

VERMONT AGENCY OF TRANSPORTATION

**Materials & Research Section
Research Report**



**NUMERICAL MODELING AND EXPERIMENTAL INVESTIGATION
OF THE LOCAL HYDROLOGY OF A POROUS CONCRETE SITE**

Report 2013 – 10

July 2013

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Reporting on SPR-RAC-709

STATE OF VERMONT
AGENCY OF TRANSPORTATION

MATERIALS & RESEARCH SECTION

BRIAN R. SEARLES, SECRETARY OF TRANSPORTATION
RICHARD M. TETREAULT, P.E., DIRECTOR OF PROGRAM DEVELOPMENT
WILLIAM E. AHEARN, P.E., MATERIALS & RESEARCH

Prepared By:
University of Vermont, College of Engineering and Mathematical Science
Christina Syrrakou, Graduate Student
George Pinder Ph.D., Professor

Transportation Research Center
Farrell Hall
210 Colchester Avenue
Burlington, VT 05405
Phone: (802) 656-1312
Website: www.uvm.edu/transportationcenter



The University of Vermont

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Technical Report Documentation Page

1. Report No. 2013-10	2. Government Accession No. - - -	3. Recipient's Catalog No. - - -	
4. Title and Subtitle NUMERICAL MODELING AND EXPERIMENTAL INVESTIGATION OF THE LOCAL HYDROLOGY OF A POROUS CONCRETE SITE		5. Report Date July, 2013	
		6. Performing Organization Code	
7. Author(s) Christina Syrrakou, Graduate Student George Pinder Ph.D., Professor		8. Performing Organization Report No. 2013-10	
9. Performing Organization Name and Address Vermont Agency of Transportation Materials and Research Section 1 National Life Drive National Life Building Montpelier, VT 05633-5001		10. Work Unit No.	
		11. Contract or Grant No. RSCH015-709	
12. Sponsoring Agency Name and Address Federal Highway Administration Division Office Federal Building Montpelier, VT 05602		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract 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.			
17. Key Words Porous Concrete, Park and Ride, Hydrology		18. Distribution Statement No Restrictions.	
19. Security Classif. (of this report) - - -	20. Security Classif. (of this page) - - -	21. No. Pages	22. Price - - -

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Acknowledgements

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.

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.

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.
- 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 [1]. 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. [2], 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 [3], 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 site's overall performance still remained satisfactory.

Another study on porous concrete sites, with more general focus, is from Henderson and Tighe [4] 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 [5].

For an additional review on porous concrete installations the reader can also refer to Ferguson [1]. 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 site's hydrologic characteristics are from Brattebo and Booth [6], 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 site's 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. [8], 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 behavior of porous pavement in cold climates was the research focus of a study by Backstrom [9]. 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. [?]. 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. Evaporation rates were measured using a "counterbalance method". More specifically, their experimental setup consisted of a beam balance attached

to a jib arm extension that on one side was attached to the structure under study and on the other was attached to counterbalance weights required to compensate for changes in weight due to rainfall, drainage or evaporation. Water gain or loss in the structure was calculated as the difference in weight between two consecutive measurements.

Extensive research on the same topic has also been performed by Nemirovski [10] with emphasis on identifying which are the parameters affecting evaporation, measuring them in the lab and finally making predictions for typical porous concrete systems. This study presented a very detailed experimental setup where a column containing a porous concrete core overlaying coarse gravel was subjected to specified solar radiation, wind speed, temperature and relative humidity conditions so that the obtained evaporation rates could match as close as possible real site conditions during a typical summer day. Their results showed that evaporation rates follow patterns similar to daily thermal fluctuations and also showed that a maximum of 12mm of rainfall can evaporate in 60 hours.

A study by Göbel et al. [11], presents evaporation rates on permeable pavement surfaces measured using a tunnel evaporation gauge. This device is able to measure evapotranspiration over a plane by means of a plexiglass tunnel and a wind ventilator which produces air running longitudinally through the tunnel. The humidity between the air inflow and outflow was measured using probes and then translated to evapotranspiration. Results showed that evaporation mainly takes place in the upper part of the structure and rates decrease as the distance from top increases. Also, evaporation rates are higher immediately following precipitation events and reach a maximum of 4 mm/h.

For further information the reader can refer to Kunzen's study [12] who measured evaporation processes inside a column filled with porous concrete and sand using pressure probes,

Fassman and Blackbourne [7], who studied losses of water inside the subbase of a block-pavers porous pavement and Gomez-Ullate et al. [13] who 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 system's 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 [14]. 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 Darcy's Law, has not been tested against field data and therefore may be unsuitable for the specific application [15].

In a different approach, Wanielista et al. [16] 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. [17]

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, although research on porous concrete has increased significantly over the last years there are still limitations regarding the mathematical models used to simulate such sites and very little information is known on their impact on the groundwater system. The limitation of the modeling approaches 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. Also, 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, especially evaporation. 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.

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 the Vermont Agency of Transportation (the agency responsible for building the site), decided the location of a set of monitoring wells.

The specific project reported here 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 part 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 ft² 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 and Figure 3.4 shows a side and top view. 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.

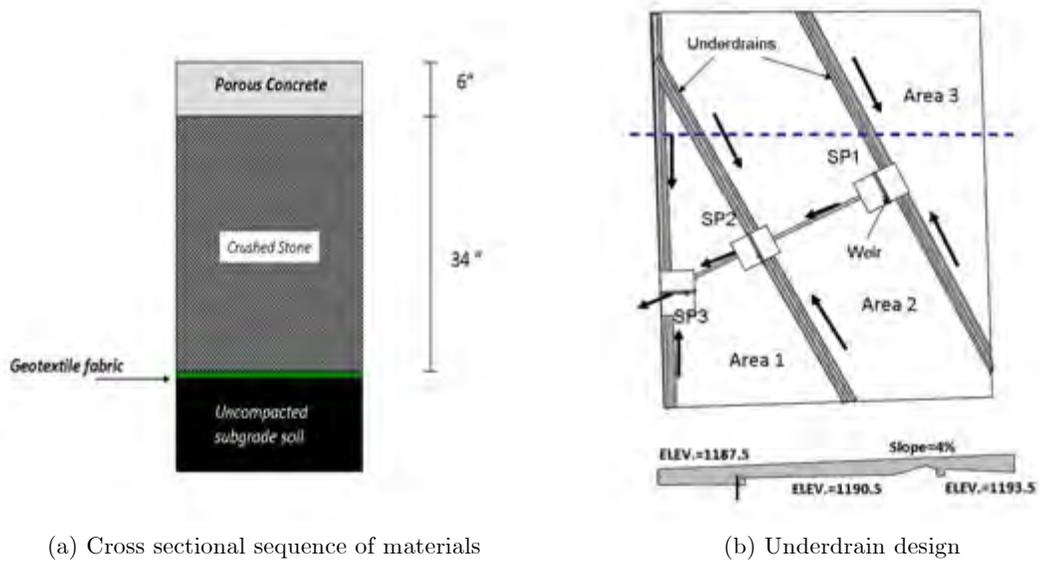


Figure 3.1: Site Design

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. Two reasonable explanations are the following:

- Water is retained by the surface area of the crushed stone and then evaporates into the atmosphere
- Water that infiltrates the porous concrete slab could somehow fail to flow towards the underdrains in the subbase.

These two hypotheses gave rise to the evaporation experiments presented in section 3.2.5 and the field experiment presented in section 5.

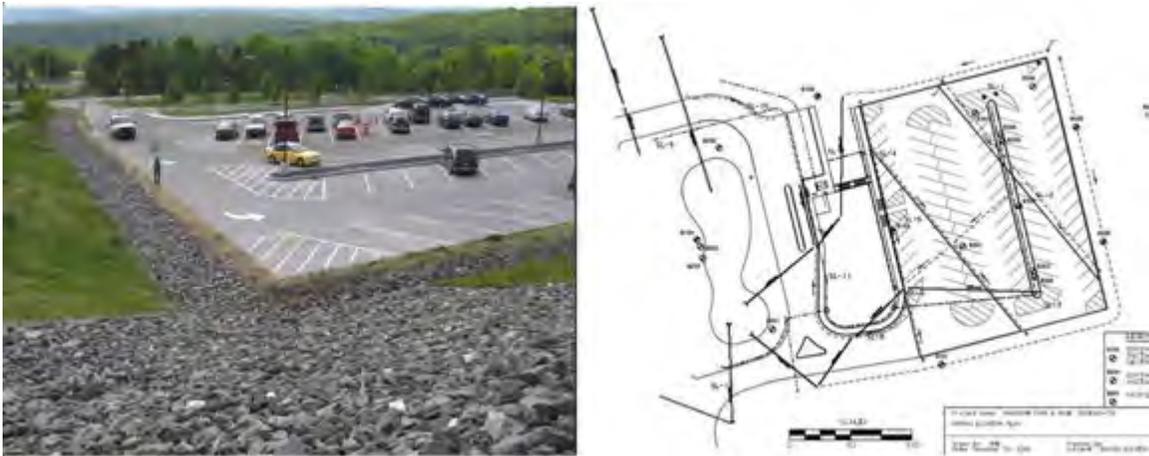


Figure 3.2: The Randolph Park and Ride Parking Lot.

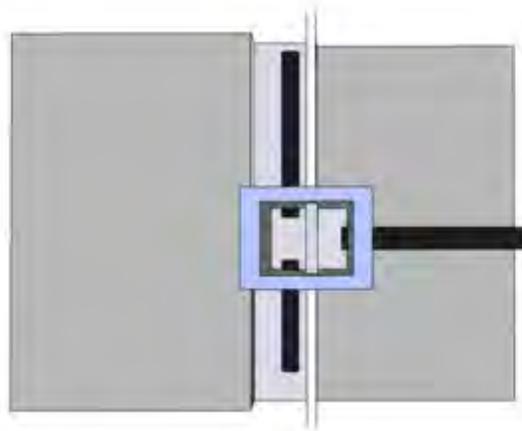


Figure 3.3: Drop inlet top view .

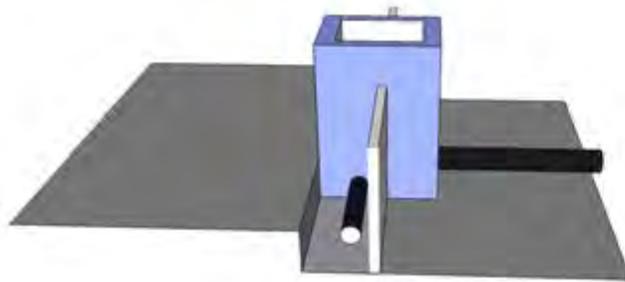


Figure 3.4: Drop inlet side view.

3.1.2 Site Instrumentation

Twenty-four monitoring wells have been installed on site (Figure 3.5).

- 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.

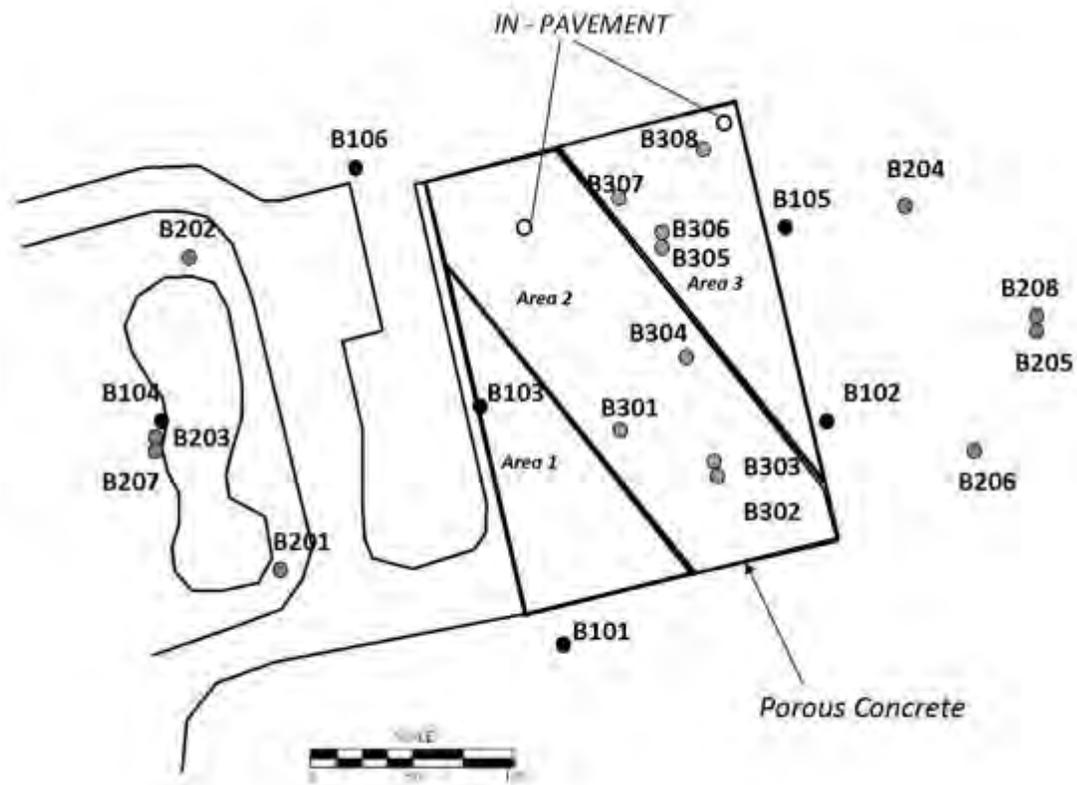


Figure 3.5: Monitoring wells.

3.1.3 Site Geology

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 (Table 3.1). Data for the 300-series wells indicated smaller permeability values ranging from "impermeable" to 1.14 ft/d (Table 3.2). Boring log information is attached in the Appendix.

MW	K (ft/day)	K (cm/sec)
B201	0.17	6.1×10^{-5}
B202	0.64	2.3×10^{-4}
B203	0.003	1.1×10^{-6}
B204	0.26	9.0×10^{-5}
B205	5.6	2×10^{-3}
B206	1.2	4.2×10^{-4}
B207	0.18	6.2×10^{-5}
B208	0.001	3.6×10^{-7}

Table 3.1: Slug test data for 200-series wells (Provided by Tom Eliassen).

MW	K (ft/day)	K (cm/sec)
B301	1.14	4.019×10^{-4}
B302	0.21	7.56×10^{-5}
B303	-	-
B304	3.3×10^{-2}	1.183×10^{-5}
B305	5.92×10^{-3}	2.091×10^{-6}
B306	1.22×10^{-3}	4.3×10^{-7}
B307	2.3×10^{-2}	8.26×10^{-6}
B308	impermeable	impermeable

Table 3.2: Slug test data for 300-series wells.

3.1.4 Short and Long Term Groundwater Level Monitoring

Groundwater level monitoring in this research will provide a better understanding of the aquifer characteristics and response to rainfall but also give the data required for the model calibration. Initially, water level data were collected from the wells using portable, hand operated water level meters but later on it became evident that more detailed measurements in time were needed. For this reason, a set of pressure transducers was purchased and installed on site. However, due to various equipment malfunctions a significant part of data collection was lost and eventually two separate sets of pressure transducers were used either at different locations on site or even at the same location for data verification. Eventually, groundwater level data collection was successful.

Data collection was performed for short periods of time (approximately a month) so that the aquifer response immediately after rainfall could be observed and also for longer periods of time (several months) showing seasonal groundwater level patterns. Figure 3.7 shows groundwater level and rainfall data for Vermont starting on December 8th, 2010 for a period of approximately 6 months. At first glance no direct correlation can be observed between the two sets of data. However, a comparison to groundwater level data for Maine (Figure 3.8) shows that there is a similar pattern in the data fluctuation, especially for the period starting around March, most probably linked to the onset of snowmelt at that time. This proves that when looking into long term groundwater level data both rainfall but also additional recharge terms such as snowmelt should be considered during modeling. Figure 3.6 shows a more short-term groundwater level response for the summer period of 2012. Additional long term groundwater level data, including Hurricane Irene can be found in

section 5.

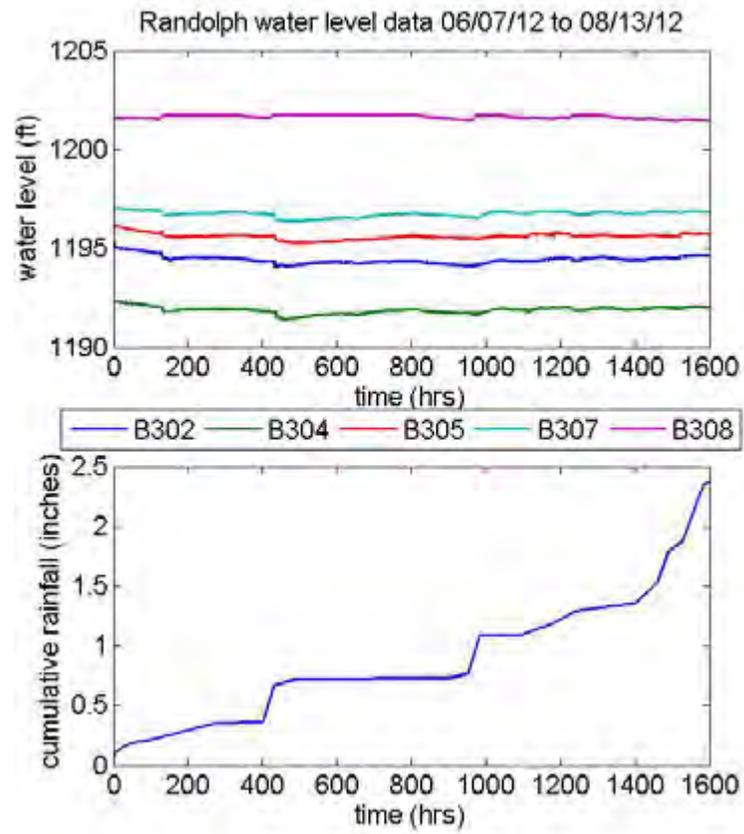


Figure 3.6: Groundwater levels in Randolph, Vermont during the summer period 2012.

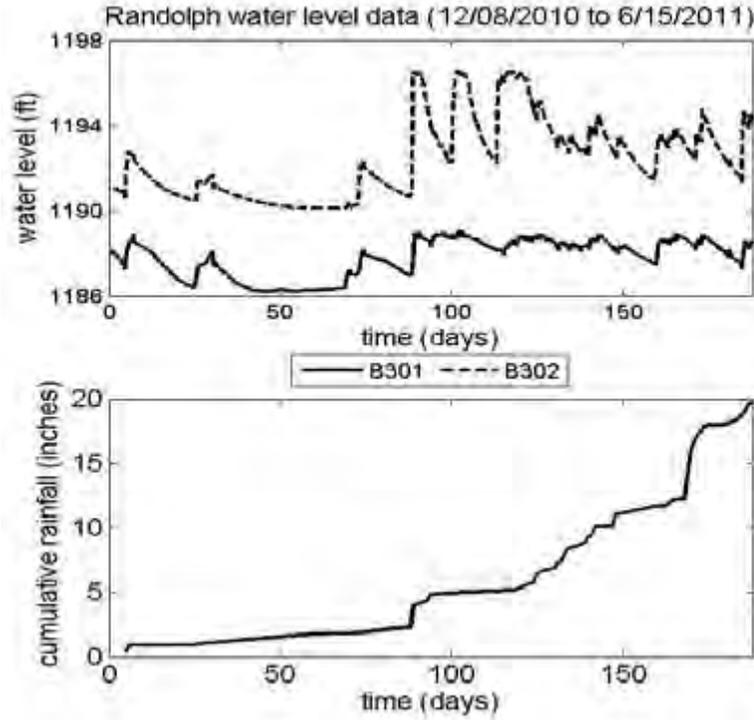


Figure 3.7: Groundwater level data in Randolph, Vermont winter during the winter period 2010-11.

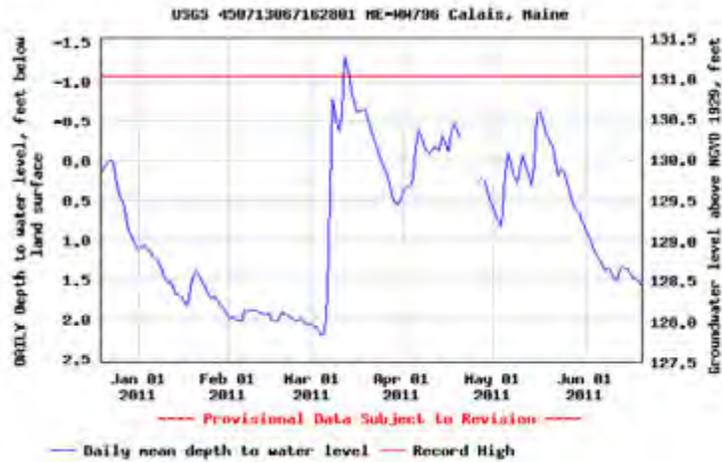


Figure 3.8: Groundwater level data in Maine during the winter period 2010-11 (off the web).

3.1.5 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 upward flow and the deep wells can be characterized as "artesian wells". Although the term "artesian wells" traditionally refers to confined aquifers in the specific case it is believed that the aquifer is unconfined but the upward gradient is present due to the flow of groundwater from the hills surrounding the site towards the area of interest.

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.



(a) Apparatus



(b) B306 Top View

Figure 3.9: Artesian Well Setup

Table 3.3 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.

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

Table 3.3: Pressure in artesian wells (in inches of water).

To calculate the gradient of flow, four 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 3.10 shows the location of the tetrahedra on site.

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 3.4).

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 in tetrahedra 1, 2 and 3. The negative sign of the gradient shows that there is a positive velocity since from Darcy's Law $v = -K \times \text{gradient}$, where K=hydraulic conductivity. This means that there is an upward direction in flow in the area

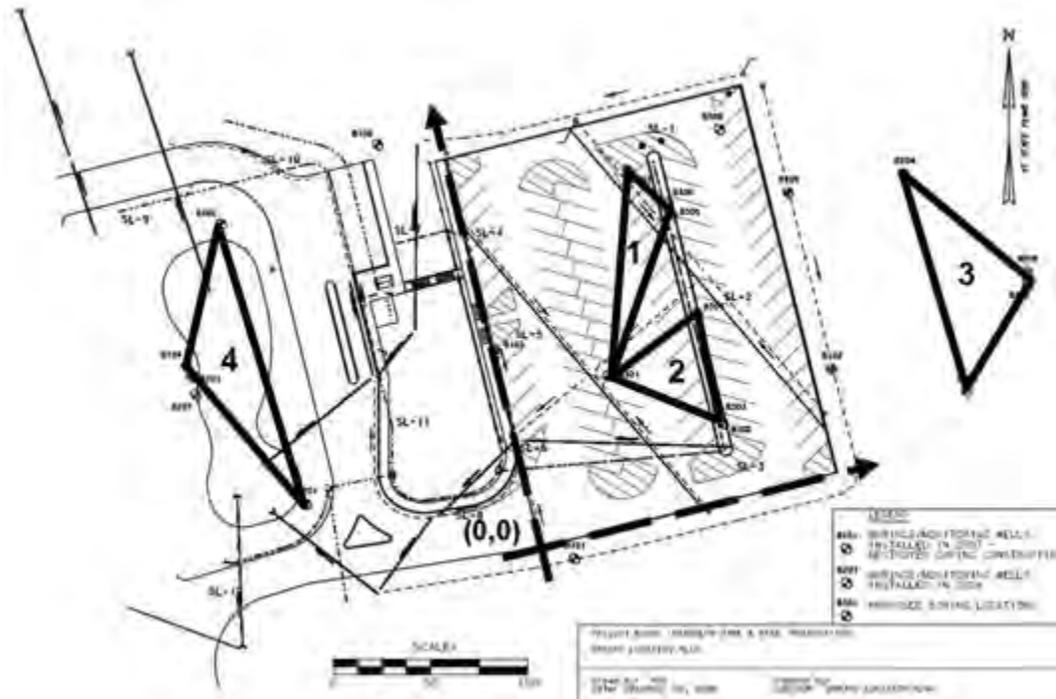


Figure 3.10: Location of conceptual tetrahedra on site.

of interest.

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	<i>0.0641</i>	<i>0.0391</i>	-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	<i>0.1036</i>	<i>0.0351</i>	-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	<i>0.0348</i>	<i>-0.0198</i>	-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			
4	B201	-113	51	-18.27	-13.689	<i>0.0383</i>	<i>-0.0145</i>	-0.0128
	B207	-155.55	117.78	-42.35	-15.978			
	B203	-155.55	128.89	-20.86	-16.413			
	B202	-122.2	200	-21.56	-16.162			

Table 3.4: Groundwater gradient : Coordinates and Calculations.

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 weighed and results are plotted [19]. Soil cores obtained from the field and

provided by VTrans were used for the grain-size distribution analysis. Figure 3.11 shows the grain-size distribution curve for a section of the soil core, for observation well B304.

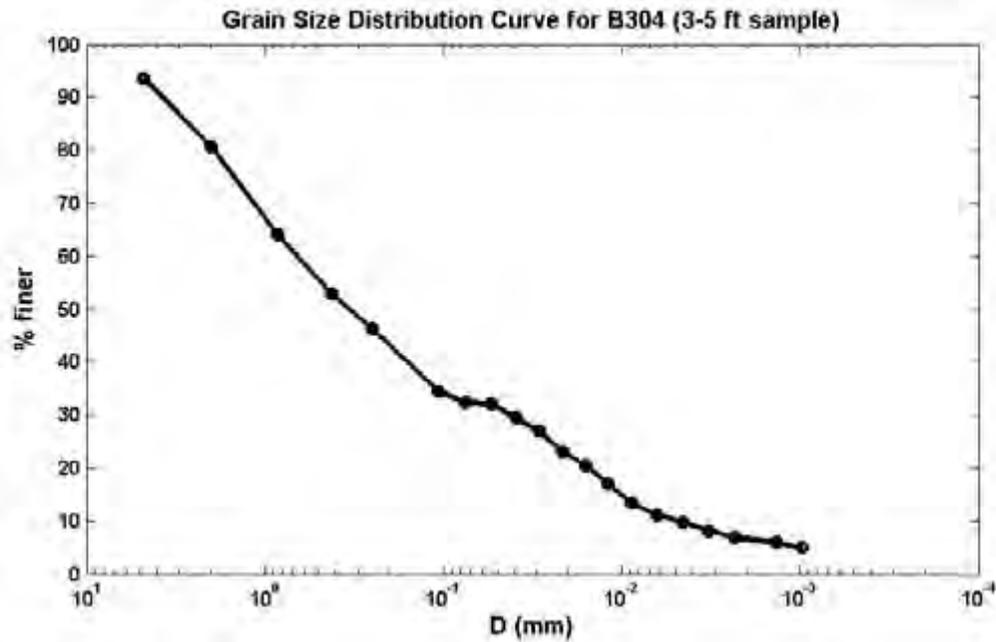


Figure 3.11: Grain Size Distribution Curve from a soil core obtained from the field.

3.2.2 Liquid and Plastic Limits

In addition to the grain size distribution analysis, liquid and plastic limits will provide a better understanding of the soil present on site.

Liquid Limit (LL)

Test No	1	2	3	4	5
Can ID #	L1	L2	L3	L4	L5
Mass of empty moisture can M1 (g)	0.9	0.9	1	1	1
Mass of (can + moist soil) M2 (g)	21.5	25	20.9	17.5	22.7
Mass of (can + dry soil) M3 (g)	18.1	20.9	17.2	14.5	18.3
Moisture Content $w = \frac{M_2 - M_3}{M_3 - M_1} \times 100\%$	19.8	20.5	22.8	22.2	25.4
Number of blows, N	30	26	23	15	9

Table 3.5: Observation table for liquid limit test.

The liquid limit is determined by plotting the number of blows N at logarithmic scale vs. water content w at arithmetic scale (Figure 3.12). Liquid limit is then determined as the water content for $N = 25$. According to the best fit equation $LL=20.5$

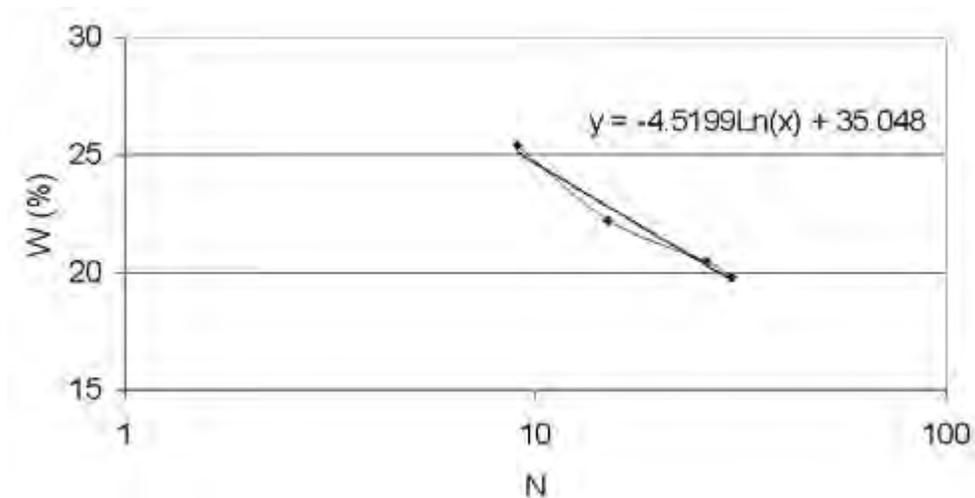


Figure 3.12: Water content vs. number of blows for liquid limit test.

Plastic Limit (PL)

Can ID #	Mass of empty can M_1 (g)	Mass of (can + moist soil) M_2 (g)	Mass of (can + dry soil) M_3 (g)	Plastic limit (%) $PL = \frac{M_2 - M_3}{M_3 - M_1} \times 100\%$
P1	0.9	6.8	5.9	18
P2	0.9	9.5	8.2	17.8
P3	1	11.2	9.7	17.2
P4	1	8.9	7.8	16.2

Table 3.6: Observation table for plastic limit test.

The plastic limit is obtained by taking the average of the values calculated in Table 3.6.

Therefore $PL=17.3$

3.2.3 Soil characterization according to the Unified Soil Classification System

Following the step by step procedure for the USC system we have the following:

$$F_{200} = 32.27\%$$

$$R_{200} = 67.73\% > 50\% \text{ which means that the soil is coarse grained}$$

$$PI = LL - PL = 20.5 - 17.3 = 3.2$$

$$R_4 = 6.34\% \text{ which means that the soil is sandy}$$

According to Table 3.13 the soil can be characterized as **Silty sand**.

Criteria for group symbol				Group symbol	Criteria for group name	Group name
F_{200}	C_u	C_c	Relationship between LL & PI		GF	
-3	≥ 5	1 ≤ C_c ≤ 3		SW	<15	Well graded sand
					≥15	Well graded sand with gravel
	$C_u < 5$ and/or $1 > C_c > 3$			SP	<15	Poorly graded sand
					≥15	Poorly graded sand with gravel
>12				SM	<15	Silty sand
					≥15	Silty sand with gravel
				SC	<15	Clayey sand
					≥15	Clayey sand with gravel
				SC-SM	<15	Silty, clayey sand
					≥15	Silty, clayey sand with gravel
3 > F_{200} ≥ 12	≥ 5	1 ≤ C_c ≤ 3		SW-SM	<15	Well graded sand with silt
					≥15	Well graded sand with silt and gravel
				SW-SC	<15	Well graded sand with clay
					≥15	Well graded sand with clay and gravel
	$C_u < 5$ and/or $1 > C_c > 3$	SP-SM	<15	Poorly graded sand with silt		
			≥15	Poorly graded sand with silt and gravel		
		SP-SC	<15	Poorly graded sand with clay		
			≥15	Poorly graded sand with clay and gravel		

Figure 3.13: USCS of Sandy Soils ($R_4 \leq 0.5R_{200}$).

3.2.4 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 (Jkg^{-1}), energy per unit volume (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, θ , m^3/m^3) or degree of saturation S (volumetric water content θ 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 [20].

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 [21].

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. [22] 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. [21], 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, i.e. over the range important to this analysis.

Experimental method

Water retention experiments involve two main processes. Drainage, where water is removed from the sample, and imbibition where water is placed back into 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

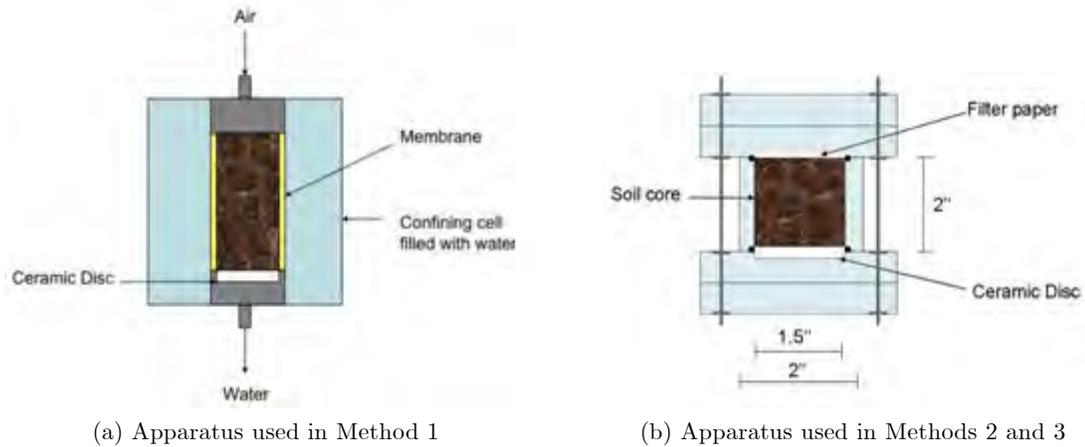


Figure 3.14: Water retention curve experimental apparatus.

method restricts maximum water pressure to -50 kPa which is the limit of the water pump.

Figure 3.14 shows the apparatus used for the different experimental methods.

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

Water retention curve - Results

Data from the three methods appear to provide slightly different results as seen in Figure 3.15. 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

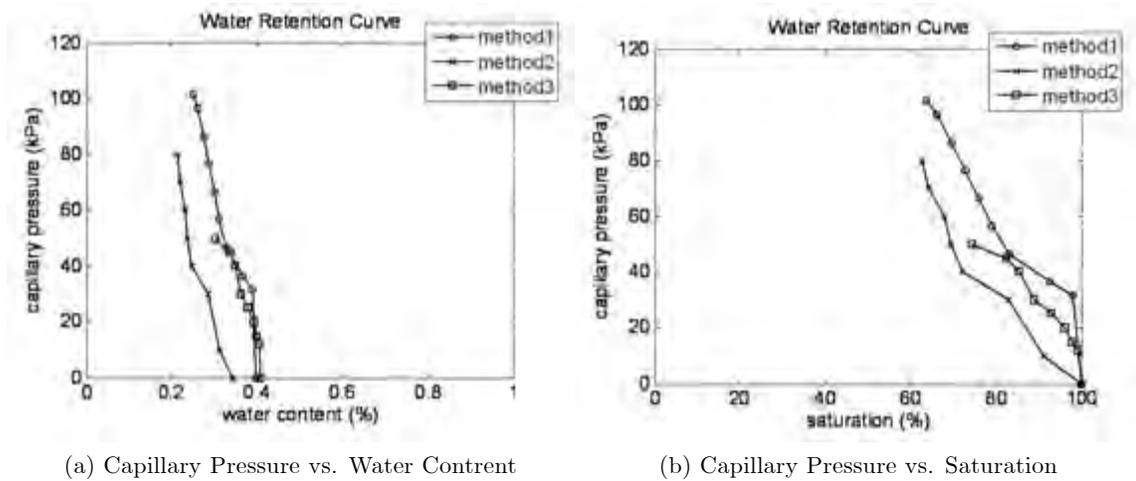


Figure 3.15: Water retention curve results.

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 SWRC Fit will be more accurate. This experiment is scheduled to take place in the near future.

3.2.5 Retention and subsequent evaporation of stormwater

As mentioned previously, 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 and 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 2 which is able to monitor the tension applied to the column through time. The setup is shown in Figure 3.16 and Figure 3.17.

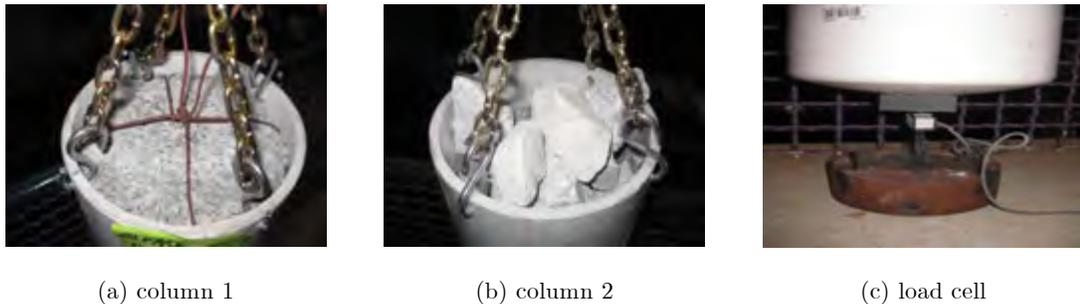


Figure 3.18: Details of Experimental Setup

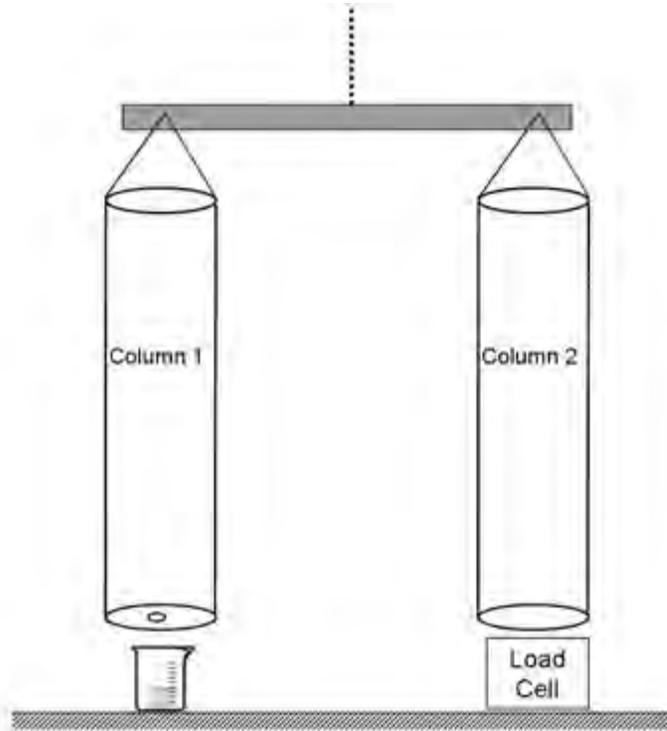


Figure 3.16: Experimental setup for evaporation experiment (sketch).



Figure 3.17: Experimental setup for evaporation experiment (photo).

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 to the top as rainfall and the amount that drained from the bottom, the water withheld by the crushed stone can be calculated. 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 sequential measurements and the rate of evaporation as the first derivative of the evaporation measurements.

Results

The experiment showed that initially the addition of water to the top of the column causes no outflow from the bottom since all the water added starts covering the surface area of the dry crushed stone. When the surface area of the crushed stone gets "saturated" then outflow from the bottom occurs and, as visually observed from these experiments, usually lasts for approximately twenty-four hours after the water was initially added. In the results shown below it is hypothesized that evaporation occurs after water stops coming out of the bottom and therefore the first part of the data is excluded. Table 3.7 shows data for the three experiments presented here.

Date	$Q_{in}(gms)$	$Q_b(gms)$	$Q_{retained}(gms)$
June '12	463	335	128
July '12	463	315	148
August '12	463	302	161

Table 3.7: Evaporation experiment results.

Figures 3.19, 3.20 and 3.21 show cumulative evaporation in mm of water together with temperature and relative humidity data. Figure 3.22 presents data for all three experiments.

Data were converted from *gms* to *mm*s using the following equation:

$$A_{column} = 38.48in^2 = 24826mm^2$$

$$E(mm) = \frac{\text{change in mass of water (g)}}{24826mm^2 \times 0.001g/mm^3}$$

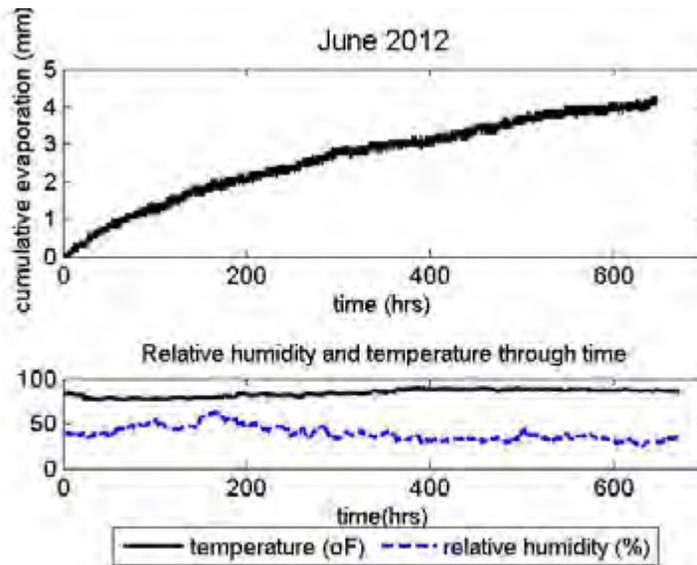


Figure 3.19: Evaporation test results - June 2012.

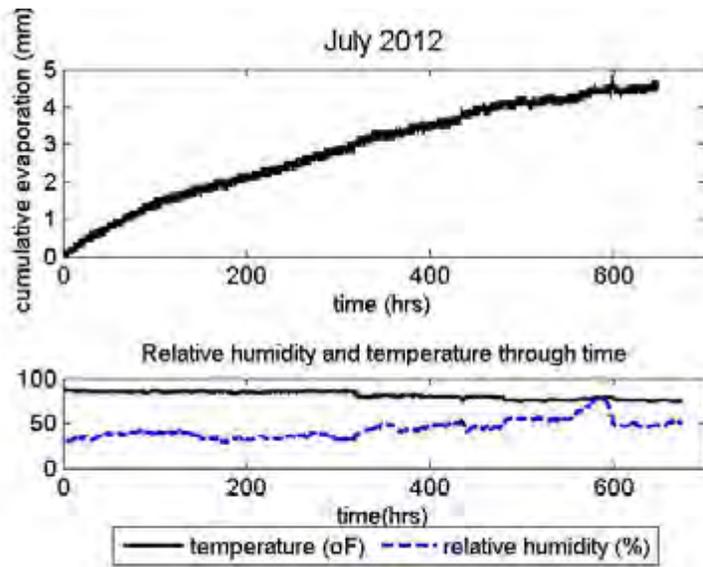


Figure 3.20: Evaporation test results - July 2012.

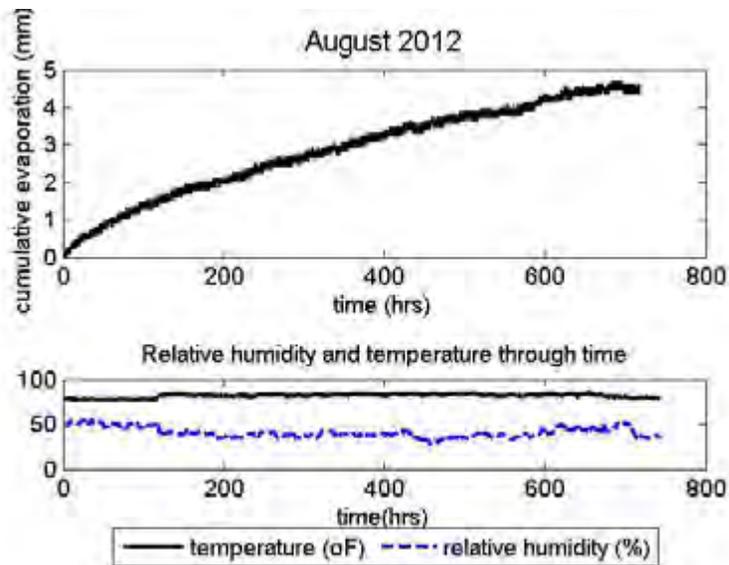


Figure 3.21: Evaporation test results - August 2012.

After taking the average of the data shown in Figure 3.22, applying analysis of variance and fitting a 6th degree polynomial, the evaporation rate can be calculated using the first derivative of the fitted polynomial (Figure 3.23). Results show that about 4.5 mm of water evaporated in approximately 700 hours. The evaporation rate is higher at the beginning of the experiment and decreases until it reaches plateau towards the end of the experiment.

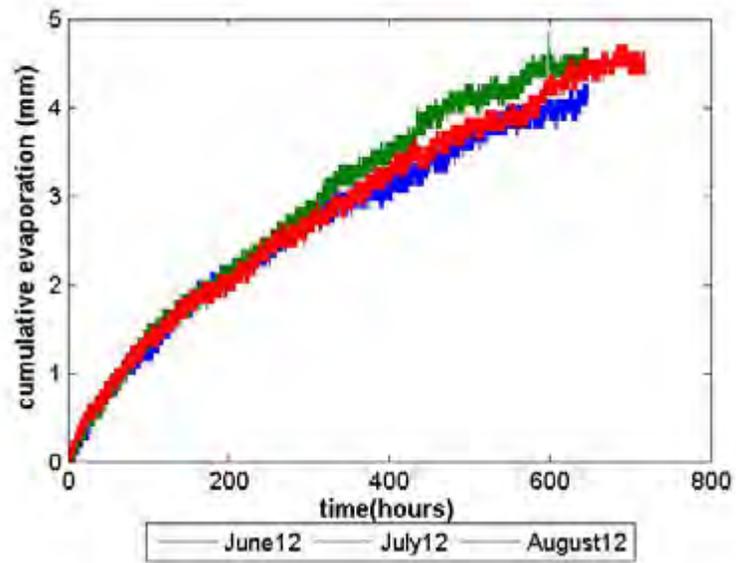


Figure 3.22: Evaporation Tests - Comparison of results

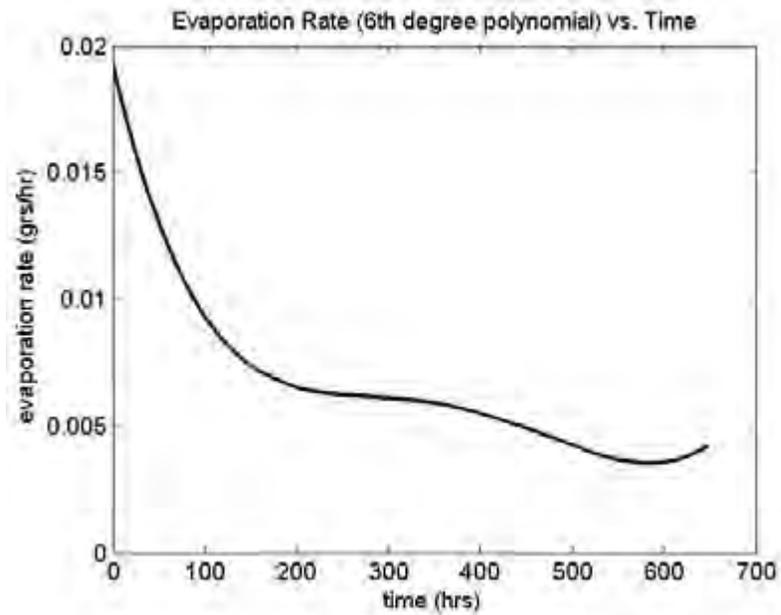


Figure 3.23: Evaporation rate.

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 (Figure 4.1).

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.

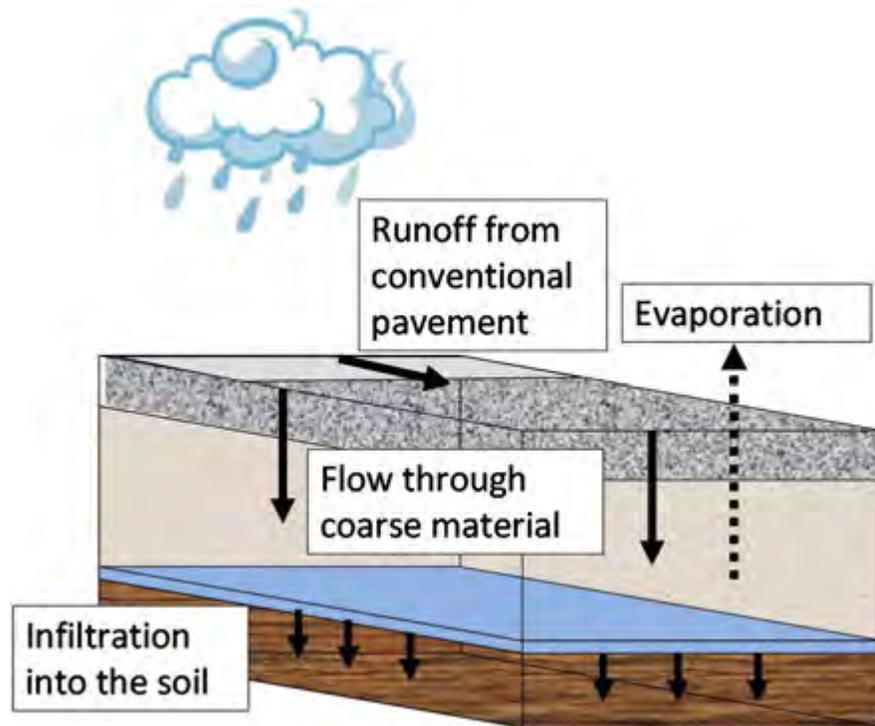


Figure 4.1: Physical processes taking place in a porous concrete system.

In this research, the physical processes mentioned above are grouped into three parts simulated by three sub-models where outflow from one model becomes inflow to the next. Rainfall is inflow to the first submodel which is a surface-water model. The model can then calculate the amount of runoff that can potentially act as recharge into the porous concrete slab. Then, the second submodel which is a "mass-balance" subroutine can calculate the amount of water that is retained by the porous concrete and crushed stone particles, the amount of water that evaporates and also the amount that reaches the bottom of the

subbase. Finally, a groundwater model receives that inflow as a "recharge" term and then calculates the flow solution in the underlying geologic material. The sub-models models are presented in more detailed in the following sections.

4.1 Sub-model 1: Surface-water model

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 [2]. 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 ¹. 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:

$$\frac{\partial HU}{\partial t} + \frac{\partial HUU}{\partial x} + \frac{\partial HVU}{\partial y} - fHV + \frac{H}{\bar{\rho}} \frac{\partial P_0}{\partial x} + g_{eff} H \frac{\rho_\zeta}{\bar{\rho}} \frac{\partial \zeta}{\partial x} + \frac{g_{eff}}{\bar{\rho}} \int_h^\zeta I_x dz \quad (4.2)$$

$$-\tau_{sx} + \tau_{bx} - \left(\frac{\partial}{\partial x} \left(H \epsilon_h \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left(H \epsilon_h \frac{\partial U}{\partial y} \right) \right) = 0$$

$$\frac{\partial HV}{\partial t} + \frac{\partial HUV}{\partial x} + \frac{\partial HVV}{\partial y} - fHU + \frac{H}{\bar{\rho}} \frac{\partial P_0}{\partial x} + g_{eff} H \frac{\rho_\zeta}{\bar{\rho}} \frac{\partial \zeta}{\partial x} + \frac{g_{eff}}{\bar{\rho}} \int_h^\zeta I_y dz \quad (4.3)$$

¹J. Laible, Professor Emeritus, UVM

$$-\tau_{sy} + \tau_{by} - \left(\frac{\partial}{\partial x} \left(H\epsilon_h \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(H\epsilon_h \frac{\partial V}{\partial y} \right) \right) = 0$$

where U and V are the vertically averaged velocities in the x and y direction, ζ 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, ϵ_h is the horizontal eddy viscosity, τ_s is the wind stress, τ_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:

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

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

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

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:

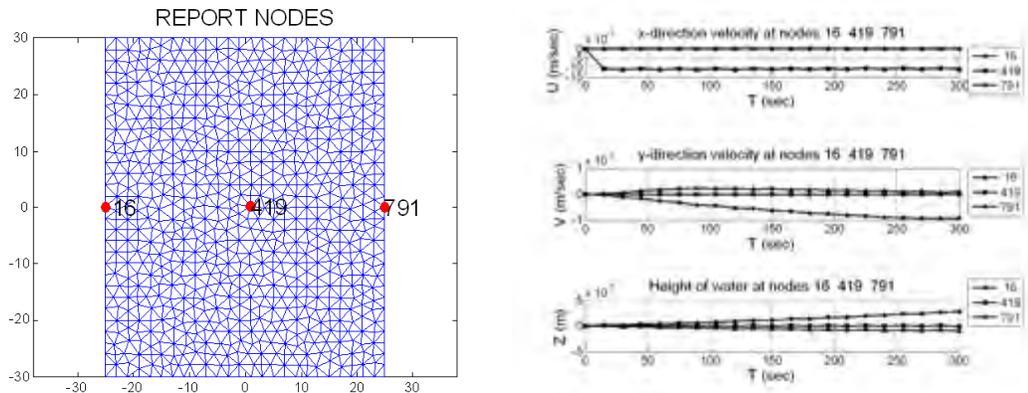
- $u = 0$. Velocity is equal to 0.
- $z = 0$. The height of water is equal to 0.
- $\frac{dz}{dx} = 0$. The slope of water surface is equal to 0.
- $z = aV_n^2$. From Bernoulli's law, the elevation head (or height of water in this case) is equal to the velocity head, where a is a calibration parameter 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. $a = 0.001$

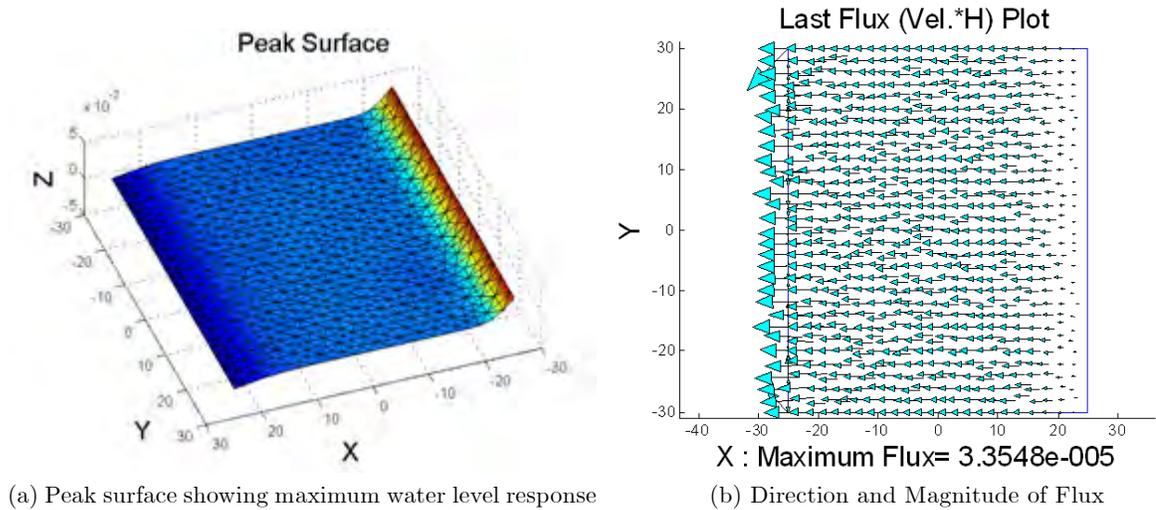
Results



(a) Location of "report" nodes

(b) Velocity and height of water at "report" nodes

Figure 4.2: Shallow water code Results - Part 1.



(a) Peak surface showing maximum water level response

(b) Direction and Magnitude of Flux

Figure 4.3: Shallow water code Results - Part 2.

Notation 1 Remark 2 *Currently although the surface-water model has been validated it has not been incorporated to the general model.*

4.2 Sub-model 2: Mass-balance model

The role of the mass-balance model is to simulate the vertical flow through the porous concrete and crushed stone material while taking into account evaporation of the water retained on the surface area of the porous material. What gave rise to the equations in this model is the evaporation experiment described in section 3.2.5. The equations are presented in the following section.

4.2.1 Retention and evaporation of water in the gravel

In the equation formulation the point of departure is the equation describing mass balance in the liquid phase. After simplifying assumptions and some math manipulation we arrive to a simple 1-D equation including the evaporation term. The formulation is the following:

The mass conservation liquid phase equation is:

$$\frac{\partial (\varepsilon s^l \rho^l)}{\partial t} + \nabla \cdot (\varepsilon s^l \mathbf{v}^l \rho^l) + \frac{1}{\delta V} \int_{S_{wg}} \rho_l (\mathbf{v}_l - \mathbf{w}) \cdot \mathbf{n}_l dS = 0 \quad (4.7)$$

where

ε is porosity

s^l is the saturation of the liquid phase

ρ^l is the macroscopic density of the liquid phase

\mathbf{v}^l is the macroscopic velocity of the liquid

$S_{\alpha\beta}$ is the interface between the α and β phases where α and β could be air and liquid

\mathbf{v}_ℓ is the microscopic velocity of liquid

\mathbf{w} is the velocity of the S_{wg} interface

\mathbf{n}_ℓ is the normal to the S_{wg} interface

δV is the REV volume

Assumptions:

1. average velocity of all fluids in the crushed stone is vertical only,
2. water density is constant at the microscopic and macroscopic levels
3. porosity is constant

which leads to the following expression:

$$\frac{\partial (s^l)}{\partial t} + \frac{\partial}{\partial z} (s^l \mathbf{v}^l) + \frac{1}{\varepsilon \delta V} \int_{S_{gl}} (\mathbf{v}_l - \mathbf{w}) \cdot \mathbf{n}_l dS = 0 \quad (4.8)$$

The experiment described in section 3.2.5 gives the evaporation rate in the entire column as units of mass over time or $q_m = \frac{dm^w}{dt}$. Adjusting the term of mass using the definition of saturation we can get the following:

$$q_m = \frac{dm^w}{dt} = \frac{d\rho^w V_l^T}{dt} = \frac{d\rho^l s^l \varepsilon V^T}{dt} = \varepsilon V^T \rho^l \frac{ds^l}{dt} \quad (4.9)$$

where q_m is the total rate of evaporation in the column (mass flux leaving column), V^T is the total volume of the column, V_l^T is the total volume of water in the column, and V_v^T is the total amount of void space in the column. Defining rate of evaporation per unit volume of porous medium

$$q^v = \frac{q_m}{V^T} = \frac{\varepsilon V^T \rho^l \frac{ds^l}{dt}}{V^T} = \varepsilon \rho^l \frac{ds^l}{dt} \quad (4.10)$$

Now multiply and divide the right hand side of Eq. 4.8 by the constant water density to give

$$\frac{1}{\rho^l \varepsilon \delta V} \int_{S_{wg}} \rho_l (\mathbf{v}_l - \mathbf{w}) \cdot \mathbf{n}_l dS \quad (4.11)$$

where $\frac{1}{\delta V} \int_{S_{wg}} \rho_l (\mathbf{v}_l - \mathbf{w}) \cdot \mathbf{n}_l dS$ is the mass of water per unit time per unit volume moving from the water phase to the air phase. Then cancelling the density terms we have

$$\frac{1}{\varepsilon \delta V} \int_{S_{wg}} (\mathbf{v}_l - \mathbf{w}) \cdot \mathbf{n}_l dS = \frac{q^v}{\rho^l \varepsilon} = \frac{q_m}{\rho^l \varepsilon V T} \quad (4.12)$$

Eq. 4.8 now becomes

$$\frac{\partial (s^l)}{\partial t} + \frac{\partial}{\partial z} (s^l \mathbf{v}^l) + \frac{q^v(s)}{\rho^l \varepsilon} = 0 \quad (4.13)$$

or

$$\frac{\partial (s^l)}{\partial t} + \frac{\partial}{\partial z} (s^l \mathbf{v}^l) + \frac{q_m}{\rho^l \varepsilon} = 0 \quad (4.14)$$

or

$$\varepsilon \frac{\partial (s^l)}{\partial t} + \varepsilon \frac{\partial}{\partial z} (s^l \mathbf{v}^l) + \frac{q_m}{\rho^l V T} = 0 \quad (4.15)$$

If we vertically integrate equations 4.15 from the bottom of the column, b to the top t we get

$$\int_b^t \left\{ \varepsilon \frac{\partial (s^l)}{\partial t} + \varepsilon \frac{\partial}{\partial z} (s^l \mathbf{v}^l) + \frac{q_m}{\rho^l V T} \right\} dz = 0 \quad (4.16)$$

If we assume the bottom and top of the column are stationary we obtain

$$\varepsilon \frac{\partial}{\partial t} \int_b^t s^l dz + \left(\varepsilon s^l v_z^l \right) \Big|_b^t + \int_b^t \frac{q_m}{\rho^l V^T} dz = 0 \quad (4.17a)$$

Now let's consider Eq. 4.17a. The first term is the change in the total amount of water present in the column. The second is the amount of water coming into or going out of the top and bottom of the column. The third is the change in the amount of water in the column due to evaporation.

We can define the first term as the vertically averaged saturation in the column using a simple finite difference expression:

$$\bar{s} \equiv \frac{1}{\ell} \int_b^t s^l dz$$

or

$$\varepsilon \frac{\partial}{\partial t} \int_b^t s^l dz = \varepsilon \ell \frac{\partial \bar{s}}{\partial t} \approx \varepsilon \ell \frac{\bar{s}_{t+\Delta t} - \bar{s}_t}{\Delta t}$$

where ℓ is $z_t - z_b$.

From this term we can hypothesize that we know the initial saturation. We also know the evaporation rate which is the slope of the curve showing the change in the mass of water through time as we measured it in the experiment.

$$\bar{q} \equiv \frac{1}{\ell} \int_b^t \frac{q_m}{\rho^l V} dz$$

and the amount of water that is going into the top of the column which is the rainfall term in the general model.

So the whole equation becomes

$$\varepsilon \ell \frac{\bar{s}_{t+\Delta t} - \bar{s}_t}{\Delta t} + q_t(t) - q_b(t) + \ell \bar{q}(t) = 0$$

where

$$\begin{aligned} q_t &= \left(\varepsilon s^l v_z^l \right) |_t \\ q_b &= \left(\varepsilon s^l v_z^l \right) |_b \end{aligned}$$

This leaves us with two unknowns that we need to solve for. That is the saturation in the new time step, \bar{s}_t and the flow coming out of the bottom, q_b .

In order to solve this problem we will use two conditions as indicated by the column experiment. The main idea behind this is that at the beginning when the stone inside the column is dry all the water that is coming in is retained by the stone's surface and therefore we have no outflow (condition 1). Then when the stone surface starts getting saturated we start having some outflow. However the stone can only hold a specific amount of water which depends on the stone's surface area. This is a "limit amount". Therefore now the column will have the limit amount of water and no more (since it cannot hold it) minus whatever evaporation is taking place. Let's now see this expression in math.

Condition 3 *if column is unsaturated* $q_{b(t)} = 0$

$$\text{Then } \varepsilon l \frac{S_{(t+\delta t)} - S_{(t)}}{\delta t} = q_{t(t)} - lq_{evap(t)} \iff \varepsilon l S_{(t+\delta t)} = S_{(t)} + (q_{t(t)} - lq_{evap(t)}) \cdot \delta t \Leftrightarrow S_{(t+\delta t)} = (S_{(t)} + (q_{t(t)} - lq_{evap(t)}) \cdot \delta t) / \varepsilon l$$

Condition 4 if column is saturated $S_{(t+\delta t)} = S_l$

$$\text{Then } q_{b(t)} = q_{t(t)} - \varepsilon l \left(\frac{S_l - S_{(t)}}{\delta t} \right) - lq_{evap(t)}$$

4.2.2 Subroutine "porous_concrete"

The equations mentioned above are coded into the Fortran subroutine "porous_concrete" which is then called in the groundwater model VTC. The subroutine can be found in the Appendix. Two main issues were addressed while coding this subroutine. First, the subroutine needs to distinguish between the nodes that refer to the porous concrete area in comparison to the rest of the domain. In order to do that a type 2 boundary condition (constant flow) equal to 0 was applied around the perimeter of the porous concrete. Testing proved that this boundary condition does not affect the model in any other way than to "flag" the nodes of interest. In this way, when subroutine porous_concrete is called it reads the nodes where porous concrete exists and perform the various calculations for vertical flow, retention and evaporation, whereas the rest of the nodes are unaffected. This technique ensures that when VTC is run the regular rainfall term is applied in the non-porous concrete nodes. The second issue addressed was caused by the fact that the subroutines responsible for calculating the flow solutions in VTC are in some cases called multiple times until the solution converges. However, calling subroutine porous_concrete more than once can give erroneous results. A solution to this problem is to force subroutine porous_concrete to be called only once in the very first convergence loop using a flag. Again, testing proved that

since the rainfall term is not affected by any of the convergence loops this technique does not create any problems for the code and the results remain accurate. It is also important to note that the porosity of the crushed stone and also the depth to the bottom of the subbase are input parameters defined by the user.

Eventually subroutine porous_concrete calculates the saturation of the crushed stone reservoir and the outflow from the bottom of the porous concrete which becomes a recharge term for VTC.

4.3 Sub-model 3 : Groundwater model (VTC)

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:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + S_s \frac{\partial h}{\partial t} - q = 0 \quad (4.18)$$

And for unsaturated groundwater flow:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + \frac{\partial \theta_w}{\partial t} - q = 0 \quad (4.19)$$

where K is the hydraulic conductivity which in the case of unsaturated flow is a function of the water content θ_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.

4.4 General Model Setup

The main concept behind the mathematical model is that subroutine "porous_concrete" will calculate the outflow of water from the porous concrete and crushed stone system which will serve as inflow to the unsaturated groundwater flow model. For this reason, the "porous concrete+crushed stone" part does not need to exist physically in the model setup in VTC.

4.4.1 Elevation of layers

The model is composed of three mathematical layers. The elevation of the top layer (Layer 3) is built according to the contours shown in the area's topographical map. The elevation in area where the "porous concrete+crushed stone" part exists represents the bottom of the subbase. The thickness of this layer is 1 foot. Layer 2 has a varying thickness of maximum of 44 ft and minimum of 4 ft. Layer 1 (bottom layer) has a uniform thickness of 5 ft. Figure 4.4 shows the top elevation of the mathematical layers in the model.

4.4.2 Mesh grid

Figure 4.5 shows the triangular model mesh grid.

4.4.3 Hydraulic Conductivity

Hydraulic conductivity values were chosen according to the slug test data provided by the site's geologist. As an initial modeling attempt, hydraulic conductivity of the overall material was chosen as 0.1 ft/day, indicating a low permeability material. Additionally, in order to force any amount of water that comes as inflow to the porous concrete area and then

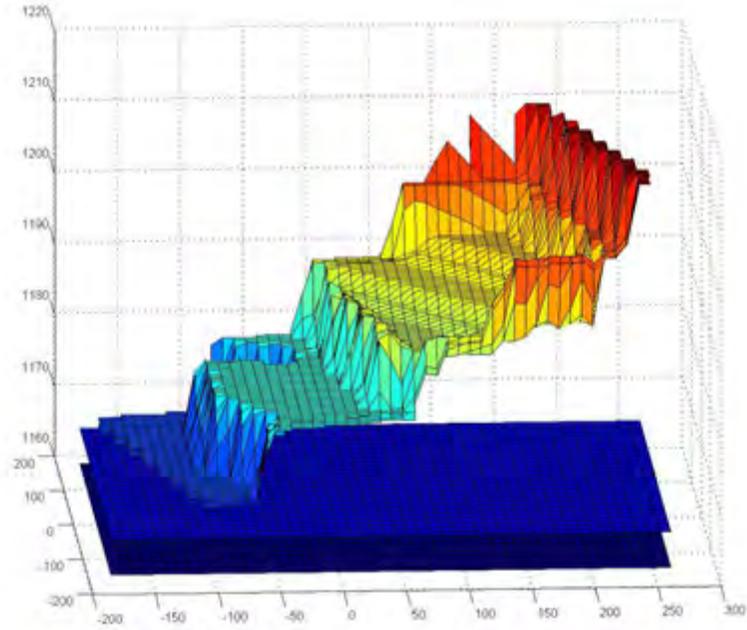


Figure 4.4: Top elevation of mathematical layers (units in ft).

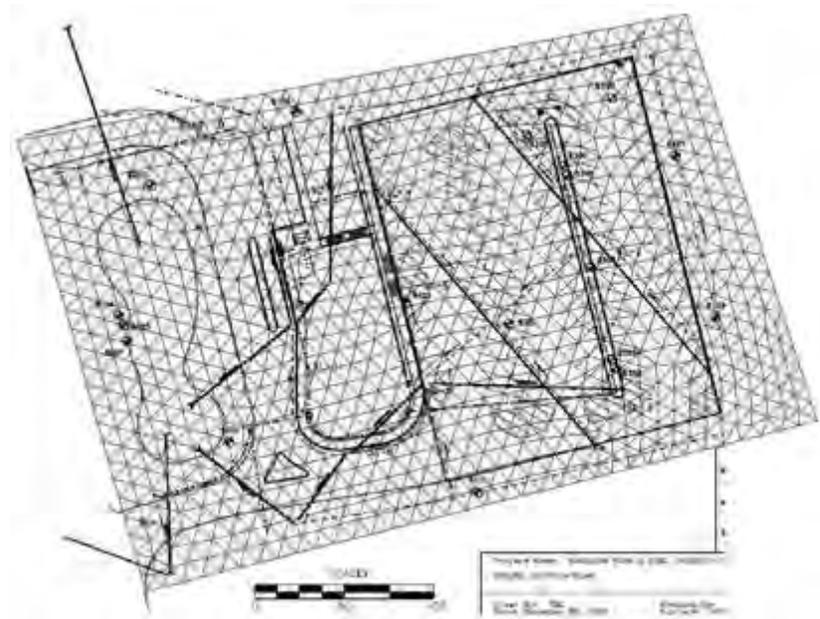


Figure 4.5: Model mesh grid (units in ft).

reaches the bottom of the subbase, to flow towards the underdrains, a highly permeable lens was placed on the top layer of the model (the layer immediately below the crushed stone reservoir). Hydraulic conductivity for the lens was chosen as 100 ft/day (Figure 4.6).

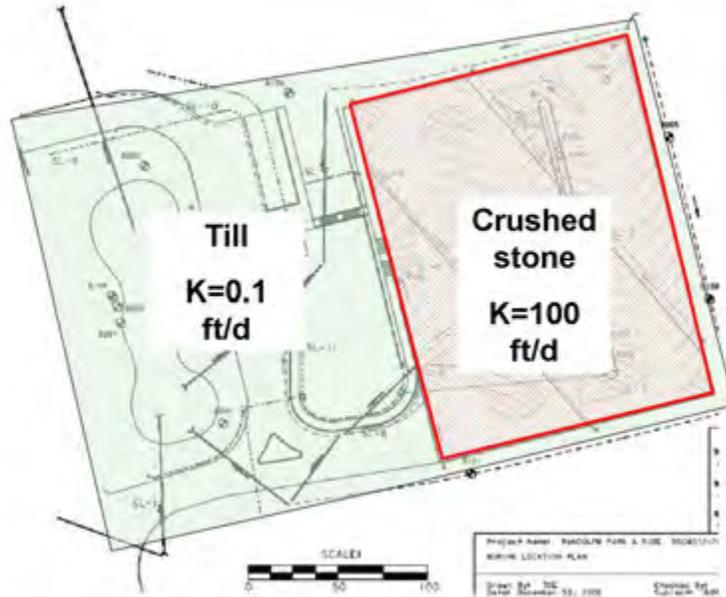


Figure 4.6: Hydraulic conductivity values.

4.4.4 Boundary Conditions

The boundary conditions imposed on the area of interest are the following (shown in Figure 4.7)

- Constant head at the left and right edges of the domain.
- Constant head along the three underdrains.
- Constant head on the retention pond.

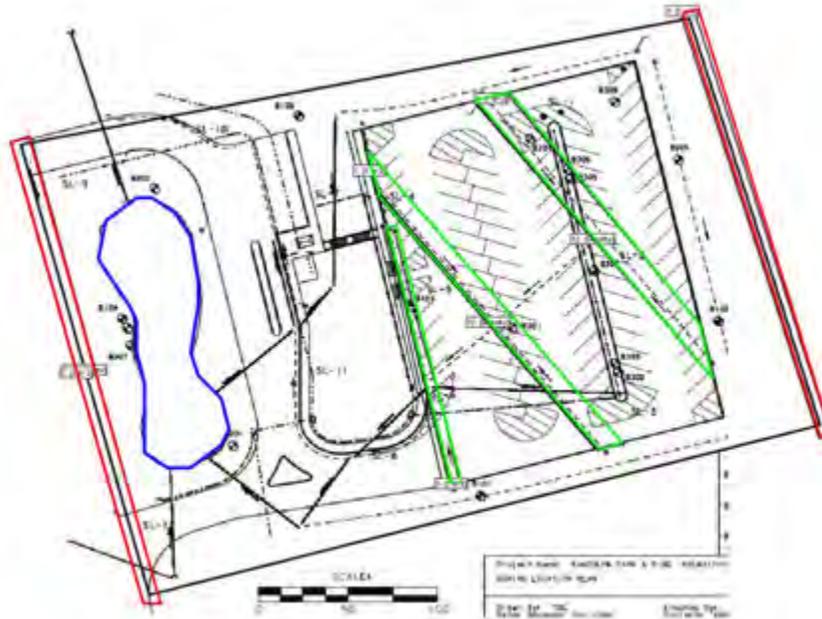


Figure 4.7: Boundary Conditions.

4.4.5 Additional model parameters

Three separate stress periods are simulated. The first lasts for 100 days and is responsible for establishing steady state conditions to the system. The second is when rainfall equal to 1 inch (0.083 ft) of rainfall is applied during one day. This stress period is expected to cause the main response to the system. During the third and last stress period rainfall is "shut off" and the system is expected to return to initial conditions. This stress period last for 10 days.

4.4.6 Model Results

Figure 4.8 shows the total head solution for steady state conditions. No rainfall is applied during this part of the simulation. Its purpose is to redistribute the head solution according

to the boundary and initial conditions applied. Figure 4.9 shows the response of the system after a 1 inch/1 day rainfall event. According to the calculations made in subroutine "porous_concrete" all the amount of rainfall added was retained by the crushed stone and therefore did not reach the bottom of the gravel subbase. This is verified by the fact that the head solution for the porous concrete area resembles steady state conditions shown in Figure 4.8 whereas there is an obvious rise in total heads for the rest of the domain. Finally Figure 4.10 shows that 10 days after the rainfall event the system returns to its initial steady state conditions.



Figure 4.8: Top Layer (3rd) - Steady state conditions for total head (units in ft).



Figure 4.9: Top Layer (3rd) - Total head (units in ft) after 1 day of rainfall.



Figure 4.10: Top Layer (3rd) - Total head (units in ft) 10 days after the rainfall event.

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 behind this issue is construction errors. Another is the retention of water in the coarse stone and subsequent evaporation into the atmosphere. The latter hypothesis was examined through the evaporation experiments

presented in section 3.2.5 and it was proven that although retention and evaporation is significant the mysterious lack of water cannot be explained solely due to this fact. So the first hypothesis remained to be examined.

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 led by Jennifer Fitch and UVM 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.

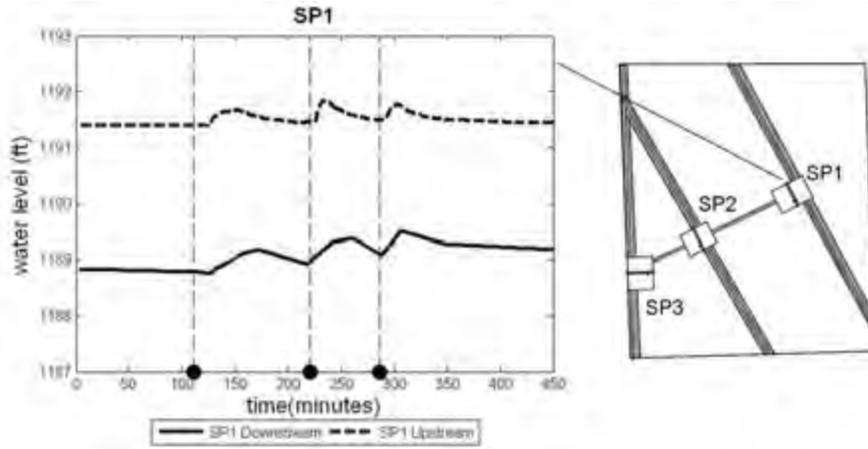


Figure 5.1: Water levels in SP1.

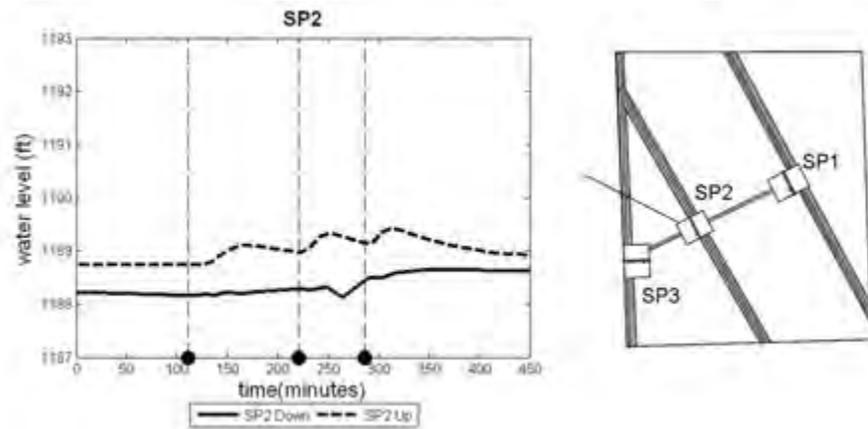


Figure 5.2: Water levels in SP2.

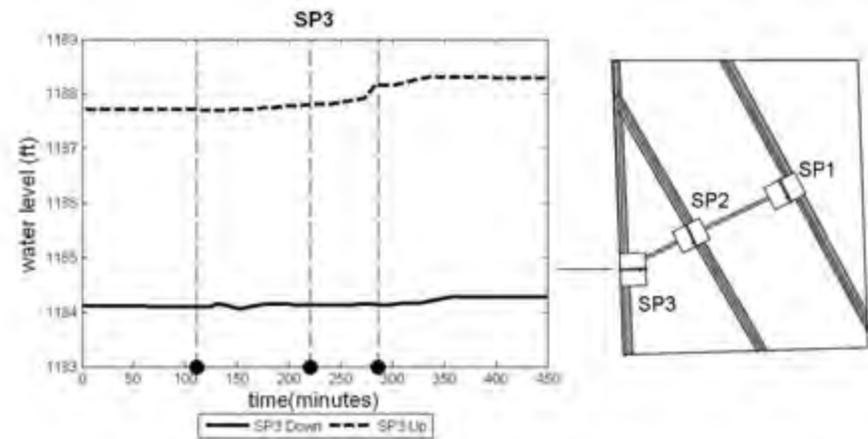


Figure 5.3: Water Levels in SP3.

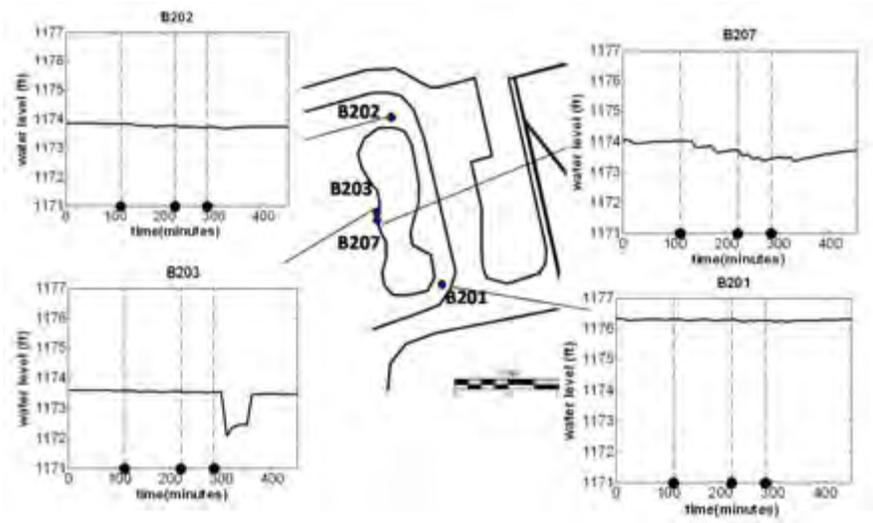


Figure 5.4: Water levels in 200-series wells (west site area).

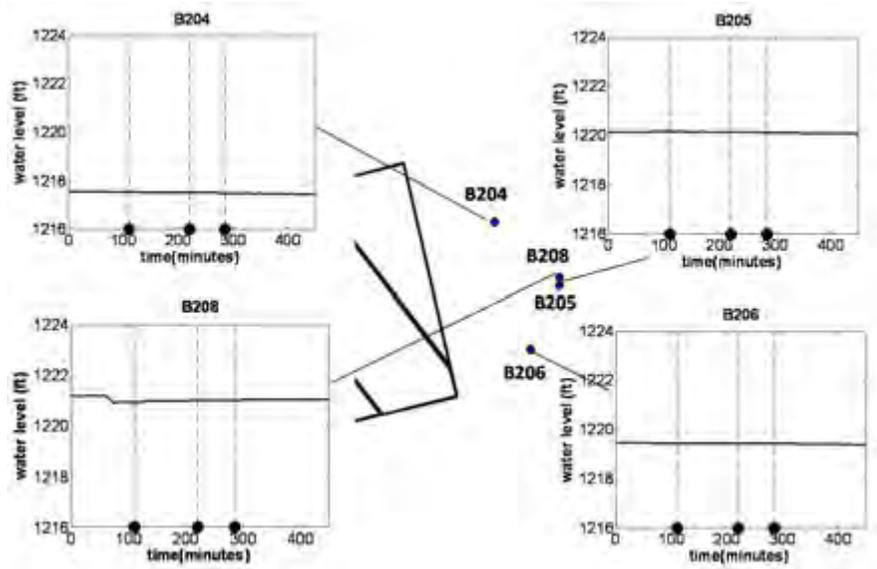


Figure 5.5: Water levels in 200-series wells (east site area)

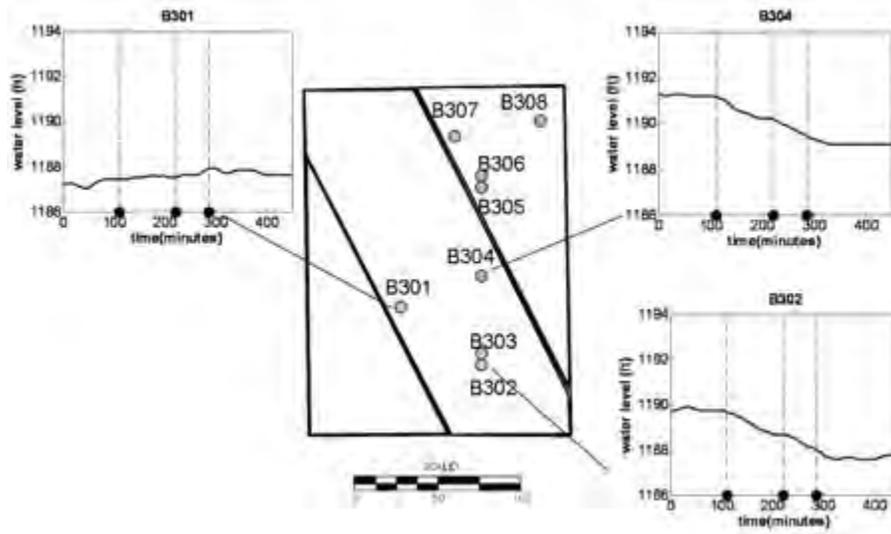


Figure 5.6: Water levels in 300-series wells (south porous concrete part).

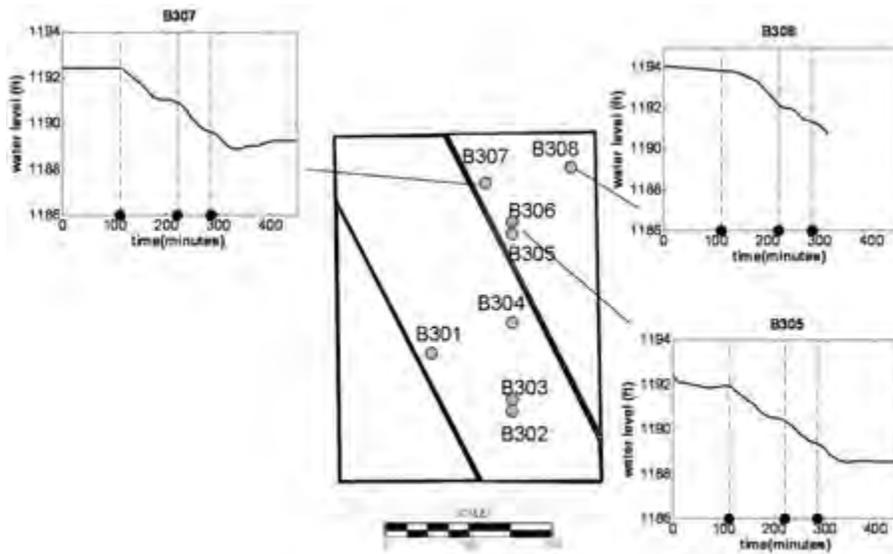


Figure 5.7: Water levels in 300-series wells (north porous concrete part).

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, 5.10 and 5.11) 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".

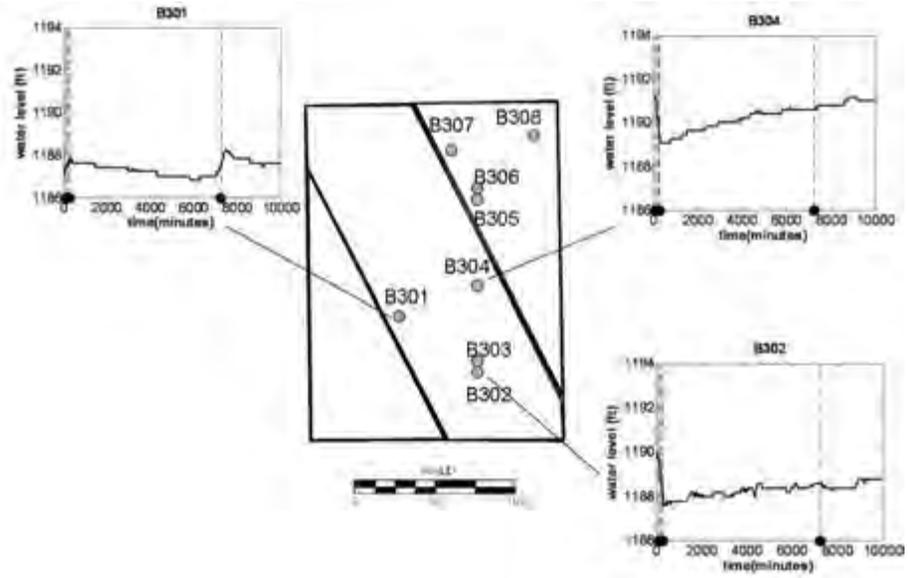


Figure 5.8: Water levels in 300-series wells - Irene response (south porous concrete part).

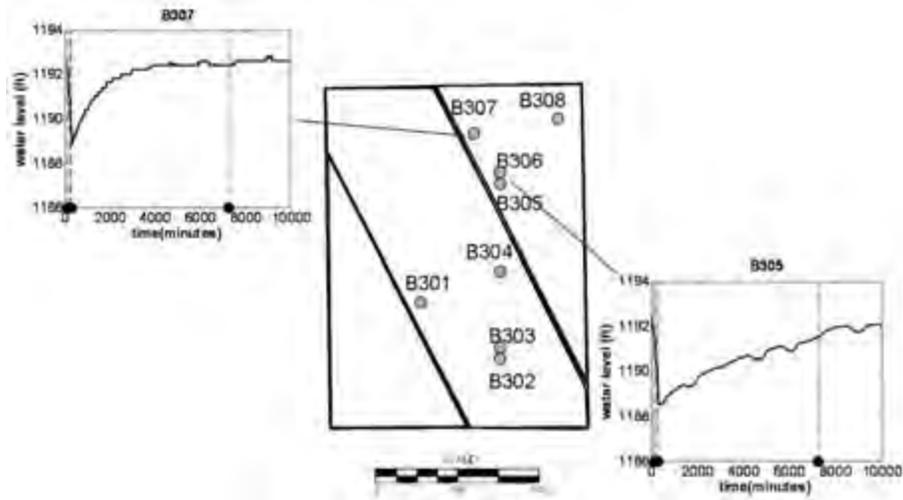


Figure 5.9: Water levels in 300-series wells - Irene response (north porous concrete part).

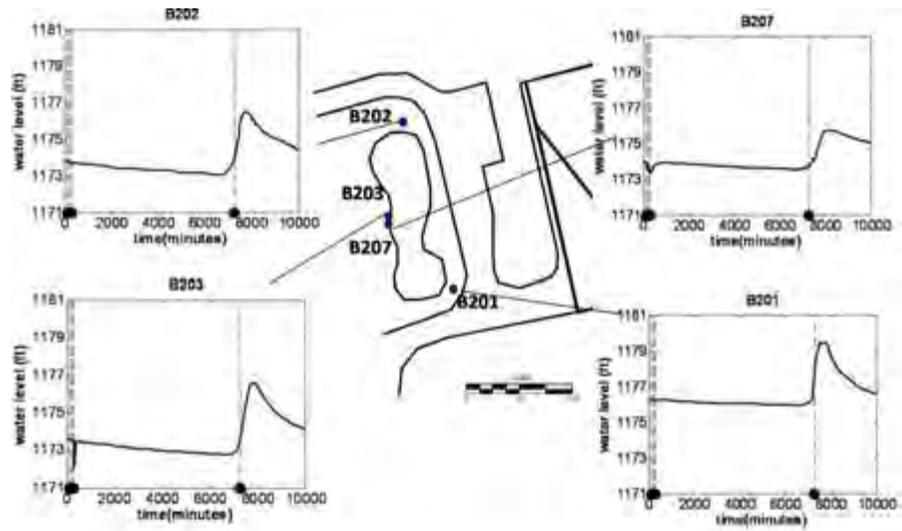


Figure 5.10: Water levels in 200-series wells - Irene response (west site area).

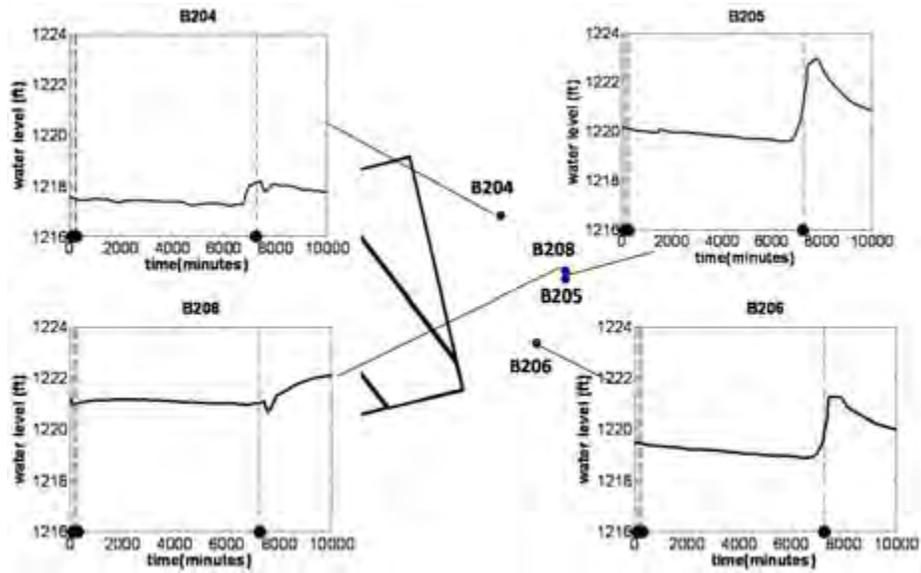


Figure 5.11: Water levels in 200-series wells - Irene response (east site area).

5.3.3 Electrical Conductivity Measurements

In addition to the water level monitoring, electrical 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.

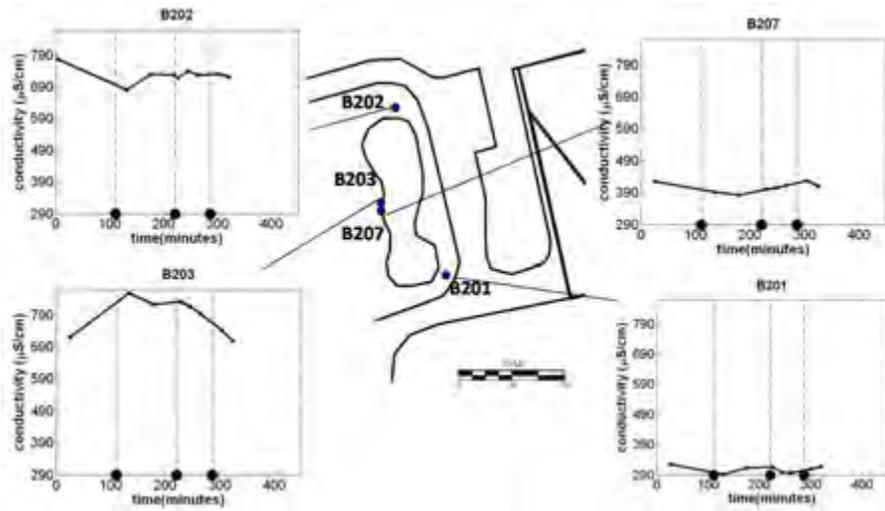


Figure 5.12: Conductivity measurements in 200-series wells (west site area).

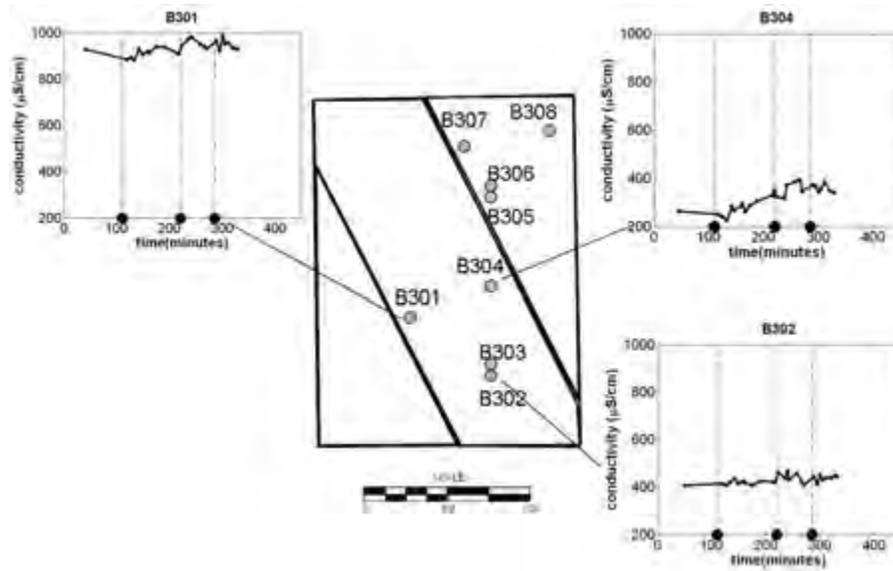


Figure 5.13: Conductivity measurements in 300-series wells (south porous concrete part).

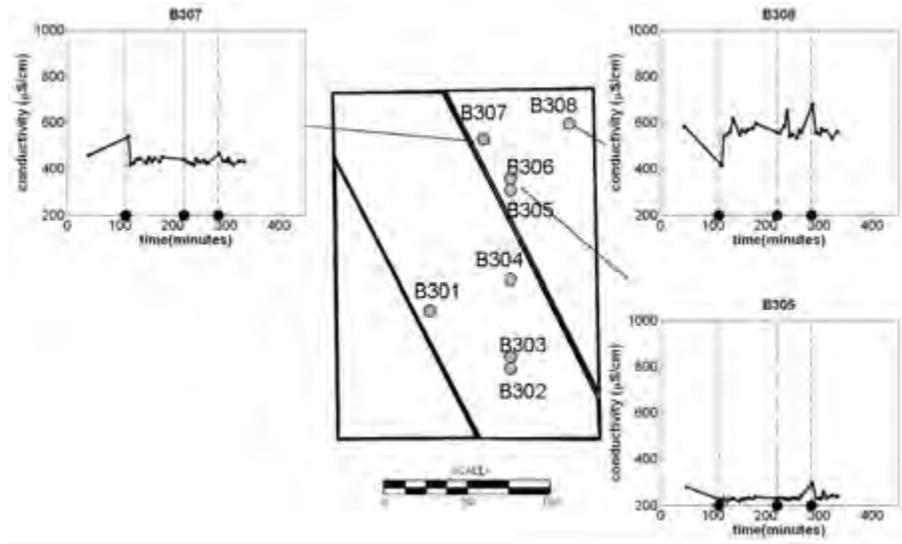


Figure 5.14: Conductivity measurements in 300-series wells (north porous concrete part).

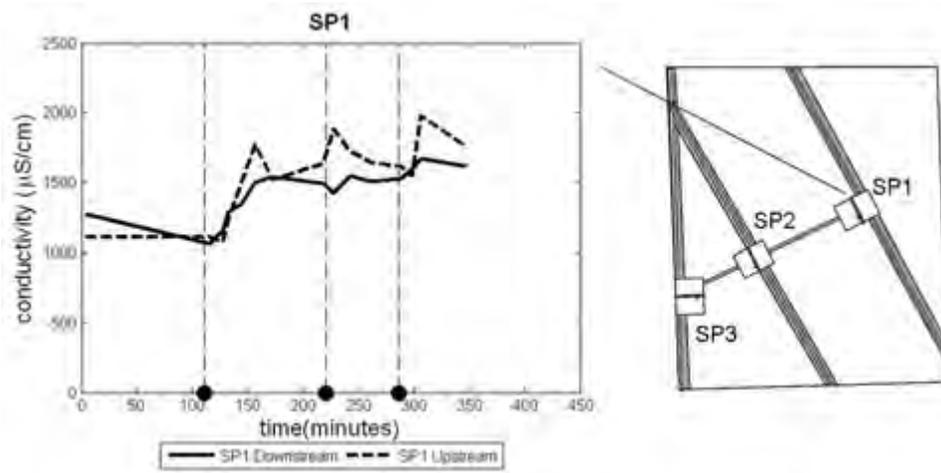


Figure 5.15: Conductivity measurements in SP1.

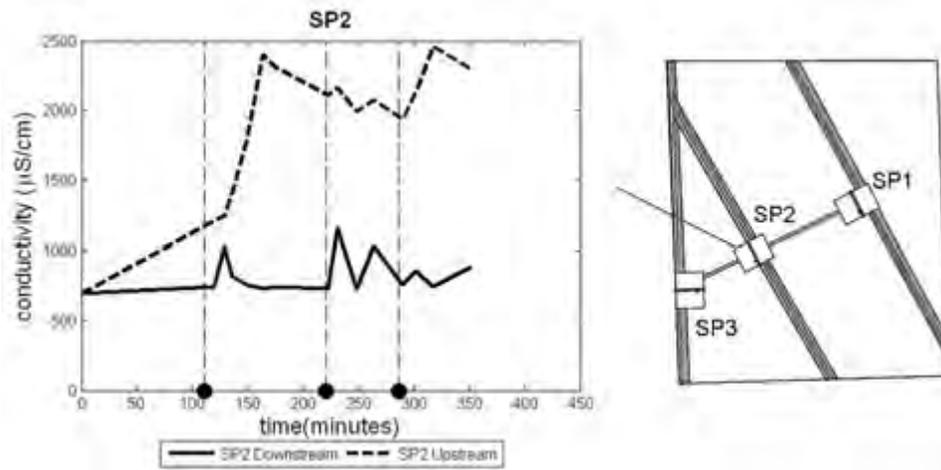


Figure 5.16: Conductivity measurements in SP2.

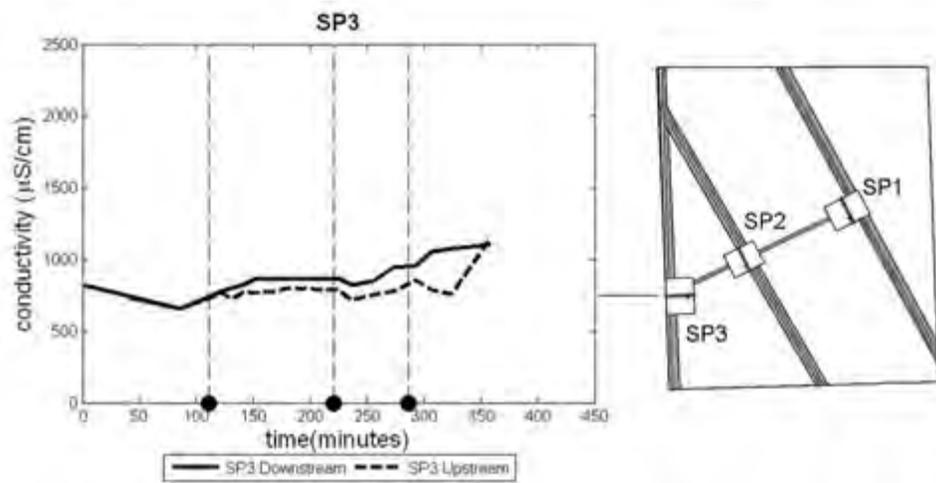


Figure 5.17: Conductivity measurements in SP3.

5.3.4 Drain and flushing basin information

Except for the water level and electrical 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.

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 response 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.

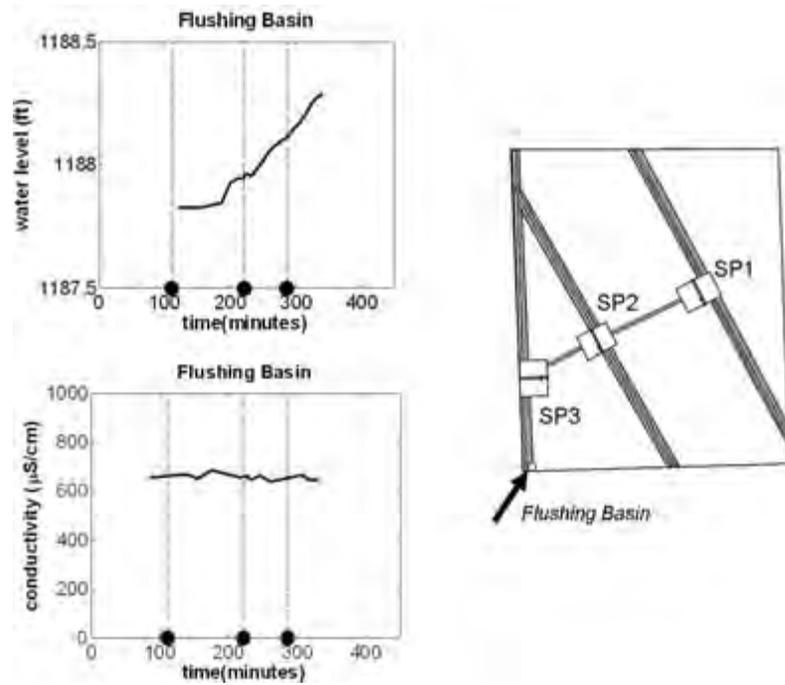


Figure 5.18: Water level data and conductivity measurements in flushing basin.

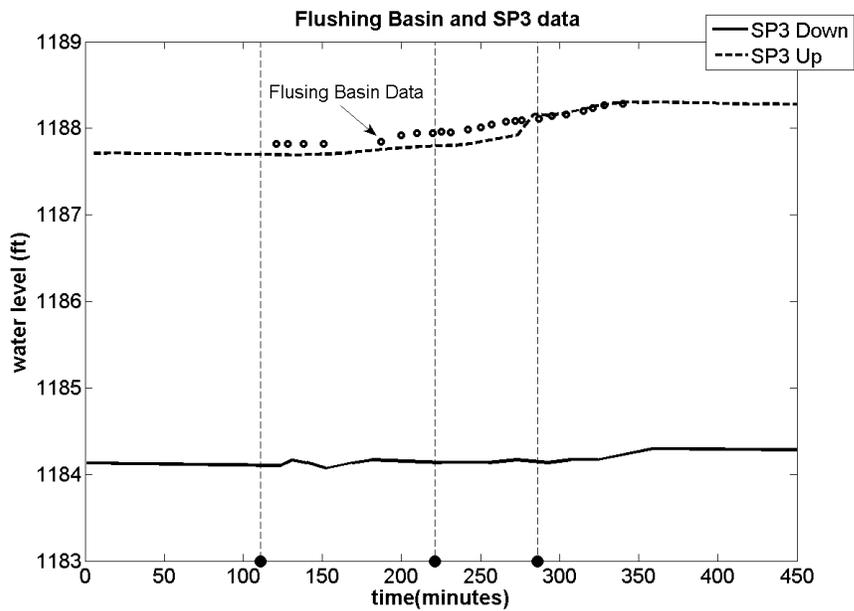


Figure 5.19: Superposition of water level measurements in flushing basin on SP3 data.

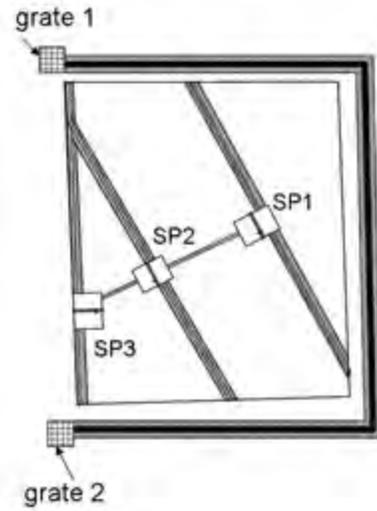


Figure 5.20: Location of openings on perimeter drain.

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

Table 5.1: Conductivity measurements in perimeter drain openings.

5.3.5 Pond/Weir data

Figure 5.21 shows the discharge data at the retention pond. The first peak is indicative of the water level exceeding the weir in SP3 after the third water release event and the second shows the response to hurricane Irene. Obviously, hurricane Irene caused higher discharge compared to the water release. Figure 5.22 focuses on the data for the first 1000 minutes so that the water release data are more obvious. From this graph it is evident that the weir was exceeded only after the third water release event. Applying Simpson's rule (using MATLAB) the amount of water released during the water release event is calculated as approximately 150 gallons. This is a very small amount considering that approximately 15000 gallons were released on the porous concrete area. However, that can be explained considering the fact that some amount of water can be gathered inside the drop inlets and ridges of drains. Also, the water level data shown previously indicate that there is some amount of water that bypassed the drop inlets and therefore perhaps was not captured by any drains.

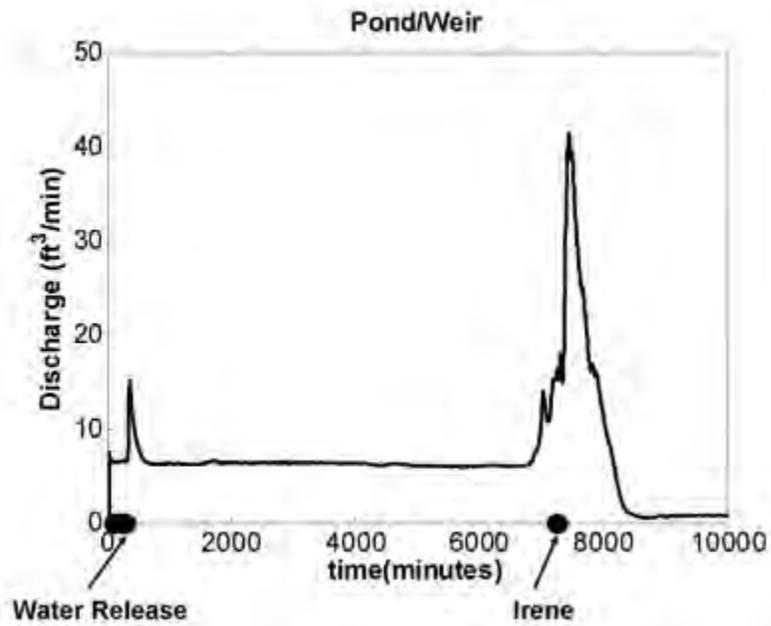


Figure 5.21: Water discharge measured in the retention pond outlet showing field experiment and Irene data.

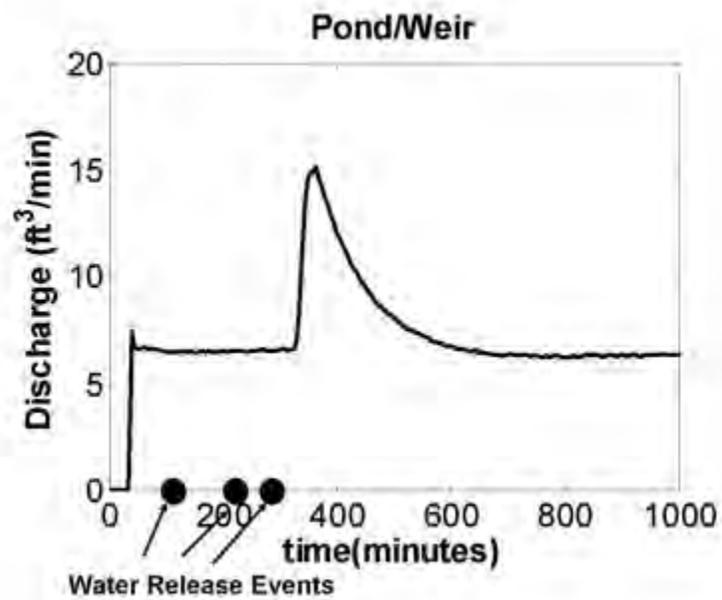


Figure 5.22: Water discharge measured in the retention pond outlet for the field experiment.

5.4 Discussion of field experiment findings

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. Since water was released on Area 3, and Areas 3 and 2 are separated through a berm (on which SP1 is located) technically it would be impossible for water to reach the rest of the sub-areas and no water level change should be observed in the rest of the locations. Moreover, taking into account that SP3 was exceeded and also that water level changes occurred in downstream locations of SP1 and SP2 it can only be inferred that there is leakage through both the berm and cutoff wall. This provides eventually the most reasonable explanation as to "where the water is going" and why it is not accumulated in the drop inlets as expected and originally designed for.

In addition, the height of water in the upstream location of SP3 and the neighboring flushing basin indicate that there is an amount of water gathered in the gravel subbase of Area 1 whereas no water is accumulated in the subbases of Areas 2 and 3.

Regarding the paradoxical and tremendous water level drop of up to 4 ft in the majority of the 300-series wells during the water release, a solid explanation is yet to be determined and more research is needed. Inverse water level response has been previously noted in literature but mainly for pumping tests where water is extracted from the aquifer and nowhere close to the intensity of the phenomenon observed in the Randolph site. The phenomenon is known as Noordbergum effect 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 [23] to 0.2 and 0.3 ft [23], [24].

What was observed in the Randolph site is believed to have been caused by the deformation of the aquifer due to the extreme and sudden load of the released water, leading to a local change in porosity and consequently permeability. A permeability change would alter the flow gradient and therefore could potentially lead to a drop in groundwater levels.

A somehow similar phenomenon has been noted in Long Island, NY where a passing railroad train caused a fluctuation of water level in an adjacent well as a result of aquifer deformation which however was in the order of less than an inch [25]. Further research is required in order to present a solid explanation for this mysterious phenomenon.

In addition, it is important to note 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". Also, conductivity measurements in the drop inlets rise in accordance to the water level response as expected. Although some fluctuation is observed, the overall electrical conductivity change pattern indicates that salt is not present in the monitoring wells. Finally, the conductivity data in the perimeter drain do not show clearly whether water is captured there.

Chapter 6

General Discussion

The Randolph Park and Ride is unique in terms of the instrumentation as well as the local geohydrology. Due to the fact that it is the first porous concrete site built in Vermont there have been some great challenges in maintaining it in a good condition and also while performing the various data collection needed for this research project. In general though it has been a successful application of porous concrete in a colder climate region, such as New England.

The field investigation showed the existence of two artesian wells on site indicating that there is a high upward gradient flow which is not frequently observed. This, in combination with the tight geologic subgrade material makes infiltration of water into the subsurface very difficult forcing the majority of stormwater that reaches the bottom of the gravel subbase below the porous concrete to be captured by the underdrains. However, hurricane Irene data and also groundwater level data for the winter period of 2010 show that groundwater fluctuates with response to rainfall and also snowmelt.

Laboratory experiments gave some interesting findings as well. It was proven 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 totally justify the lack of water accumulation in the drop inlets, which was one of the mysteries concerning the specific site, and therefore a controlled water release experiment was set up in order to solve this mystery. The data collected from the controlled water release field experiment indicated that most probably there is leakage through the cutoff wall and berm, allowing water to move from one sub-area to another without exceeding the weir. This hypothesis remains to be examined by VTrans for further verification.

In addition to answering where the water is going once it enters the porous concrete slab, the field experiment gave rise to yet another mysterious phenomenon. An extreme water level drop of up to 4 ft in the monitoring wells was observed and analyzed. The collected data have been compared to measurements obtained during the water release events using a manual water level meter which verifies that the counter-intuitive response was real and not some sort of equipment malfunction. The phenomenon is assumed to have been caused by the deformation of the aquifer due to the extreme and sudden load of the released water, leading to a local change in porosity and consequently permeability. A permeability change would alter the flow gradient and therefore could potentially lead to a drop in groundwater levels. A solid explanation on the phenomenon has not been presented yet. Initial modeling attempts using the finite element analysis software ABAQUS have been performed and so far results are encouraging in terms of verifying our hypothesis but further modeling effort is needed.

Finally, a mathematical model that can simulate flow through porous concrete has been

created and preliminary modeling results are presented for the "Randolph Park and Ride" site. The model at this point can calculate flow, retention and evaporation related to porous concrete as well as groundwater flow. As future work, runoff from conventionally paved areas will be added to the model.

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Appendices

Appendix A

Fortran code for Subroutine

"porous _ concrete"

```
subroutine porous _ concrete
```

```
  Include 'impltype.inc'
```

```
  Include 'PTCsiz.inc'
```

```
  if (qrain1.gt.0) then
```

```
    if (istp.eq.1)then !do it only for the 1st iteration in each convergence loop
```

```
      limitr=0.396 !limit of water the system can hold
```

```
      qevap=0.000027 !1/T=1/day
```

```
      eps=0.504 !porosity of stone
```

```
      vertlen=36 !depth of gravel in inches
```

```
      qt(ifstep,node1)=qrain1
```

```
      !!!!when column in unsaturated
```

```

qb(ifstep,node1)=0
Sws(ifstep,node1)=(eps*vertlen*Sws(ifstep-1,node1)
+(qt(ifstep,node1)-vertlen*qevap)*delth)/(eps*vertlen)
if (Sws(ifstep,node1).gt.1) then !make sure saturation does not exceed 1
Sws(ifstep,node1)=1
endif

!!!when column is saturated
if (Sws(ifstep,node1).gt.limitr) then
Sws(ifstep,node1)=limitr
qb(ifstep,node1)=qt(ifstep,node1)-eps*vertlen*
% (limitr-Sws(ifstep-1,node1))/delth-vertlen*qevap
elseif (Sws(ifstep,node1).lt.0) then
Sws(ifstep,node1)=0
endif
qrain1=qb(ifstep,node1)
write(2012,*) node1,qb(ifstep,node1),Sws(ifstep,node1),itflow
endif

Return

End

```

Appendix B

100-series wells



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-88
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	16.1	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	26.6	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		38	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	9.8	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 BY: WERNER, MARGO (P) - CMG PARK(21) (B) - VT-88 (21) - 7/10/07



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 (%)	PL (%)
0		A-4, SaSi, br, Moist, Rec. = 1.6 ft, Top of Well casing is 2.5 ft. above ground level. Solid casing with Rebaronite around it		8	20.1	7.1	30.6	62.3		
1.6		A-4, SaSi, br, Moist, Rec. = 1.6 ft		6	20.0	5.9	27.3	66.8		
3.2		A-4, SaSi, br-gry, Moist, Rec. = 2.0 ft		5	22.1	6.0	28.0	66.0		
5.2		A-1-b, SiGrSa, br, Moist, Rec. = 1.4 ft. Broken rock was within sample. Cobbles at 7.0 ft.		99	11.1	37.0	39.3	23.7		
6.6		Visual Classification, Broken rock with silty sand, br, Moist, Rec. = 0.7 ft, Cobbles from 8.0-10 ft.		40	4.8					
7.3		Visual Classification, Broken rock with sand, gry, Moist, Rec. = 0.4 ft. (Cobbles)		R	4.2					
7.7		Field Note, 10.7-11.5, Cobble area has ended.								
8.8		A-4, SaSi, gry, Moist, Rec. = 1.7 ft		10	17.7	14.0	22.1	63.9		
10.5		A-4, SaSi, gry, Wet, Rec. = 1.65 ft		9	14.8	17.6	22.9	59.5	23	1
12.15		A-4, SaSi, gry, Wet, Rec. = 1.8 ft		18	14.7	18.4	21.8	59.8	23	2
13.95		Field Note, No recovery. Appears to be same material, gry, Wet		11						
15.75		A-4, GrSaSi, gry, Wet, Rec. = 1.5 ft		31	12.9	20.7	29.1	50.2		
17.25		Hole stopped @ 22.0 ft								
22.0		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 0.9 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 PARK&RIDE CMG(21) LAMA, VT AGT DIST 7/10/07



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 (%)
0.0 - 0.2		Topsoil, brn, 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	57.5		
0.2 - 1.5		A-4, SaSl, brn, Moist, Rec. = 1.5 ft		8	19.9	7.3	26.1	66.6		
1.5 - 1.8		A-4, SaSl, brn, Moist, Rec. = 1.8 ft		4	20.4	5.2	26.8	68.0		
1.8 - 1.9		A-4, SaSl, brn, Moist, Rec. = 1.9 ft		4	20.2	9.9	23.6	66.5		
1.9 - 1.7		A-4, SaSl, brn, Moist, Rec. = 1.7 ft		11	17.3	15.5	22.4	62.1		
1.7 - 1.7		A-4, GrSl, gry, Wet, Rec. = 1.7 ft		12	18.2	21.3	18.9	59.8		
1.7 - 1.7		A-4, Sl, gry, Wet, Rec. = 1.7 ft		8	18.1	12.8	19.3	67.9		
2.0 - 2.0		A-4, Sl, gry, Wet, Rec. = 2.0 ft		5	16.9	10.7	18.3	71.0	23	2
2.0 - 2.0		A-4, Sl, gry, Wet, Rec. = 2.0 ft		8	16.4	15.6	17.8	66.6	24	3
1.6 - 1.6		A-4, GrSl, gry, Wet, Rec. = 1.6 ft		12	14.3	26.0	15.4	58.6	23	2
1.5 - 1.5		A-4, GrSl, gry, Wet, Rec. = 1.5 ft		14	14.2	22.6	16.7	60.7	21	2
22.0		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.								

LOCAL ADDRESS: RANDOLPH PARK & RIDE, VT 05047-2197



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-68
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, SaSl, gry, Moist, Rec. = 1.7 ft	8	20.8	18.2	21.7	59.1
10		A-4, GrSaSl, gry, Moist, Rec. = 2.0 ft	12	18.0	21.1	25.8	53.1
		A-4, SaSl, gry, Moist, Rec. = 2.0 ft	11	17.5	15.8	22.3	61.9
		A-4, SaSl, gry, Moist, Rec. = 1.0 ft	15	16.0	9.8	32.8	57.4
		A-4, SaSl, gry, Wet, Rec. = 0.9 ft	19	15.3	18.0	25.1	56.9
		Boulder, 15.0 ft - 19.0 ft					
		A-4, GrSaSl, gry, Wet, Rec. = 1.0 ft		18.1	20.8	27.2	52.0
20		A-4, GrSaSl (rP), gry, Wet, Rec. = 2.0 ft	25	12.5	21.8	30.8	47.2
		A-4, SaSlGr (HP), gry, Wet, Rec. = 1.4 ft, Tough drilling in (rP) & Cobbles	41	11.4	38.6	23.5	37.9
		A-4, SaGrSl (HP), gry, Moist, Rec. = 1.4 ft, Tough drilling in (HP) & Cobbles	R	9.4	32.8	25.5	41.7
		A-4, SaGrSl (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) BY VT ACT 001 11/8/07



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-86
 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 (%)
3		A-4, SaSl, brn, Moist, Rec. = 1.4 ft	3	25.5	11.4	30.1	56.5		
6		A-4, SaSl, brn, Wet, Rec. = 1.8 ft	6	21.6	13.9	24.0	62.1		
9		A-4, SaSl, brn, Wet, Rec. = 1.9 ft	3	23.7	8.0	22.1	69.9		
12		A-4, SaSl, brn, Wet, Rec. = 1.9 ft	3	21.5	16.3	22.1	61.6		
15		A-4, SaSl, gry, Wet, Rec. = 1.7 ft	17	19.2	9.3	24.5	66.2		
18		Field Note, Appears to be same material, gry, Wet	18						
21		A-4, SaSl, gry, Wet, Rec. = 1.7 ft	7	15.6	13.3	22.9	63.8		
24		A-4, SaSl, gry, Moist, Rec. = 2.0 ft	8	15.2	9.1	23.7	67.2		
27		A-4, SaSl, gry, Moist, Rec. = 2.0 ft	7	14.8	16.1	21.8	62.1	24	2
30		A-4, SaSl, gry, Wet, Rec. = 2.0 ft	11	15.3	17.7	21.6	60.7		
33		A-4, CrSl, gry, Wet, Rec. = 1.7 ft	9	14.4	24.7	19.6	55.7	23	3
36		Hole stopped @ 22.0 ft							
39		DRILLER'S NOTES: 1. Hole caved in at around 8.0 ft.							

LOG OF BORING: RANDOLPH, CMG PARK(21), DRU, VT DOT, CORR. 7/12/07

Appendix C

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 526856.23 ft E 1506992.18 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 #08 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, S-						
5		Possible Cobbles, 4.0 ft - 5.0 ft						
		Visual Classification: A-4, S-						
10		Visual Classification: A-w, Gr(SuS)						
15								
20		Hole stopped @ 21.0 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 1.0 ft of solid casing above ground. 5. Soil classifications made from auger cuttings.						

LOG OF BORING: RANDOLPH PARK & RIDE, VT ACT 008, 11/2008



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: 5.1 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	MC (%)	GRAVEL (%)	SAND (%)	FINES (%)
		Top of Well Elevation: 1179.94 ft						
		Visual Classification: A-4, S						
5		Possible Cobbles, 4.0 ft - 5.0 ft						
		Visual Classification: A-4, S						
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 PARK, RANDOLPH, VT, 11/05/08 (03/09)



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: 1190.64 ft								
		A-4, SaSl. DkBrn. Moist. Rec. = 1.6 ft		4	18.6	17.1	36.7	46.6
		A-4, GrSaSl. DkBrn. Moist. Rec. = 1.6 ft		10	17.1	21.3	23.6	55.1
5		A-4, SaSl. DkBrn. Moist. Rec. = 1.5 ft		4	21.2	6.2	22.8	71.0
		A-4, SaSl. DkBrn. MTW. Rec. = 1.8 ft		6	20.9	6.5	22.9	68.6
		A-4, SaSl. mottled, gy. Moist. Rec. = 1.6 ft		10	16.6	10.9	20.5	66.6
10		A-4, SaSl. gry. Moist. Rec. = 2.0 ft		9	18.5	12.7	20.3	66.4
		No Recovery, Rec. = 0.0 ft, 12.0 ft - 14.0 ft		12				
15		A-4, SaSl. gry. Moist. Rec. = 1.5 ft		9	18.8	12.0	22.4	65.6
		A-4, Sk. gry. Moist. Rec. = 1.0 ft		6	15.7	16.5	19.4	65.1
		A-4, SaSl. gray. Moist. Rec. = 1.2 ft		R	16.6	6.6	20.3	71.1
20		<p>Wide stopped @ 19.0 ft</p> <p>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.</p>						
25								

LOG GENERATED BY: P:\BOLTON\DATA\BOLTON\110308\VT_A01.dwg: c:\adsl



STATE OF VERMONT
AGENCY OF TRANSPORTATION
MATERIALS & RESEARCH SECTION
SUBSURFACE INFORMATION

BORING NUMBER: B-204
SHEET 1 of 1
DATE STARTED: 10/29/08
DATE COMPLETED: 10/29/08

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	MC (%)	GRAVEL (%)	SAND (%)	FINES (%)
		Top of Well Elevation: 1219.31 ft						
		Visual Classification: Cr Si No Samples taken						
0								
5								
10								
13.0		Note 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								

1003345 (REV) 08 RANDOLPH PARK AND RIDE (2) (1) (3) (4) (5) (6) (7) (8) (9) (10) (11) (12) (13) (14) (15) (16) (17) (18) (19) (20) (21) (22) (23) (24) (25) (26) (27) (28) (29) (30)



STATE OF VERMONT
AGENCY OF TRANSPORTATION
MATERIALS & RESEARCH SECTION
SUBSURFACE INFORMATION

BORING NUMBER: B-205
SHEET 1 of 1
DATE STARTED: 10/28/08
DATE COMPLETED: 10/28/08

PROJECT NAME: RANDOLPH
SITE NAME: RANDOLPH PARK & RIDE
STATION: 21+92
OFFSET: 250.40
VTSPG: N 526978.42 ft E 1509363.63 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: 1224.89 ft								
0.0 ft - 5.0 ft		No Samples taken						
5.0 ft - 10.0 ft		Visual Classification: A-4, sil. Extrim, Wet, Rec = 1.9 ft		2				
10.0 ft - 12.0 ft		Visual Classification: A-2-4, Gr. Sil. Extrim, Wet, Rec = 1.6 ft		6				
12.0 ft - 15.0 ft		No Samples taken						
15.0 ft		Flow 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 5.05 ft. of solid casing above ground level.								

LOG OF BORING, RANDOLPH PARK (MATERIALS) (S&R) 40101001 - 10/28/08



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 11/03/06
 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	MC (%)	GRAVEL (%)	SAND (%)	FINES (%)
		Top of Well Elevation: 1221.04 ft						
		Visual Classification: (3%) No Samples Taken						
2.5								
5.0								
7.5								
10.0								
12.5								
15.0		Hole stopped @ 15.0 ft						
17.0		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 12.5 ft below ground.						

LOG OF BORING: RANDOLPH PARK & RIDE (21+48), VT 4317507, 10/29/08



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 626922.15 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	MC (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1180.65 ft								
0.0 ft - 25.0 ft		No Samples Taken						
29.0		Visual Classification: A-4, Sl. gry, Moist, Rec = 2.0 ft		13				
25.0		Visual Classification: A-4, Cl. gry, Moist, Rec = 2.0 ft		11				
30.0		Visual Classification: A-4, QSL gry, MTW, Rec = 2.0 ft		7				
35.0		Visual Classification: A-4, Sl. gry, Wet, Rec = 1.5 ft		22				
37.0		Hole stopped @ 37.0 ft						
40.0		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						

1000 G&S ECHOLS; RANDOLPH PARK & RIDE; VT; NOT ABB; 12/08



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 525984.99 ft E 1609363.45 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	MC (%)	GRAVEL (%)	SAND (%)	FINES (%)
Top of Well Elevation: 1223.8 ft								
0		A-4, SaSi, Dk/bm, Moist, Rec. = 1.6 ft		4	20.7	7.7	36.1	56.2
1.6		A-4, SaSi, Dk/bm, Moist, Rec. = 1.2 ft		20	17.9	14.6	37.0	49.4
2.8		A-4, GrSaSi, Dk/bm, MTW, Rec. = 1.5 ft		3	20.8	20.5	30.7	49.7
4.3		A-4, SaSi, brn, Wet, Rec. = 1.7 ft		2	38.8	11.8	38.1	50.1
6.0		A-2-4, SiSa, fm, Sat, Rec. = 1.3 ft		5	31.7	14.1	51.7	34.2
7.3		A-4, SaGrSi, gry, Moist, Rec. = 1.5 ft		14	17.6	28.8	22.6	48.7
8.8		A-4, SaGrSi mottled, gry-brn, Moist, Rec. = 1.8 ft		30	13.8	28.0	24.3	48.7
10.6		A-4, SaGrSi HP, gry, Moist, Rec. = 1.7 ft		27	10.9	25.6	20.6	64.2
12.3		A-4, GrSaSi HP, gry, Moist, Rec. = 1.9 ft		32	10.4	23.3	28.6	48.1
14.2		A-4, SaSi HP, gry, Moist, Rec. = 1.8 ft		10	10.2	14.0	27.7	58.8
16.0		A-4, GrSaSi HP, gry, Moist, Rec. = 1.4 ft		52	11.1	22.3	25.6	51.9
17.4								
18.8								
20.2								
21.6								
23.0		Visual Classification, A-2-4, Sil & Stones HP, gry, Moist, Rec. = 1.4 ft		61				
24.4								
25.8								
27.2		Visual Classification, A-2-4, Gr Si HP, gry, Moist, Rec. = 2.0 ft		79				
29.2		Hole stopped @ 32.0 ft						
30.0								
31.0								
32.0								
33.0								
34.0								
35.0								

LOG OF BORING RANDOLPH PARK & RIDE, VT NOTICE 0308

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

Appendix D

300-series wells



STATE OF VERMONT
AGENCY OF TRANSPORTATION
MATERIALS & RESEARCH SECTION
SUBSURFACE INFORMATION

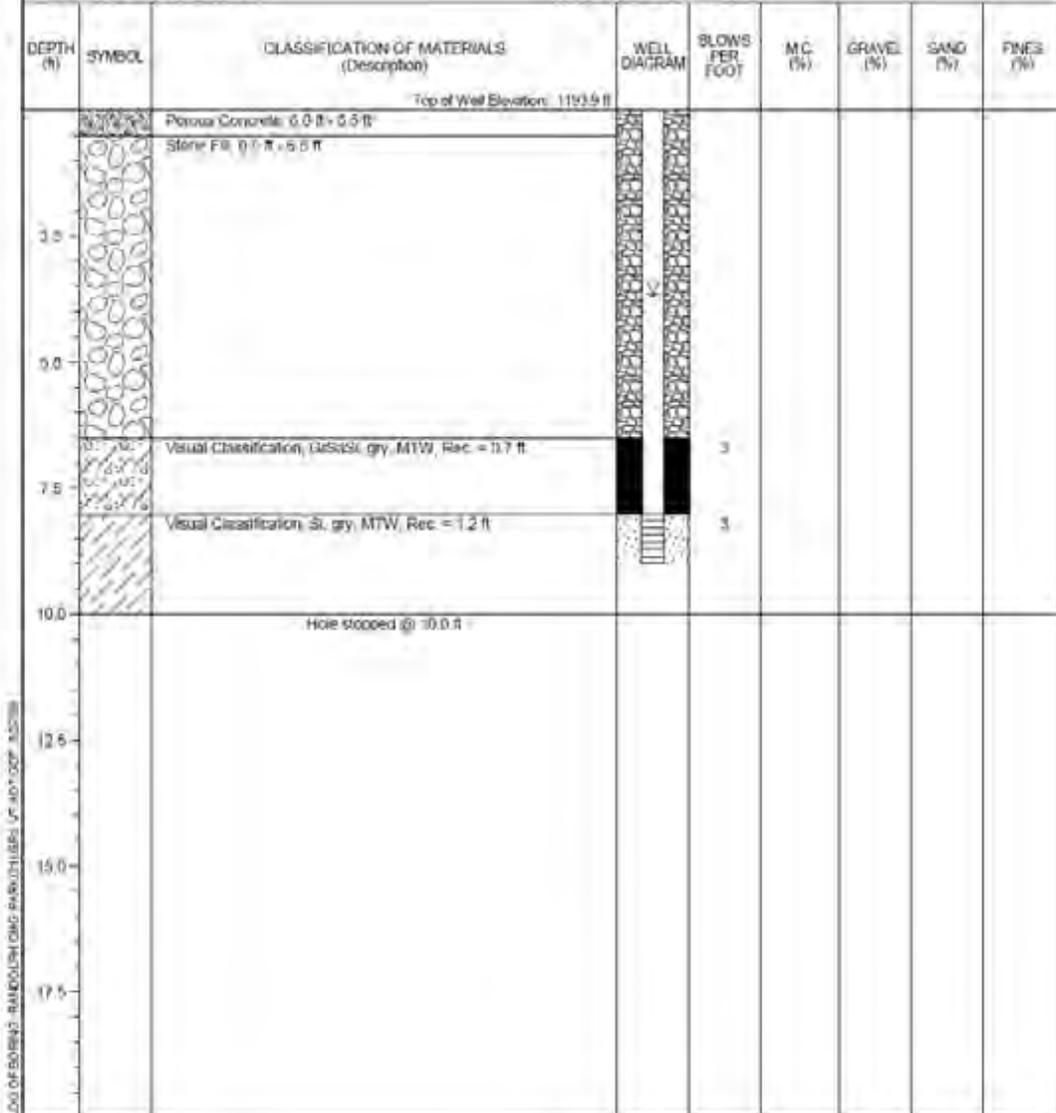
BORING NUMBER: B-301
SHEET 1 of 1
DATE STARTED: 3/30/09
DATE COMPLETED: 3/30/09

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





STATE OF VERMONT
 AGENCY OF TRANSPORTATION
 MATERIALS & RESEARCH SECTION
 SUBSURFACE INFORMATION

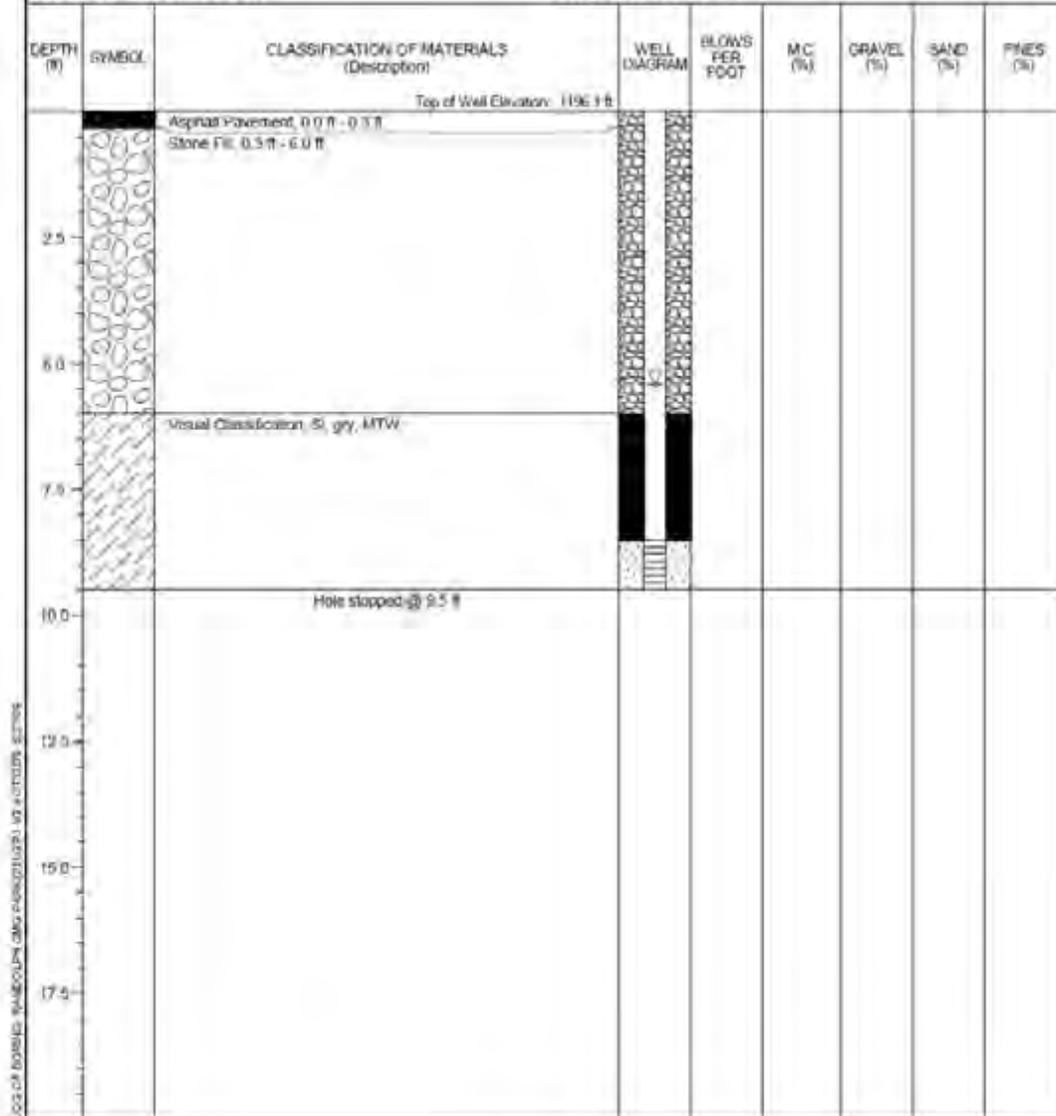
BORING NUMBER: B-302
 SHEET 1 of 1
 DATE STARTED: 3/27/09
 DATE COMPLETED: 3/27/09

PROJECT NAME: RANDOLPH
 SITE NAME: RANDOLPH PARK & RIDE
 STATION: 21+62
 OFFSET: 80.40
 VTSPG: N 525908.14 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





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 1609205.69 ft

PROJECT NUMBER: RSCHD12-708
 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 Wall 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						
3		Visual Classification: Sl. gry, MTW, Rec. = 1.4 ft		8				
		Visual Classification: Sl. gry, MTW, Rec. = 1.5 ft		14				
10		Visual Classification: Sl. gry, MTW, Rec. = 1.75 ft		11				
		Visual Classification: Sl. 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. = 1.3 ft						
20		Hole stopped @ 19.5 ft						
25								

008-39-B-303-RS RANDOLPH PARK & RIDE VTS-03-09-018 4/27/09



STATE OF VERMONT
 AGENCY OF TRANSPORTATION
 MATERIALS & RESEARCH SECTION
 SUBSURFACE INFORMATION

BORING NUMBER: B-304
 SHEET 1 of 1
 DATE STARTED: 3/27/09
 DATE COMPLETED: 3/27/09

PROJECT NAME: RANDOLPH
 SITE NAME: RANDOLPH PARK & RIDE
 STATION: 22+19
 OFFSET: 80.10
 VTSPG: N 526964.29 ft E 1609194.08 ft

PROJECT NUMBER: RSCH012-705
 SITE NUMBER: VT-68
 GROUND ELEVATION: 1197.27 ft
 GROUNDWATER DEPTH: 5.57 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: 1197.14 ft								
0.0 - 0.3 ft		Asphalt Pavement, 0.0 ft - 0.3 ft						
0.3 - 4.25 ft		Stone Fill, 0.3 ft - 4.25 ft						
4.25 - 5.0 ft		Visual Classification: sil. gry. Moist. Rec = 0.4 ft						
5.0 - 6.5 ft		Visual Classification: sil. gry. MTW. Rec = 1.5 ft		7				
6.5 - 8.0 ft		Visual Classification: sil. gry. MTW. Rec = 1.5 ft		10				
8.0 - 10.0 ft		Visual Classification: sil. gry. MTW. Rec = 1.0 ft		13				
10.0 - 10.5 ft		Hole stopped @ 10.5 ft						
10.5 - 12.5 ft								
12.5 - 15.0 ft								
15.0 - 17.5 ft								

LOG OF BORING: RANDOLPH PARK & RIDE, VT, NOT G.T. SECTION



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-86
 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	MC (%)	GRAVEL (%)	SAND (%)	FINES (%)
		Top of Wall Elevation: 1198.21 ft						
0.0		0.0 ft - 11.3 ft: No Samples taken. See Boring B-306 for Soil Descriptions.						
3.5								
6.0								
7.5								
10.0								
11.3		Hole stopped @ 11.3 ft						
12.5								
15.0								
17.5								

Log cell checked. Rev 02/08/09. This is a copy of the log for Boring B-305.



STATE OF VERMONT
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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 0.6 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 = 0.8 ft		11				
10		Visual Classification, GrSi, gry, MTW, Rec = 1.4 ft		8				
		Visual Classification, GrSi, gry, Wet, Rec = 1.4 ft		14				
15		Field Note: No Recovery		18				
		Visual Classification, GrSi, gry, Wet, Rec = 1.2 ft		22				
		Visual Classification, GrSi, gry, MTW, Rec = 1.3 ft		25				
20		Visual Classification, GrSi, gry, MTW, Rec = 1.0 ft		62				
		Here stopped @ 21.5 ft						
25								

LOG OF BOREHOLE MAHMUTOVIC (LOG) OF B-306



STATE OF VERMONT
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 MATERIALS & RESEARCH SECTION
 SUBSURFACE INFORMATION

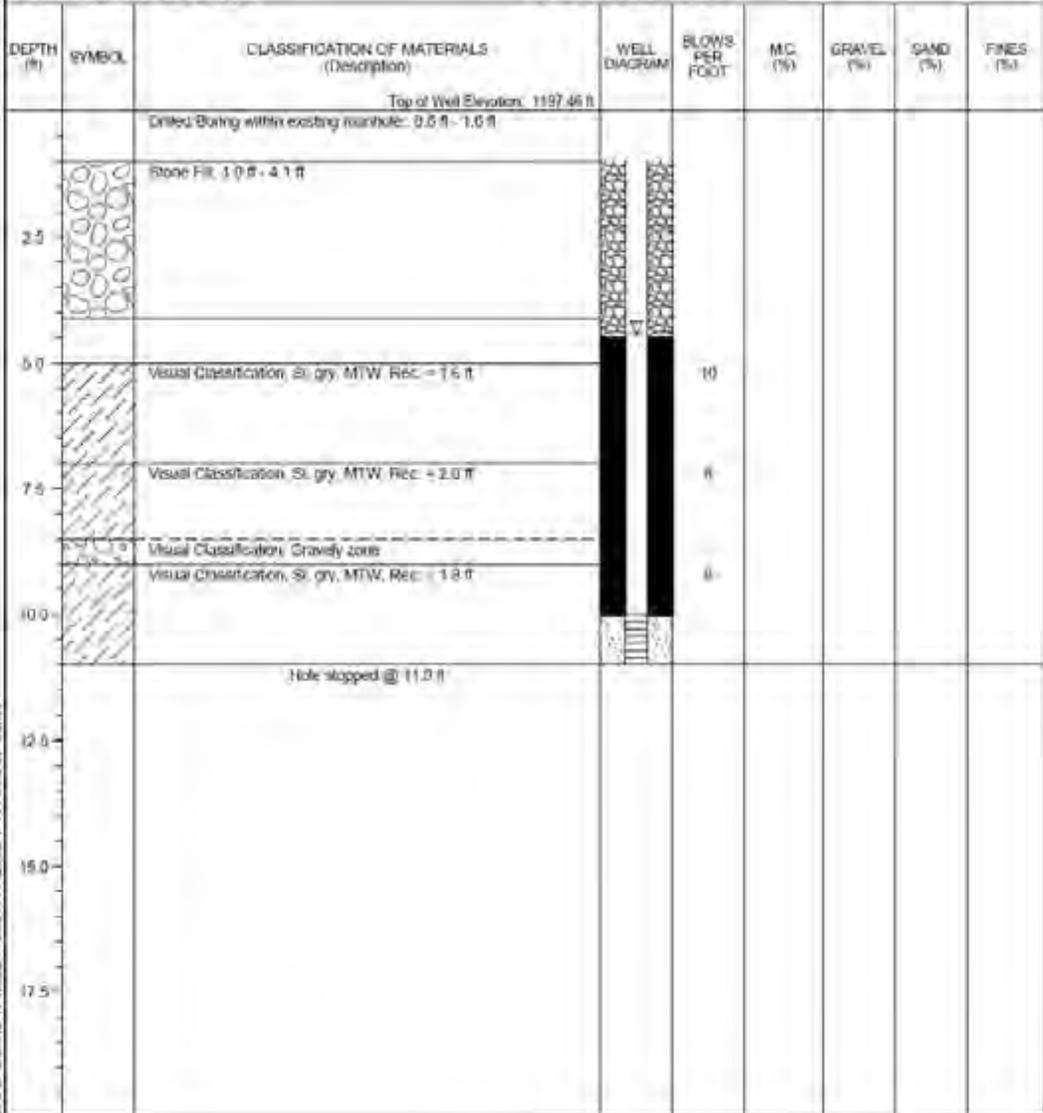
BORING NUMBER: B-307
 SHEET 1 of 1
 DATE STARTED: 5/07/09
 DATE COMPLETED: 5/07/09

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



LOG OF BOREHOLE: RANDOLPH PARK & RIDE, GPS: VT 4030107 88205



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: 8.96 ft 5/19/09
 PROJECT PIN NUMBER: 00K130

BORING CREW
 CREW CHIEF: GARROW
 DRILLER: GARROW
 LOGGER: MAHMLITOVIC

BORING RIG: LAG TRACK RIG #09 w/AUTO HAMMER
 BORING TYPE: WASH BORE
 SAMPLE TYPE: SPLIT BARREL
 CHECKED BY: TDE

