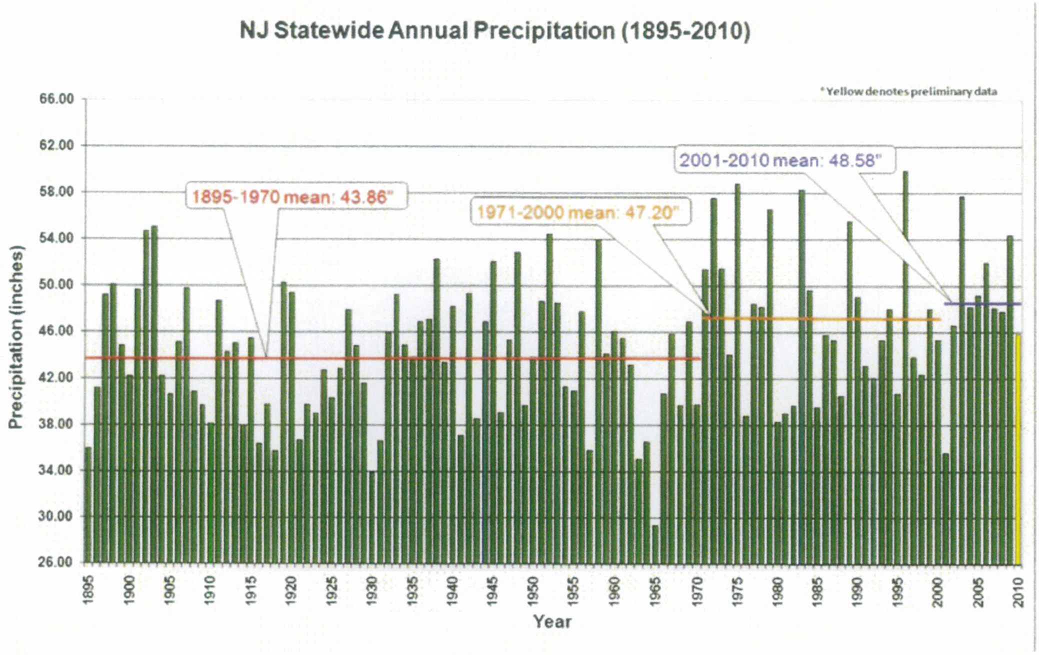
Recharge in the EOWR, 1975. The southeast and north central surfaces of the Canoe Brook well field drained/recharged most rapidly (green bounded). Medium recharge characteristics (black bounded) existed in the northeast, south and central areas including west of the Canoe Brook. Central areas above wells were low infiltration surfaces (white areas).

Appendix D



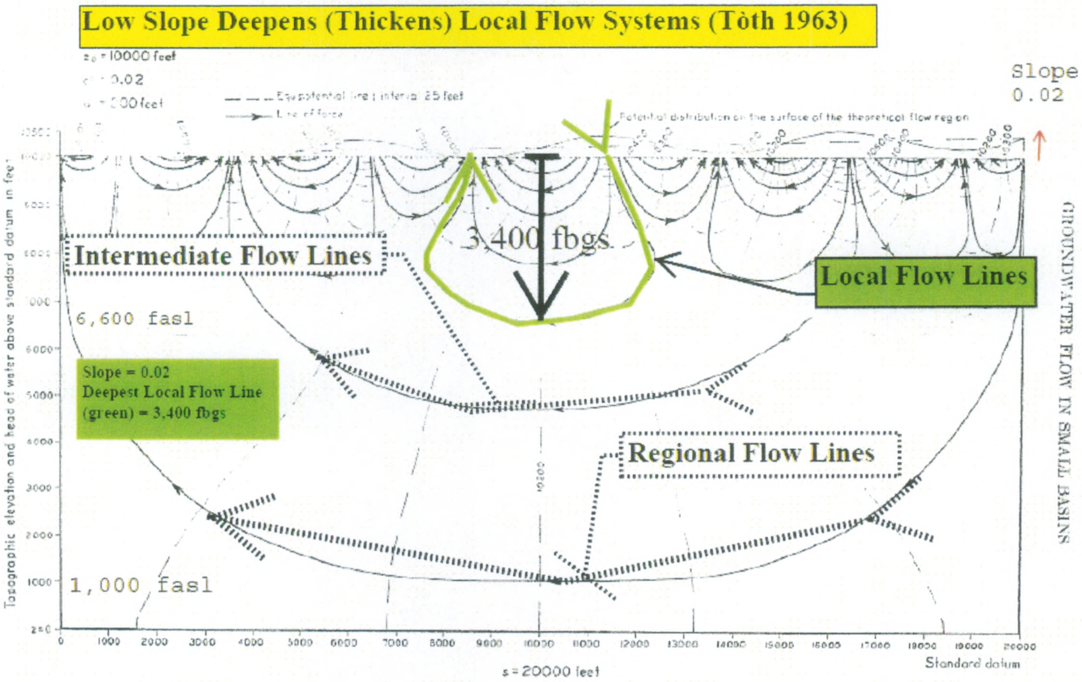
Watersheds and Development in the EOWR. The EOWR includes the Canoe Brook watershed, the Slough Brook watershed and the Passaic River flood plain. Development spread from the southeast in 1955 (yellow) to surround the northern and eastern boundaries by 1970 (red).

Appendix E



New Jerseys Climate has been getting wetter for the last 100 years.

Appendix F



Tòth (1963) demonstrated that local flow lines (green) penetrate to 3,400 feet below ground surface (fbgs) when the slope is 0.02 in the low slope case.

Appendix G

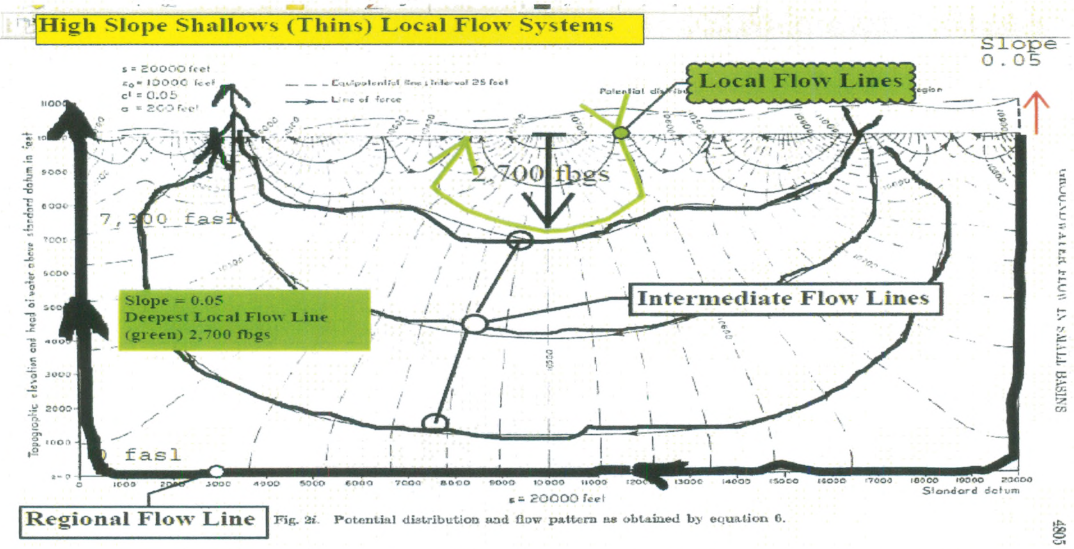
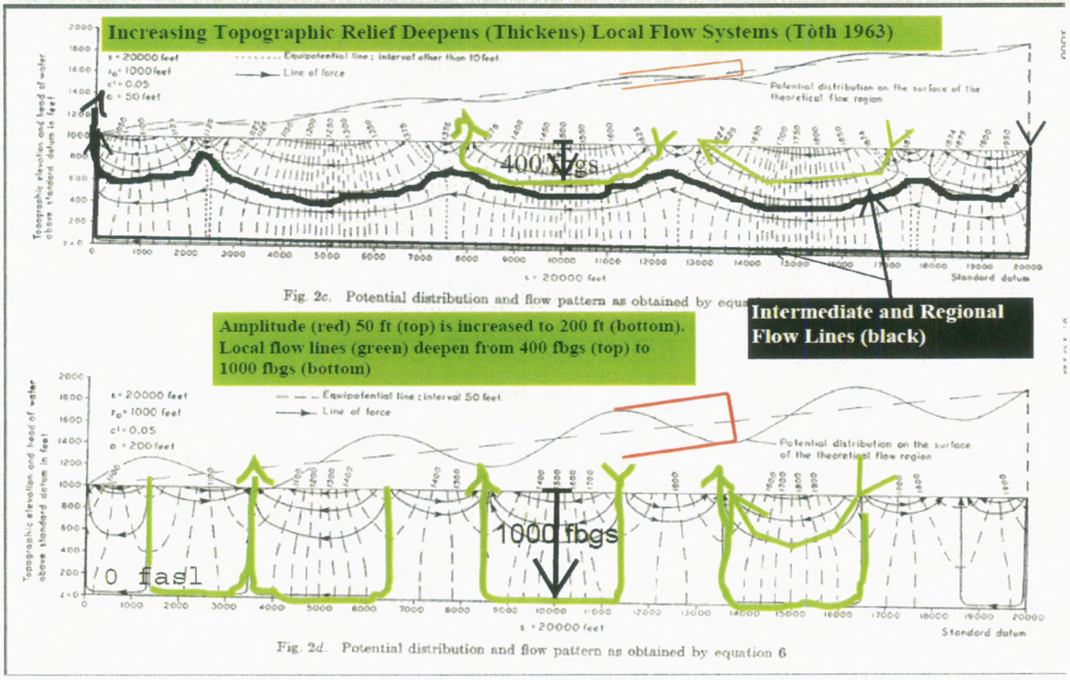


Fig. 2i. Potential distribution and flow pattern as obtained by equation 6.

In Tòths high basin slope case, regional flow lines (thick black line) flow deeper, to 10,000 fbgs from 8,500 fbgs (Appendix F). The net effect is that the local flow systems (green) shallow to 2,700 fbgs and intermediate-regional flow systems take up a greater thickness of the porous media when basin slope is increased.

Appendix H



Increasing Topographic Relief Deepens (Thickens) Local Flow Systems (Tòth 1963)

Intermediate and Regional Flow Lines (black)

Amplitude (red) 50 ft (top) is increased to 200 ft (bottom). Local flow lines (green) deepen from 400 fbgs (top) to 1000 fbgs (bottom)

Fig. 2c. Potential distribution and flow pattern as obtained by equ

Fig. 2d. Potential distribution and flow pattern as obtained by equation 6

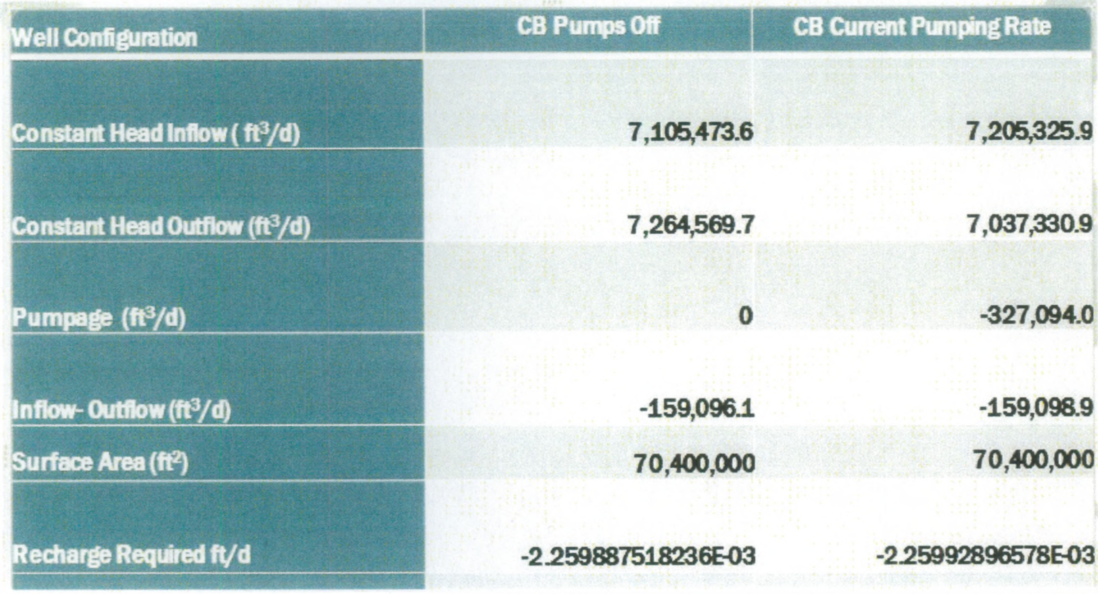
Local groundwater flow lines (green) increased in depth from 400 fbgs to 1000 fbgs when Tòth increased the amplitude of the relief. Regional groundwater flow lines (black) vanished.

Appendix I

Model Well Specifications

Well	Pumping Rate (ft^3/d)	Layer #	Depth (fbgs)
CB-1	107,870	5	89
CB-2	101,572	5	86
CB-3	102,108	4	79
CB-4	15,544	4	71

Appendix J



Well Configuration	CB Pumps Off	CB Current Pumping Rate
Constant Head Inflow (ft^3/d)	7,105,473.6	7,205,325.9
Constant Head Outflow (ft^3/d)	7,264,569.7	7,037,330.9
Pumpage (ft^3/d)	0	-327,094.0
Inflow- Outflow (ft^3/d)	-159,096.1	-159,098.9
Surface Area (ft^2)	70,400,000	70,400,000
Recharge Required ft/d	-2.259887518236E-03	-2.25992896578E-03

Canoe Brook Well Field Water Budget. The quantity of water flowing out must equal the quantity flowing into the model to be steady state. The difference, Inflow minus Outflow, -159,099 ft3/d, is the amount that must be replaced by recharge to ensure no change in water storage in the model. Recharge estimates from New Jersey, New York and Connecticut range from 5.80 x 10^{-4} ft/d to 7.30 x 10^{-3} ft/d (Council of Governments 2011; Findley 2010; NJGS 2005)