



A Report from the University of Vermont Transportation Research Center

# Numerical Modeling and Experimental Investigation of the Local Hydrology of a Porous Concrete Site



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Project funded by the Vermont Agency of Transportation and UVM Transportation Research Center

October, 2011

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This project was funded by the Vermont Agency of Transportation (Vtrans) and the UVM Transportation Research Center (UVM TRC). The authors would like to acknowledge Dr. Dewoolkar and his students: Mark Suozzo, Ian Anderson, Lalita Oka and Jaron Borg for their help during the field visits and in the lab. In addition, we acknowledge Dylan Burns for providing the equipment for the evaporation experiments and Floyd Vilmont for his help in manufacturing the water-retention cells and overall input in the mechanical issues of this project. Finally, the authors wish to thank Vtrans and especially Jeniffer Fitch, Jason Trembley, Philip Dessureau, Thomas Eliassen and William Ahearn for providing data and their valuable cooperation through the course of this project.

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# Chapter 1

## Introduction

Although porous pavement use has been accepted as a successful stormwater management practice in warm climates, application in regions with colder climates, like New England, is still under investigation. The Randolph Park and Ride Site, which is the area of interest of this specific study, is the first porous concrete site constructed in Vermont. The site, which was built in 2008 and is under use up to today, is quite unique in terms of the geology of the underlying materials and also the extensive instrumentation that has been applied in the field. The purpose of building this site was in part “commercial”, to provide the town of Randolph with a public parking lot, and part “experimental”, aiming at giving insight to the optimal design of porous pavements in New England. This study focuses on the experimental use of the site.

More specifically, this study initially aims at investigating the interaction between porous concrete utilization and local hydrology at porous concrete sites in New England. With this part achieved, a mathematical model can be developed and used prior to construction as a design tool for other porous concrete sites. The final model will take into account a variety of physical processes and treat the system as a whole, starting from rainfall falling on the top of the porous concrete, to the point where water meets the groundwater system. It is also a secondary goal of this study to combine the mathematical model created with an optimization algorithm that will allow for optimal design of porous concrete sites in terms of minimal expense. Therefore the key goals of this study are the following.

- Investigate the local hydrology and understand the geologic characteristics of the soil in the Randolph Site.
- Enhance knowledge of field observations through laboratory experiments and determine the parameters needed by the mathematical model.
- Create a mathematical model that incorporates all the different processes taking place in a porous concrete system.
- Use the constructed model to evaluate the site design.
- Use the model in combination with an optimization code to provide the optimal design in terms of least cost.
- Extend the use of the resulting model for other sites.

## Chapter 2

# State of Knowledge

The use of porous concrete for its reduced environmental impact started in the 1970s in Florida [8]. Besides porous concrete, which is the main focus here, other kinds of permeable pavement installations include porous asphalt and various kinds of pavers.

The following literature review aims at providing a general background on existing porous pavement studies with emphasis placed on the hydrologic impact of porous concrete.

### **2.1 Interaction of porous concrete utilization and hydrology**

#### **2.1.1 Review of studies focusing on site monitoring with respect to runoff and infiltration**

In a study by Bean et al. [3], four permeable pavement applications (consisting of porous concrete, concrete grid pavers and permeable interlocking concrete pavers) were monitored in order to determine effectiveness in terms of reducing runoff quantity and improving water quality. Hardware instrumentation allowed detailed runoff and rainfall measurements in time and the study results showed that runoff was not only reduced but for some events even eliminated.

Kwiatkowski [17], describes a hydrologic study on a porous concrete site on campus at Villanova University. There, porous concrete was overlaid on storage beds filled with coarse aggregate, on top of a sandy-silt well draining soil. The specific study although mostly focused on water quality data, describes the ability of the site to accept a significant amount of infiltration from surrounding areas and reduce runoff as well. In this study it is also mentioned that the porous concrete area was later reduced by paving over part of it with conventional concrete, but the sites overall performance still remained satisfactory.

Another study on porous concrete sites, with more general focus, is from Henderson and Tighe [11] who performed a research study on five porous concrete test areas in Canada in order to test concrete strength characteristics during freeze-thaw cycles. Also, a university research study in Auburn, Alabama, presents five porous concrete projects constructed and designed by students in collaboration with professors, inside the campus area to monitor site performance regarding concrete failure and infiltration of rainfall [10].

For an additional review on porous concrete installations the reader can also refer to Ferguson [8]. His review contains a comparison of successful and unsuccessful installations in

close proximity locations, installations on sandy or fine-grained soils and finally installations on the west coast or towards colder climates.

Studies on other types of porous pavement with emphasis on the sites hydrologic characteristics are from Brattebo and Booth [4], who studied the long-term effectiveness of four permeable pavement parking lots consisting of block pavers, in terms of stormwater quantity and quality and Fassman and Blackbourne [7] who monitored runoff from a permeable pavement roadway site on a relatively impermeable subgrade soil in New Zealand for a period of two years. In the latter study, the sites design incorporated an underdrain system to collect water stored in the crushed stone layer and also took into account retention of water and subsequent evaporation into the atmosphere.

On a slightly different note, installation of porous pavement on clayey soils has been studied by Dreelin et al. [6], who tested the effectiveness of a porous pavement consisting of grass pavers during natural storm events and found that stormwater was actually being infiltrated into the clayey subgrade material. Also, the behaviour of porous pavement in cold climates was the research focus of a study by Backstrom [2]. Temperature of porous pavement during freezing and thawing was monitored on a porous asphalt site in northern Sweden. This study is actually one of the few found in the literature where the groundwater table is monitored carefully through the period of analysis and shows how the groundwater changes compared to the rest of the monitoring area.

### **2.1.2 Review of studies focusing on retention and evaporation**

The idea of evaporation of water inside the porous pavement's coarse stone storage area has been addressed by Andersen et al. [1]. Results of their study showed that an average of 55 percent of a one hour duration 15 mm rainfall could be retained by an initially dry structure and 30 percent of a similar rainfall by an initially wet structure. Also, evaporation losses proved to be dependent on the environmental conditions and the grain size of the substrate. Small grain sizes showed lower drainage from the bottom of the structure and higher evaporation rates.

Also, Kunzen [16] measured evaporation processes inside a column filled with porous concrete and sand using pressure probes and used a mass balance approach to calculate evaporation. In another study by Fassman and Blackbourne [7], losses of water inside the subbase of a block-pavers porous pavement were also attributed to evaporation losses. Finally, long-term evaporation of water inside a porous pavement parking lot in Spain was mentioned in a study by Gomez-Ullate et al. [9], although their study mostly focused on the influence of the geotextile on water retention in pervious pavements.

## 2.2 Porous pavement models

### 2.2.1 Review of commercial porous pavement models to date

During the time that porous pavements have been used in the field, various attempts have been made in order to model the systems hydraulic and hydrologic characteristics.

One of the models that has been used extensively in the porous concrete research area in the United States is the EPA Stormwater Management Model (SWMM). SWMM is a dynamic rainfall-runoff model used for simulation of single event or continuous runoff quality and quantity from urban areas. Runoff is perceived as the sum of inflows from various sub-catchment areas that receive precipitation. SWMM uses a routing subroutine to transport this runoff through pipes, storage areas, pumps and regulators. In each simulation period comprised of multiple time-steps, the runoff generated from each sub-catchment is calculated using an explicit finite-difference solution of the complete Saint-Venant equations. Flow rate, flow depth and quality of water in each pipe are also calculated [22]. This software is easy to use and takes into account a wide range of physical processes that can occur inside the porous pavement system. However, the percolation equation used for vertical flow inside the crushed stone reservoir, derived from Darcys Law, has not been tested against field data and therefore may be unsuitable for the specific application [14].

In a different approach, Wanielista et al. [26] used a mass balance model in order to simulate runoff and recharge volumes on a porous concrete slab for different rainfall events over a period of a year in sites in Florida. Their method however is limited to a 1-D approach and also cannot simulate systems with gravel reservoir layers.

Researchers in the United Kingdom have used the Stormwater Software package Erwin to model the outflow of a porous pavement system. Erwin is an icon-driven rainfall-runoff model for urban drainage used to evaluate sustainable urban drainage designs. It uses the Horton/Paulsen approach for infiltration into the ground and calculates outflow through time according to precipitation data. [23]

Ong and Fwa [18] have used SEEP/W, a 1-D saturated/unsaturated model for seepage analysis in an asphalt pavement installation in Singapore. Their model allows for calculation of a pavement's thickness that is required for various rainfall events.

## 2.3 Open Questions

According to the existing literature review, the limitation of the modeling approaches mentioned above lies on the simplifying assumptions, especially in the case of 1-D flow models, and the lack of validation of the equations used against real data. Finally, it appears that most models focus on one part of the problem and neglect the interconnection of the various pieces that comprise the complicated overall system. SWMM, seems to be the most complete model existing in literature, however the writers acknowledge that the percolation equation used in the model for flow through the coarse stone material may be unsuitable and has not been properly validated. Therefore, there is still a need for a 3-D general model that treats the system as a whole and uses the correct representation of the flow through the coarse stone.

Also, the majority of existing on-site porous concrete studies focus more on runoff reduction and infiltration of water into the porous concrete slab and very few provide information on the impact of such an installation on the groundwater.

## Chapter 3

# Research Approach and Methods

As mentioned previously, this research is focused on a specific porous concrete site called Randolph Park and Ride located in the town of Randolph, Vermont. The site has operated as a public parking lot facility since 2008 and is the first porous concrete site built in Vermont. At the onset of this research, in the beginning of Fall 2008, the site was already designed and under construction. At that point, the authors, in collaboration with Vtrans (the agency responsible for building the site), decided the location of a set of monitoring wells.

The specific project reported upon herein is the combination of three interconnected pieces.

- The field investigation
- the laboratory procedures
- and finally the mathematical model.

The **field investigation** part is a key part of this study. The main problem of porous pavement studies is the lack of the model's calibration according to field data. The fact that the Randolph site is equipped with a number of monitoring wells and scientific equipment is a significant advantage of this study. The **laboratory procedures** part helps to strengthen knowledge of the field conditions. Finally, all data that derive from both the field investigation and the laboratory experiments serve as an input to the **mathematical model**, which is the final and most important piece of this research.

### 3.1 Field Investigation

#### 3.1.1 Site Description

The field-test site is located at the intersection of VT Route 66 and T.H. 46 in the town of Randolph, Vermont. The area of interest is the porous concrete parking lot. The broader area also includes a conventional asphalt road section. As mentioned previously, the facility has been in use since the fall of 2008. During the second year of operation the first signs of deterioration of the porous concrete area became evident. The deterioration continued and became worse during the 3rd year of operation. A solution for this issue is yet to

be determined. However, Vtrans early on suggested that there is a possibility of paving over the failing areas with conventional concrete. If this were the case, runoff from the conventionally paved areas would result in a recharge term on the porous concrete surface.

The porous concrete slab parking area is 36,000 ft<sup>2</sup> and consists of 6 inches of pervious concrete, underlain by 2 inches of AASHTO No. 57 crushed stone and 34 inches minimum of AASHTO No. 2 crushed stone which, in combination, forms the reservoir where water can be stored before infiltration into the subsurface. A woven geotextile fabric is located at the bottom of the No.2 stone to prevent migration of the subgrade soil inside the stone. In addition to that, an underdrain system is installed inside the reservoir. This system is able to collect the water that infiltrates through the porous concrete into special 'boxes' called drop inlets and from there direct it to a retention pond away from the porous concrete slab. Water can be measured inside the inlets and provide insight on the amount infiltrated into the system. One of the reasons that the underdrain system was incorporated in the design is the extremely low permeability of the underlying soil. Underdrains in this case make sure that the porous concrete does not overflow after an intense rainfall. In addition, the underdrain system was incorporated in case the porous concrete concept failed. In that case, the area could be paved over with conventional concrete but still meet the stormwater regulations for the town of Randolph. Figure 3.1 shows the site design. In addition to the underdrains, the site is also equipped with a perforated pipe located along the perimeter of the porous concrete area. The usage of this "perimeter drain" is to collect any amount of runoff from the surrounding site area.

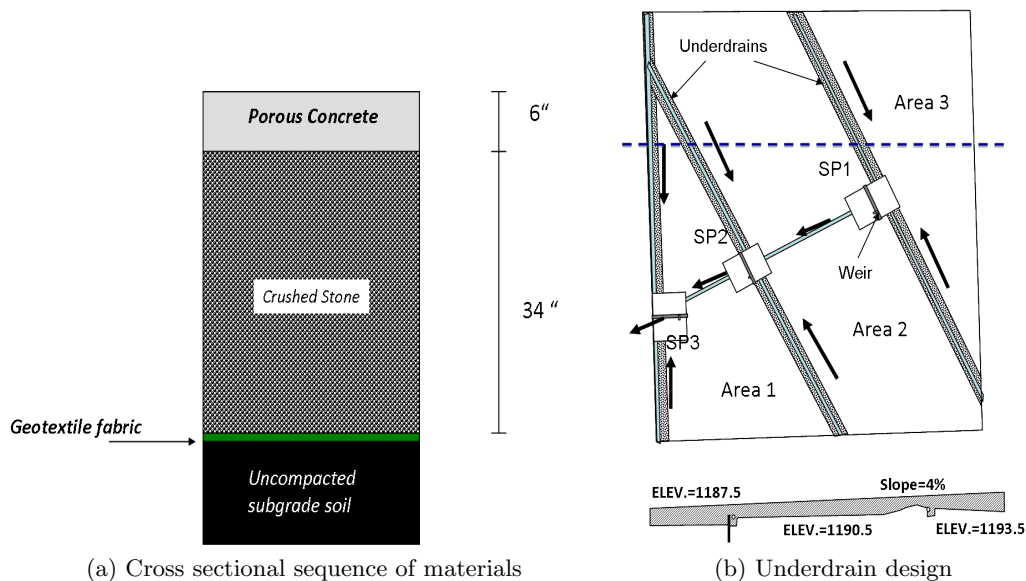


Figure 3.1: Site design

Vtrans has been monitoring water level data inside the drop inlets over time. However, the initially collected data showed that, strangely enough, water levels in the drop inlets remained stable and relatively unaffected by the rainfall events. Since the drop inlets are supposed to collect any amount of water infiltrated into the porous pavement that does



not infiltrate the soil, and the subgrade soil is quite impermeable prohibiting infiltration of water, questions arose as to where the water is actually going. This was a mysterious phenomenon in the field and up to this day a solid answer has not been provided. Various hypotheses have been made, the most dominant being water could be retained by the crushed stone surface and then evaporate into the atmosphere. Another hypothesis is that water that infiltrates the porous concrete slab could somehow leak towards the "perimeter drain" and therefore fail to flow towards the underdrains in the subbase.

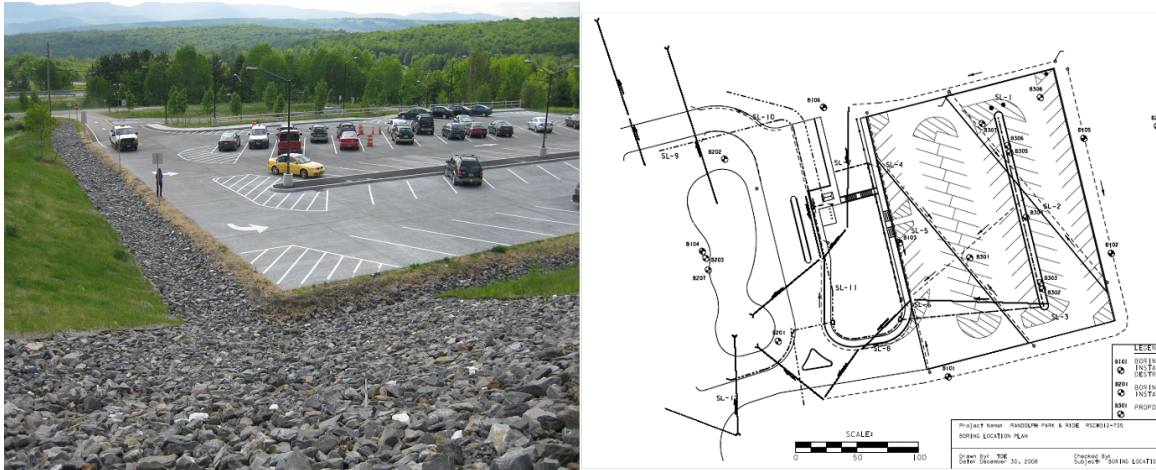


Figure 3.2: The Randolph Park and Ride porous concrete parking lot

### 3.1.2 Site Instrumentation

Twenty-four monitoring wells have been installed on site.

- Six belong to the 100-series which were placed in 2007 prior installation and later closed. Boring logs exist for these locations but no further information.
- Eight wells belong to the 200-series, drilled in 2008. Maximum depth is 37 ft and minimum 13 ft. These wells are used up to today for water level and solute concentration measurements. The 200-series wells are located on the perimeter of the site. Boring logs and slug test data exist.
- Eight wells belong to the 300-series which is the most recent well installation series. They were drilled in 2009 and are all located on the porous concrete area. Maximum depth for the 300-series wells is 21 ft and minimum is 9ft. These wells are mostly used for water level data acquisition. Boring logs and slug test data exist for these wells.
- The remaining two wells are shallow, in-pavement wells. Their depth is to the bottom of the subbase. These wells were placed in order to provide water level measurements for water captured in the coarse stone subbase. However, the wells have been dry since the beginning of their operation.

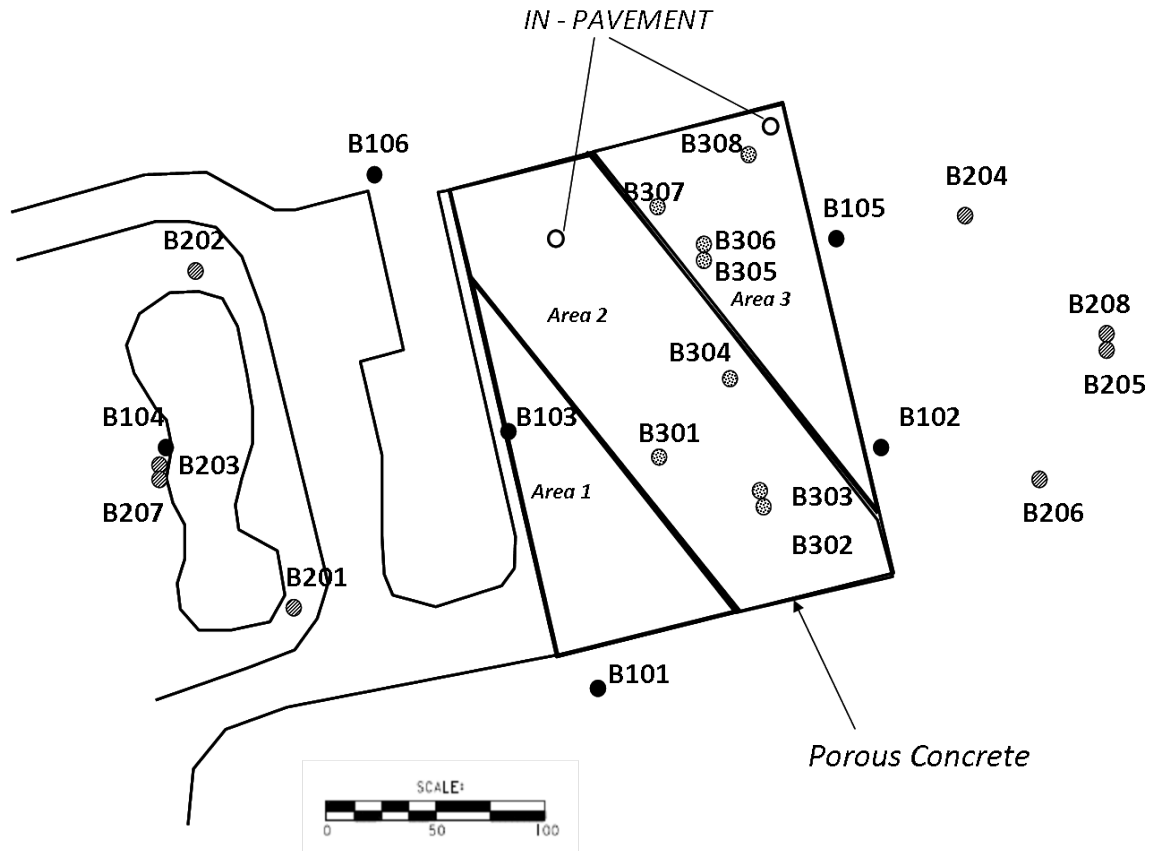


Figure 3.3: Monitoring Wells

### 3.1.3 Site Geology

#### Information provided by Vtrans

At the onset of this research, the site geologist provided the boring logs and slug test data for the monitoring wells. Boring logs were provided for all monitoring wells (100, 200 and 300-series), whereas slug test data were provided for the 200 and 300-series wells. According to the slug test data, hydraulic conductivity for the 200-series wells ranged from 0.001 ft/day to 5.6 ft/d. However, data for the 300-series wells indicated quite impermeable material. Boring log information is attached in the Appendix.

#### Groundwater monitoring

Initially groundwater level data were acquired monthly using water level probes. It became evident though, that these point measurements in time would not be able to indicate the quick water level response after or during a rainfall event. Therefore, a set of pressure transducers, that would allow very detailed water level data acquisition in time was purchased in 2009. Unfortunately, the initial system proved to be malfunctioning and an alternative plan had to be introduced. As a result, a new pressure transducer system was borrowed from UVM and was installed in the field in the Fall of 2010.

Figure 3.4 shows water level data for a period of approximately one month. Rainfall does not seem to affect the groundwater data significantly with the exception of B301.

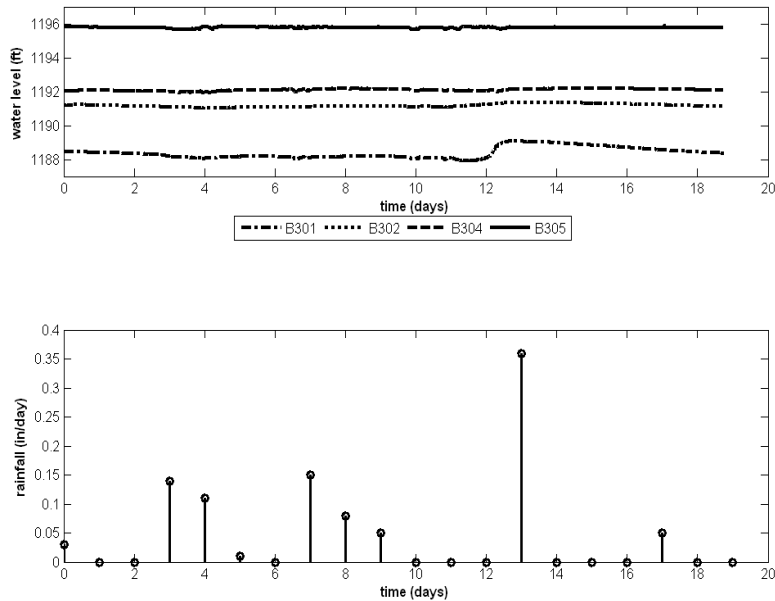
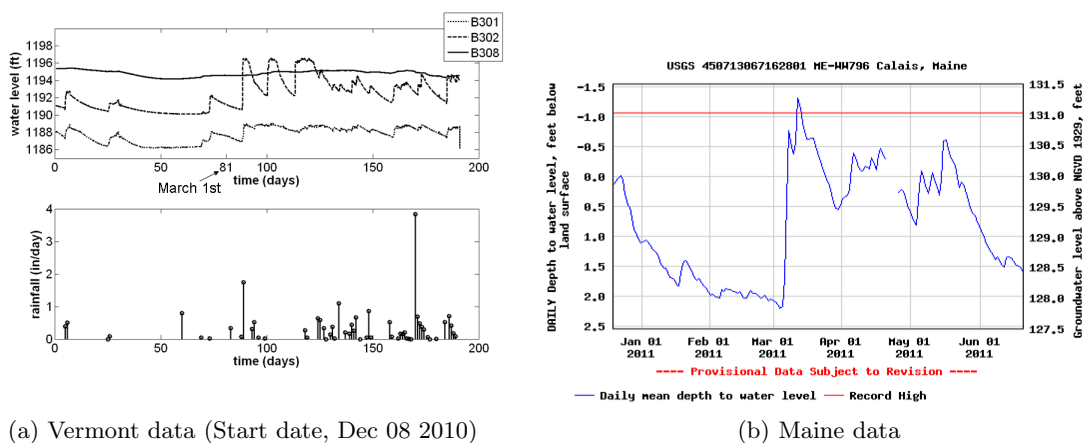


Figure 3.4: Groundwater response during rainfall events (11/19/10 to 12/8/10).

Figure 3.5 presents groundwater level data for the winter period of 2010. Comparison with rainfall data do not show a direct correlation. However, comparison with water level data for Maine (obtained online), for the same monitoring period, show that there is a resemblance in the general trendline, especially for the time period starting in March. This suggests that the data set is correct and it shows the groundwater responds in a seasonal patterns.



(a) Vermont data (Start date, Dec 08 2010)

(b) Maine data

Figure 3.5: Winter 2011 groundwater level data

### Direction of groundwater flow

During the drilling process for the deep wells B303 and B306, the drillers noticed that the groundwater level kept rising and finally exceeded the ground elevation. However, head values in their coupled shallow wells were below ground elevation. This shows that there is an upward gradient in flow and the deep wells are artesian wells.

To measure pressure in the artesian wells, a custom made simple apparatus was manufactured. The apparatus consisted of a pressure gage, which gave measurements in feet of water, attached to the well cap (Figure 3.6).

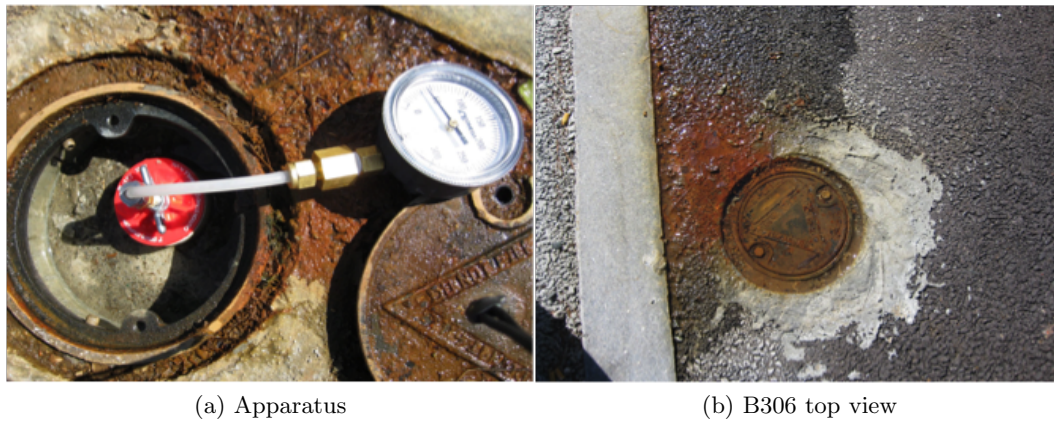


Figure 3.6: Artesian well setup

Table 3.1 shows the pressure measurements in the artesian wells. According to the data, well B306 reaches maximum of 85 inches of pressure, which is an extremely high value not commonly observed in the field. Well B303 initially showed much less pressure equal to 15 inches which later on dissipated even more. The extremely high value of upward gradient as shown mostly by well B306, indicates that stormwater coming in contact with the soil cannot be easily infiltrated into the subsurface.

Table 3.1: Pressure in artesian wells (in inches of H<sub>2</sub>O)

Date	B306	B303
5/7/2010	67	15
6/9/2010	82	15
7/12/2010	85	5
10/14/2010	85	10
8/23/2011	82	5

To calculate the gradient of flow, three conceptual tetrahedra were used, where the edges of each tetrahedron are well locations. The combination of three shallow wells and one deep well form the tetrahedron.

Figure 3.7 shows the location of the tetrahedra on site.

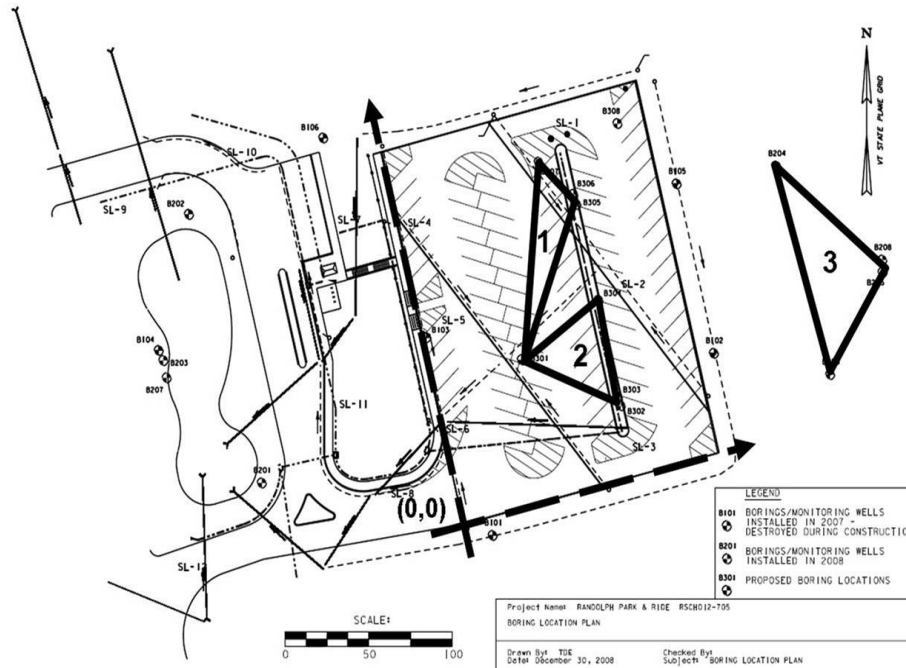


Figure 3.7: Location of tetrahedra on the site's map

The equation that relates the hydraulic head in each well to the well coordinates in the tetrahedron is the following:  $h = a + bx + cy + dz$

Using the coordinates (x,y,z) and head values for each location, the components of the groundwater gradient within the tetrahedron can be calculated.

Table 3.2: Groundwater gradient : Coordinates and calculations

Tetrahedron	Well	x	y	z	h	$\frac{dh}{dx}$	$\frac{dh}{dy}$	$\frac{dh}{dz}$
1	B301	52.17	73.91	-4.6	-2.348	0.0641	0.0391	-0.6841
	B305	102.17	143.48	-2.29	2			
	B307	86.96	171.74	-3.02	2.63			
	B306	102.17	152.17	-11.66	8.75			
2	B301	52.17	73.91	-4.6	-2.348	0.1036	0.0351	-1.3505
	B303	102.17	43.48	-12.87	12.93			
	B302	102.17	39.96	-2.9	-0.658			
	B304	104.35	93.48	-2.86	1.393			
3	B204	221.74	134.78	21.31	27.403	0.0348	-0.0198	-0.1536
	B206	228.26	26.09	24.54	29.283			
	B205	269.56	65.22	24.69	29.903			
	B208	271.74	76.09	6.8	32.511			

*Note: In the coordinates  $z = 0$  at 1190 ft. Flow is positive upwards.*

The results indicate that the flow gradient in the z-direction is one order of magnitude higher than the x and y directions. The negative sign of the gradient shows that there is a positive

velocity since from Darcy's Law  $v = -K * gradient$ , where  $K$ =hydraulic conductivity. This means that there is an upward direction in flow in the area of interest.

## 3.2 Laboratory procedures

### 3.2.1 Grain size distribution analysis

As an initial attempt to categorize the type of soil present in the field, the most inexpensive and rather simple analysis that can be performed is the grain-size distribution analysis. Grain size distribution analysis is performed using sieves of various openings stacked upon each other, with the sieve with the smallest screen size on the bottom. A known weight of soil is placed in the uppermost sieve. After shaking the sieves, the grains smaller than the opening in the top sieve eventually pass to the next lower sieve. The procedure continues until the grains retained in the container at the bottom of the column are smaller than the diameter of the sieve with the smallest mesh. The soil fraction retained on each sieve is removed and weighted and results are plotted [19]. Soil cores obtained from the field and provided by Vtrans were used for the grain-size distribution analysis.

### GSD Analysis -Results

The following graph shows the grain-size distribution curve for two sections of the soil core, for observation well B306.

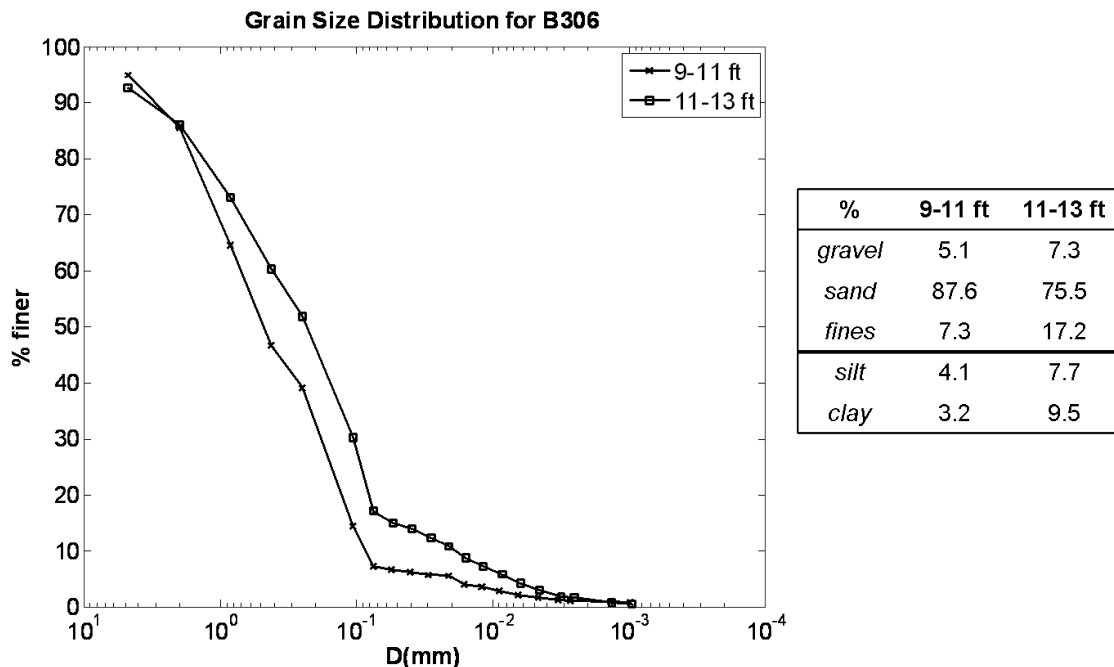


Figure 3.8: Grain Size Distribution curve for a soil core obtained in the field

According to the experimental results, the grain size distribution curve shows that the material is well graded, which verifies the existence of till as the dominant soil material.

Till is a typical material for the New England area and it is characterized by being very well graded (poorly sorted). This means that till material can include a wide range of grain sizes, from gravel to fines.

More specifically, according to the Unified Soil Classification System the material in B306 can be characterized as well-graded sand with silty clay, and the material in B306 as silty, clayey sand. However, it has to be noted, that the grain size distribution information presents a greater amount of sandy material compared to the boring log information as defined by the site's geologist, where fines are more dominant. This could be due to an error introduced in the grain size distribution analysis due to clogging of the sieves from the fines present in the soil.

### 3.2.2 Water retention curve for glacial till

In order to characterize the hydraulic properties of a soil it is important to know the relation between soil water content and matric potential. This relation is called a water-retention curve, water characteristic curve, water content-matric potential curve and capillary pressure-saturation relation, and it describes the negative forces that hold the water in the soil pores above the capillary fringe. These negative forces are known as the capillary pressure or suction. The units used are energy per unit mass ( $\text{Jkg}^{-1}$ ), energy per unit volume ( $\text{Nm}^{-2}$  or Pa) or energy per unit weight (m) (referred to as head). Soil water content can be expressed on a weight basis (gravimetric water content, kg/kg), a volume basis (volumetric water content,  $\theta$ ,  $\text{m}^3/\text{m}^3$ ) or degree of saturation S (volumetric water content  $\theta$  divided by porosity).

The water retention curves are important because they can help in characterizing the soil type present and also are required to solve the unsaturated water flow equation. The slope of the water retention curve or water capacity is used in this calculation. The various experimental methods used require that for each point on the saturation-pressure curve the retention data be obtained with the soil water at hydrostatic equilibrium, meaning the soil water is at rest and has adjusted to the changing pressures applied [5].

The water retention curve exhibits hysteresis caused by size differences between the primary pores and the interconnecting pore throats, changes in the contact angle during wetting and drying and trapped air. Usually there are difficulties in obtaining the imbibition curves so only the drainage curve is traditionally measured [24].

The soil present at the Randolph site has been characterized as till. Water retention curves for till have been successfully determined by Vanapalli et. al [25] using a pressure plate apparatus for suction range from 0 to 1500 kPa, and osmotic desiccators for the range of 2500 to 300 000 kPa. According to their study, it took 6-7 days to attain equilibrium under the applied suction. Their sample had a 63.5 mm diameter.

Tinjum et. al [24], have studied water retention curves for compacted clays using pressure plate extractors and obtained the Van Genuchten and Brooks and Corey parameters using a least square fit to the water retention data. In their study equilibrium was attained after between 5-8 days for each applied suction value.

Water retention experiments for tight soil materials, like the material in the Randolph site, are quite challenging and time consuming. In terms of experimental methods there is great variety, mainly varying according to the type of soil present. In literature, the general

guidance on tight soil samples (for example clay) suggests using very high water and air pressures in order to simulate drainage conditions. However, for the purposes of this specific study, and mainly taking into account the fact that in field conditions such high pressures are not very easily reached, the authors decided to use much lower pressures and define the curve partially.

### **Experimental method**

Water retention experiments involve two main processes. Drainage, where water is removed from the sample, and imbibition where water is placed back in the sample. In this study focus was given on the drainage curves.

The essence of the experimental procedure used in the specific study to acquire the drainage curve is the following:

The experiment starts with a fully saturated sample. Air pressure is applied at the top of the sample (provided by an air supply) and water pressure at the bottom (applied by a water pump). Capillary pressure is then defined as the difference between the air and water pressure. The air pressure stays stable through the experiment and water pressure is reduced in incremental steps. By watching the data recorded on the computer, that is volume withdrawn over time, the user can decide whether equilibrium is reached for the given step and move to the next pressure step. Each capillary pressure-saturation couple is a point in the water retention curve.

So far 3 experimental methods have been used in order to obtain the drainage curve. The common instrument in all three methods is a pump used to pressurize water, which enters the soil from the bottom according to the user-defined pressure. The volume of water moving through the pump through time is also monitored through the pump and logged into a computer.

- **Method 1:** The soil sample is retained by a plastic membrane and placed inside a confining cell. The cell is filled with water and put under pressure so that the plastic membrane pushes against the sides of the sample and preferential flow around the sample is prohibited. A porous disc is used as a contact surface between the soil sample and the water pump outlet tube.
- **Method 2:** No confining cell filled with water is present. The sample is placed inside a conventional pressure cell instead.
- **Method 3:** Instead of applying air pressure on the top of the sample, the top is left open to the atmosphere and negative values of water pressure are used. However, this method restricts maximum water pressure to -50 kPa which is the limit of the water pump.



Figure 3.9 shows the apparatus used for the different experimental methods.

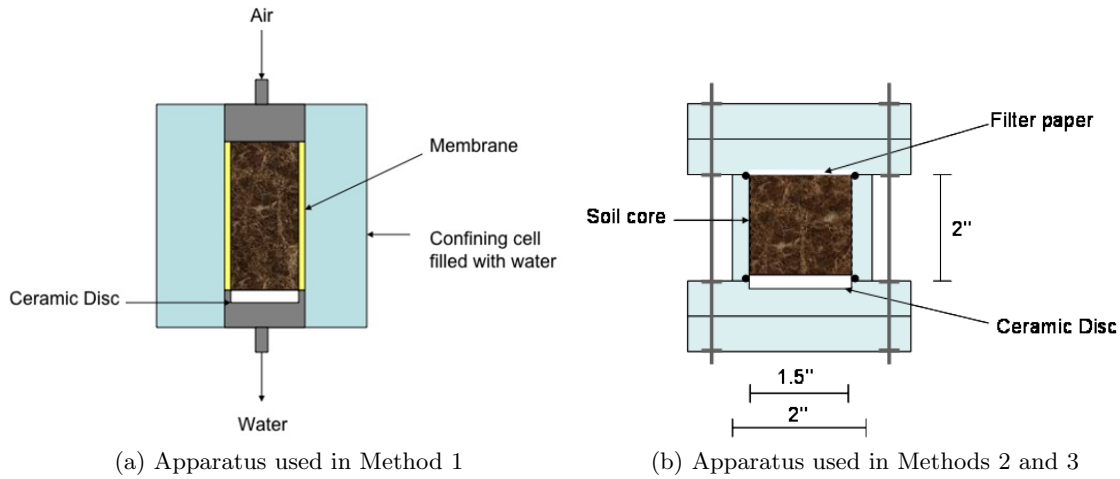


Figure 3.9: Water Retention Curve Experimental Apparatus

*Note: Each sample is preprocessed by crushing and oven drying. Then it is reconstituted inside the cell by matching the dry density of the soil in the field.*

### Water retention curve - Results

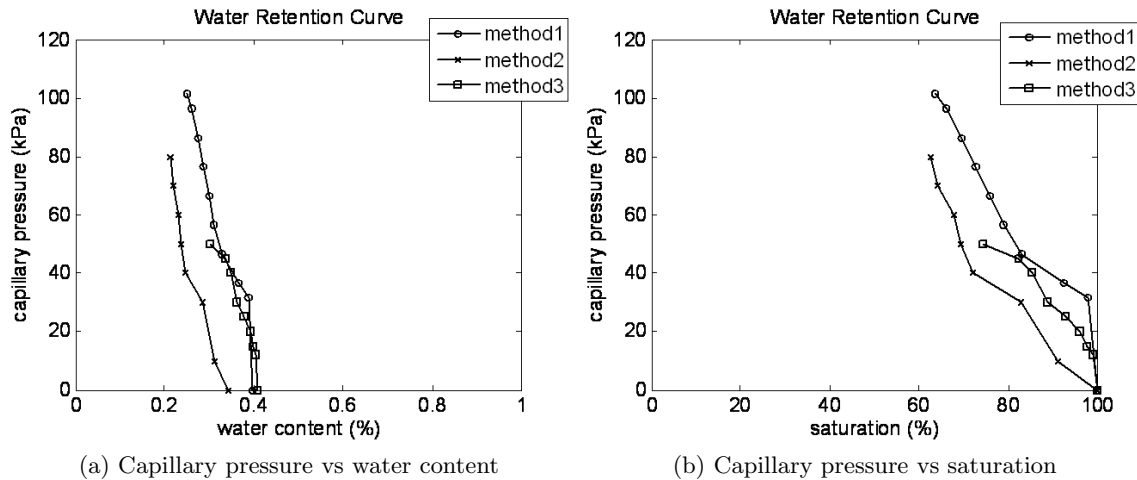


Figure 3.10: Water Retention Curve results

Data from the three methods appear to provide slightly different results. However, taking into consideration the scaling of the water content axis, the results are acceptable, since there is a small deviation compared to the full range of the curve.

After obtaining these curves, the next step is to insert the curve's "information" into the groundwater model that will be used for the site simulation. The curve's "information" is in the form of fitting parameters, which are characteristic of the shape of the specific curve.

These parameters can be obtained using least square's fitting software, such as the online software SWRC Fit. However, the lack of data points close to residual saturation provided erroneous results during the initial trials of the model fitting. In order to overcome this problem, another phase of the water-retention experiments needs to be performed. This phase will include full saturation of the soil sample and then on-top application of high air pressure, which will allow the water to drain from the bottom. This way a value close to the residual saturation will be obtained and results from SRWC Fit will be more accurate. This experiment is scheduled to take place in the near future.

### 3.3 Retention and subsequent evaporation of stormwater

Lack of water accumulation in the drop inlets led to the hypothesis that an amount of water could be retained by the coarse stone's surface and then evaporate into the air. In order to test the hypothesis the following experiment was performed.

#### Experimental Setup

Two columns of similar weight are hanging in balance. Column 1 is supposed to mimic the sequence of materials found at the site. Therefore it is filled with 36 inches of crushed stone and a porous concrete core is placed on top. Column 2 serves as the counterbalance (in this case it is also filled with crushed stone). A load cell is placed below column two. The load cell is able to monitor the tension applied to Column 2 through time. The setup is shown in Figure 3.11 and Figure 3.12.

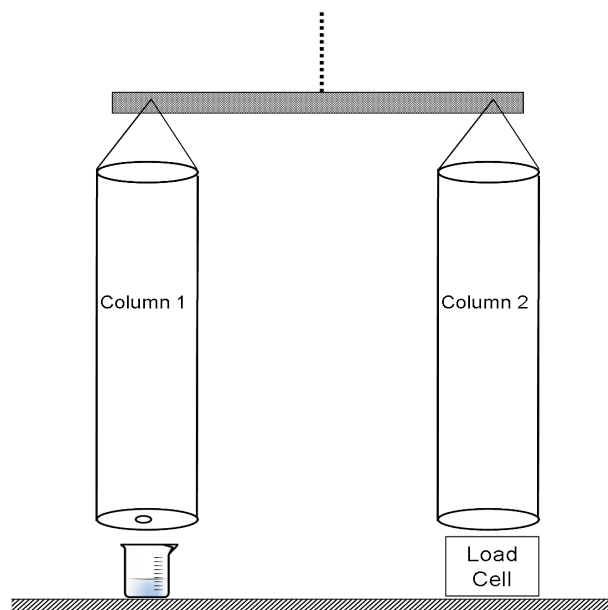


Figure 3.11: Experimental setup for evaporation experiment

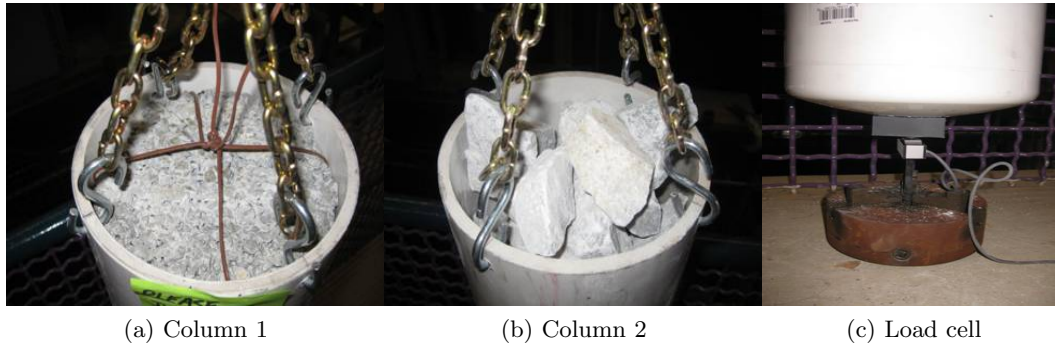


Figure 3.12: Detail of Experimental setup

### Experimental method

In the first part of the experiment a known amount of water is added as rainfall on top of Column 1 causing the balance to shift. Column 1 is left to drain excess water not retained on the crushed stone through a small opening in the bottom. By knowing the amount of water that was added from the top as rainfall and the amount that drained from the bottom, the water withheld by the crushed stone can be calculated. Once water stops draining from the column, a rubber plug is used to seal the opening. Water is then left to evaporate.

As the balance shifts with the addition, drainage or evaporation of water, the load cell is able to record all the pressure changes. The amount of evaporation can be then measured as the difference between two adjacent sequential measurements.

So far 3 tests have been performed.

- **Test 1:** Column 1 contained only crushed stone. The bottom of Column 1 was open to the atmosphere.
- **Test 2:** A core of porous concrete was added on top of the crushed stone in column 1. The bottom of Column 1 was open to the atmosphere.
- **Test 3:** Similar to Test 2. The bottom of Column 1 was sealed using a plug.
- **Test 4:** Similar to Test 2. The bottom of Column 1 was open to the atmosphere.

### Results

It should be noted that the different time durations between the tests was mainly due to technical difficulties and user mistakes while getting acquainted with the equipment. In addition, for the same reason, data from the computer in Test 2 were partially scaled so that the ending point of the computer data would match the starting point of the data from the load cell display. This was a safe assumption though, since it was known that these two measurements were taken on the same day and, considering the low evaporation rates observed from the other tests at this stage, the deviation should be minimal.

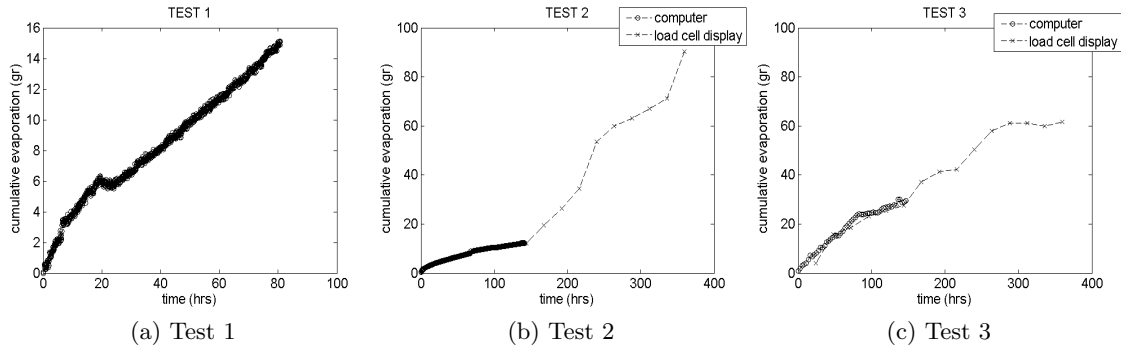


Figure 3.13: Evaporation experiment results for Tests 1, 2 and 3. Test 2 and 3 show combination of data obtained through the computer and on the load cell display.

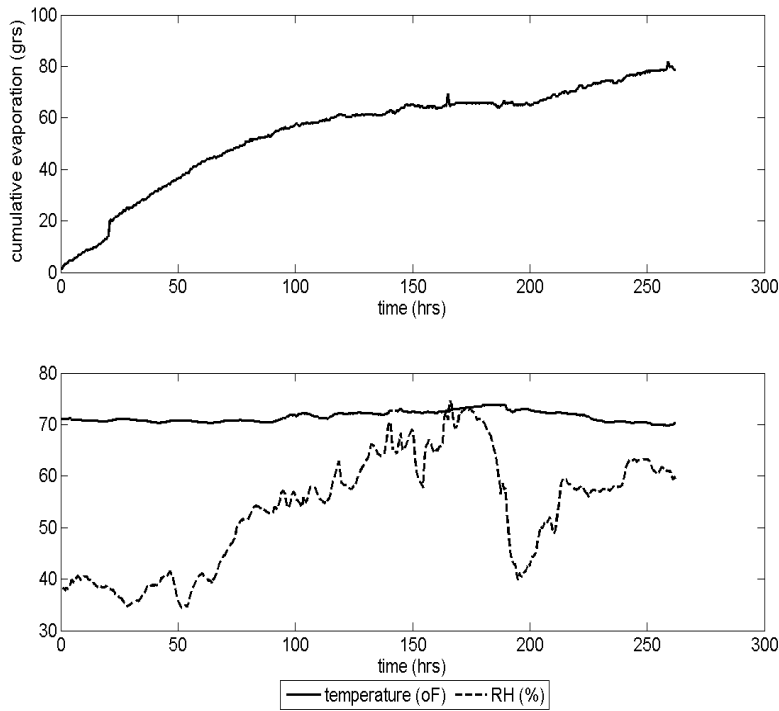


Figure 3.14: Evaporation experiment results for Test 4. Temperature and relative humidity was also monitored during this Test.

Table 3.3: Evaporation Test Results

	Test 1	Test 2	Test 3	Test 4
mass evaporated (grs)	15.102	90.2664	61.6896	78.6738
total time (hrs)	80.787	360	360	262
evaporation rate (grs/hr)	0.187	0.25	0.171	0.3
mass of water retained (grs)	(not measured)	(not measured)	293	163

Experimental results show that there is a significant amount of water retention and evaporation inside the coarse stone subbase. However, it does not fully explain the lack of water accumulation in the drop inlets.

## Chapter 4

# Mathematical Model

The challenge with constructing a mathematical model for a porous concrete system, such as the one in Randolph, lies in the fact that the physical system is composed of hydrodynamically different interconnected pieces due to the variety of physical processes that take place. These processes include:

- surface recharge from rainfall
- runoff from the porous pavement or surrounding conventionally paved areas
- vertical flow into the porous concrete and crushed stone
- potential storage of water inside the crushed stone excavated area
- evaporation
- flow towards the underdrains
- and infiltration into the subsurface.

Therefore the mathematical model that will be used to simulate a porous concrete site must not only account for all these processes independently, but also take into account the interconnection of the different pieces.

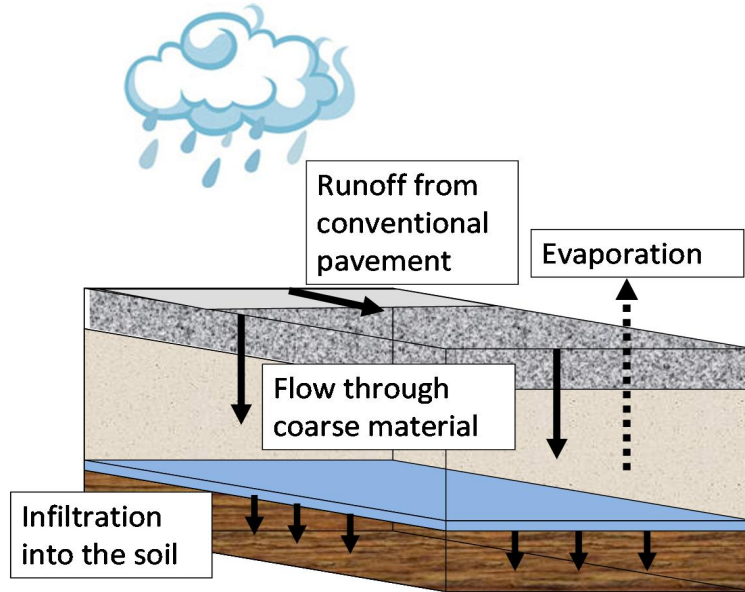


Figure 4.1: Physical processes taking place in a porous concrete system

Due to the complexity of the problem, two different modeling approaches were used.

- **First modeling approach:** A surface-water model is used to simulate runoff from conventionally paved areas that at the edges could potentially act as recharge into the porous concrete slab. A groundwater model (VTC) is used to simulate flow through the porous concrete to the coarse stone subbase, and finally to the subgrade soil.

*Challenge:* In this specific modeling approach, there is an extra modelling challenge due to the existence of underdrains inside the coarse stone subbase, which dictate the flow. A 'correct' boundary condition is required. Also, the coarse stone material is not a conventional 'porous media' since the term containing capillary pressure is not valid, therefore there is a significant error in the results that the classical porous medium equations provide.

- **Second modeling approach:** A surface-water model is used to simulate runoff from conventionally paved areas that could potentially act as recharge into the porous concrete slab. Flow through the porous concrete and the coarse stone subbase is simulated through a mass balance model. The surface-water model is also used to simulate flow towards the underdrains at the bottom of the subbase. Finally a groundwater model (VTC) is used to simulate flow from the subbase to the subgrade soil.

*Challenge:* There is a high degree of complexity in connecting the three different codes, some of which are written in fortran and others in matlab.

In the following sections the different models are summarized.

## 4.1 Runoff on pavement module

The runoff component in a porous pavement system is very important since at its perimeter it can add an extra recharge term to the porous pavement. In order to avoid any confusion,

at this point it is important to note that in this specific study, runoff from the porous pavement itself was considered negligible, a hypothesis which agrees with literature examples [3]. The term runoff here represents runoff from conventionally paved areas in direct contact with the porous pavement.

The surface model that will be used in the specific study is a modification of a code written by Professor J. Laible<sup>1</sup>. The original code solves the full form of the vertically (depth) averaged Navier-Stokes equations known as the St. Venant equations shown below.

*Continuity:*

$$\frac{\partial H}{\partial t} + \frac{\partial HU}{\partial x} + \frac{\partial HV}{\partial y} = 0 \quad (4.1)$$

*Momentum:*

$$\begin{aligned} \frac{\partial HU}{\partial t} + \frac{\partial HUU}{\partial x} + \frac{\partial HVU}{\partial y} - fHV + \frac{H}{\bar{\rho}} \frac{\partial P_0}{\partial x} + g_{eff} H \frac{\rho_\zeta}{\bar{\rho}} \frac{\partial \zeta}{\partial x} + \frac{g_{eff}}{\bar{\rho}} \int_h^\zeta I_x dz \\ - \tau_{sx} + \tau_{bx} - \left( \frac{\partial}{\partial x} \left( H \epsilon_h \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( H \epsilon_h \frac{\partial U}{\partial y} \right) \right) = 0 \end{aligned} \quad (4.2)$$

$$\begin{aligned} \frac{\partial HV}{\partial t} + \frac{\partial HUV}{\partial x} + \frac{\partial HVV}{\partial y} - fHU + \frac{H}{\bar{\rho}} \frac{\partial P_0}{\partial x} + g_{eff} H \frac{\rho_\zeta}{\bar{\rho}} \frac{\partial \zeta}{\partial x} + \frac{g_{eff}}{\bar{\rho}} \int_h^\zeta I_y dz \\ - \tau_{sy} + \tau_{by} - \left( \frac{\partial}{\partial x} \left( H \epsilon_h \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left( H \epsilon_h \frac{\partial V}{\partial y} \right) \right) = 0 \end{aligned} \quad (4.3)$$

where  $U$  and  $V$  are the vertically averaged velocities in the  $x$  and  $y$  direction,  $\zeta$  is the deviation of the water depth from mean sea level,  $H$  is total water depth,  $g_{eff}$  is the effective gravity,  $P_0$  is the surface pressure,  $f$  is the Coriolis coefficient,  $\epsilon_h$  is the horizontal eddy viscosity,  $\tau_s$  is the wind stress,  $\tau_b$  is the bottom friction, and  $I$  is the baroclinic term.

After adding a ‘‘rainfall’’ term in the continuity equation and considering the coriolis parameter and baroclinic term as negligible for the case of runoff on a concrete surface, the equations become:

*Continuity:*

$$\frac{\partial H}{\partial t} + \frac{\partial HU}{\partial x} + \frac{\partial HV}{\partial y} = q \quad (4.4)$$

*Momentum:*

$$\frac{\partial HU}{\partial t} + \frac{\partial HUU}{\partial x} + \frac{\partial HVU}{\partial y} + \frac{H}{\bar{\rho}} \frac{\partial P_0}{\partial x} + g_{eff} H \frac{\rho_\zeta}{\bar{\rho}} \frac{\partial \zeta}{\partial x} - \tau_{sx} + \tau_{bx} - \left( \frac{\partial}{\partial x} \left( H \epsilon_h \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( H \epsilon_h \frac{\partial U}{\partial y} \right) \right) = 0 \quad (4.5)$$

$$\frac{\partial HV}{\partial t} + \frac{\partial HUV}{\partial x} + \frac{\partial HVV}{\partial y} + \frac{H}{\bar{\rho}} \frac{\partial P_0}{\partial x} + g_{eff} H \frac{\rho_\zeta}{\bar{\rho}} \frac{\partial \zeta}{\partial x} - \tau_{sy} + \tau_{by} - \left( \frac{\partial}{\partial x} \left( H \epsilon_h \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left( H \epsilon_h \frac{\partial V}{\partial y} \right) \right) = 0 \quad (4.6)$$

The code finally solves for velocity and height of water at the edge, as well as on the pavement. The source term to the porous pavement will be represented by the product of

<sup>1</sup>J. Laible, Professor Emeritus, UVM



the fluid water thickness times the normal velocity at the boundary of the porous concrete pavement and the conventional pavement.

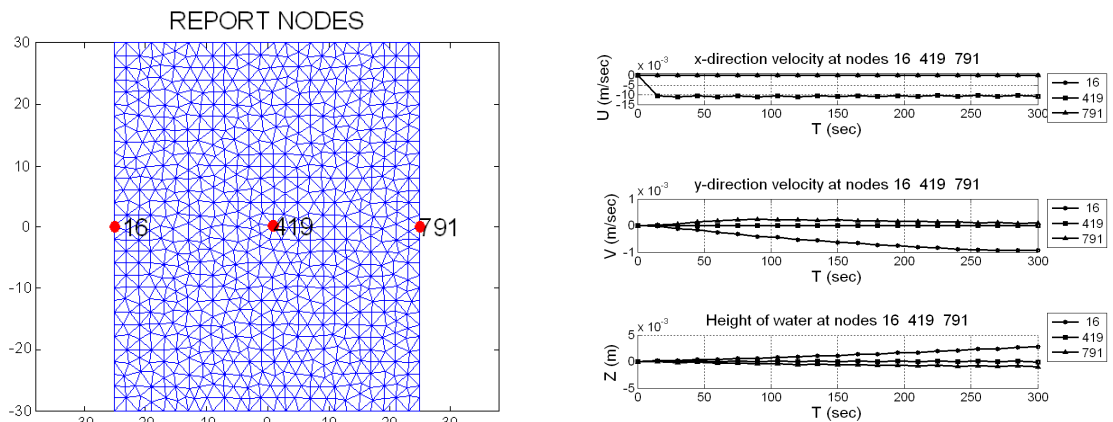
One of the challenges in using a surface water model, which is typically used to simulate flow patterns in large water bodies such as oceans or lakes, to simulate runoff on a pavement surface, is the fact that friction is now an important component. This means that friction coefficients in the model needed to be altered in order to provide meaningful results. In addition, the model requires a value of the initial height of water on the pavement that, for the purposes of this simulation, was kept to values on the order of a millimeter. Finally, the main modification in the existing code involved the boundary condition that should be used to simulate flow over the edge of the pavement. The various boundary conditions that were tested are the following:

- $u = 0$ . Velocity is equal to 0.
- $z = 0$ . The height of water is equal to 0.
- $\frac{dz}{dx} = 0$ . The slope of water surface is equal to 0.
- $z = aV_n^2$ . From Bernoulli’s law, the elevation head (or height of water in this case) is equal to the velocity head, where  $a$  is a calibration parameter and  $V_n$  the velocity vertical to the boundary. This boundary condition proved to provide the most meaningful results and was used in the majority of the simulations.

### 4.1.1 Example

In the following example a rainfall event of 1 in/hr on a 50m X 60m domain with slope of 0.1 % is simulated. The simulated period for this example was kept to 5 minutes. The boundary condition used was no flow for the perimeter of the domain with the exception of the downslope side, where the  $z = aV_n^2$  boundary condition was used.  $a = 0.001$

### Results



(a) Location of “report” nodes

(b) Velocity and height of water at “report” nodes

Figure 4.2: Results - Part 1

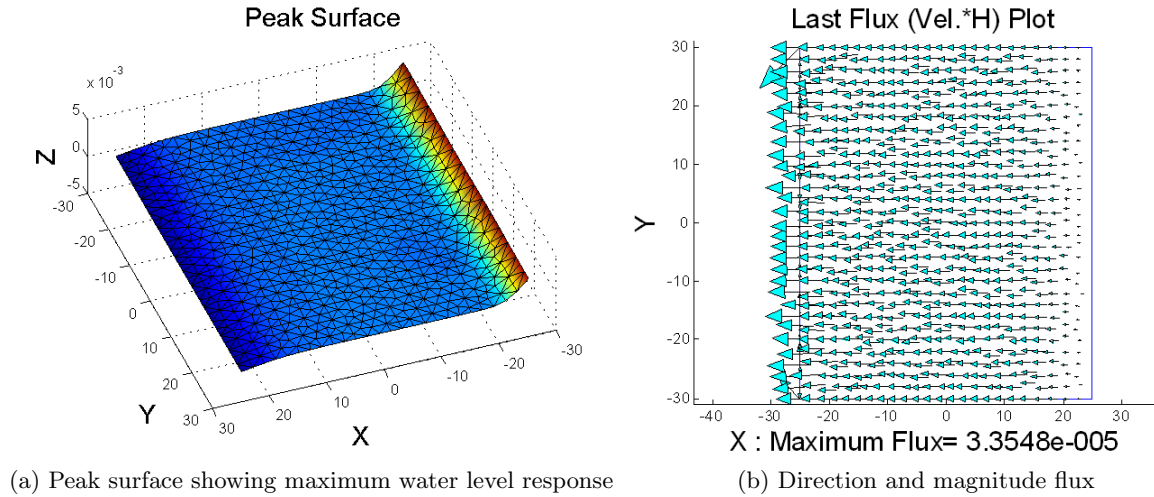


Figure 4.3: Results - Part 2

## 4.2 VTC Module

The groundwater model that will be used in this study is called the Vermont Variably-Saturated Transport Code (VTC). It is a three-dimensional groundwater flow and contaminant transport model that uses a set of partial differential equations to represent saturated and unsaturated subsurface flow as well as contaminant transport. The equations are solved using finite element and finite differences methods. More specifically, the domain of interest is discretized in horizontal layers and a finite element method is used within each layer allowing the representation of an irregular domain. The layers are then connected vertically using a finite difference approximation.

To represent saturated groundwater flow as a function of hydraulic head  $h$  the following equation can be used:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + S_s \frac{\partial h}{\partial t} - q = 0 \quad (4.7)$$

And for unsaturated groundwater flow:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + \frac{\partial \theta_w}{\partial t} - q = 0 \quad (4.8)$$

where  $K$  is the hydraulic conductivity which in the case of unsaturated flow is a function of the water content  $\theta_w$ . The variable  $S_s$  is the specific storage and  $q$  is the flux entering the groundwater system.

VTC uses an iteration scheme to solve the non-linear equations of unsaturated groundwater flow, during which relative permeability values are being updated using the Van Genuchten model. The iteration scheme stops when a user-specified convergence criterion is reached. Parameters needed for the Van Genuchten model can be provided experimentally through the definition of the water retention curve. Upon successful execution of the code the user is able to plot the solution in the form of a contoured surface or 3-D graph via the Argus

interface. The VTC graphical user interface (GUI) is written in Fortran. The code has been successfully validated by previous researchers but use for the specific application required further modifications in the code. At this point the code is able to compute difference in saturation values and plot their contour graph.

As mentioned previously, VTC will be used to either simulate flow through the whole system (porous concrete, coarse stone and subgrade soil) or just the subgrade soil, according to the modeling approach that will provide the most accurate results. In the following example, VTC was used as part of the first modeling approach, meaning to simulate flow through the whole system.

#### 4.2.1 Example

This example shows a simple simulation of the site during rainfall. Figure 4.4 shows the “conceptual” layer setup in the model. The term “conceptual” refers to the fact that in VTC all geometry information is entered through Argus into a 2-D top view and then integrated vertically. So Figure 4.4 is a visual representation and not the explicit way that layers are entered in the model.

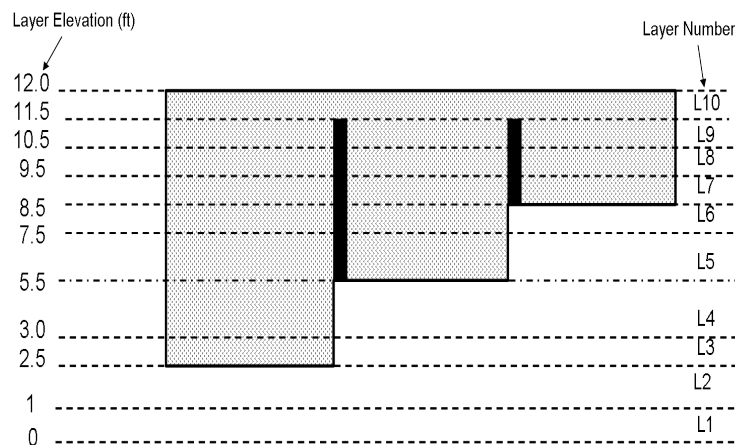


Figure 4.4: Layer setup in VTC

Also, it is important to note, that the purpose of this example was to test whether water can be accumulated at the bottom of the subbase. For this reason a no flow boundary condition was used for the underdrains. However, according to the way the Randolph site was designed, all water that potentially reaches the subbase, is then captured by the underdrains and flows towards the drop inlets. This means that significant water accumulation in the subbase is highly improbable. Even though the specific example is not accounting for flow towards the underdrains, it is a good point of departure to test whether the model can simulate accurately flow inside the coarse stone.

## Results

Figures 4.5, 4.6 and 4.7 show the simulation results after a 2-hour, 1-inch rainfall event. Hydraulic Conductivity for the porous concrete and coarse stone is 1000 ft/hr and for the subsoil 0.00004 ft/hr.

Results showed that there was a higher difference in saturation in the top layer (Layer 10), which decreased in the lower layers. This means that for the duration of this simulation water was retained by the coarse stone and did not reach the bottom of the subbase. Although this seems reasonable for the duration of the simulation, further testing showed that the code was not able to capture any water accumulation at the bottom of the subbase. This requires some further testing.

In addition, results show a significant amount of noise, which is evident in the contour graphs. The reason behind this lies on the way that VTC solves the non-linear equations for the coarse material in the porous concrete subbase. Changes need to be made in the code so that the noise is minimized.

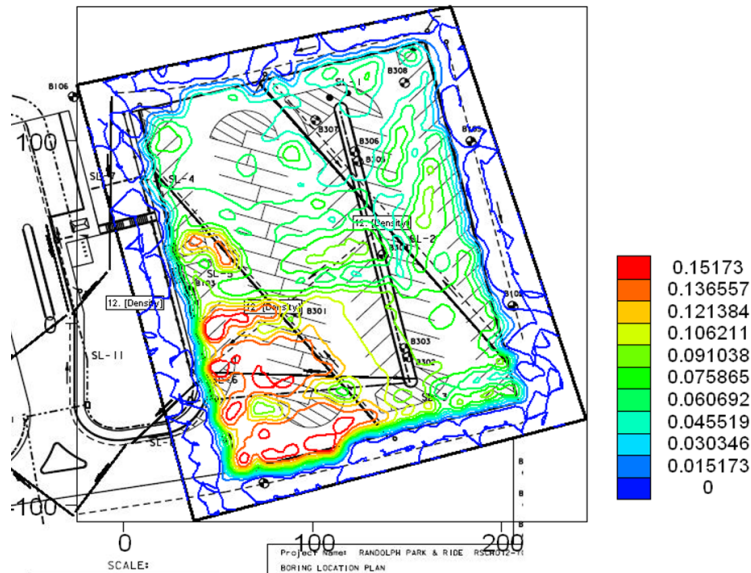


Figure 4.5: Simulation results in Layer 10 (top layer)

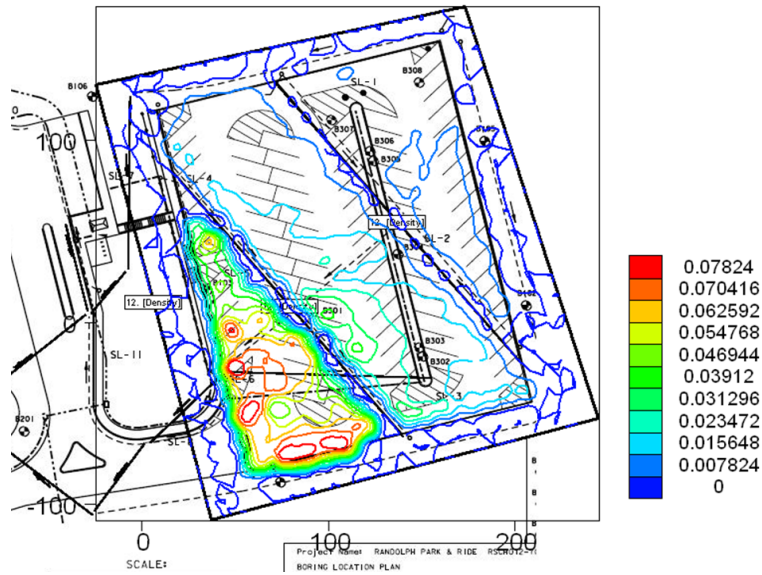


Figure 4.6: Simulation results in Layer 7

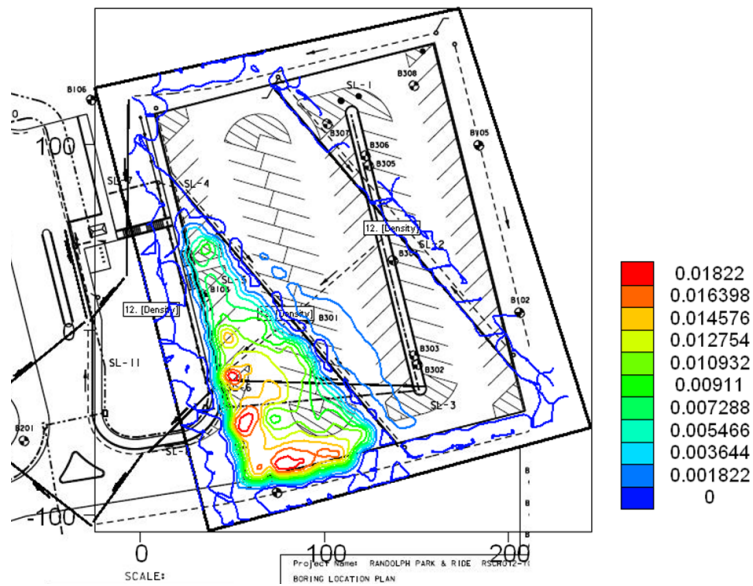


Figure 4.7: Simulation results in Layer 5

## Conclusions

- There is significant noise in the results which is related to the way that VTC solves the non-linear equations for the coarse material in the porous concrete subbase.
- Results up to date did not show water accumulation in the bottom of the subbase as water seemed to be retained in the intermediate layers.
- The boundary conditions for the underdrains need to be further examined.

Taking the above into consideration the code needs to be further modified in order to represent the system more accurately.

### 4.3 Retention and evaporation of water in the gravel

For the purposes of this study and due to the lack of existing equations found in the literature, a separate piece of code is currently being developed to describe flow through the coarse stone. In the derivation of the appropriate equations the point of departure is the definition of the mass balance equations for the liquid and gas phases. Then the equations describing water in the gas phase, air in the gas phase, air in the liquid phase and water in the liquid phase are specified. An evaporation term is used to define the amount of water leaving the system. Additional terms for velocity and porosity are present. After simplifying assumptions equation 4.9 is derived:

$$\int_b^t \frac{\partial s^l}{\partial t} dz + \int_b^t \frac{\partial s^l v_z^l}{\partial z} dz + \int_b^t \frac{q^v s}{\rho^l \epsilon} dz = 0 \quad (4.9)$$

where the limits  $b$  and  $t$  are the bottom and the top of the crushed stone,  $s^l$  is the liquid water saturation,  $v_z$  is the vertical velocity of the water and  $q^v s$  is the evaporation flux.

At this point an initial attempt at coding the equations has been performed but the code needs to be further enhanced and tested. In this work a simple mass balance code was used in order to simulate flow through the coarse stone and subsequent evaporation. The input into this code is rainfall (in incremental steps), the percentage of water that can be retained by the coarse stone (as defined in the lab), and the evaporation rate (also defined in the lab). Output is the outflow which is defined as:

Outflow = Rainfall - Evaporation - Amount of water retained by the stone

#### 4.3.1 Example

In this example:

- Rainfall is added sequentially for the first 4 hours and then it stops.
- Evaporation starts when rainfall has ceased and is equal to 0.171 grs/hr.
- Amount of rainfall retained is 63 % of the original amount of rainfall. After the maximum amount of rainfall is retained any additional rainfall becomes outflow.

## Results

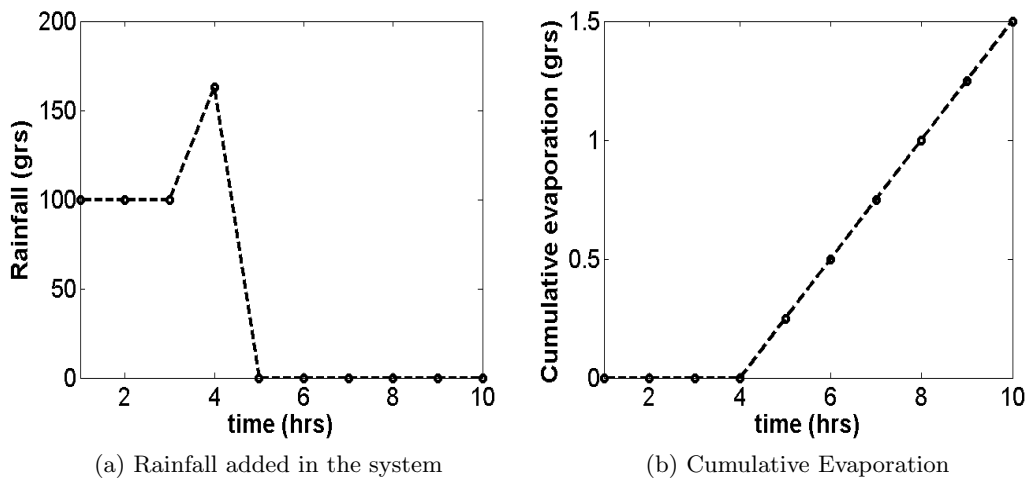


Figure 4.8: Model results simulating flow through coarse stone and evaporation (a)

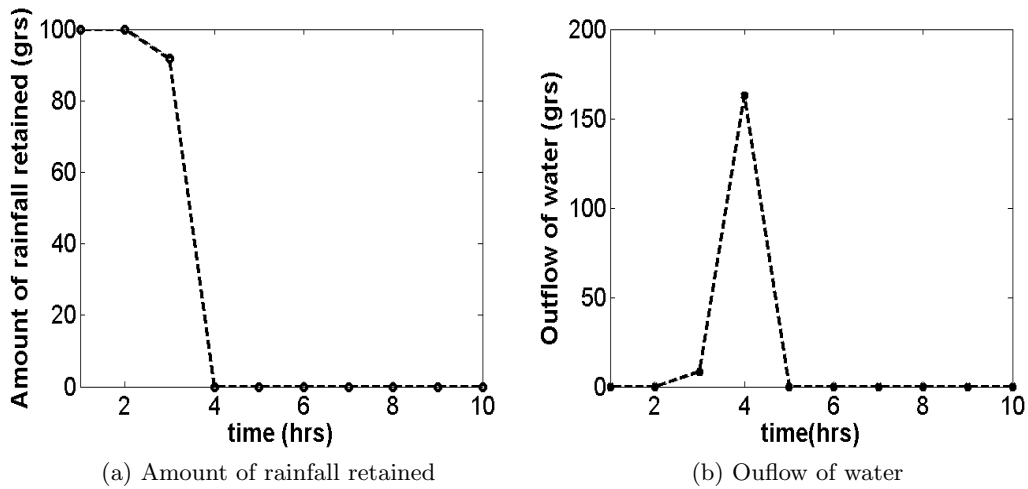


Figure 4.9: Model results simulating flow through coarse stone and evaporation (b)

The "outflow" term for this model can then be used as the recharge term to VTC, which will then calculate infiltration to the subgrade soil.

## 4.4 Discussion

At this point, both modeling approaches have been used to model the site. However, both approaches have advantages and disadvantages.

As mentioned previously, the main challenge with the first modeling approach or in other words with using VTC to handle the simulation of the whole system (with the exception of

runoff), lies in the fact that significant changes are required to the computer code in order to simulate the coarse stone material. These are changes in the equations used, addition of an evaporation term (which has been incorporated into the code with questionable success) and perhaps changes in the numerical methods that VTC uses to solve these equations.

Regarding the second modeling approach, where all the different model pieces will be used, the main challenge lies on the way that the pieces will be connected. Connection of matlab with fortran codes is plausible using matlab MEX files and has been tried successfully by the authors of this research. However, this also introduces extra mini challenges such as making sure that the same time step is used for all different codes, and also technical code issues.

Taking the above into consideration, it becomes evident that although all the different pieces that will compose the final mathematical model are present at this point, more time is required in order to evaluate the two modeling approaches and overcome the various difficulties.



## Chapter 5

# The Field Experiment

### 5.1 Reason behind the experiment

Although the Randolph site is equipped with numerous monitoring wells and drain inlets, its complicated design in combination with various equipment malfunctions made on-site groundwater level monitoring a challenging task.

According to the site's design, as soon as water enters the porous concrete slab, and taking into consideration that the subsoil is composed of dense till deposits, water should gather in the drop inlets. However, water level data in the drop inlets did not respond as expected. Initial observations could have somehow been skewed by the malfunction of the equipment as mentioned previously. However, even visual observations verified the assumption that the water level gathered inside the inlets did not sum up to the amount of water that was expected.

A possible explanation for this issue, except possible construction errors, is the retention of water in the coarse stone reservoir and subsequent evaporation.

In order to finally come up with a solid theory of "where the water is going" Vtrans in collaboration with UVM decided to run a field experiment where a controlled release of water would take place on site. Salt would also be added in the water as a tracer.

### 5.2 The day of the experiment

On August 23rd a crew composed of members of Vtrans, UVM and the local Montpelier fire department gathered on site at Randolph Park and Ride for the controlled water release. Around 9.00 am background conductivity and initial water level measurements took place.

The water release took place in three separate events. The first water release took place at 10:55, the second at 12:45 and the third at 13:50. The release took place on the upper portion of the lot (A3) using the hose and not a sprinkler as was initially suggested mostly due to time constraints. During the experiment water samples were collected from key locations around the site.

The following sections present and discuss the data acquired.

## 5.3 Results

### 5.3.1 Water Levels

The following graphs present the water level response in the drop inlets during the three water release events. In the graphs time 0 refers to August 23rd, 9.04 am. and the three dots indicate the onset of the three separate water release events.

Figure 5.1 shows that both upstream and downstream locations in SP1 respond to the events in a similar way. The onset of each water release event is accompanied with a slight increase in water level followed by a slight drop. However, a comparison of the maximum water level value (1192 ft) to the height of the weir in that location (1194.5 ft) shows that the weir was not exceeded.

In SP2, as shown in Figure 5.2, the upstream location responds in a similar manner to the downstream location of SP1. Actually, the water levels are almost identical which verifies the interconnectivity of the two locations through a drain according to the site plans. The downstream location is slightly increasing through time. Once again, in the upstream location of SP2 the maximum water level value (1189.5 ft) is still lower than the height of the weir (1191.5 ft).

Figure 5.3 shows that there is a water level increase in the upstream location of SP3 whereas the downstream location is rather unaffected until the third water release event (third dot) when the weir was exceeded. This observation was also visually verified on site.

Water levels in the 200 series wells, as shown in Figure 5.4 and Figure 5.5 do not seem to be affected by the water release events, with the exception of B203 and B207 where there is a slight decrease in water level. More specifically in B203 there is a sudden drop in water level after the third event, whereas B207 presents a smoother water level decline.

The 300 series wells showed more clear response to the water release as shown in Figure 5.6 and Figure 5.7. However the response was quite surprising. Instead of an increase in water levels as it would be expected the specific locations show a significant decline in head which starts as soon as the first event takes place. We can see that the phenomenon is obvious in all locations with the exception of well B301 which is the furthest away from the water release location. The drop in head reaches a maximum of almost 4 ft which is a tremendous response for the time frame over which it occurred.

Inverse water level response has been previously noted in literature but only for pumping tests where water is extracted from the aquifer. The phenomenon is known as the Noordbergum effect <sup>1</sup> and is usually observed in confined and clayey aquifers. The range of inverse water level response found in literature, related to the Noordbergum effect is approximately 0.05 ft [20] to 0.2 and 0.3 ft [20], [21]. Further research is required in order to present a solid explanation of the paradox water level response during the field experiment.

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<sup>1</sup>More information on the Noordbergum effect can be found in Appendix D

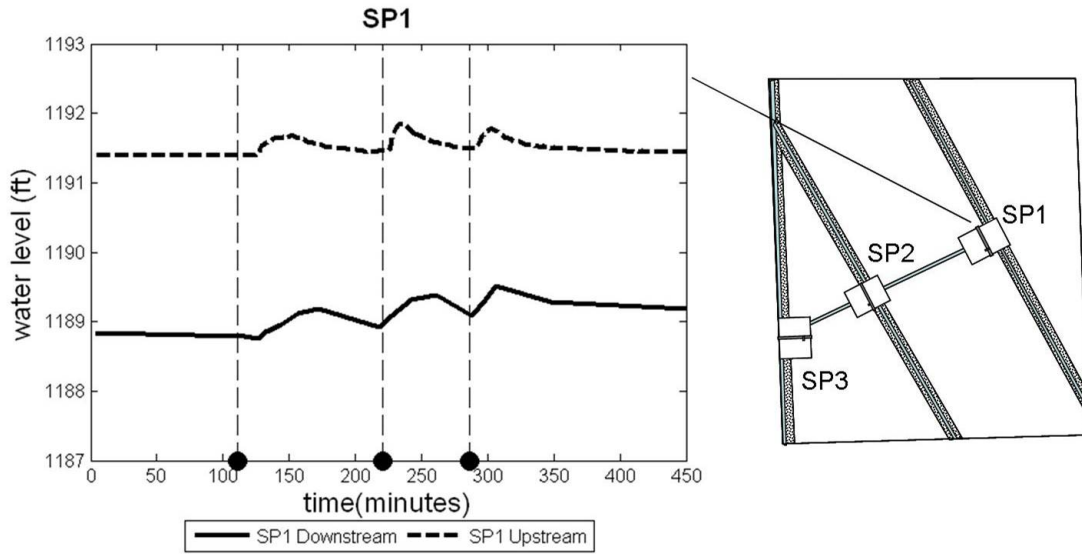


Figure 5.1: Water Levels in SP1.

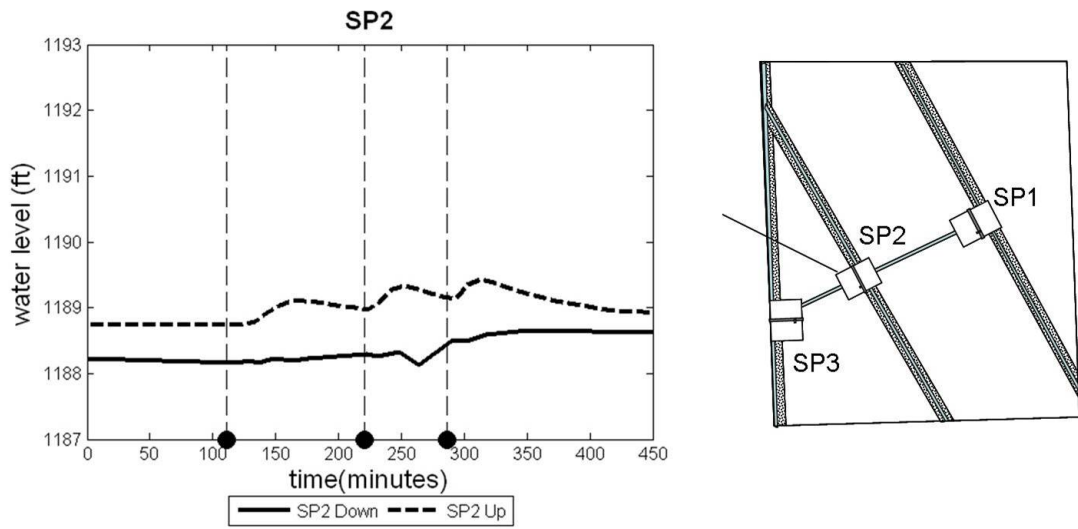


Figure 5.2: Water Levels in SP2.

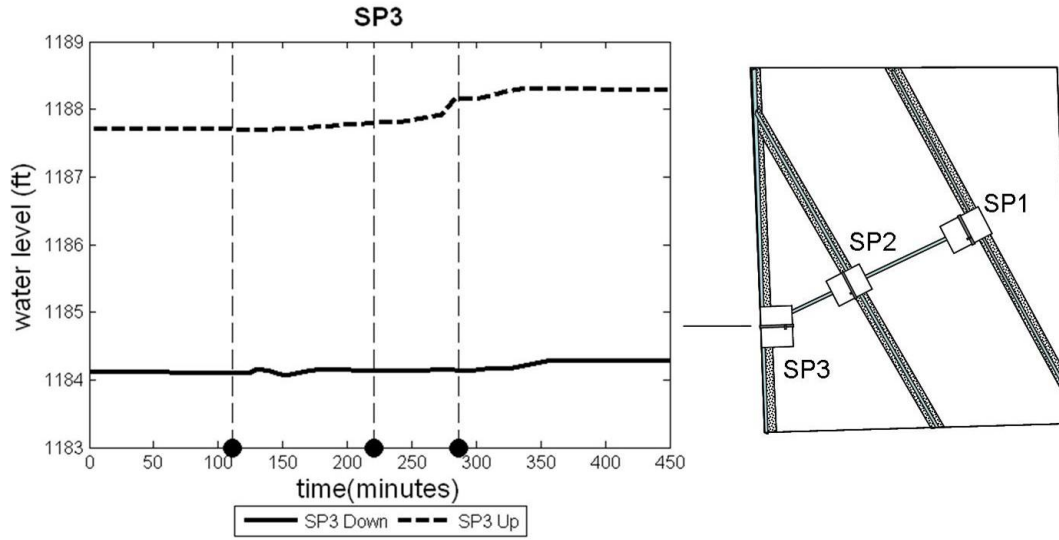


Figure 5.3: Water Levels in SP3.

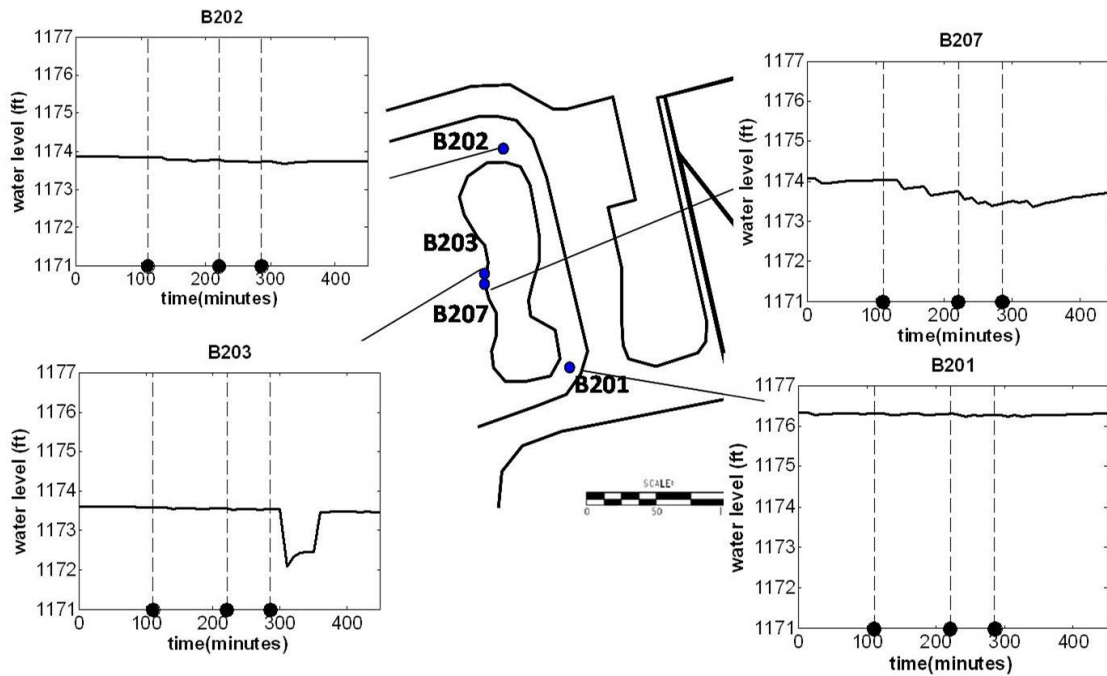


Figure 5.4: Water Levels in 200-series wells (right site area).

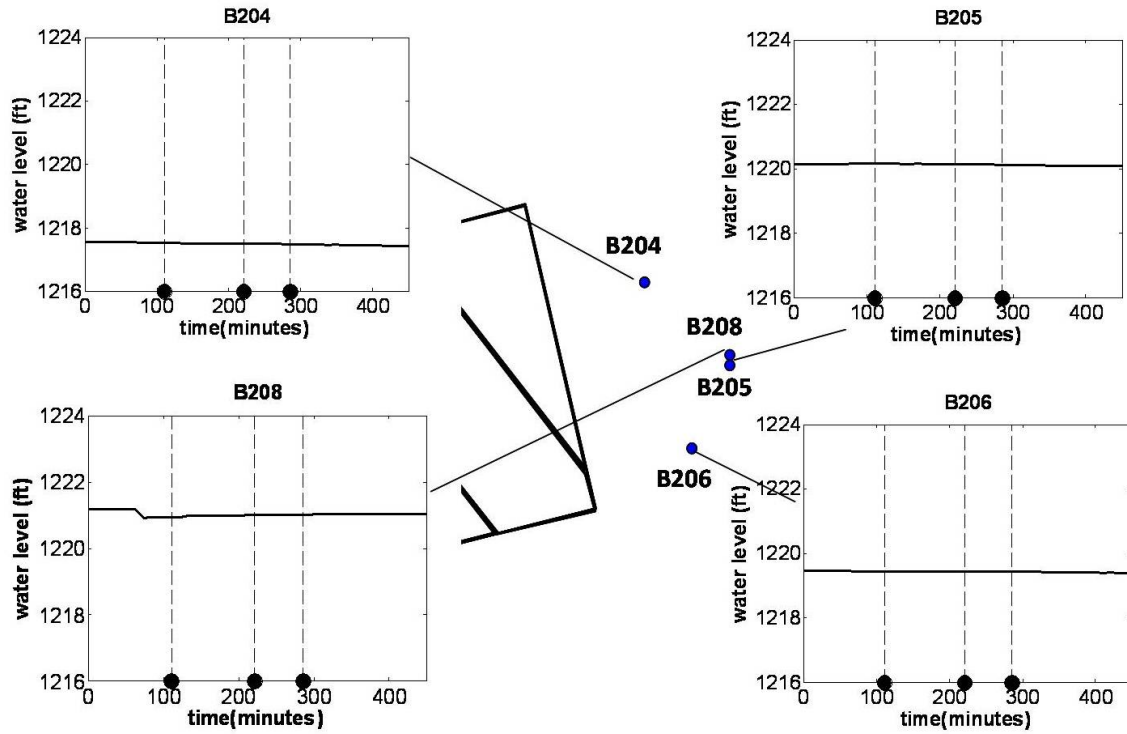


Figure 5.5: Water Levels in 200-series wells (left site area).

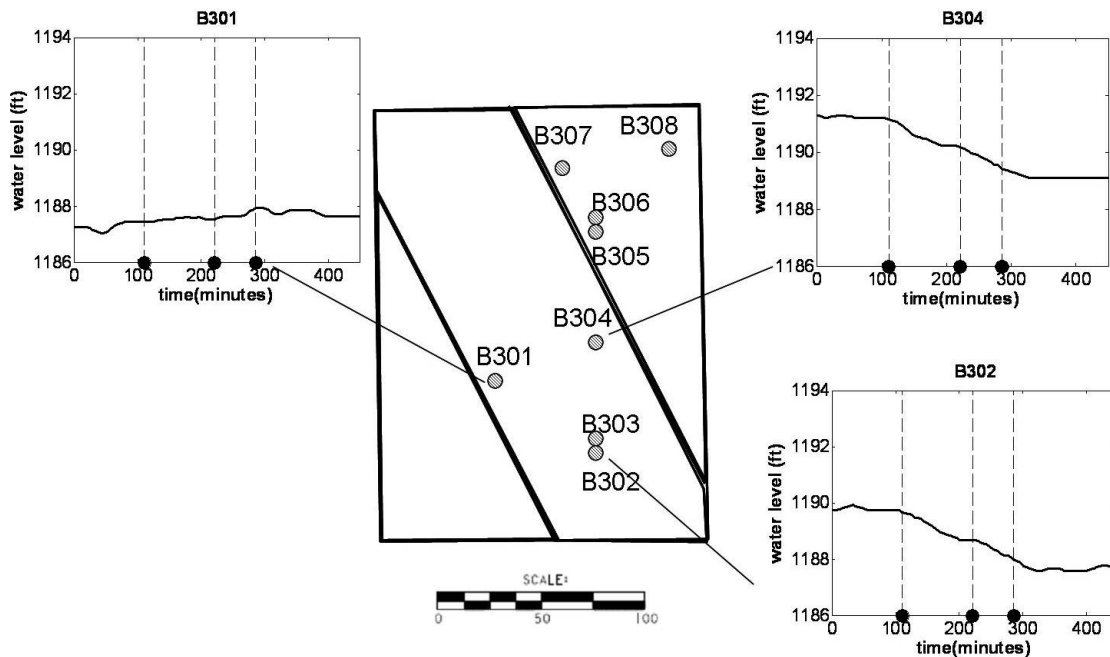


Figure 5.6: Water Levels in 300-series wells (part a).

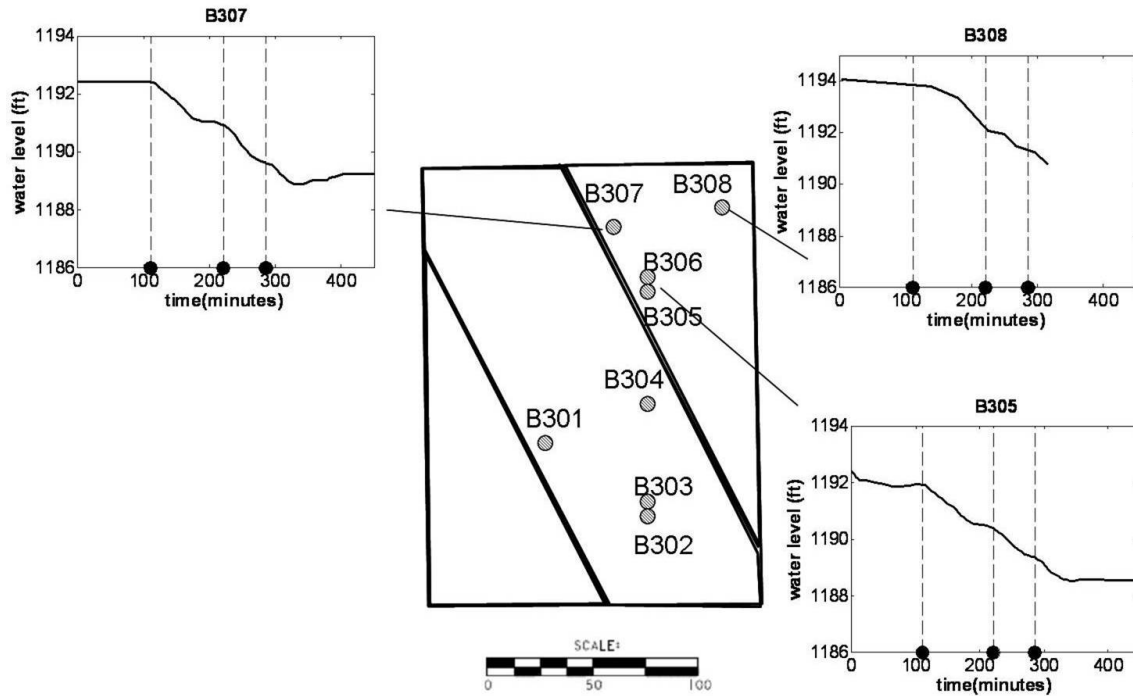


Figure 5.7: Water Levels in 300-series wells (part b).

### 5.3.2 Hurricane Irene

A comparison of the water levels during the field experiment and the impact of Hurricane Irene in Vermont (Figures 5.8, 5.9 and 5.10) proves that the inverse water level response in the 300-series wells is unique for the field experiment duration. Again, in the graphs time 0 refers to August 23rd, 9:04 am. The cluster of dots at the beginning of the time scale refer to the three water release events. The dot at 7256 minutes indicates the onset of hurricane Irene. The time chosen as the onset was August 28th at 10:00 am.

More specifically in the results:

- The 300-series wells do not respond to the storm event with the exception of B301. The recovery period is also obvious from the graphs.
- The 200-series wells however show a significant response to the hurricane. Water level rises up to a maximum of 4 ft compared to prehurricane conditions. Wells B204 and B206 seem to show a slight drop in heads.

To sum up, the 300-series wells respond during the field experiment and remain unaffected during "Irene" whereas the 200-series wells are unaffected during the field experiment and show a significant response during "Irene".

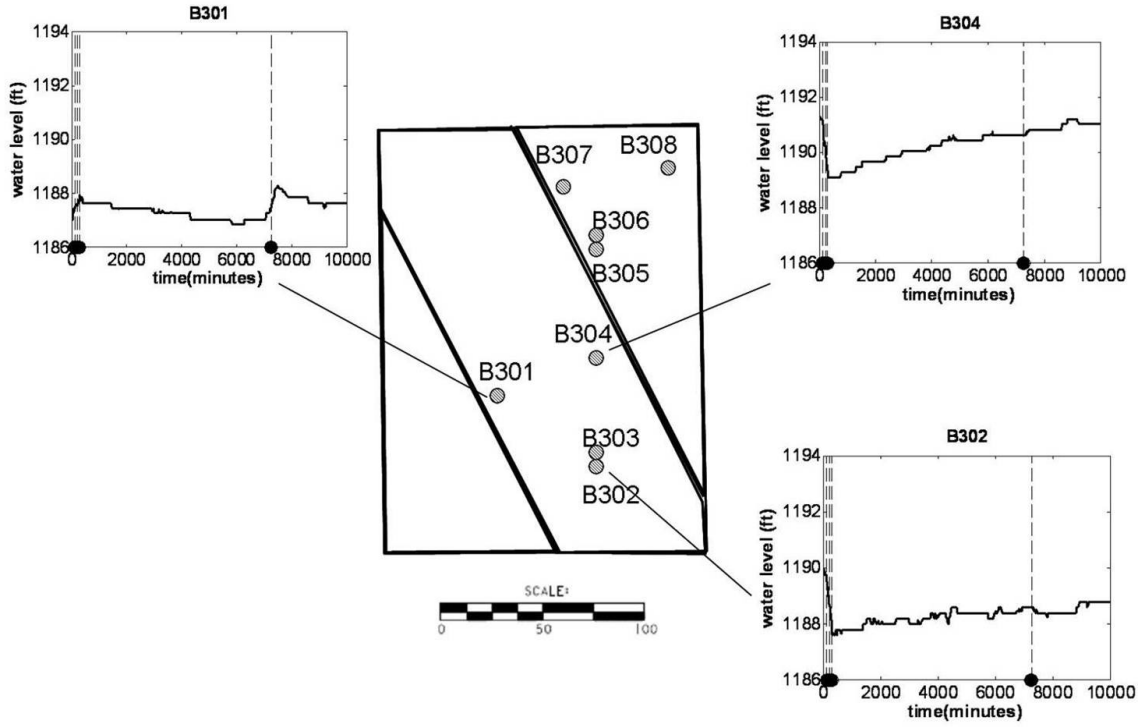


Figure 5.8: Water Levels in 300-series wells (part a) - Irene response.

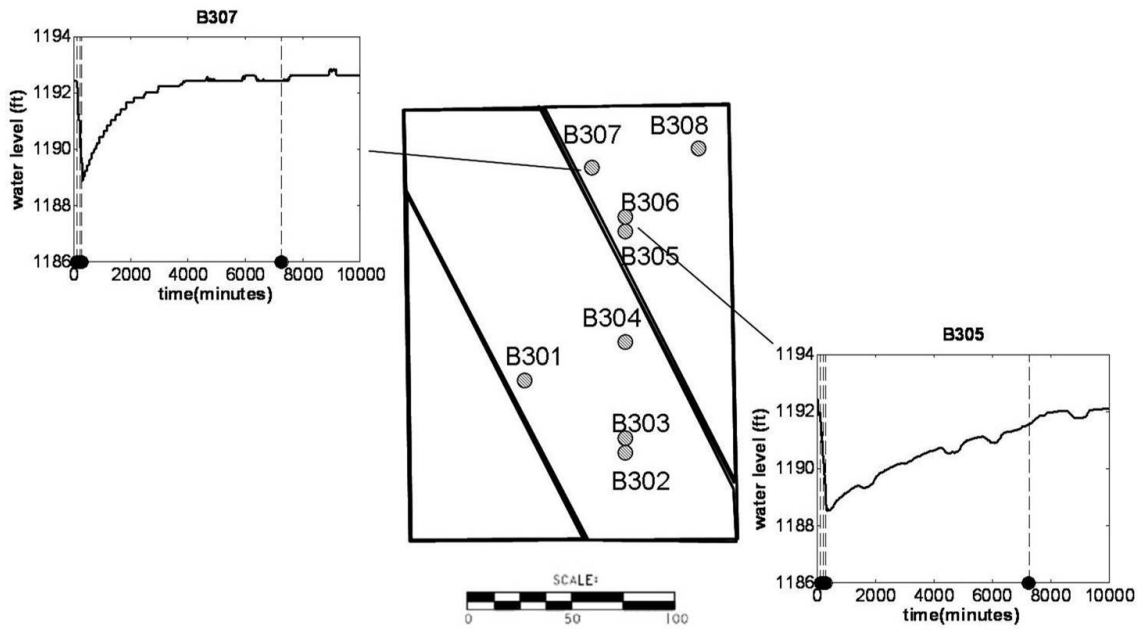


Figure 5.9: Water Levels in 300-series wells (part b) - Irene response.

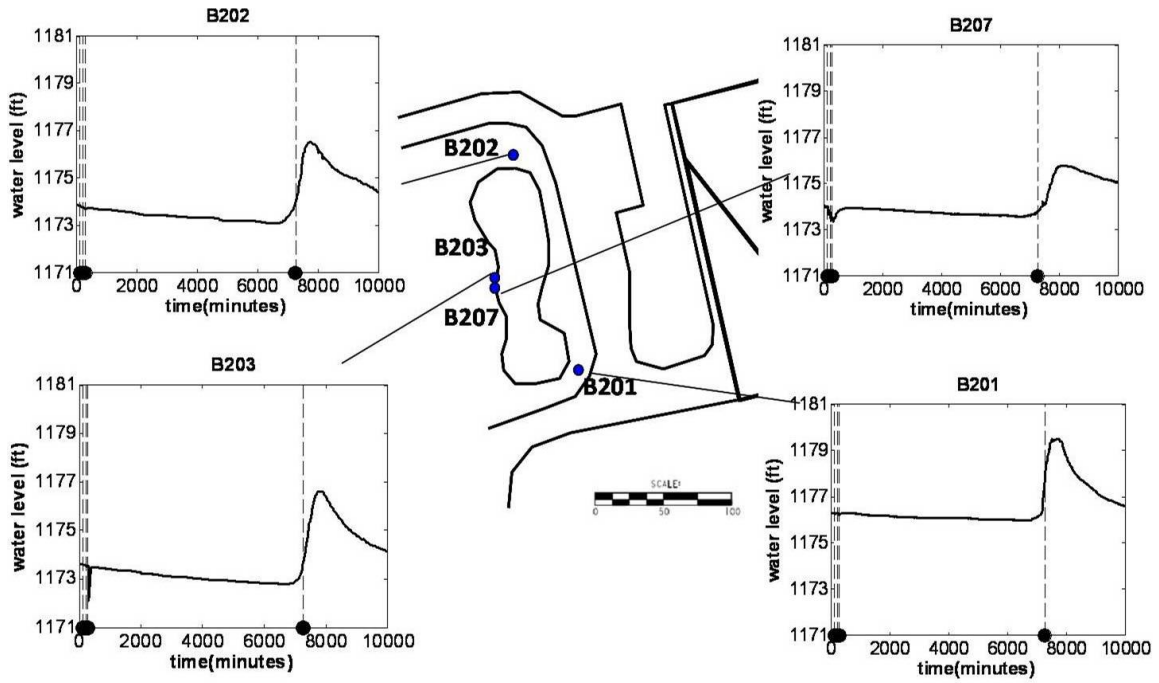


Figure 5.10: Water Levels in 200-series wells (part a) - Irene response.

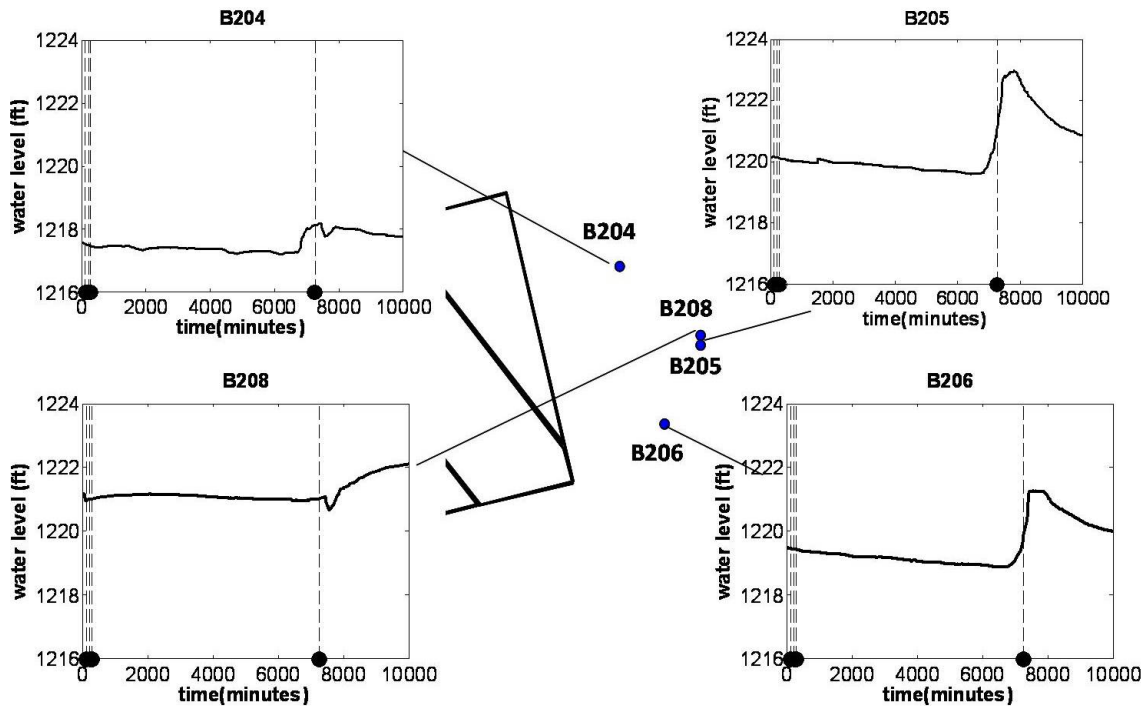


Figure 5.11: Water Levels in 200-series wells (part b) - Irene response.



### 5.3.3 Conductivity Measurements

In addition to the water level monitoring, conductivity measurements were also performed in the various monitoring locations. At first look the data show spiking. However, it must be noted that due to time constraints the conductivity measurements were performed quickly so the spiking could be due to the fact that the conductivity meter has not reached a stable value. Also, a different meter was used for the very first measurement compared to the rest of the measurements so that might explain the initial sudden response.

Taking the above into consideration, the majority of the wells do not show a clear response with the exception of B304 as shown in Figure 5.13 which implies that salt water has reached the well.

Figure 5.15 shows that conductivity for SP1 presents a similar pattern to the water level response. In other words saltwater enters both upstream and downstream locations quickly.

The upstream location for SP2 (Figure 5.16) shows a clear increase in conductivity. The downstream location shows some peaks which imply salt migration to that area.

In SP3 upstream (Figure 5.17) we see that there is a gradual increase in the concentration, which agrees with the rise in water level. The downstream location presents an increase in concentration around 320 minutes which is the time that the weir was exceeded.

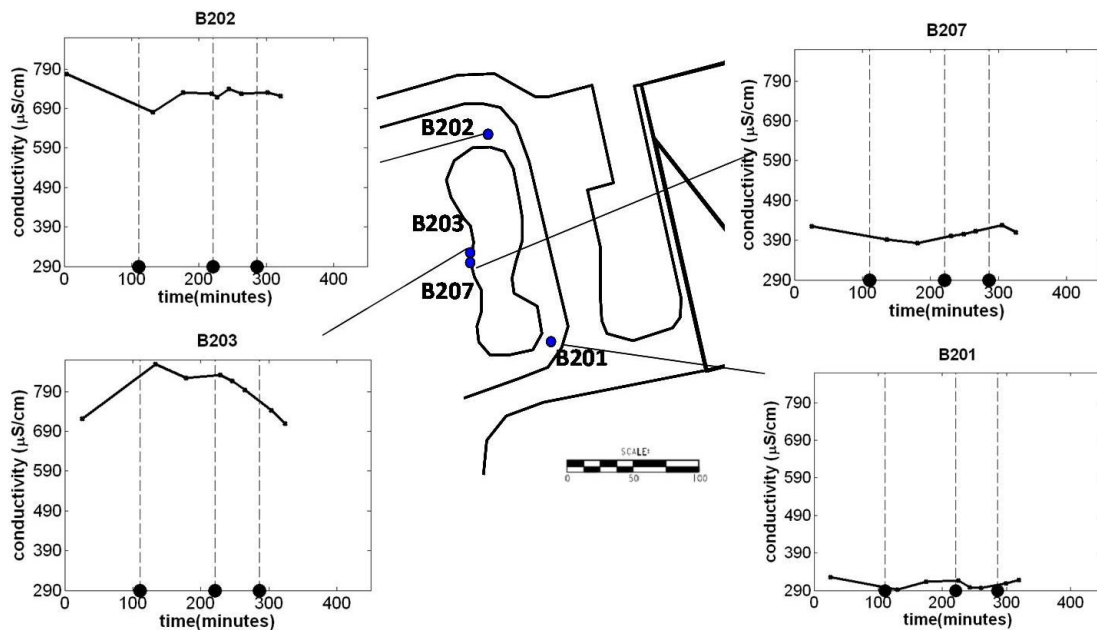


Figure 5.12: Conductivity measurements in 200-series wells (right side).

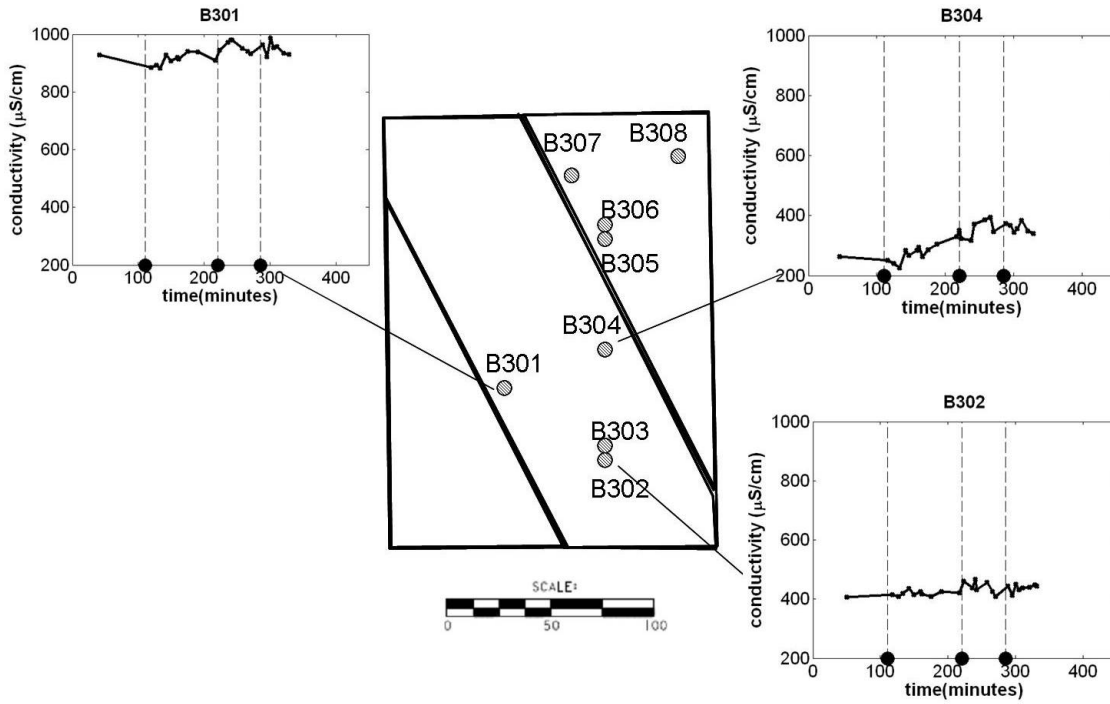


Figure 5.13: Conductivity measurements in 300-series wells (part a).

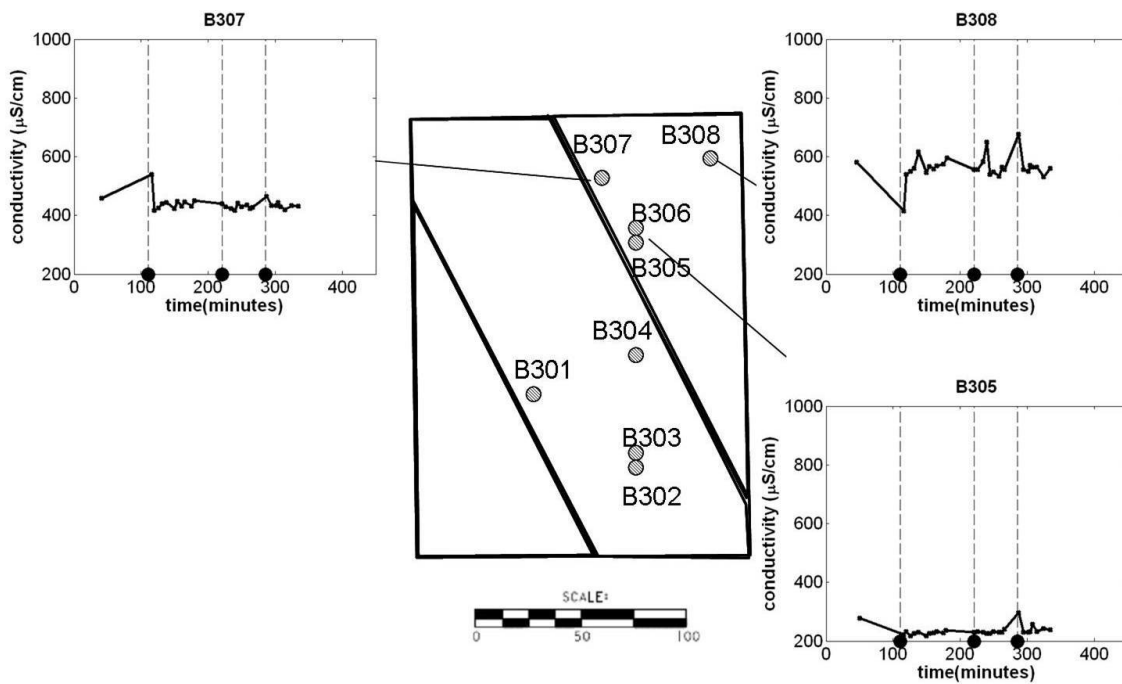


Figure 5.14: Conductivity measurements in 300-series wells (part b).

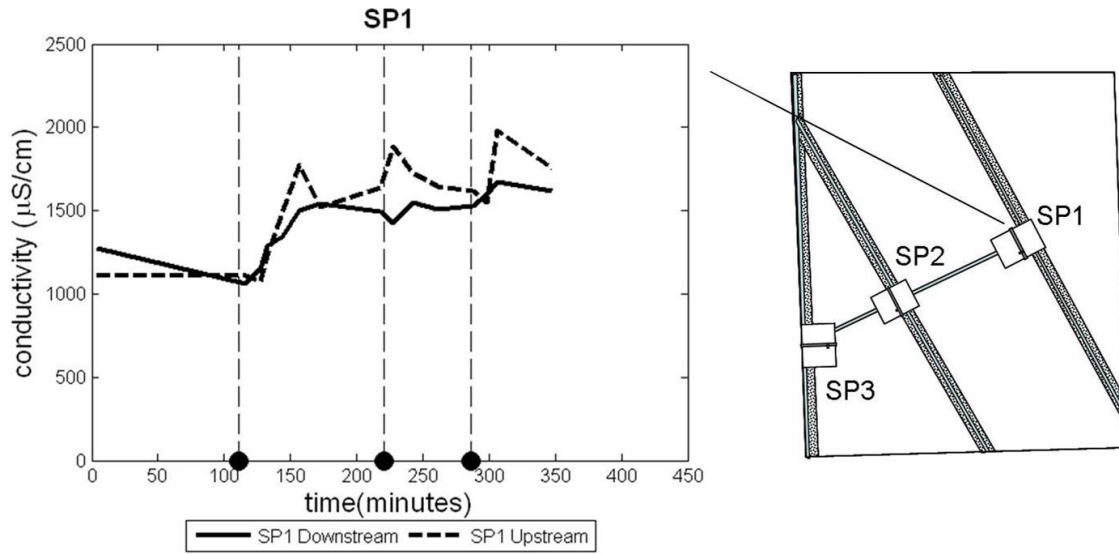


Figure 5.15: Conductivity measurements in SP1.

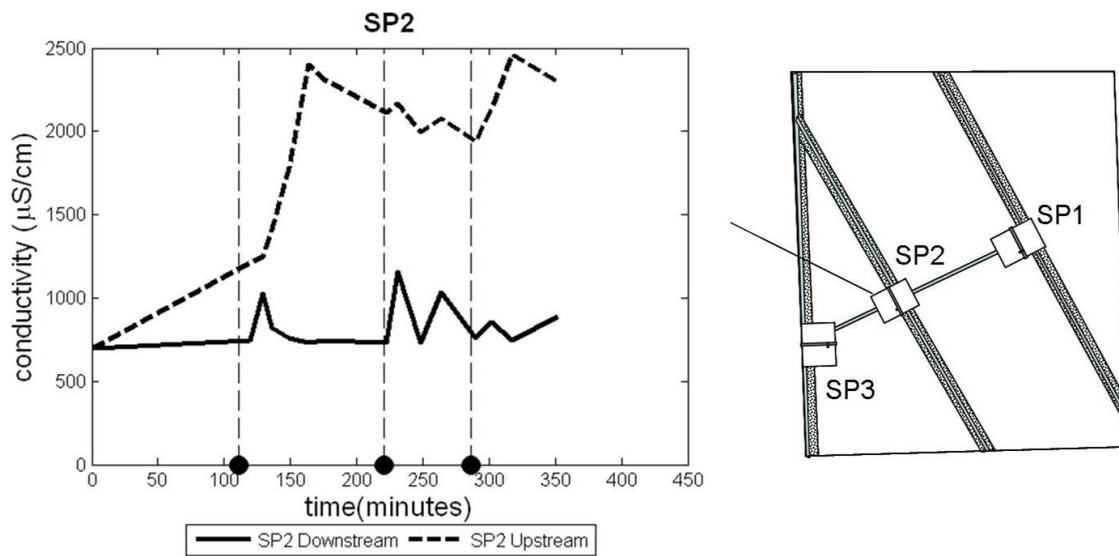


Figure 5.16: Conductivity measurements in SP2.

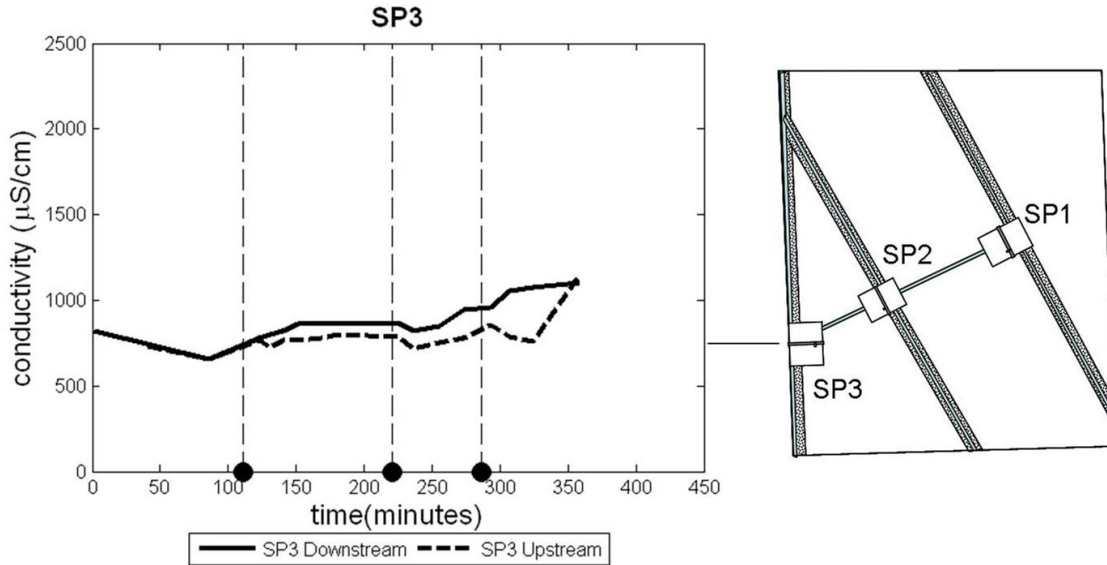
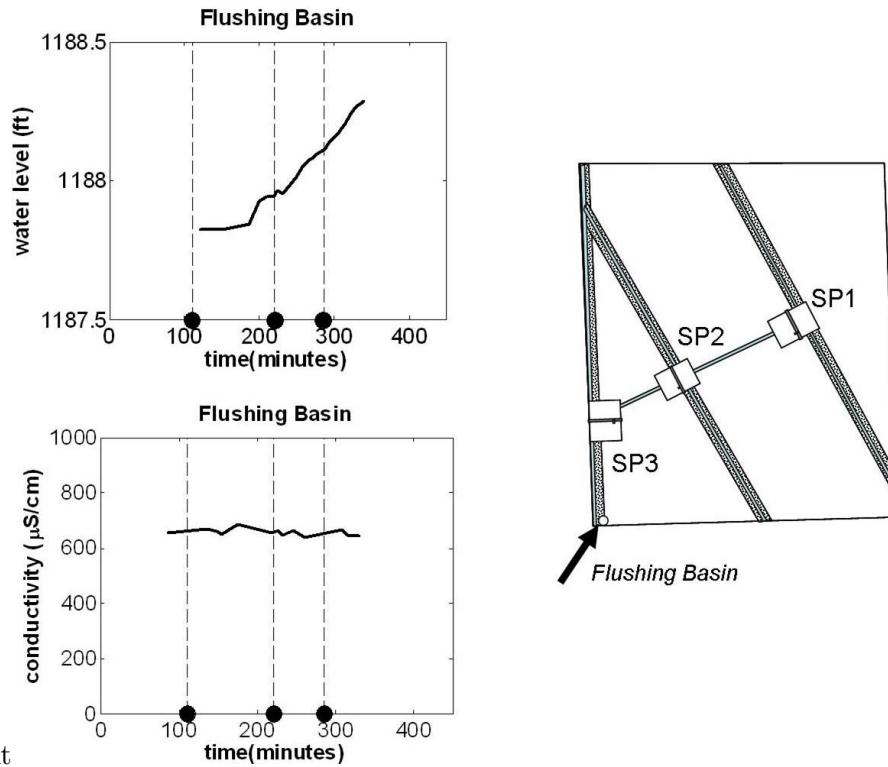


Figure 5.17: Conductivity measurements in SP3.

### 5.3.4 Drain and flushing basin information

Except the water level and conductivity measurements in the wells and drop inlets, additional measurements were obtained in key locations around the site. These locations include the openings of the underdrains at the edges of the porous concrete site, called flushing basins, and the openings of the perimeter drain or grates.

From all the locations monitored, significant response was observed at the flushing basin closest to SP3 as indicated in Figure 5.18. There, the water level starting rising at some point in time between the first and second water release and kept rising until the end of the experiment. Actually, superposition of the water level data from the flushing basin on the water level data from SP3 shows that the water level response in that location exactly matches the response in the upstream location of SP3 (Figure 5.19). The maximum value of water level in these locations is close to 1188.2 ft which is well above the bottom of the subbase in the specific area (1187.7 ft). This indicates that an amount of water is captured in the gravel subbase of Area 1.



.height.height

Figure 5.18: Water level and conductivity measurements in flushing basin.

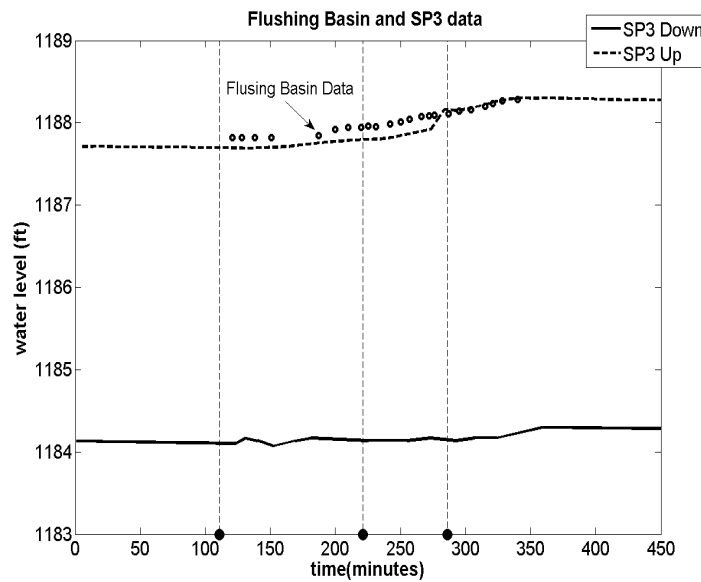


Figure 5.19: Superposition of water level measurements in flushing basin on SP3 data.

Regarding the perimeter drain openings or grates (Figure 5.20), few conductivity measurements were performed. The measurements as shown in Table 5.1 present a small increase through the duration of the field experiment. However, the small magnitude of the re-

sponse cannot provide a solid conclusion whether there is an amount of water migrating to the perimeter drain or whether this observation is due to noise in the conductivity meter.

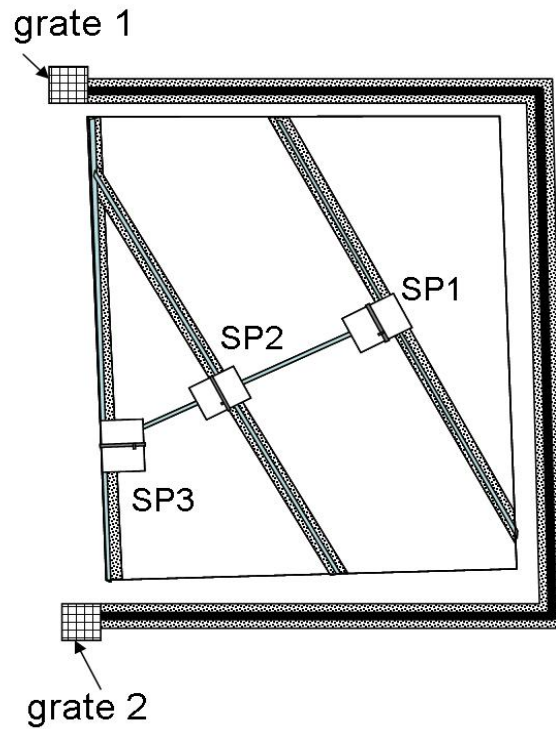


Figure 5.20: Location of openings on perimeter drain

Table 5.1: Conductivity measurements in perimeter drain openings

Grate 1		Grate 2	
time	conductivity( $\mu S/cm$ )	time	conductivity( $\mu S/cm$ )
12:05	444	12:15	818
-	-	13:02	823
14:10	450	14:07	848

## 5.4 Discussion

Water level measurements in the upstream locations of the three drop inlets show that the weir was not exceeded in SP1 and SP2 but was exceeded in SP3. However, water level changes in the downstream locations imply that there is a possibility of leakage through the berm and cutoff wall which are used to separate the three sub-areas of the site. In addition, the height of water in the upstream location of SP3 and the neighbouring flushing basin indicate that there is an amount of water gathered in the gravel subbase of the Area 1.

The 300-series wells shows an inverse water level response during the three water release events. Despite common logic the water levels dropped in response to recharge of the aquifer. The phenomenon shows a tremendous drop close to 4 ft. Although an exact explanation of this phenomenon is yet to be determined according to the literature it seems that it might be connected to the Noordbergum effect only recorded for pumping tests up to this day. Further research needs to be done.

Another strange phenomenon revealed in the site is the fact that the 300-series wells respond during the field experiment and remain unaffected during "Irene" whereas the 200-series wells are unaffected during the field experiment and show a significant response during "Irene".

Conductivity measurements in the drop inlets rise in accordance to the water level response as expected. Although some fluctuation is observed the overall pattern indicates that not salt is present in the monitoring wells.

Finally, the conductivity data in the perimeter drain do not show clearly whether water is captured in the perimeter drain.

## Chapter 6

# General Discussion

The Randolph Park and Ride is unique in terms of the instrumentation as well as the local geohydrology. The existence of the two artesian wells indicate a high gradient upward flow, which in combination with the tight geologic subgrade material makes infiltration of water into the subsurface very difficult. However, during hurricane Irene and according to groundwater level information for the winter monitoring period of 2010, the groundwater levels showed fluctuation. This possibly means that even if water cannot be infiltrated easily on the area of interest, the local groundwater levels are affected by infiltration in locations uphill of the porous concrete site.

Laboratory experiments showed that once water infiltrates the porous concrete and coarse stone reservoir, a significant amount is retained by the stone's surface and then evaporates into the atmosphere. However, this combination of phenomena do not justify the lack of water accumulation in the drop inlets. The data collected from the controlled water release field experiment indicated that there might be some leakage through the cutoff wall and berm, allowing water to move from one "area" to another without exceeding the weir.

Concerning the hypothesis that an amount of water could be leaking towards the perimeter drain, there are still no solid conclusions. Conductivity measurements in the drain inlets did not show a clear salt presence in these locations.

In terms of the mathematical model that is used to simulate the site, it is obvious that there are many challenges, mainly due to the complexity of the problem. Although the various model pieces are present, and provide reasonable results individually, more time is needed in order to compose the final model and to perform a simulation of the whole system. Also, the implementation of the optimization algorithm remains a secondary goal of this research.

The field experiment showed inverse water level response during recharge of the aquifer. The data set collected showed clearly the inverse respond from the wells located on the porous concrete area. The first hypothesis is that the phenomenon observed in the field is a form of the Noordbergum effect. Taking into consideration the rarity of the specific phenomenon and more importantly the rarity of such a well-documented data set, it becomes clear that this finding is very significant for the literature. Further research into the phenomenon will provide better understanding of the field conditions.



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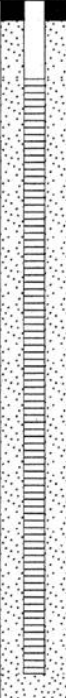












# Appendices

# Appendix A


## 100-series wells

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-101 SHEET 1 of 1 DATE STARTED: 7/06/07 DATE COMPLETED: 7/06/07				
PROJECT NAME: RANDOLPH SITE NAME: PARK & RIDE STATION: 21+13 OFFSET: -10.00 VTSPG: N 526838.19 ft E 1609130.31 ft				PROJECT NUMBER: CMG PARK(21) SITE NUMBER: VT-66 GROUND ELEVATION: GROUNDWATER DEPTH: 3.7 ft 7/10/07 PROJECT PIN NUMBER: 00K130					
BORING CREW CREW CHIEF: PORTER DRILLER: PORTER LOGGER: WERNER				BORING RIG: LAG TRACK RIG w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: CAA					
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	LL (%)	PI (%)
5									
5.5		A-4, SaSi, gry, Moist, Rec. = 1.5 ft	10	14.3	14.1	24.9	61.0	20	3
6.5		A-4, SaSi, gry, Moist, Rec. = 1.8 ft	5	14.6	15.2	28.6	56.2	20	3
7.5		A-4, SaSi, gry, Moist, Rec. = 1.7 ft	5	14.4	16.2	26.3	57.5	21	3
8.5		A-4, SaSi, gry, Moist, Rec. = 1.8 ft	10	12.6	15.9	25.2	58.9	21	2
9.5		A-4, SaGrSi, gry, Moist, Rec. = 1.3 ft	22	11.9	24.7	24.2	51.1		
10.5		A-4, GrSaSi, gry, Wet, Rec. = 1.6 ft	12	11.9	23.6	25.3	51.1		
11.5		A-4, GrSaSi, gry, Wet, Rec. = 2.0 ft	19	11.9	22.3	24.2	53.5		
12.5		A-4, SaSi, gry, Wet, Rec. = 1.2 ft	26	13.9	15.1	23.6	61.3		
22.0		Hole stopped @ 22.0 ft							
25		DRILLER'S NOTES: 1. Groundwater Depth on 07/12/07 was 2.0 ft.							


LOG OF BORING RANDOLPH CMG PARK(21).GPJ VT ADT.GDT 7/16/07

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-102 SHEET 1 of 1 DATE STARTED: 7/02/07 DATE COMPLETED: 7/10/07				
PROJECT NAME: RANDOLPH SITE NAME: PARK & RIDE STATION: 21+75 OFFSET: 142.00 VTSPG: N 526935.19 ft E 1609262.75 ft		PROJECT NUMBER: CMG PARK(21) SITE NUMBER: VT-66 GROUND ELEVATION: GROUNDWATER DEPTH: See Note #6 PROJECT PIN NUMBER: 00K130							
BORING CREW CREW CHIEF: PORTER DRILLER: PORTER LOGGER: WERNER		BORING RIG: LAG TRACK RIG w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: CAA							
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	
		Field Note, Top of Well casing is 2.5 ft. above ground level. Solid casing with Bentonite around it.							
5		A-4, SaSi, gry, Moist, Rec. = 2.0 ft		6	22.5	16.4	23.0	60.6	
10		A-4, SaGrSi, gry, Moist, Rec. = 2.0 ft		18	18.1	23.5	21.1	55.4	
15		A-4, SaSi, gry, Moist, Rec. = 1.3 ft		18	17.9	14.9	27.0	58.1	
		A-4, SaSi, gry, Moist, Rec. = 1.7 ft		9	14.7	16.1	26.1	57.8	
20		A-4, SaGrSi (HP), gry, Moist, Rec. = 1.2 ft		9	12.6	26.8	24.5	48.7	
		A-4, GrSaSi (HP), gry, Moist, Rec. = 1.3 ft		31	9.4	23.5	23.5	53.0	
25		A-4, GrSaSi (HP), gry, Moist, Rec. = 1.5 ft		39	8.5	28.6	31.1	40.3	
		A-4, SaGrSi (HP), gry, Wet, Rec. = 1.3 ft		36	10.6	29.4	22.5	48.1	
		A-4, SaGrSi (HP), gry, Moist, Rec. = 0.4 ft		R	9.4	35.0	22.3	42.7	
30		A-4, SaGrSi (HP), gry, Moist, Rec. = 1.3 ft		98	9.4	31.2	25.4	43.4	
		A-4, SaGrSi (HP), gry, Moist, Rec. = 1.7 ft		87	9.9	25.6	23.4	51.0	
35		A-4, SaSi (HP), gry, Moist, Rec. = 1.8 ft		89	12.5	17.1	24.8	58.1	
		Hole stopped @ 36.0 ft							
40		DRILLER'S NOTES: 1. Monitoring Well was installed. 2. There is 30.0 ft. of screen casing in ground. 3. There is 4.0 ft. of solid casing in ground. 4. There is 2.5 ft. of solid casing above ground. 5. End Cap added 0.3 ft. of casing length. 6. The following Groundwater Depths are reported from top of ground surface. 07/10/07 = 9.2 ft. 07/18/07 = 5.3 ft.							
45									

LOG OF BORING - RANDOLPH, CMG PARK(21), GPJ, VT, AOT, GDT, 7/19/07













		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-103 SHEET 1 of 1 DATE STARTED: 7/10/07 DATE COMPLETED: 7/10/07					
PROJECT NAME: RANDOLPH SITE NAME: PARK & RIDE STATION: 22+25 OFFSET: -23.00 VTSPG: N 526943.68 ft E 1609090.45 ft				PROJECT NUMBER: CMG PARK(21) SITE NUMBER: VT-66 GROUND ELEVATION: GROUNDWATER DEPTH: See Note #6 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: PORTER DRILLER: PORTER LOGGER: WERNER				BORING RIG: LAG TRACK RIG w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: CAA						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	LL (%)	PI (%)
0		A-4, SaSi, brn, Moist, Rec. = 1.6 ft, Top of Well casing is 2.5 ft. above ground level. Solid casing with Bentonite around it.		8	20.1	7.1	30.6	62.3		
2		A-4, SaSi, brn, Moist, Rec. = 1.6 ft		6	20.0	5.9	27.3	66.8		
4		A-4, SaSi, brn-gry, Moist, Rec. = 2.0 ft		5	22.1	6.0	28.0	66.0		
6		A-1-b, SiGrSa, brn, Moist, Rec. = 1.4 ft, Broken rock was within sample. Cobbles at 7.0 ft.		99	11.1	37.0	39.3	23.7		
8		Visual Classification, Broken rock with silty sand., brn, Moist, Rec. = 0.7 ft, Cobbles from 8.0-10 ft.		40	4.8					
10		Visual Classification, Broken rock with sand., gry, Moist, Rec. = 0.4 ft, (Cobbles)		R	4.2					
10		Field Note, 10.7'-11.5', Cobble area has ended.								
12		A-4, SaSi, gry, Moist, Rec. = 1.7 ft		10	17.7	14.0	22.1	63.9		
14		A-4, SaSi, gry, Wet, Rec. = 1.65 ft		9	14.8	17.6	22.9	59.5	23	1
16		A-4, SaSi, gry, Wet, Rec. = 1.8 ft		18	14.7	18.4	21.8	59.8	23	2
18		Field Note, No recovery. Appears to be same material., gry, Wet		11						
20		A-4, GrSaSi, gry, Wet, Rec. = 1.5 ft		31	12.9	20.7	29.1	50.2		
22		Hole stopped @ 22.0 ft								
25		DRILLER'S NOTES: 1. Monitoring Well was installed. 2. There is 15.0 ft. of screen casing in ground. 3. There is 3.9 ft. of solid casing in ground. 4. There is 2.5 ft. of solid casing above ground. 5. End Cap added 0.3 ft. of casing length. 6. The following Groundwater Depths are reported from top of ground surface. 07/12/07 = 8.8 ft. 07/18/07 = 9.5 ft.								

LOG OF BORING RANDOLPH CMG PARK(21).GPJ VT AOT GDT 7/19/07



		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-104 SHEET 1 of 1 DATE STARTED: 7/12/07 DATE COMPLETED: 7/13/07					
PROJECT NAME: RANDOLPH SITE NAME: PARK & RIDE STATION: 22+57 OFFSET: -180.00 VTSPG: N 526936.69 ft E 1608930.47 ft				PROJECT NUMBER: CMG PARK(21) SITE NUMBER: VT-66 GROUND ELEVATION: GROUNDWATER DEPTH: See Note #6 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: PORTER DRILLER: PORTER LOGGER: WERNER				BORING RIG: LAG TRACK RIG w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: CAA						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	LL (%)	PI (%)
		Topsoil, bm, Moist, 0.0 ft - 0.2 ft, Top of Well casing is 2.8 ft. above ground level.		2	25.4	8.9	33.7	57.4		
		A-4, SaSi, bm, Moist, Rec. = 1.5 ft								
		A-4, SaSi, bm, Moist, Rec. = 1.8 ft		8	19.9	7.3	26.1	66.6		
5		A-4, SaSi, bm, Moist, Rec. = 1.9 ft		4	20.4	5.2	26.8	68.0		
10		A-4, SaSi, bm, Moist, Rec. = 1.9 ft		4	20.2	9.9	23.6	66.5		
		A-4, SaSi, bm, Moist, Rec. = 1.7 ft		11	17.3	15.5	22.4	62.1		
		A-4, GrSi, gry, Wet, Rec. = 1.7 ft		12	18.2	21.3	18.9	59.8		
		A-4, Si, gry, Wet, Rec. = 1.7 ft		8	18.1	12.8	19.3	67.9		
15		A-4, Si, gry, Wet, Rec. = 2.0 ft		5	16.9	10.7	18.3	71.0	23	2
		A-4, Si, gry, Wet, Rec. = 2.0 ft		6	16.4	15.6	17.8	66.6	24	3
		A-4, GrSi, gry, Wet, Rec. = 1.6 ft		12	14.3	26.0	15.4	58.6	23	2
20		A-4, GrSi, gry, Wet, Rec. = 1.5 ft		14	14.2	22.6	16.7	60.7	21	2
		Hole stopped @ 22.0 ft								
25		DRILLER'S NOTES: 1. Monitoring Well was installed. 2. There is 15.0 ft. of screen casing in ground. 3. There is 5.0 ft. of solid casing in ground. 4. There is 2.8 ft. of solid casing above ground. 5. End Cap added 0.3 ft. of casing length. 6. The following Groundwater Depths are reported from top of ground surface. 07/12/07 = 6.3 ft. 07/18/07 = 5.9 ft.								

LOG OF BORING RANDOLPH, CMG PARK(21), GPJ, VT, AOT, GDT, 7/13/07



		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-105 SHEET 1 of 1 DATE STARTED: 6/29/07 DATE COMPLETED: 7/02/07		
PROJECT NAME: RANDOLPH SITE NAME: PARK & RIDE STATION: 22+68 OFFSET: 142.00 VTSPG: N 527025.42 ft E 1609240.20 ft				PROJECT NUMBER: CMG PARK(21) SITE NUMBER: VT-66 GROUND ELEVATION: GROUNDWATER DEPTH: 5.3 ft 7/02/07 PROJECT PIN NUMBER: 00K130			
BORING CREW CREW CHIEF: PORTER DRILLER: PORTER LOGGER: WERNER				BORING RIG: LAG TRACK RIG w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: CAA			
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
5		A-4, SaSi, gry, Moist, Rec. = 1.7 ft	8	20.8	19.2	21.7	59.1
10		A-4, GrSaSi, gry, Moist, Rec. = 2.0 ft	12	18.0	21.1	25.8	53.1
		A-4, SaSi, gry, Moist, Rec. = 2.0 ft	11	17.5	15.8	22.3	61.9
		A-4, SaSi, gry, Moist, Rec. = 1.0 ft	15	16.0	9.8	32.8	57.4
		A-4, SaSi, gry, Wet, Rec. = 0.9 ft	19	15.3	18.0	25.1	56.9
		Boulder, 18.0 ft - 19.0 ft					
		A-4, GrSaSi, gry, Wet, Rec. = 1.0 ft		18.1	20.8	27.2	52.0
		A-4, GrSaSi (HP), gry, Wet, Rec. = 2.0 ft	25	12.5	21.8	30.8	47.4
		A-4, SaSiGr (HP), gry, Wet, Rec. = 1.4 ft, Tough drilling in (HP) & Cobbles	41	11.4	38.6	23.5	37.9
		A-4, SaGrSi (HP), gry, Moist, Rec. = 1.4 ft, Tough drilling in (HP) & Cobbles	R	9.4	32.8	25.5	41.7
		A-4, SaGrSi (HP), gry, Moist, Rec. = 0.8 ft, Tough drilling in (HP) & Cobbles	R	11.1	33.2	23.5	43.3
		Hole stopped @ 26.8 ft					
		DRILLER'S NOTES: 1. Groundwater Depth on 07/12/07 was 0.4 ft.					













LOG OF BORING RANDOLPH, CMG PARK(21), GPJ, VT, AOT, GDT, 7/19/07

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION				BORING NUMBER: B-106 SHEET 1 of 1 DATE STARTED: 7/12/07 DATE COMPLETED: 7/12/07			
PROJECT NAME: RANDOLPH SITE NAME: PARK & RIDE STATION: 23+43 OFFSET: -57.00 VTSPG: N 527049.94 ft E 1609028.96 ft		PROJECT NUMBER: CMG PARK(21) SITE NUMBER: VT-66 GROUND ELEVATION: GROUNDWATER DEPTH: 1.1 ft 7/12/07 PROJECT PIN NUMBER: 00K130							
BORING CREW CREW CHIEF: PORTER DRILLER: PORTER LOGGER: WERNER		BORING RIG: LAG TRACK RIG w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: CAA							
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	LL (%)	PI (%)
5		A-4, SaSi, brn, Moist, Rec. = 1.4 ft	3	25.5	11.4	30.1	58.5		
		A-4, SaSi, brn, Wet, Rec. = 1.8 ft	6	21.6	13.9	24.0	62.1		
		A-4, SaSi, brn, Wet, Rec. = 1.9 ft	3	23.7	8.0	22.1	69.9		
		A-4, SaSi, brn, Wet, Rec. = 1.9 ft	3	21.5	16.3	22.1	61.6		
		A-4, SaSi, gry, Wet, Rec. = 1.7 ft	17	19.2	9.3	24.5	66.2		
		Field Note, Appears to be same material., gry, Wet	18						
		A-4, SaSi, gry, Wet, Rec. = 1.7 ft	7	15.6	13.3	22.9	63.8		
		A-4, SaSi, gry, Moist, Rec. = 2.0 ft	8	15.2	9.1	23.7	67.2		
		A-4, SaSi, gry, Moist, Rec. = 2.0 ft	7	14.8	16.1	21.8	62.1	24	2
		A-4, SaSi, gry, Wet, Rec. = 2.0 ft	11	15.3	17.7	21.6	60.7		
20		A-4, GrSi, gry, Wet, Rec. = 1.7 ft	9	14.4	24.7	19.6	55.7	23	3
		Hole stopped @ 22.0 ft							
		DRILLER'S NOTES: 1. Hole caved in at around 8.0 ft.							
25									


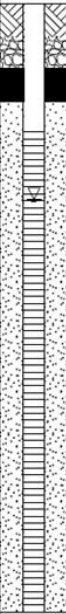
LOG OF BORING: RANDOLPH, CMG PARK(21), GP1, VT, AOT, GBT, 7/19/07

# Appendix B


## 200-series wells

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-201 SHEET 1 of 1 DATE STARTED: 11/12/08 DATE COMPLETED: 11/12/08				
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 21+71 OFFSET: -136.90 VTSPG: N 526866.23 ft E 1608992.18 ft			PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1181.9 ft GROUNDWATER DEPTH: 4.6 ft 11/13/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: PORTER			BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: AUGER CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	
Top of Well Elevation: 1181.73 ft									
		Visual Classification, A-4, Si							
5		Possible Cobbles, 4.0 ft - 5.0 ft							
		Visual Classification, A-4, Si							
10		Visual Classification, A-4, GrSaSi							
15									
20		Hole stopped @ 20.0 ft							
		DRILLER'S NOTES: 1. Monitoring Well was installed. 2. There is 15.0 ft of screen casing in ground. 3. There is 5.0 ft of solid casing in ground. 4. There is 0.0 ft of solid casing above ground. 5. Soil classifications made from auger cuttings.							
25									



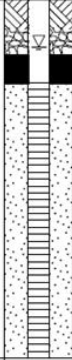
LOG OF BORING: RANDOLPH CMG PARK(21).GRJ VT AOT.GDT 12/3/08

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-202 SHEET 1 of 1 DATE STARTED: 11/05/08 DATE COMPLETED: 11/05/08			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 23+22 OFFSET: -144.80 VTSPG: N 527009.32 ft E 1608948.56 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1180.1 ft GROUNDWATER DEPTH: 6.1 ft 11/12/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: AUGER CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1179.94 ft								
		Visual Classification, A-4, Si						
5		Possible Cobbles, 4.0 ft - 5.0 ft						
		Visual Classification, A-4, Si						
10								
15								
20		Hole stopped @ 19.0 ft						
		DRILLER'S NOTES: 1. Monitoring Well was installed. 2. There is 15.0 ft of screen casing in ground. 3. There is 4.0 ft of solid casing in ground. 4. There is 0.0 ft of solid casing above ground. 5. Soil classifications made from auger cuttings.						
25								









LOG OF BORING RANDOLPH CMG PARK(21).GPJ VT\_AOT.GDT 12/3/08

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-203 SHEET 1 of 1 DATE STARTED: 11/03/08 DATE COMPLETED: 11/04/08				
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+44 OFFSET: -178.80 VTSPG: N 526931.40 ft E 1608933.28 ft			PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1180.9 ft GROUNDWATER DEPTH: 7.4 ft 11/04/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: ELIASSEN			BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: AUGER CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	
Top of Well Elevation: 1180.64 ft									
		A-4, SaSi, Dk/brn, Moist, Rec. = 1.6 ft		4	18.6	17.1	36.1	46.8	
		A-4, GrSaSi, Dk/brn, Moist, Rec. = 1.6 ft		10	17.1	21.3	23.6	55.1	
5		A-4, SaSi, Dk/brn, Moist, Rec. = 1.5 ft		4	21.2	6.2	22.8	71.0	
		A-4, SaSi, Dk/brn, MTW, Rec. = 1.8 ft		5	20.9	8.5	22.9	68.6	
		A-4, SaSi mottled, gry, Moist, Rec. = 1.8 ft		10	18.6	10.9	20.5	68.6	
10		A-4, SaSi, gry, Moist, Rec. = 2.0 ft		9	18.5	12.7	20.9	66.4	
		No Recovery, Rec. = 0.0 ft, 12.0 ft - 14.0 ft		12					
15		A-4, SaSi, gry, Moist, Rec. = 1.5 ft		9	18.8	12.0	22.4	65.6	
		A-4, Si, gry, Moist, Rec. = 1.5 ft		6	15.7	15.5	18.4	66.1	
		A-4, SaSi, gray, Moist, Rec. = 1.2 ft		R	16.6	8.6	20.3	71.1	
20		Hole stopped @ 19.0 ft  DRILLER'S NOTES: 1. Monitoring well was installed. 2. There is 15.0 ft. of screen casing in ground. 3. There is 4.0 ft. of solid casing in ground. 4. There is 0 ft. of solid casing above ground.							
25									

LOG OF BORING - RANDOLPH CMG PARK(Z1).GPI VT AOT.GDT 12/3/08



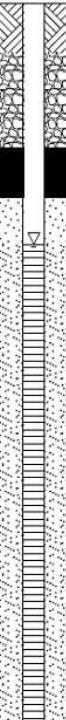





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PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+67 OFFSET: 202.40 VTSPG: N 527034.87 ft E 1609300.11 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1217.7 ft GROUNDWATER DEPTH: 1.7 ft 10/29/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: HOLT		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1219.31 ft								
5		Visual Classification, Gr Si, No Samples taken						
10								
Hole stopped @ 13.0 ft								
15		DRILLER'S NOTES: 1. Soil Descriptions made from Auger Cuttings. 2. Monitoring Well was installed. 3. There is 10.0 ft of screen casing in ground. 4. There is 3.0 ft of solid casing in ground. 5. There is 2.3 ft of solid casing above ground level.						
20								
25								
30								

LOG OF BORING RANDOLPH CMG PARK(21).GPJ VT AOT.GDT 12/3/08



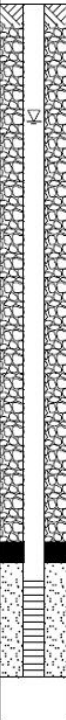



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PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 21+92 OFFSET: 250.40 VTSPG: N 526978.42 ft E 1609363.63 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1222.0 ft GROUNDWATER DEPTH: 3.9 ft 10/28/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1224.69 ft								
0.0 ft - 8.0 ft		No Samples taken.						
5								
9.9 ft - 10.8 ft		Visual Classification, A-4, Si, Dk/brn, Wet, Rec. = 1.9 ft		2				
10.8 ft - 12.6 ft		Visual Classification, A-2-4, Gr Si, Dk/brn, Wet, Rec. = 1.8 ft		5				
12.6 ft - 15.0 ft		No Samples taken.						
15		Hole stopped @ 15.0 ft						
		DRILLER'S NOTES: 1. Monitoring Well was installed. 2. There is 10.0 ft. of screen casing in ground. 3. There is 5.0 ft. of solid casing in ground. 4. There is 3.05 ft. of solid casing above ground level.						
20								
25								
30								

LOG OF BORING: RANDOLPH CMG PARK(21).GPI VT AOT.GDT 12/3/08



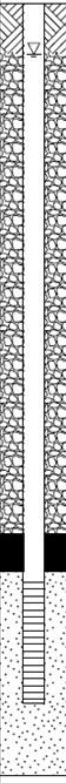














		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-206 SHEET 1 of 1 DATE STARTED: 10/29/08 DATE COMPLETED: 10/29/08				
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 21+48 OFFSET: 206.90 VTSPG: N 526923.95 ft E 1609332.31 ft			PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1221.5 ft GROUNDWATER DEPTH: 5.0 ft 11/03/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: HOLT			BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: AUGER CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	
Top of Well Elevation: 1224.04 ft									
2.5		Visual Classification, GrSi, No Samples Taken							
5.0									
7.5									
10.0									
12.5									
15.0		Hole stopped @ 15.0 ft							
17.5		DRILLER'S NOTES: 1. Soil Descriptions made from Auger Cuttings. 2. Monitoring Well was installed. 3. There is 10.0 ft of screen casing in ground. 4. There is 5.0 ft of solid casing in ground. 5. There is 2.4 ft of solid casing above ground. 6. A firm layer was hit at 12.8 ft below ground.							

LOG OF BORING RANDOLPH CMG PARK(21).GPIJ VT AOT.GDT 12/3/08

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-207 SHEET 1 of 1 DATE STARTED: 11/04/08 DATE COMPLETED: 11/05/08			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+12 OFFSET: -178.90 VTSPG: N 526922.15 ft E 1608935.27 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1180.9 ft GROUNDWATER DEPTH: 6.1 ft 11/12/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1180.65 ft								
0.0		0.0 ft - 20.0 ft, No Samples Taken						
5								
10								
15								
20		Visual Classification, A-4, Si, gry, Moist, Rec. = 2.0 ft		13				
25		Visual Classification, A-4, CIsI, gry, Moist, Rec. = 2.0 ft		11				
30		Visual Classification, A-4, CIsI, gry, MTW, Rec. = 2.0 ft		7				
35		Visual Classification, A-4, Si, gry, Wet, Rec. = 1.3 ft		22				
40		Hole stopped @ 37.0 ft						
45		DRILLER'S NOTES: 1. Driller Noted firm layer present at 34.3 ft 2. Monitoring Well was installed. 3. There is 5.0 ft of screen casing in ground. 4. There is 30.0 ft of solid casing in ground. 5. There is 0.0 ft of solid casing above ground. 6. No ledge to depth						


LOG OF BORING RANDOLPH CMG PARK(21).GPI VT AOT.GDT 12/3/08

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-208 SHEET 1 of 1 DATE STARTED: 10/23/08 DATE COMPLETED: 10/27/08			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+00 OFFSET: 251.70 VTSPG: N 526984.99 ft E 1609363.46 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1221.8 ft GROUNDWATER DEPTH: 2.1 ft 10/27/08 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: HOLLOW STEM AUGER SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1223.8 ft								
		A-4, SaSi, Dk/brn, Moist, Rec. = 1.6 ft		4	20.7	7.7	36.1	56.2
		A-4, SaSi, Dk/brn, Moist, Rec. = 1.2 ft		20	17.9	14.6	37.0	48.4
5		A-4, GrSaSi, Dk/brn, MTW, Rec. = 1.5 ft		3	20.8	20.6	30.7	48.7
		A-4, SaSi, brn, Wet, Rec. = 1.7 ft		2	30.6	11.8	38.1	50.1
		A-2-4, SiSa, brn, Sat, Rec. = 1.3 ft		5	31.7	14.1	51.7	34.2
10		A-4, SaGrSi, gry, Moist, Rec. = 1.9 ft		14	17.6	28.8	22.5	48.7
		A-4, SaGrSi mottled, gry-brn, Moist, Rec. = 1.8 ft		30	13.8	26.0	24.3	49.7
15		A-4, SaGrSi HP, gry, Moist, Rec. = 1.7 ft		23	10.9	25.5	20.3	54.2
		A-4, GrSaSi HP, gry, Moist, Rec. = 1.9 ft		32	10.4	23.3	28.6	48.1
20		A-4, SaSi HP, gry, Moist, Rec. = 1.6 ft		50	10.2	14.0	27.7	58.3
		A-4, GrSaSi HP, gry, Moist, Rec. = 1.4 ft	52	11.1	22.3	25.8	51.9	
25		Visual Classification, A-2-4, Silt & Stones HP, gry, Moist, Rec. = 1.4 ft	81					
30		Visual Classification, A-2-4, Gr Si HP, gry, Moist, Rec. = 2.0 ft	76					
Hole stopped @ 32.0 ft								
35	DRILLER'S NOTES: 1. No ledge to depth. 2. Monitoring Well was installed. 3. There is 5.0 ft. of screen casing in ground. 4. There is 24.0 ft. of solid casing in ground. 5. There is 2.1 ft. of solid casing above ground level.							


LOG OF BORING RANDOLPH OMG PARK(21).GPJ VT AOT.GDT 12/3/08

# Appendix C


## 300-series wells

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-301 SHEET 1 of 1 DATE STARTED: 3/30/09 DATE COMPLETED: 3/30/09			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+00 OFFSET: 29.26 VTSPG: N 526932.61 ft E 1609148.19 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1194.11 ft GROUNDWATER DEPTH: 3.64 ft 4/14/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1193.9 ft								
0.0 - 0.5	[Stippled pattern]	Porous Concrete, 0.0 ft - 0.5 ft	[Well diagram showing concrete and stone fill]					
0.5 - 6.5	[Stone pattern]	Stone Fill, 0.5 ft - 6.5 ft						
6.5 - 7.2	[Gravel pattern]	Visual Classification, GrSaSi, gry, MTW, Rec. = 0.7 ft	[Well diagram showing gravel]	3				
7.2 - 8.4	[Sand pattern]	Visual Classification, Si, gry, MTW, Rec. = 1.2 ft	[Well diagram showing sand]	3				
8.4 - 10.0	[Diagonal lines]	Hole stopped @ 10.0 ft	[Well diagram showing stop]					
10.0 - 12.5								
12.5 - 15.0								
15.0 - 17.5								
17.5 - 20.0								

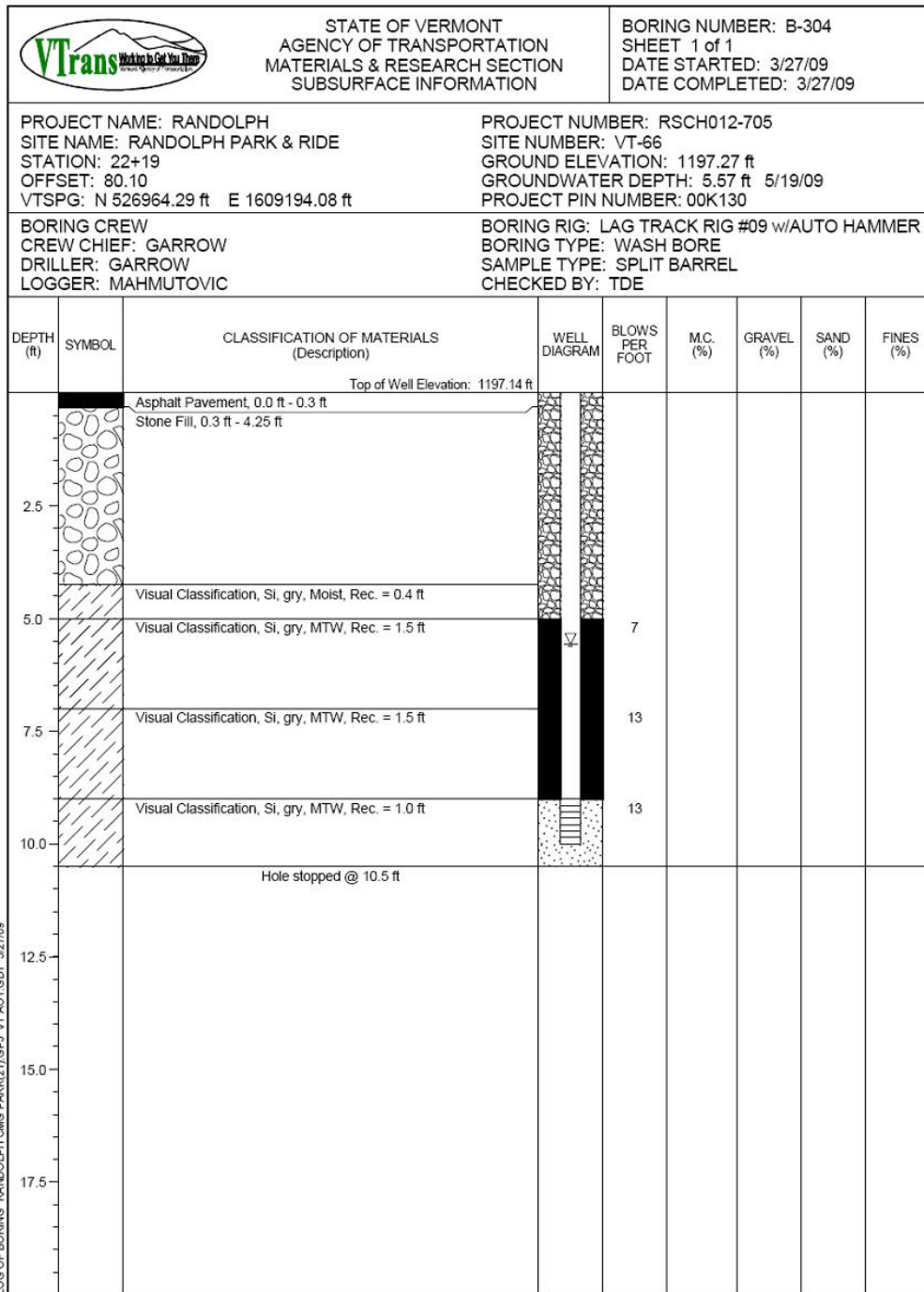
LOG OF BORING RANDOLPH CMG PARK(21).GPJ VT AOT.GDT 5/27/09

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-302 SHEET 1 of 1 DATE STARTED: 3/27/09 DATE COMPLETED: 3/27/09				
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 21+62 OFFSET: 80.40 VTSPG: N 526908.14 ft E 1609207.42 ft			PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1196.26 ft GROUNDWATER DEPTH: 5.41 ft 4/14/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC			BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	
		Top of Well Elevation: 1196.1 ft							
0.0 - 0.3		Asphalt Pavement, 0.0 ft - 0.3 ft							
0.3 - 6.0		Stone Fill, 0.3 ft - 6.0 ft							
6.0 - 9.5		Visual Classification, Si, gry, MTW							
9.5 - 10.0		Hole stopped @ 9.5 ft							
10.0 - 17.5									


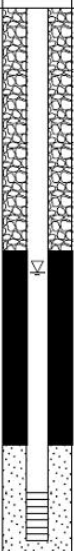
LOG OF BORING RANDOLPH CMG PARK(21), GPJ VT AOT.GDT 5/27/09

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-303 SHEET 1 of 1 DATE STARTED: 3/26/09 DATE COMPLETED: 3/26/09			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 21+67 OFFSET: 80.40 VTSPG: N 526912.88 ft E 1609205.59 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1196.34 ft GROUNDWATER DEPTH: FLOWING 4/14/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1196.13 ft								
		Asphalt Pavement, 0.0 ft - 0.3 ft						
		Crushed Stone, 0.3 ft - 3.0 ft						
		Stone Fill, 3.0 ft - 6.0 ft						
5		Visual Classification, Si, gry, MTW, Rec. = 1.4 ft		8				
		Visual Classification, Si, gry, MTW, Rec. = 1.5 ft		14				
10		Visual Classification, Si, gry, MTW, Rec. = 1.75 ft		14				
		Visual Classification, Si, gry, MTW, Rec. = 1.5 ft, Hard Pack at 13.5 ft.		73				
15		Visual Classification, NXMDC, HP, gry, MTW, Rec. = 1.0 ft, Water Loss at 15.4 ft.						
		Visual Classification, NXMDC, HP, gry, MTW, Rec. = 1.2 ft						
20		Hole stopped @ 19.5 ft						
25								


LOG OF BORING RANDOLPH OMS PARK(21).GPI VT AOT.GDT 5/27/09




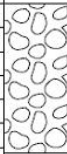












		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-305 SHEET 1 of 1 DATE STARTED: 5/05/09 DATE COMPLETED: 5/05/09				
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+70.4 OFFSET: 79.60 VTSPG: N 527015.42 ft E 1609180.88 ft			PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1198.44 ft GROUNDWATER DEPTH: 5.46 ft 5/19/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC			BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)	
		Top of Well Elevation: 1198.21 ft							
0.0		0.0 ft - 11.3 ft, No Samples taken. See Boring B-306 for Soil Descriptions.							
2.5									
5.0									
7.5									
10.0									
11.3		Hole stopped @ 11.3 ft							
12.5									
15.0									
17.5									












LOG OF BORING RANDOLPH CMG PARK(21) GPJ VT AOT/GDT 5/27/09

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-306 SHEET 1 of 1 DATE STARTED: 5/04/09 DATE COMPLETED: 5/04/09			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 22+75.8 OFFSET: 79.60 VTSPG: N 527020.73 ft E 1609179.07 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1198.53 ft GROUNDWATER DEPTH: 1.87 ft 5/19/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1198.34 ft								
		Asphalt Pavement, 0.0 ft - 0.3 ft						
		Stone Fill, 0.3 ft - 5.0 ft						
5		Visual Classification, Si, gry, Moist, Rec. = 1.3 ft		7				
		Visual Classification, GrSi, gry, MTW, Rec. = 0.9 ft		11				
10		Visual Classification, GrSi, gry, MTW, Rec. = 1.9 ft		9				
		Visual Classification, GrSi, gry, Wet, Rec. = 1.4 ft		14				
		Field Note: No Recovery		18				
15		Visual Classification, GrSaSi, gry, Wet, Rec. = 1.3 ft		35				
		Visual Classification, GrSi, gry, MTW, Rec. = 1.3 ft		25				
20		Visual Classification, GrSi, gry, MTW, Rec. = 1.9 ft		52				
		Hole stopped @ 21.5 ft						
25								

LOG OF BORING RANDOLPH CMG PARK(21) GPJ VT AOT.GDT 5/27/09

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-307 SHEET 1 of 1 DATE STARTED: 5/07/09 DATE COMPLETED: 5/07/09			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 23+00 OFFSET: 68.00 VTSPG: N 527039.11 ft E 1609160.40 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1197.75 ft GROUNDWATER DEPTH: 4.42 ft 5/19/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
		Top of Well Elevation: 1197.46 ft						
		Drilled Boring within existing manhole., 0.0 ft - 1.0 ft						
2.5		Stone Fill, 1.0 ft - 4.1 ft						
5.0		Visual Classification, Si, gry, MTW, Rec. = 1.6 ft		10				
7.5		Visual Classification, Si, gry, MTW, Rec. = 2.0 ft		8				
		Visual Classification, Gravely zone						
10.0		Visual Classification, Si, gry, MTW, Rec. = 1.8 ft		8				
		Hole stopped @ 11.0 ft						
12.5								
15.0								
17.5								

LOG OF BORING RANDOLPH CMG PARK(21).GPI VT AOT.GDT 5/27/09

		STATE OF VERMONT AGENCY OF TRANSPORTATION MATERIALS & RESEARCH SECTION SUBSURFACE INFORMATION			BORING NUMBER: B-308 SHEET 1 of 1 DATE STARTED: 5/06/09 DATE COMPLETED: 5/06/09			
PROJECT NAME: RANDOLPH SITE NAME: RANDOLPH PARK & RIDE STATION: 23+80 OFFSET: 112.90 VTSPG: N 527058.53 ft E 1609205.45 ft		PROJECT NUMBER: RSCH012-705 SITE NUMBER: VT-66 GROUND ELEVATION: 1199.77 ft GROUNDWATER DEPTH: 8.95 ft 5/19/09 PROJECT PIN NUMBER: 00K130						
BORING CREW CREW CHIEF: GARROW DRILLER: GARROW LOGGER: MAHMUTOVIC		BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER BORING TYPE: WASH BORE SAMPLE TYPE: SPLIT BARREL CHECKED BY: TDE						
DEPTH (ft)	SYMBOL	CLASSIFICATION OF MATERIALS (Description)	WELL DIAGRAM	BLOWS PER FOOT	M.C. (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1199.45 ft								
		Porous Concrete, 0.0 ft - 0.6 ft						
		Stone Fill, 0.6 ft - 6.0 ft						
2.5								
5.0								
7.5		Field Note: No Recovery		22				
10.0		Visual Classification, SiCl, gry, Moist, Rec. = 0.8 ft		17				
12.5		Visual Classification, Cisi & Stones, gry, Moist, Rec. = 1.2 ft		35				
		Hole stopped @ 12.5 ft						
15.0								
17.5								

LOG OF BORING RANDOLPH CMS PARK(21)GPU VT AOT.GDT 5/27/09

## Appendix D

# The Noordbergum effect

The Noordbergum effect, or in other words a reverse (upward) water level response due to pumping, is a rare phenomenon that has however been reported in literature as early as the 1980s. The effect occurs axially symmetrically around pumping wells in aquitards and unpumped aquifers adjacent to pumped aquifers. The rapid head rise at the beginning of groundwater pumping is called the Noordbergum effect while the rapid head drops at the end of the pumping is called the Rhade effect. These names derive from the locations where the effects were first observed [15].

One of the first observations of the Noordbergum effect was by Jose Delgado Rodrigues [21] in 1983. As part of a project aiming at exploiting the Rio Maior lignite deposits an aquifer characterization was needed, and therefore pumping tests were performed in the field. The pumping test showed inverse water level response in several piezometers in distances up to 140 m from the pumping well. The author defined the Noordbergum effect as a reverse water level response in aquitards or in aquifers separated from the pumped aquifer by aquitards, during early stages of pumping and recovery tests. The paradoxical behavior of the piezometric surface is similar to effects obtained due to three dimensional consolidation and can therefore also be called the Mandel-Cryer effect. In the specific research the author considered that pumping of the upper layer of an aquifer would attract water from the lower layer and promote a decrease in volume with a tendency to compression in the lower layer. Since pore water opposes compression of the soil, there would be an increase in pore-water pressure causing the water levels to rise in the piezometers.

Hoffman [12] presents different definitions of the Noordbergum effect including one for unconfined aquifers. In this case as sediments are dewatered in the aquifer during pumping an amount of water is retained in the vadose zone. This water has contributed to the hydrostatic force when it was part of the saturated zone but as part of the unsaturated it does not. This means that hydrostatic pressure in the saturate zone decreases faster than the total pressure and consequently intergranular pressure increases.

A more detailed definition of the Noordbergum effect is provided by Piper [20] in a report investigating a confined sandy aquifer underlain by a clay layer and an unconfined also sandy aquifer in Maryland. The intergranular pressure at the bottom of the confining layer is equivalent to the weight of the soil and water above it, minus the hydrostatic pressure exerted upward by the confined aquifer. When pumping begins the weight of the soil and water remain the same since this is a confined aquifer and a decline in the piezometric zone does not cause desaturation but the hydrostatic pressure decreases. This causes the

intergranular pressure to be greater during pumping. The increase in the intergranular pressure causes the pore water to be squeezed out of the pores and the soil matrix and soil compression takes place. The reduction in the volume of the compressed layers is the same as the volume of the water squeezed out.

Finally, the Noordergum effect has been modeled by Hsieh [13]. The model is a finite element model which solves the axisymmetric form of the poroelastic equations and analyzes deformation-induced changes in hydraulic head.