**Conceptual flow model of hydrocarbon impacted ground water in an undifferentiated gneiss**

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## Abstract

Flow of oxygenate impacted ground water through glacial till (Pleistocene) and underlying undifferentiated Fordham Gneiss (Upper Proterozoic) was evaluated in northern Westchester County, New York, USA. A conceptual model of hydraulic flow within and between the aquifers is developed by incorporating historic and other local data with results of investigations focused on two private water supply wells at neighboring gas stations.

One 347-foot borehole (PW-A) was logged by geophysical methods revealing five primary zones of fracturing: two are hydraulically significant, at elevations of 164 to 167 feet and 330 to 337 feet. Results show upward flow from deep fractures to the shallower zone, likely related to higher head at deep fractures suggested by observations of higher hydraulic head at PW-A than wells open only to shallow fractures. Rapid drawdown response resulting from fracture flow during pumping tests conducted within the bedrock, and historic video-logs of a neighboring 185-foot borehole (PW-B), confirm the shallow fracture zone is laterally significant. Drawdown response in the deep portions of the overburden till confirms hydraulic connectivity between aquifers. Analysis of drawdown data with the Moench solution provides transmissivity and storativity values within bedrock ranging from 9.70 to 14.15 $ft^2$ /day and $6.669e^{-5}$ to $6.798e^{-4}$, respectively, within expected ranges for this material.

Comparison of concentrations of MTBE sampled during three different pumping scenarios from PW-A and PW-B suggests hydrocarbon impact is not homogenous between the deep and shallow fracture zones, but is concentrated proximal to the overburden aquifer. Ground water flows horizontally through this shallow fracture zone to a downgradient zone of discharge corresponding with deposits of stratified drift and supply wells. Geometric orientations of fractures provide pathways for down-dip transport to the shallow fracture zone and horizontal flow along the plane of strike to the zone of discharge.

## Introduction

Conceptual models of any hydrogeologic system require constant review based on additional information, and in the case of contaminated sites, in consideration of remedial strategies. Prior to 2005, conceptual models of ground water flow and transport of methyl tertiary-butyl ether (MTBE) released from a combination of two adjacent retail

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petroleum service stations served to direct investigations and remedial efforts that focused on source identification and removal. Currently, attention is focused on remediation of oxygenates within the bedrock aquifer. To distinguish party responsibilities, protect regional bedrock aquifers, and implement a pump and treat remedial strategy, the conceptual model of the hydrogeologic and contaminant flow framework must reflect these changing objectives and incorporate the findings of remedial investigations and broader-scale studies.

U.S. Geological Survey (USGS) studies of the hydrogeology of northern Westchester County are incorporated with information from hydrogeologic investigations at the study area to describe flow within the overburden and bedrock aquifers (Wolcott and Irwin, 1988, Wolcott and Snow, 1995). A qualitative description of the transport of oxygenates at the study area uses this conceptual framework of ground water flow. Additional verification is needed to test the hypothetical model presented herein, and to determine to what aerial extent the model holds validity. The conceptual model refers to a unique geologic setting and may be appropriate for the description of aquifer interactions where similar glacial deposits overlie bedrock with similar interface boundaries and fracture geometries.

**Background and Hydrogeologic Setting**

Initial investigations of hydrogeology at the study area were conducted in response to the detection of MTBE below guidance values in September 1990 at potable water supply wells located approximately 500 feet to 600 feet downgradient of the study area. To determine the mechanism for transport of MTBE into and through the bedrock aquifer, a series of hydrogeologic investigations were conducted throughout 2005 and 2006. The investigations included the downhole geophysical logging of potable supply well PW-A, a series of pumping tests at potable supply wells PW-A and PW-B, and ground water sample analyses. Additionally, installation of nested well clusters, gamma-logging of overburden, downhole televiewer inspection, and fracture zone sampling of PW-B was conducted by other investigators. PW-A is a 347-foot open borehole potable well that is the primary source of water for the western service station, and PW-B is a 185-foot open borehole potable well that is the primary source of water for a residence immediately adjacent to both service stations. PW-A is located approximately 70 linear feet southwest from PW-B at the ground surface (Figure 1). Investigations associated with the study area were conducted at the mandate of the New York State Department of Environmental Conservation.

Potable water is supplied to the service stations and to the adjacent residence from wells PW-A, PW-B, and additional wells not included in investigations to date. A restaurant located immediately south of the study area operates an open borehole potable supply well. A condominium development located directly west of the study area operates three open borehole potable supply wells. All potable wells described above have maintained point of entry treatment (POET) systems to remove dissolved phase hydrocarbons,

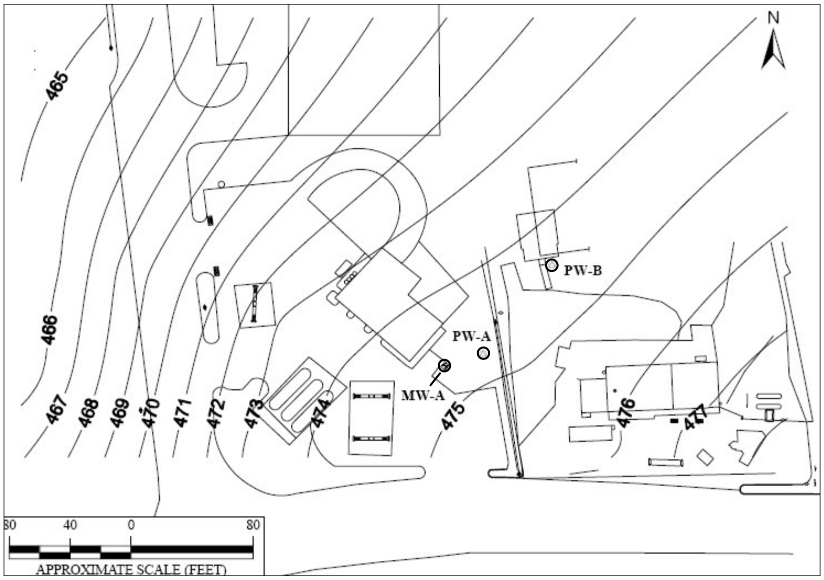



**Figure 1:** Site plan including the adjacent retail petroleum service stations and residence at the study area with water table elevation contours derived and inferred from 21 overburden wells not depicted.

particularly MTBE and tertiary-butyl alcohol (TBA). Beyond the condominium development wells lies an unnamed stream that drains to the Croton Reservoir system, which supplies potable water for New York City and southern Westchester County. The study area is located in the Croton River drainage basin, which occupies approximately 111,246 acres (173.821 miles$^2$) of northern Westchester County (Westchester County Department of Planning, 1977).

*Geologic Setting:* The study area is located in southeastern New York State within the Highlands Province where the Hudson Highlands meet the northern-most portions of the Manhattan Prong in northern Westchester County (Stoffer and Messina, 2003). Consolidated bedrock of the Highlands Province in the vicinity of the study area (Figure 2) consists of two Proterozoic gneiss members (Fordham Gneiss and Poundridge Gneiss) and the Ordovician Inwood Marble (Stoffer and Messina, 2003; Fisher and others, 1970). The Fordham Gneiss, Poundridge Gneiss, and Inwood Marble are considered to be the result of amphibolite facies metamorphism of greywacke, granite, and cherty limestone parent materials with no preserved evidence of antecedent bedding planes (Scotford, 1956). Fisher and others (1970) identify a thin heavily folded unit of the Inwood Marble at the location of the study area, bounded on either side by the Fordham Gneiss. Bedrock core obtained by other investigators from the uppermost five feet of competent bedrock at the study area suggest consistency with the Fordham Gneiss (low-grade felsic gneiss). The core showed extensive weathering as rock quality

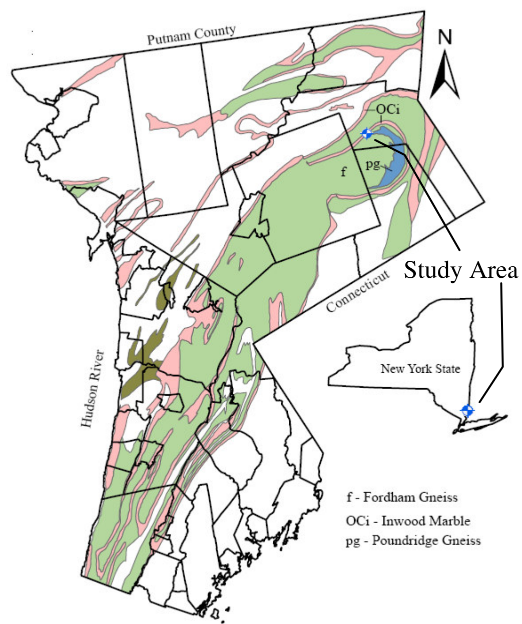



**Figure 2:** Location of study area and bedrock geology in northern Westchester County, New York (Fisher and others, 1970). Study area is depicted on narrow band of Inwood Marble.

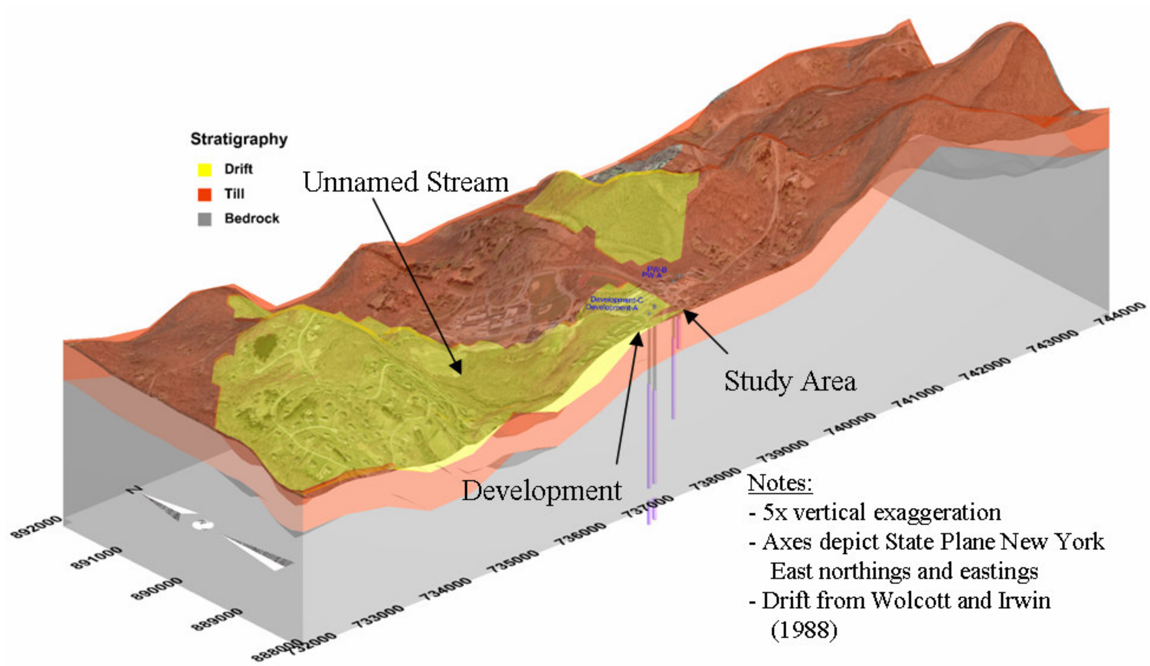
designations (RQDs) of 50% and 57% and iron-oxide weathering along fracture planes. These samples suggest that the Inwood Marble does not directly underlie the study area as mapped by Fisher and others (1970), which is consistent with the observation that the Inwood Marble generally exists within valleys throughout Westchester County (Leggette, Brashears & Graham, Inc., ).

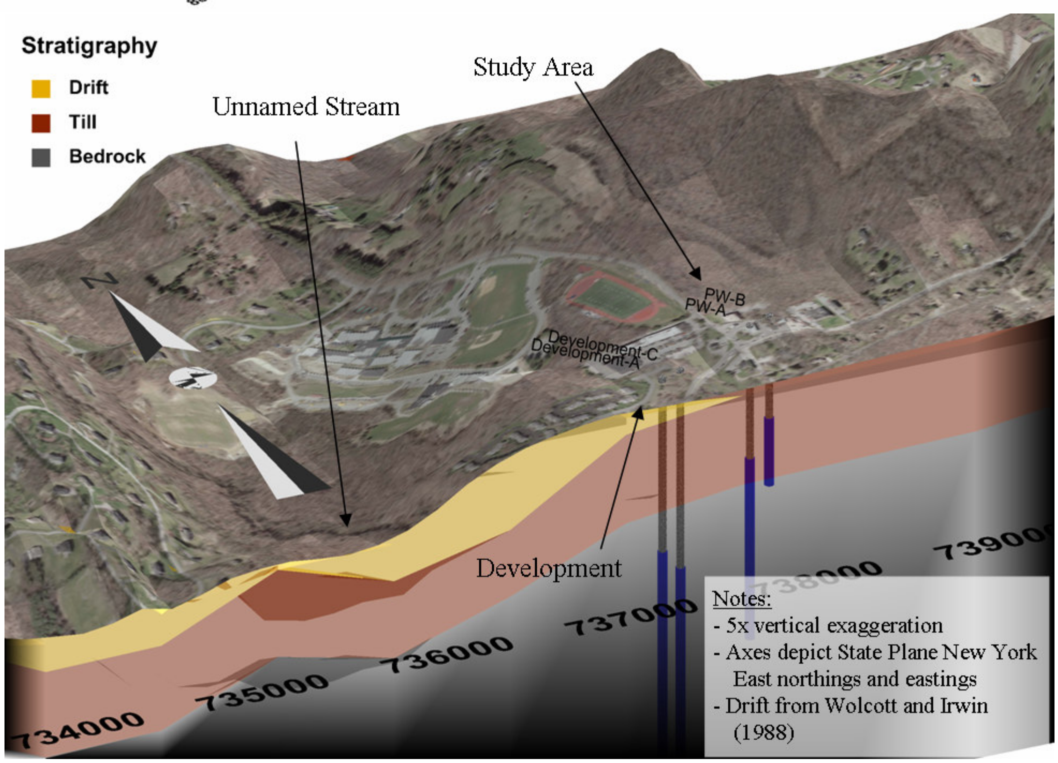
The overburden geology of northern Westchester County, like most of the northeastern United States, is principally controlled by episodic glaciation, the most recent period of which occurred during the Wisconsin (Fullerton, 1992) or Stage 2 (Stoffer and Messina, 2003). The majority of northern Westchester County is covered with a veneer of unsorted glacial till consisting of a range of particle sizes from clay to boulders (Fullerton, 1992; Caldwell and others, 1988). Stratified drift deposits are also present in northern Westchester County and are better characterized as a hydrogeologic unit than are the tills. Wolcott and Irwin (1988) estimated the thickness of stratified drift deposits in northern Westchester County from previous research and soil maps and provided a graphical summary of known well yields of the deposits. The plates depict a wedge of stratified deposits directly west of the study area with thicknesses ranging from less than 20 feet at the eastern boundary of the wedge nearest the study area, to between 50 and 100 feet adjacent to the Croton Reservoir system (Figures 3 and 4). These data have been combined with topography of the National Elevation Dataset (NED) and projected within a Geographic Information System (GIS) to prepare Figures 3, 4, and 6 (USGS, 2007). All azimuths are relative to grid north. Elevations discussed in text are relative to the 1929 North American Vertical Datum (NAVD29); however, the elevations depicted by Figures 3, 4, and 6 use data from NAVD88 (USGS, 1998; USGS, 2007).

**Summary of Hydrogeologic Investigations**

The USGS reported results of hydrogeologic investigations in 1995. Initial investigations of the study area geology and hydrogeology were conducted in 1984, 1990, and 1992 in response to releases of petroleum and the subsequent detection of MTBE in potable water supply wells on behalf of identified responsible parties.

*Local USGS Investigations:* Wolcott and Snow (1995) conducted a comprehensive investigation of bedrock aquifer recharge and movement within northern Westchester County. Their study included the evaluation of recharge rates and chemical quality of the bedrock aquifers, the development an empirical model of bedrock aquifer recharge, and subsequent calibration of the model for an area west of the study area presented herein. Wolcott and Snow (1995) estimate the horizontal hydraulic conductivity of a shallow model layer (0 – 150 feet below grade) based on aquifer testing results and published literature as ranging from 0.010 feet per day (ft/d) to 0.500 ft/d, and estimate horizontal conductivity of a deep model layer (150 – 300 feet below grade) as less than half the shallow layer's value (0.005 ft/d to 0.125 ft/d). The shallow model layer consisted of overburden and bedrock that was identified as highly fractured in geophysical logs.




Figures 3 and 4: Oblique angle views of study area and surroundings showing block diagram representations of overburden and bedrock units in reference to topography. Figures developed from NED, aerial imagery from the New York State GIS Clearinghouse, and plates prepared by Wolcott and Irwin (1988).

*Investigations of Glacial Till:* Initial investigations of hydrogeology at the study area were limited to the surficial glacial aquifer with the exception of the installation of one screened bedrock monitoring well to 145 feet and the sampling of potable wells set in bedrock. Four hydraulic conductivity values for the surficial till aquifer calculated from results of slug tests performed on water table monitoring wells ranged from $1.66e^{-2}$ ft/day to $9.49e^{-2}$ ft/day and averaged $6.72e^{-2}$ ft/day. Remediation of petroleum impact to the glacial till was conducted by soil vapor extraction and excavation.

Reports of local increases in natural gamma through the overburden glacial till, as logged by down-hole methods in 2005 by other investigators, suggest locally increased clay content as lenses from 32 to 74.5 feet below grade. Hydraulic head measurements from well clusters set throughout the profile of glacial till with screening horizons indicate downward gradients ranging from 0.338 foot/foot to 0.470 foot/foot.

*Geophysical Investigations of Bedrock:* One open borehole well (PW-B) was inspected by down-hole televiewer in April 2005 by other investigators. The open borehole well was cased through overburden to 370 feet and open to 295 feet below grade. Nearly vertical fractures were reported from 357 to 367 feet and from 337 to 343 feet.

In November 2006, the bedrock aquifer was characterized by the downhole geophysical logging of PW-A. Downhole geophysical logging methods at PW-A included acoustic televiewer (ATV), acoustic travel time, three-arm caliper, heat-pulse flow meter, fluid temperature, and fluid resistivity logs. ATV and acoustic travel time data were collected at 0.01-foot intervals from within casing at 351 feet to the bottom of the borehole at 132 feet and used to calculate the number and orientations of planar elements within the borehole. Caliper, fluid temperature, and fluid resistivity data were collected at 0.10-foot intervals and used to qualitatively determine the size and potential hydraulic significance of features. Heat-pulse flow meter data were collected at discrete depths during both ambient conditions and pumping conditions. Measurement locations were determined by review of ATV, acoustic travel time, caliper logs, fluid temperature, and fluid resistivity logs. Water was pumped from PW-A at a rate of 0.8 gallons per minute (gpm) with a submersible impeller pump set within the well casing at 404 feet during the pumping flow meter test. Sixteen heat-pulse flow meter measurements were collected between 144 to 349 feet.

Planar elements identified within PW-A were grouped qualitatively based on aperture by evaluation of ATV, acoustic travel time, and caliper tests. Class I and II features are considered to be related to foliation and minor fractures; the distribution of orientations for both classes is similar (Figure 5). Class III features are considered to be fractures of significant aperture, mimic Class I and II orientation distributions, and were evaluated using flow meter tests under the assumption that this class of features would be more hydraulically significant. Class III features constitute 23 of the 175 total identified features in the borehole and are grouped in five zones located from 330 – 337 feet, 307 – 320 feet, 290 – 291 feet, at 272 feet, and 164 – 167 feet. The shallowest set of fractures measured in PW-A are approximately six feet lower in elevation than the lowest intensely fractured zone identified in PW-B; however, the zones are both approximately six feet in thickness. Angular mean and 95% confidence limits of the geometric orientations relative to grid north of planar features identified during logging are presented as Table 1.

Poles to planes of planar features observed during downhole logging are depicted as lower hemisphere plots on Figure 5.

**Table 1:** Angular mean and 95% confidence limits for the orientations of feature strike and feature dip for the three classes of planar features identified during borehole geophysical logging.

| Class | | Mean ± 95% Confidence |
|---|---|---|
| **I** | Dip | 60º ± 4º |
| n = 70 | Strike | 345º ± 35º |
| **I (NE)** | Dip | 69º ± 2º |
| n = 28 | Strike | 42º ± 2º |
| **II** | Dip | 60º ± 3º |
| n = 82 | Strike | 340º ± 25º |
| **II (NE)** | Dip | 69º ± 2º |
| n = 36 | Strike | 42º ± 2º |
| **III** | Dip | 57º ± 5º |
| n =23 | Strike | 273º ± 32º |

The geometric orientations of Class I and II features are seen to group into a tight cluster with feature strikes of 42º ± 2º northeast (NE in Table 1), and steep dip angles of approximately 69º ± 2º degrees to the south and east (Figures 5a and 5b). These tight clusters of features are interpreted to be associated with the geometric orientation of foliation at the study area. The contact between the Fordham Gneiss and Inwood Marble in the vicinity of the study area is also approximately 40º (Fisher and others, 1970). The remainder of planar features in Classes I and II, as well as a majority of features in Class III have geometries that are scattered throughout a range of strike orientations including southeast trends, east trends, and northeast trends (Figure 5).

*Evaluation of Aquifer Pumping Tests:* Aquifer pumping tests were performed at PW-A and PW-B to evaluate aquifer transmissivity and storativity, to qualitatively determine the interconnectivity of fractures intersected by the tested boreholes, and to qualitatively determine the interconnectivity of the bedrock and overburden aquifers. Pumping rates of 5 gpm and 3 gpm were determined to be sustainable by step drawdown tests at PW-A and PW-B, respectively. Drawdown was measured in the three bedrock wells, including MW-A a 145-foot monitoring well screened from 364 feet to 334 feet, and selected overburden monitoring wells manually and by data-logging pressure transducers during a 51-hour pumping test at PW-A, a 9-hour pumping test at PW-B, and an 8-hour combined

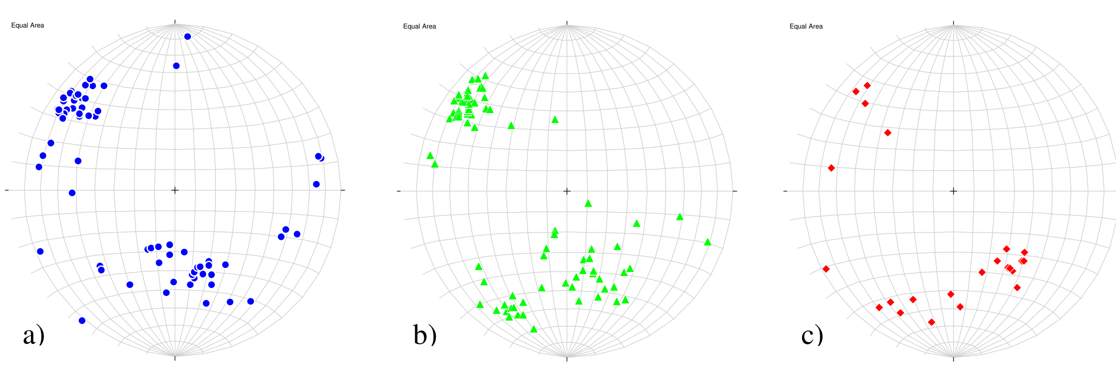



**Figure 5:** Lower hemisphere plots of poles to planes for planar features identified by ATV. The features are separated into three classes based on apparent aperture: Class I is depicted in (a), Class II in (b), and Class III in (c). Note the tight clustering of poles in (a) and (b) corresponding to planar features with northeastern strikes and south and east dips.

pumping test including both wells. Data-logging pressure transducers recorded recharge data for a similar period of time at a number of wells throughout the network.

Qualitative evaluations of the drawdown response in the three wells open to portions of the bedrock aquifer indicate rapid response to pumping from both PW-A and PW-B; 1-foot of drawdown was observed within the wells within 42 minutes of pumping. Overburden monitoring wells exhibited an increasing trend of attenuation and delayed response as stress to the aquifer migrated upwards. Stress to the deep portions of the overburden is expected due to the poor reported RQD near the bedrock interface and steep fracture dip angles. Shallow overburden wells throughout the study area exhibited no response to pumping. Clay-rich zones identified during gamma logging of overburden till materials appear to act as a semiconfining unit to the deeper portions of the overburden and the bedrock aquifers.

Aquifer characteristic analysis was conducted with AQTESOLV for Windows Pro using the Moench solution for a leaky confined aquifer with an overlying constant head boundary using drawdown data observed at PW-B and MW-A during pumping from PW-A (HydroSOLVE, 2002; Moench, 1985). Due to the high fracture density observed throughout the shallow portions of the bedrock aquifer and the poor RQDs reported, simulation as a porous media was determined appropriate. The resultant values are within the expected range of fractured metamorphic rocks (Freeze and Cherry, 1979). The transmissivity value calculated for the aquifer at PW-A using drawdown response from MW-A is approximately 46% greater than the value calculated using the drawdown response from PW-B (Table 2). The lower transmissivity observed between PW-A and PW-B is attributed to more fractures terminating over the longer span between the wells than the span between PW-A and MW-A. The mean hydraulic conductivity values assuming PW-A fully penetrates the aquifer (231 feet) is 0.052 ft/d, slightly lower than values reported by Wolcott and Snow, who calculated hydraulic conductivity values ranging from 0.054 ft/d to 0.939 ft/d by analysis of results from a combination of aquifer pumping tests and specific capacity tests. Assuming a shallower common aquifer would increase conductivity values to within ranges measured by Wolcott and Snow (1995).

**Table 2:** Bedrock aquifer characteristics calculated using the Moench leaky aquifer solution from drawdown response data collected during pumping from PW-A (HydroSOLVE, 2002; Moench, 1985). Distances are relative to PW-A at the ground surface.

| Observation Well | Distance (feet) | Transmissivity ($ft^2$/day) | Storativity |
|---|---|---|---|
| MW-A | 23 | 9.70 | $6.798e^{-4}$ |
| PW-B | 70 | 14.15 | $6.669e^{-5}$ |
| mean | | 11.93 | $3.732e^{-4}$ |

*Vertical Gradient within Bedrock:* Ground water elevations are inversely related to the depth of boreholes set in the bedrock aquifer. Gauging data for bedrock boreholes indicate increasing hydraulic head with depth, or an increasing average head at the fracture zones intersected by the tested boreholes. No hydraulic head data for specific fracture zones within any borehole was measured during this study. Hydraulic head was measured above the bedrock surface at all ground water monitoring wells open to the bedrock aquifer; however, hydraulic head measured in bedrock was approximately equal to hydraulic head measured at the deepest portions of the overburden.

*Proportional Transmissivity of Fracture Intervals:* Comparison of the proportional differences in response of each fracture zone to ambient and pumping conditions during heat-pulse flow meter logging conducted at PW-A provides an estimate of the relative transmissivity of each measured fracture zone, similar to the methods of Paillet (1998) and Robledo (1998). The difference in the rate of inflow or outflow between ambient and pumping tests is calculated for each interval sampled by the flow meter. The difference of inflow/outflow at each interval sampled is related as a proportion to the total of differences of inflow/outflow, and the transmissivity of the borehole can then be divided proportionally between the intervals (Table 3). A constant head difference between pumping and non-pumping conditions at each interval is assumed.

**Table 3:** Proportionality analysis of inflow/outflow in PW-A at discrete fracture zones relative to the total observed transmissivity. Angular mean and 95% confidence limits are presented for features within each evaluated zone.

| Elevation Range feet | Number Features Class: 1, 2, 3 | Strike Azimuth / Dip degrees | Ambient HPFM g/min | Pumped HPFM g/min | Inflow - Outflow g/min | Inflow - Outflow % | Trans-missivity $ft^2$/day |
|---|---|---|---|---|---|---|---|
| 330-337 | 0, 4, 5 | 8° ± NA / 57° ± 12° | 0.40 | 0.067 | 0.33 | 40 | **4.7** |
| 307-327 | 3, 19, 7 | 299° ± 18° / 65° ± 3° | 0.13 | 0 | 0.13 | 16 | **1.8** |
| 284-293 | 3, 8, 3 | 36° ± 44° / 60° ± 5° | 0.073 | 0.06 | 0.01 | 1 | **0.1** |
| 275-284 | 7, 5, 0 | 301° ± NA / 53° ± 12° | -0.067 | -0.067 | 0 | 0 | **0.0** |
| 266-275 | 7, 7, 1 | 268° ± 29° / 46° ± 7° | 0.033 | -0.10 | 0.13 | 16 | **1.8** |
| 222-247 | 9, 2, 0 | 54° ± 67° / 69° ± 6° | -0.067 | -0.13 | 0.06 | 7 | **0.8** |
| 175-192 | 5, 8, 0 | 329° ± NA / 61° ± 7° | -0.067 | -0.067 | 0 | 0 | **0.0** |
| 158-175 | 7, 1, 6 | 293° ± NA / 60° ± 7° | -0.40 | -0.57 | 0.17 | 20 | **2.4** |
| | | **Total** | 0.04 | -0.81 | 0.83 | 100 | 11.7 |

Zones with estimated transmissivities contain 22 of the 23 Class III features. During the flow meter test of ambient conditions a slight loss of water from the borehole was observed, possibly due to recharge of shallow fracture networks drained by nearby wells. The majority of water entering PW-A entered through a series of Class III features at an elevation of approximately 164 to 167 feet with an estimated transmissivity of 2.4 square feet per day ($ft^2$/day). The majority of water exiting PW-A exited through a group of Class III features at an elevation of approximately 332 to 337 feet with an estimated transmissivity of 4.7 $ft^2$/day. The majority of the water enters the borehole below 222 feet (0.53 gallons), and exits the borehole between 330 feet and 266 feet (0.57 gallons), yielding an upward flow throughout the borehole (Table 3).

*Geologic Controls of Flow:* The strike of foliation is observed in geophysical logs of PW-A, and parallels the contact between the Fordham Gneiss and Inwood Marble at the study area (Fisher and others, 1970). When smaller aperture features are disregarded, the angular means of strike and dip of six consistent Class III features between 164 to 167 feet and calculate to 229° and 49°, approximately opposite in orientation from foliation. The angular means of strike and dip of Class III features between 332 and 337 feet calculate to 318° and 53° when smaller aperture features are disregarded; however, three of the five Class III features in this zone align to foliation strike (41°), or nearly opposite foliation strike (227° and 237°). The consistencies in strike orientation or opposite strike orientation of the most productive fractures suggest increased permeability along the orientation of strike and the contact of major geologic units proximal to the study area. Increased permeability along the contact of the geologic units may be coincidental with the topographic changes associated with valley formation by differential erosion of the Inwood Marble (Leggette, Brashears, and Graham, Inc.), which have been identified as being more significant in secondary porosity of crystalline rock than lithologic changes (Wolcott and Snow, 1995; Freeze and Cherry, 1979). Wolcott and Snow reported that adjustment of hydraulic conductivity values according to bedrock lithology failed to calibrate an empirical model of the bedrock aquifers in northern Westchester to measured head; however, adjustment based on the relative surrounding topography aided in model calibration.

The highest transmissivities are estimated in the shallowest portions of the bedrock aquifer measured, which is consistent with low reported rock qualities. Wolcott and Snow (1995) identified fracturing by caliper logs of the bedrock aquifer, and the corresponding fracture flow, is most abundant within 100 to 150 feet of the land surface (Wolcott and Scott, 1995). The findings of Wolcott and Snow are consistent with the findings of this investigation, as well as findings from Meinzer and Stearns (1929) for materials within the Pomperaug Basin of the Housatonic Highlands of Connecticut, and summaries by Heath (1984) and Freeze and Cherry (1979) for crystalline rocks.

## Conceptual Model Development

Previous conceptual models of ground water flow and contaminant transport suggested downward migration due to the withdrawal of water from the bedrock aquifer by potable wells located within the study area. Findings from investigations conducted in 2006 elaborate on the natural and anthropogenic mechanisms for vertical ground water flow and contaminant transport at the study area.

*Recharge and Input Boundaries:* Gradients inferred from water table elevation contours in the unconfined glacial till aquifer yield horizontal flow components directed from east to west and from east-southeast to west-northwest. Gradients inferred from potentiometric surface contours from deep overburden wells suggest a horizontal flow component parallel to the observed unconfined flow. Considering the observed connectivity of the deep overburden with the shallow bedrock aquifer, differing flow direction in the bedrock is not considered possible. Including hydraulic head measured at MW-A and PW-B with deep overburden wells does not alter the resultant contours other than by extending their aerial extent.

Local topography and landforms can generate horizontal flow components measured in overburden and inferred in bedrock (Figures 3, 4, and 5). Wetlands correspond with an isolated deposit of stratified drift located northeast of the study area. Topography increases east of the study area to a series of small ridges. Both the wetlands and ridges are relatively free of impervious surfaces and expected to provide adequate sources of ground water recharge. Hydraulic head measurements through the vertical profile of overburden at the study area indicate downward vertical flow components. Connectivity between the overburden and the shallow bedrock aquifers is sufficient for recharge at the study area.

*Discharge and Output Boundaries:* Discharge of ground water after flowing through the ground water system at the study area is considered to discharge to a combination of natural and anthropogenic boundaries. Stratified drift deposits form a wedge filling a depression in bedrock topography west of the study area; the thickest stratified drift deposits are located west-northwest of the study area, directly downgradient. These drift deposits correspond with a valley associated with an unnamed stream, part of the Croton Reservoir system, at an elevation of approximately 331 feet, 148 feet lower than grade at the study area and at a comparable elevation to the intensely fractured zone identified within PW-A at 330 feet to 337 feet (U.S. Geological Survey, 1998).

A series of potable wells exist both at the study area and directly downgradient. PW-A removes water from the bedrock aquifer to provide supply for the service station and car wash. During pumping tests water was supplied to the property at a rate of approximately 2,500 gallons per day (gpd), suggesting that a similar quantity of water is removed from the well daily during normal operation. During initial operation of a treatment system from downgradient wells at the condominium complex, water removal rates were estimated at 29,000 gpd, 49,000 gpd, and 72,000 gpd. Even considering high estimates of per capita water use for residents of the condominium complex of 150 gpd, including potential irrigation demands, these pumping rates are not required to sustain water supply to the development (Leggette, Brashears & Graham, Inc., ). Withdrawal of an estimated 26,000 gpd provides additional stress along the observed strike orientation to the southwest. However, flow to supply wells at the development is drawn partially from a deeper source or the production would deplete the capacity of the shallow aquifer.

*Flow system:* Wolcott and Scott (1995) generalize ground water flow as being directed from hilltops to streams or reservoirs with downward vertical components at hilltops and valley sides, and upward vertical components at valley bottoms. Williams and Eckhardt (1987) presented similar generalizations of flow in reference to borehole yields. It is hypothesized that at the study area downward flow components exist between the bedrock and stratified drift aquifers along the valley sides west of the study area, but at a shallower angle than that of the steeper downward slope of the bedrock and stratified drift interface. The hypothesis suggests that ground water may be flowing from shallow portions of the bedrock aquifer and discharging to the overburden along the valley sides and valley bottom as the reservoir drains the stratified drift aquifer (Figure 6) and to the supply wells at the development complex. Flow in these directions would occur through random series of interconnected fractures, potentially aided by increased permeability along the strike of foliation to the southwest and up-dipping planes to the north and west. Interconnectivity observed between the overburden and bedrock aquifers during pumping tests suggests that overcoming static hydraulic head differences between the two aquifers is the most significant factor governing flow between aquifers. Hydraulic head differences that are static to downward at the study area and upward at the reservoir stream and development wells would create such a flow system.

*Oxygenate Transport:* For the purposes of the presented model development, oxygenates are considered to closely mimic ground water flow velocity (Zogorski and others, 1996). Organic content of fractures at the study area, which may provide a substrate for organic compound adsorption have not been assessed but are assumed to be minimal. Other gasoline constituents are considered to be retarded by the clay-rich zones in overburden. Oxygenates pass through these clay-rich zones to the bedrock aquifer due to higher aqueous solubilities and lower potential for adsorption.

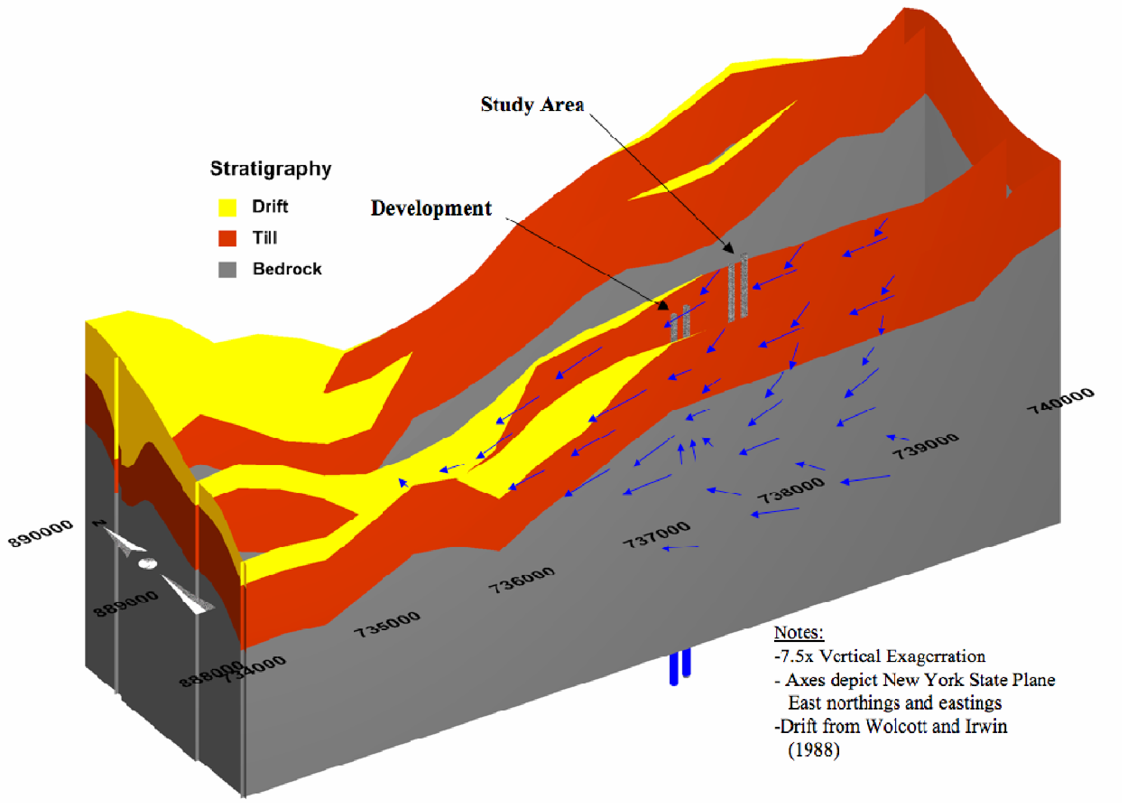



**Figure 6:** Suspected ground water flow within and between the bedrock and glacial aquifers.

The flow system presented above isolates oxygenates to shallow portions of the aquifer. Samples of ground water from both PW-A and PW-B during aquifer pumping were analyzed for MTBE. Comparison of the concentrations during the three pumping scenarios suggests an uncontaminated deep productive zone in bedrock. Concentrations of MTBE decreased one to three orders of magnitude in PW-A during a combined pumping test at PW-A and PW-B from concentrations detected while pumping at PW-A individually. Concentrations at PW-B remained consistent throughout pumping tests and orders of magnitude higher than observed at PW-A. Water was withdrawn at higher pumping rates during aquifer testing and sampling than withdrawn during flow meter tests. Draining of fractures throughout the depth of PW-A when pumping at 5 gpm is expected. During pumping from both PW-A and PW-B, water from the shallow fracture zones is drawn away from PW-A by PW-B, expressed as 7.28-feet more drawdown after eight hours in PW-A. More water is produced by PW-A from deeper fractures under these conditions comes, and it is inferred that these fractures contain lower concentrations or no MTBE. The decreased concentrations of MTBE in PW-A detected during combined pumping are therefore attributed to dilution by water from these deeper fractures. The stagnation of vertical migration of oxygenates within the shallow fracture zone is consistent with the physical evidence of upward flow within PW-A, increasing hydraulic head with depth, and the flow system described.

## Conclusion

The conceptual model of a study area in northern Westchester County, New York is enhanced by the evaluation of downhole geophysical logging, aquifer pumping tests, and the incorporation of other local information. Geophysical logging of a 347-foot deep potable well indicates high fracture densities within a shallow bedrock aquifer, consistent with televiewer inspection of a neighboring potable well, rapid drawdown response within wells open to the shallow aquifer, and previous work that identified the most fracturing within 150 of the ground surface. A general trend of upward flow was observed between fractures below elevations of 222 feet and fractures above 266 feet during heat-pulse flow meter tests conducted under ambient conditions. The groundwater flow system is presented as being governed by flow from a wetland and topographic ridge generally east of the study area to zones of discharge, including supply wells and stratified drift deposits drained by the Croton Reservoir system, located generally west of the study area. Vertical flow through overburden recharges the bedrock aquifer; connectivity between the aquifers is illustrated by pumping test response and is expected considering the observed fracture densities, steep fracture dips, and poor RQDs near the overburden bedrock interface. The vertical migration of oxygenates appear to stagnate within the shallow fracture zone. Additional discrete zone packer tests that measure hydraulic head within specific fracture zones can be used in combination with flow meter testing to more accurately characterize vertical flow within boreholes and the aquifer, and discrete fracture zone samples can be used to better evaluate the vertical profile of dissolved oxygenates. Cross-borehole flow meter tests can evaluate which fracture zones are disturbed during aquifer stress conditions. These data can be used to evaluate the effectiveness of recovery wells for removal of oxygenates from the aquifer at the study area without disturbing deeper aquifer zones inferred to contain concentrations of dissolved-phase hydrocarbons orders of magnitude less than in the shallow aquifer. Operating conceptual models of the study area would evolve based on the results of such tests and the observed efficiencies of recovery wells.

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