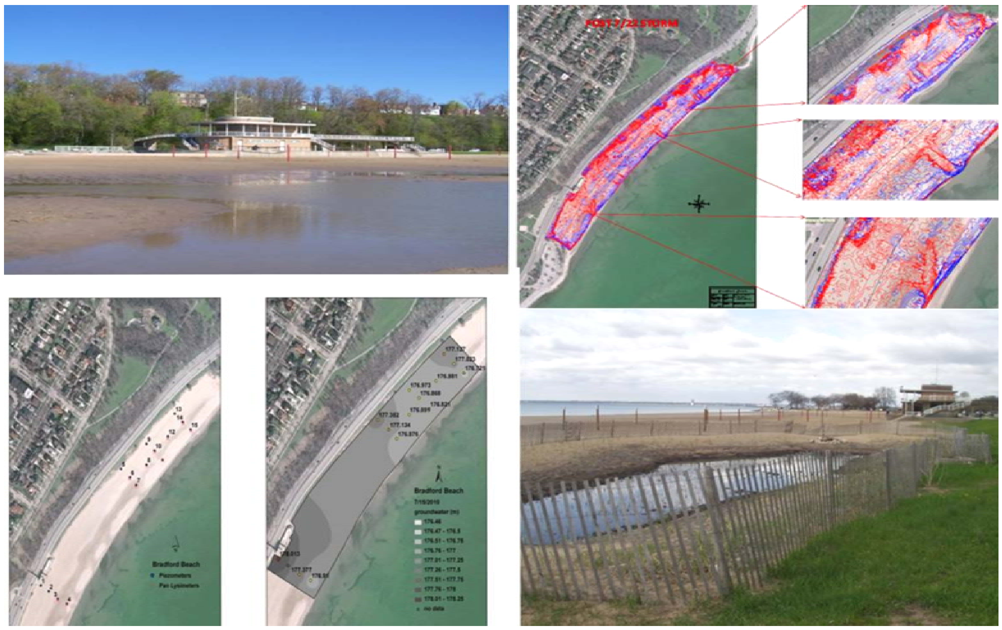
Bradford Beach Standing Water Investigation



Authors:
Marcia Silva, M.S.
Dr. Sandra L. McLellan
Dr. Hector Bravo
Dr. William Kean
Dr. Val Klump

Contributors:
Dr. Douglas Cherkauer
Daniel Talarczyc, P.E.
Bonnie Bills
Donald Szmania
Jessica VandeWalle
Jenny Ulbricht
Colin Peake
Jessica R. Sielick

School of Freshwater Sciences
Department of Civil Engineering and Mechanics UWM
Geosciences Department UWM
University of Wisconsin-Milwaukee
Released: March 2012

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

DEFINITION OF TERMS AND ABBREVIATIONS

Berm - a narrow path of sand typically at the top of the beach slope, where there is a constant beach swash, and they are labeled from BB1 to BB10 in Figure ES- 2.

Submerged sand- sand by the shoreline that is constantly under water. They are located east of the berm sites, on the shallow end of the swash zone. Berm sites are marked in Figure ES- 2.

Swash zone - The zone of wave action on the beach, which moves as water levels vary, extending from the limit of run-down to the limit of run-up.

Backshore- It is the region of the beach in which the sand is constantly wet (wet area shown by the dark strip in Figure ES- 2).

Top sand– sand just west of the backshore sand samples, passing the wet sand region. Berm sites are marked in Figure ES-2.

PZ – Piezometer. Piezometer IS A nonpumping well, generally of small diameter, for measuring the elevation of a water table.

PL – Pan lysimeter. Pan Lysimeter is a device for collecting water from the pore spaces of soils and for determining the soluble constituents removed in the drainage.

TOC – top of casing. toc is the elevation of the top of the protective cover of the wells.

FIB – Fecal Indicator Bacteria. In this study: *E. coli* and enterococci.

Hydraulic conductivity (K)- It is a property of soils that describes the ease with which water can move through pore spaces or fractures. It has units with dimensions of length per time (e.g., cm/s).

Shelby tubes - Shelby tube samplers consisted of a one piece, thin-walled, hollow plastic tube with an open-end that has been honed to a cutting edge. The tube is pushed into the soil and then extracted with a sample of the soil intact inside. This tube may then be transported as-is with a threaded sealing cap on the open end or have the sample pushed out and sealed in a purpose made tube for later examination. The purpose of taking soil samples in this way is to obtain relatively undisturbed samples and preserve the delicate strata or layers and any other defining characteristics of the soil sample intact.

vibracoring- It is one subsurface sediment acquisition (sediment coring) technique. Vibracoring obtains sediment samples by vibrating a core barrel, which is attached to a pneumatic vibrator head,into the sediment.

geoestatistical modeling – ArcGIS Geostatistical Analyst is an extension in ArcGIS that provides capability for surface modeling using deterministic and geostatistical methods, in which it creates surfaces from sample data using three interpolation methods. in this study the inverse distance weighted (IDW) method was used.

EXECUTIVE SUMMARY

Background and Significance

The Bradford Beach area is an artificial urban beach in Milwaukee County on the shore of Lake Michigan (43º03'41.30” N, 87º52'20.41” W). The beach spans a total distance of approximately 700 meters along shore and cross shore extends 125 meters to the water's edge from Lincoln Memorial Drive, covering approximately 0.08 km^2 (18.6 acres). The beach was originally built around the 1930s, and through the years has seen different construction processes and efforts to help limit erosion, enhance visual appeal, and promote environmental development. It is one of Milwaukee's most popular beaches for swimming and sunbathing, being located just north of downtown. Dolostone boulders and concrete rip rap encompass the beaches north and south ends (erosion protection), and across the road from the beach, a 25 meter glacial bluff rises up from the original natural shore line. The beach consists of a flat region of medium to fine grained sand that overlies glacial till. Shoreline processes that affect Bradford Beach include: wave action which produces a sand berm, longshore drift, movement of infiltrated water through sand, and human activities (stormwater outfalls, grooming).

Bradford Beach historically has had elevated *Escherichia coli* (*E. coli*) levels in beach water. This bacterium is used as an indicator of fecal pollution. Fecal pollution can contain pathogens. Therefore elevated levels indicate that a health risk may be present. Water quality advisories are issued when levels in the water are above 235 colony forming units (CFU) per 100 ml. Past investigations have identified multiple sources of *E. coli* at Bradford Beach, for example, stormwater outfalls above the beach were found to be major sources of *E. coli*. *E. coli* from the outfalls along with fecal material from gulls were found to accumulate in the sand and persist for long periods of time in moist sand and in accumulated *Cladophora* along the shore. Wave action can wash *E. coli* from these reservoirs into beach water, causing elevated levels even in the absence of a new fecal pollution sources. In addition, outfalls located north of the beach discharge contaminated water directly to the lake, which can reach the beach through longshore currents.

In June of 2008, installation of rain gardens mitigated one major source of *E. coli*. Stormwater runoff from six outfalls is no longer discharged across the beach unless there are heavy rainfall events. In this case, stormwater is allowed to overflow from the rain gardens and run across the sand toward the lake. A gull determent program also has reduced the number of gulls during the years the program has been in place (2008-2010). As a result, lake water and beach sand quality at Bradford Beach has improved since 2008.

E. coli can persist in beach sand when the moisture content is high. Standing water along Bradford Beach has been observed behind a shoreward sand berm throughout the years, and has been very evident the past three or four years. The standing water and /or wet sand areas that stretch across the middle of the beach may contribute to prolonged survival of *E. coli* or other fecal bacteria in the sand. The causes of standing water were unclear. Therefore, studies were initiated at Bradford Beach to investigate the causes of standing water, mainly on the northern side of the beach (as shown in Figure ES- 1), and to evaluate if there would be a health concern with the standing water. Possible explanations for the standing water include: a) beach erosion creating a depression and bringing the ground surface close to the water table; b) sand deposition that produced a berm, allowing water to be caught shoreward of the berm; c) finer sand on the northern part of the beach, implicating in slower infiltration, and d) transient increases in the water table due to infiltration of water in the rain gardens.

The purpose of this investigation was to monitor selected hydrological and geophysical elements including precipitation, groundwater and surface water, and water quality variation within the area. The resulting data was used to aid in determining the relationship of standing water to: a) the topography of the beach; b) waves and currents; c) rainfall events; d) installation of rain gardens; e) sand properties; f) geophysical properties of Bradford Beach, and g) health concern.

The scientific approach was therefore to: 1) gather historical microbiological sand and lake water data obtained by the McLellan Lab before and after the rain gardens; 2) gather historical data of physical properties of sand cores obtained by Bravo Lab in collaboration with the Klump Lab and the Soils lab at UWM; 3) install 15 piezometers and 10 pan lysimeters at Bradford Beach to monitor groundwater level and microbiological and physical properties of subsurface water, 4) conduct geophysical surveys in collaboration with the Kean Lab, 5) perform additional sand and lake water surveys, as well as geophysical surveys as needed, and 6) perform three topographical surveys during different seasons of the year and before and after rainfall events. Location of piezometers and surface sand sampling sites are shown in Figure ES- 2.

Results and Discussion

1- <u>Formation of standing water:</u> The primary mechanism of ***formation*** of standing water is a rise in groundwater levels caused by the infiltration of precipitation (both directly and indirectly from surface runoff), as shown in Figure ES- 3. A secondary mechanism, but not significant at the

0.05 level, is flow from high waves crashing onto the beach (represented by wave height in Figure ES- 3).

2- Retention of standing water: The main mechanisms of ***retention*** of standing water have to do with beach topography resulting from the beach processes listed below.

2.1 *Beach erosion and deposition* - Beach erosion was observed mainly in the central part of the beach (cross-shore direction, where the wet sand can be observed on Figure ES- 2), with the deeper depressions located mostly on the northern part of the beach. Beach deposition produced a near shore sand berm after erosion lowered the beach elevation, allowing water to be caught shoreward of the berm. Three comprehensive topographical surveys were conducted at Bradford Beach in November 2009, April 2010, and July 2010. The main objectives of the topographic surveys were to provide a grading plan and to quantify the beach erosion due to the July 2010 storms. The accuracy parameters were predetermined with the intention of capturing the topographic relief of the site within 0.1 U.S. Survey Feet (3.048 cm). Topographical surveys show that there are regions with deeper depressions on the northern part of the beach, thereby contributing to concentration of standing water in that region.

2.2 Finer sand on the northern part of the beach implicating in slower infiltration: Bucket samples and sand core samples were analyzed for grain size distribution before and after the rain gardens were built. On the southern part of the beach sand has medium size and is less uniform where d_{50} is 326±83 μm (n=28) whereas on the northern part of the beach sand has fine size where d_{50} is 243±26 μm (n=51). According to Krumbein phi scale, sand is classified into five categories: very fine sand (62.5-125 μm), fine sand (125-250 μm), medium sand (1/4-1/2 mm), coarse sand (1/2-1 mm) and very coarse sand (1-2 mm).

2.3. Transient increases in the water table - Rain gardens can augment transient increases in the water table level. A rise of the water table could produce less storage volume in the sand for newly infiltrated water, resulting in more surface runoff once that storage is used up. Overall, the groundwater level is very responsive to rainfall, rising within 24 hrs of the precipitation (Figure ES- 3). Groundwater levels drop quite rapidly, with slower decay near the outfalls possibly because of the closer connection to the source of water being infiltrated by the rain gardens. Decay was also slow near standing water sites compared to areas where the unsaturated sand is thicker, with some exceptions.

<u>3-Groundwater conditions:</u> The water table is just below the beach surface (10 cm in the worst case scenario, when there is a maximum groundwater level), creating chronic moist areas and minimizing the infiltration process. The mean depth of groundwater table in the standing water zones is 0.5 m; in the non-saturated zones is 0.8 m, and in the whole beach is 0.7 m. Fifteen piezometers, four on the southern part of the beach and 11 on the northern part of the beach, were monitored from October 2009 until November 2011. For high and low water table conditions, groundwater dominantly flows from West to East toward the lake, with a weak component from South to North, according to Figure ES- 5. Data showed that the groundwater table is deeper on the northern part of the beach. However, that is also the region where the deeper ground depressions are found. The potential for infiltration is reduced where the groundwater is closer to ground surface because there is less open pore space for the infiltrating

water to fill. Pore water and groundwater were found positive for Human *Bacteroides* marker, indicating sewage contamination, only during very heavy rainfall events when stormwater is allowed to overflow from the rain gardens and run across the sand toward the lake. Stormwater directly discharged to the lake from northern outfalls may also impact the beach with wave run-up.

4- Beach lithology and structure: Geophysical surveys characterized the beach lithology. Vertical electrical soundings and electrical profiles were conducted parallel to the shoreline. In the sounding surveys, Bradford Beach was modeled as a three layer system consisting of a southward thickening sand body approximately 3.35 m thick. The electrical profiles show more resistive surface material toward the central part of the study area. This suggests either sand containing less fine-grained sediment or a deeper water table toward the center. The beach exhibited very little natural sedimentary history as noted by the lack of depositional structures in the sand from the limited ground penetrating radar studies. This could be expected because it is an artificial beach and any natural sand was either removed, altered through reconstruction processes, or never existed in the survey areas. The electrical profiling data also showed some low resistivity areas at depth that may correlate with one storm drain outflow. The natural geologic material below the sand body was determined through multiple techniques to be located at approximately 3.66 m and from regional geology was characterized to be Wisconsian age glacial till. All the geophysical surveys suggest a fairly uniform sand surface layer that may be as thick as three meters. The electrical sounding and profile results show some lateral variations at a depth of about three meter which could be pre -1930 beach material, or different levels of sub-sand saturation, possibly due to the drain outfalls near Lincoln Memorial Drive. However, changes at this depth are unlikely to be affecting the surface sands, or causing the standing water.

<u>5- Bacteria in Standing Water:</u> Standing water contains high levels of FIB and is a health concern mainly during heavy rainfall events when samples were found positive for Human *Bacteroides* marker, indicating human sewage contamination. During heavy rainfall events, rain gardens are allowed to overflow letting stormwater run across the sand beach toward the lake. Human sewage contamination continues to be intermittently detected in outfalls along Bradford Beach, and more commonly, in the outfalls north of the beach. The rain gardens retain contaminated water and prevent it from running across the beach. In contrast, the outfalls located to the north of Bradford Beach discharge directly to the lake, where contamination delivered to the beach in the southward longshore current is a health concern. Further, standing water has been found to have high FIB levels in the absence of human sewage bacterial markers. This could indicate fecal pollution from birds. The health risk due to avian fecal pollution is not well quantified, but gulls have been noted to carry pathogens.

<u>6- Beach Grooming:</u> Beach grooming may improve conditions, but cannot compensate for lack of sand. Grooming aerates the top layer of sand, allowing it to dry out. Moisture content is strongly linked to *E. coli* survival; therefore, grooming potentially can reduce *E. coli* levels. However, the combination of minimal sand with a high water table creates areas that have standing water or chronic saturation. In addition, grooming should not reduce the berm formation at the water line, as this serves as a barrier to wave run-up.

7. <u>Beach nourishment:</u> Bradford Beach is located in a region with two physical barriers that may attenuate longshore currents and therefore reduce longshore drift. The Linnwood drinking water treatment plant is located just north of the beach and the harbor breakwater is located just south of the beach. When a wave breaks, a portion of the energy is directed laterally along the beach and this reinforces the longshore currents. Even a very gentle current can carry fine grained sediments such as silts and clays along the beach and also to and from the beach (perpendicular to the longshore currents). Therefore, beach nourishment at Bradford Beach would be effective and economically attractive, since it would likely last long.

Beach nourishment would have two objectives: eliminate standing water and keep the beach above the mean lake level. A grading plan was prepared with the purpose of simultaneously rectifying the loss of material due to the storms while filling the longitudinal swale running the length of the beach.

The recommended grading plan consists of two surfaces defined between three contour elevations. The first grading plan surface is bounded by the contours of 580.25 ft (176.86 m) and 582 ft (177.39 m) and has the purpose of filling the breaches of the berm created by the storms. The surface was linearly interpolated in the cross shore direction between the bounding contour elevations. The second grading plan surface was linearly interpolated in the cross shore direction between the contours of 583.00 ft (177.70 m) on the landward side and 582.00 ft (177.39 m) on the lakeside, and comprised most of what was seen as the large longitudinal swale of the beach. The interpolated design surfaces created a relatively small slope (+/-1%). It should be noted with both surfaces that the natural contours bounding these planes were artificially spliced at the breaches, thereby reestablishing the berm as it existed before the storms.

Topographical surveys show that a total of approximately 5,400 cubic yards of material would need to be imported to execute the design of the grading plan. The survey data analysis provided a sample grading plan, which would simultaneously rectify the loss of material due to the storms while filling the longitudinal swale running the length of the beach.

All these elevations mentioned are above the mean annual level between 1860 and 2008. Between 1860 and 2008 the mean annual lake level was 579.53 ft (176.64 m), the maximum annual lake level was 581.99 ft (year 1886), the minimum annual lake level was 576.51 ft (year 1964), and the range was 5.48 ft (1.67 m)[1]. In conclusion the proposed grading would keep the beach above the mean annual level between 1860 and 2008. It is expected that extremes of the hydrologic cycle will global warming, causing precipitation intensity to increase, particularly in middle and high latitudes. The Great Lakes region is projected to experience a rise in these extreme precipitation events [2], which does not imply in higher overall precipitation. Therefore, nourishment would unquestionably be the one action that would raise the beach and minimize inundation. In addition, building a few cross-shore drainage channels on the beach will help to drain the beach and minimize beach erosion. The cross shore drainage channels could be built at the locations that experienced significant breaches to the berm that runs longitudinally to the shore adjacent to the water's edge during the July 2010 storms. The three breaches were located across from the pumping station that is west of Lincoln Memorial Drive, opposite the beach house, and midway between the two larger breaches, respectively.

In conclusion addressing the material deficit without also recommending mitigating measures for the erosion mechanism would be remiss. This could be accomplished through the consultation of a coastal engineer. Also, when lake levels were really high in the 70s and waves would crash upon Lincoln Drive in storms, a lot of sand was eroded from the beach (and went offshore). As water levels have subsequently declined, that sand has moved even farther offshore. This sand could be pumped back onto the beach, but a coastal engineer needs to determine how any removal will affect offshore stability.

Conclusions and Recommendations

There are two mechanisms of formation of standing water. The primary mechanism is a rise in groundwater levels caused by the infiltration of precipitation and a secondary mechanism is wash from high waves crashing onto the beach. The main mechanisms of retention of standing water have to do with beach topography resulting from beach erosion and deposition, coarser sand on the southern part of the beach when compared to the northern part, allowing quicker infiltration and less presence of standing water, and transient increases in the water table augmented by the rain gardens.

When heavy rainfall events happen, stormwater is allowed to overflow from the rain gardens and run across the beach. Under these circumstances, standing water was found positive for sewage indicator, as well as pore water and groundwater, which is a health concern. Beach nourishment is therefore recommended to eliminate standing water and assure that the beach elevation will remain above lake level, avoiding flooding of the area. Beach grooming is a technique encouraged to continue to be applied at Bradford Beach. In addition, building channels through the berms along the beach from swales toward the lake would help to drain the swales. Consultation of a coastal engineer is encouraged for recommendation of mitigating measures for the erosion mechanism.

Figure ES- 1- Picture captured by a camera on the top of the beach house showing impact of heavy rainfall event on 7/22/10, such as beach erosion and accumulation of standing water at Bradford Beach.

Figure ES- 2- Sampling sites. The yellow circles show the sites where sand cores were collected with Shelby tubes in 2007, the blue stars show the transects of sand cores collected in 2009 with a vibracore, the black circles show were piezometers were installed in October 2009, the red triangles show where the stormwater outfalls are located and the red circles show where the berm surface sand sites are located. Please note the region of wet sand along the beach.

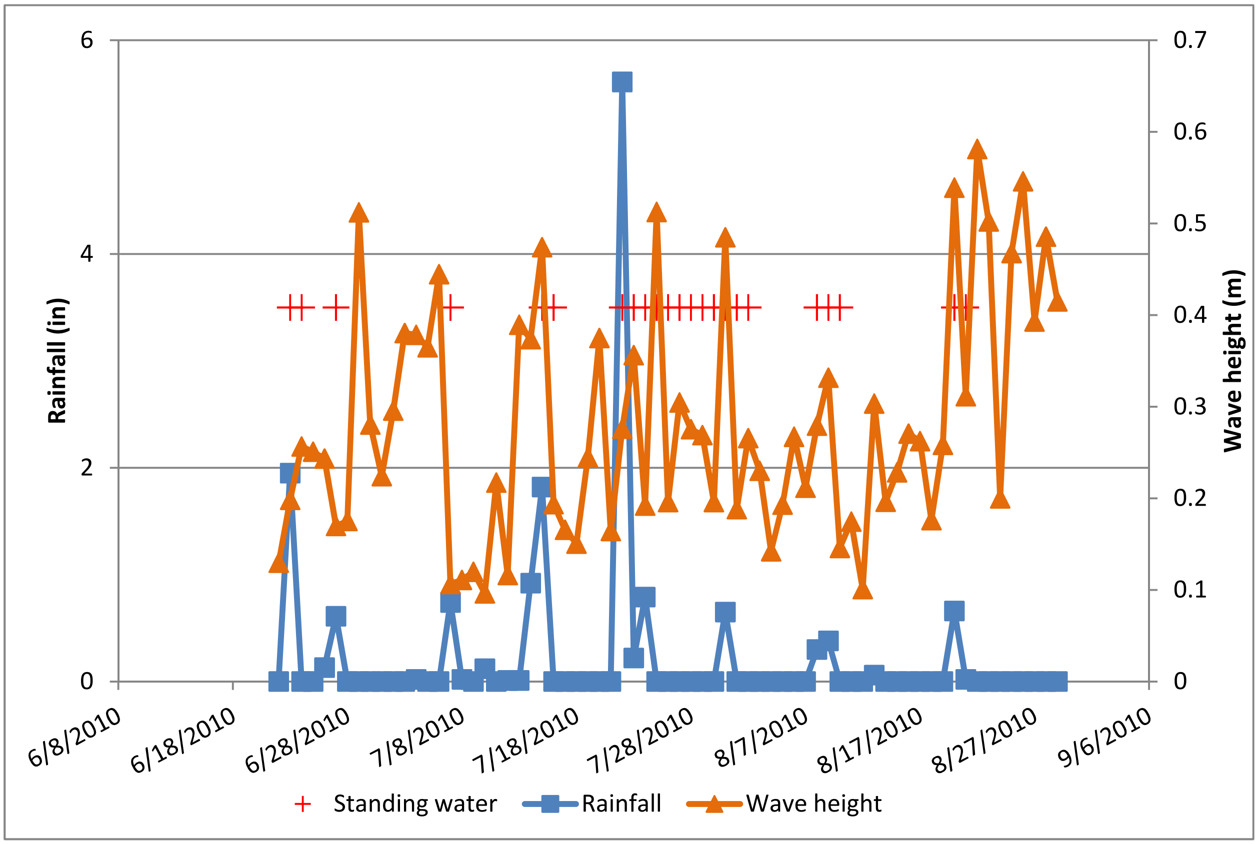


Figure ES- 3– Evaluation of relationship of formation of standing water and wave height & rainfall. Standing water is strongly related to rainfall and weakly related to waves.

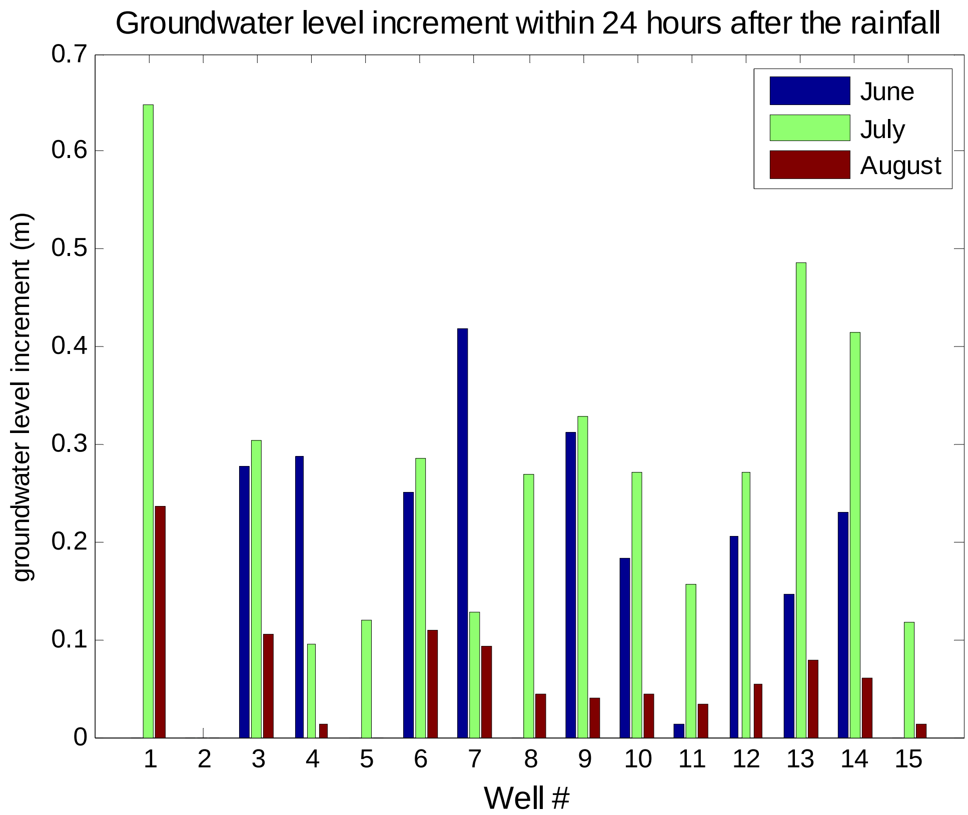


Figure ES- 4- Groundwater level increment within 24 hours after the rainfall. Data presented is from June, July, and August 2010.

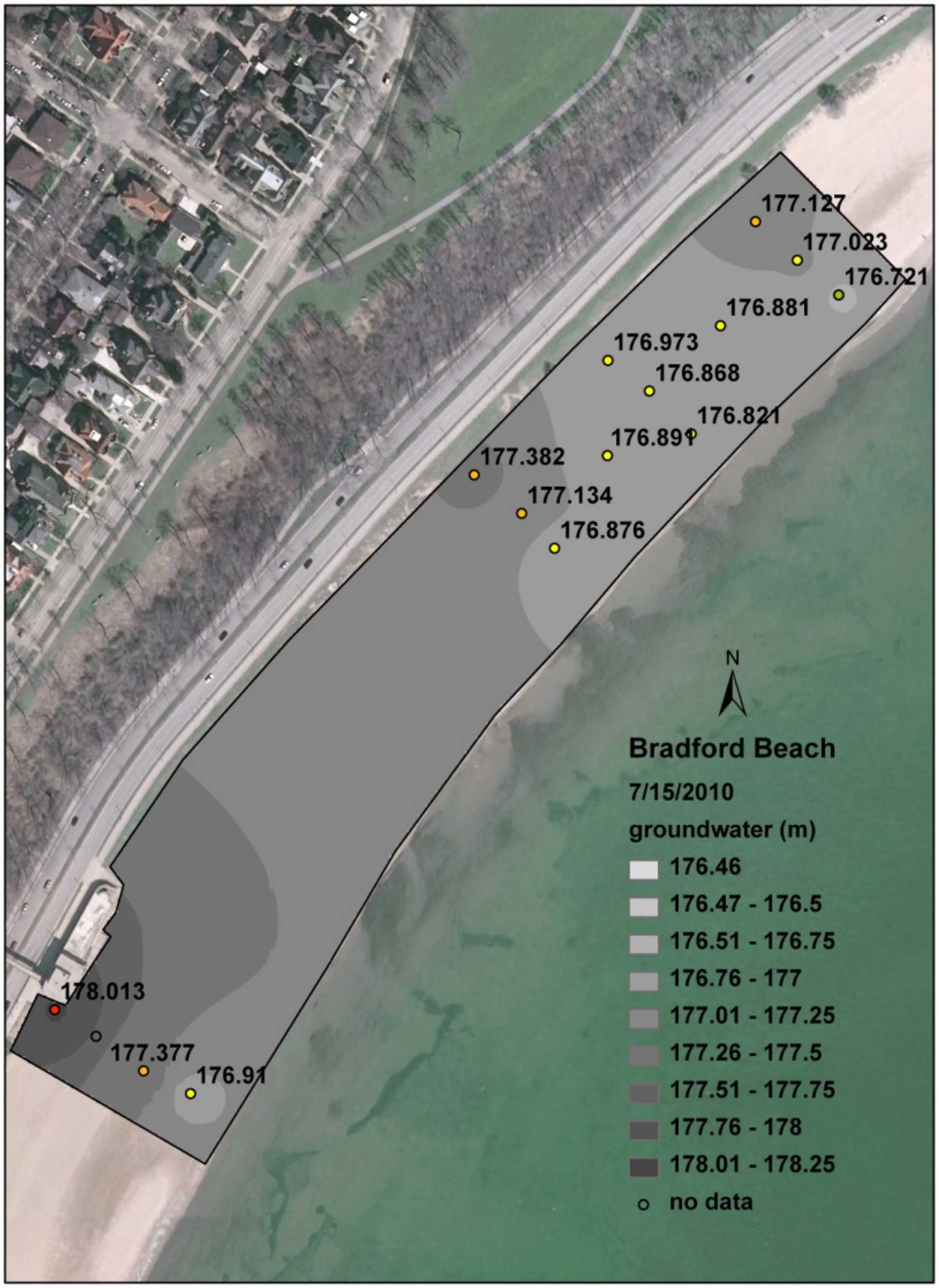


Figure ES- 5- Typical groundwater table for Bradford Beach, obtained by geoestatistical modeling. Data presented was collected on 7/15/10. Prediction map was generated in ArcMap using IDW as the interpolator.

1 INTRODUCTION

The Bradford Beach area is an urban beach in Milwaukee County on the shore of Lake Michigan (43º03'41.30" N, 87º52'20.41" W). The beach has a longshore length of approximately 700 meters and a cross shore width of 125 meters from the water's edge to Lincoln Memorial Drive and it is one of Milwaukee's most popular beaches for swimming and sunbathing, and it is located just north of downtown. Dolostone boulders and concrete rip rap encompass the beaches north and south ends (erosion protection) and across the road from the beach, a 25 meter glacial bluff rises up from where the natural shore line used to be. The beach consists of a flat, southerly dipping region of medium to fine grained sand that overlays glacial till. The beach was originally built around the 1930s, and through the years has seen different construction processes and efforts to help limit erosion, enhance visual appeal, and promote environmental development. Figure 1 shows the 1938 and 2005 map of Bradford Beach overlaid. It is possible to see that the lake water used to reach Lincoln Memorial Drive.

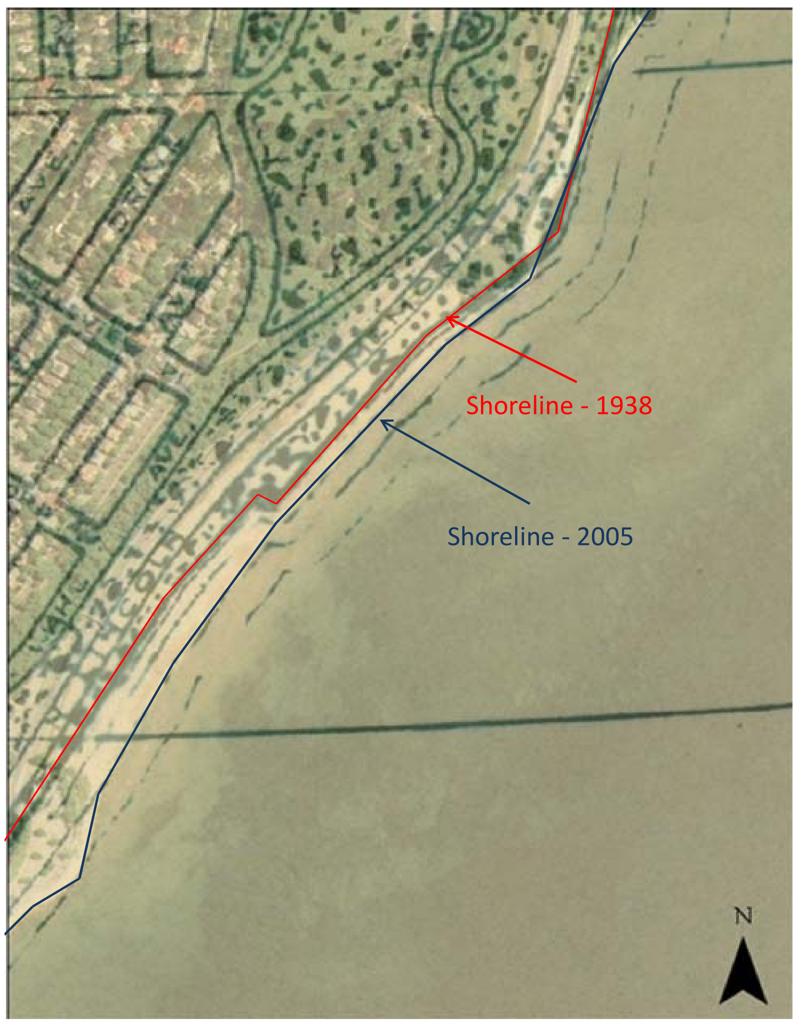


Figure 1-Bradford Beach 1938 and 2005 map overlaid

In 2009 and 2010, an intense study was performed at Bradford Beach. The study included topographical surveys and geophysical surveys, groundwater level measurements, bacteria measurements at standing water, groundwater, runoff infiltrating through the sand, lake water, stormwater outfalls, sand cores, and surface sand, as well as visual data acquired by a WATER Institute camera on the top of the beach house. The purpose of this study was to evaluate the causes of formation and retention of standing water and also assess if standing water was a health concern.

2 METHODOLOGY

2.1 Study site

Locations of the sampling sites are shown in Figure ES- 2.The yellow circles show the sites where sand cores were collected with Shelby tubes in 2007, the blue stars show the transects of sand cores collected in 2009 with a vibracore, the black circles show were piezometers were installed in October 2009, the red triangles show where the stormwater outfalls are located and the red circles show where the berm sand sites are located. The submerged, backshore, and top sites are not shown in the map.

2.2 Sample Collection

2.2.1 Lake water samples

Water samples were collected 1-2 m from shore in knee-deep water using a grab sampler and transferred to 500-ml bottles, and stored on ice and in darkness until filtering in the lab. Grab samples were full-volume flushed at least three times with water from the sample site. Lake water samples are shown in Figure 2.

Figure 2-Sampling sites of beach water samples and outfalls

2.2.2 Sand samples

Sand cores by Shelby tubes: Sediment core samples were obtained at Bradford Beach on 10/13/07. Three transects with a total of nine sites were established, according to Figure 3. The main purpose of the 3 ft long and 3 in. inner diameter Shelby tube samplers was to recover relatively undisturbed soil samples. Shelby tubes were inserted into the sand using a rubber mallet. Total core depth was divided into three equal parts and samples were removed from the tube by gravity. Samples were tested for moisture content, organic content, sieve analysis, *E. coli* and enterococci.

Sand cores by vibracore: Beach cores were acquired by mechanically vibrating a 1m or less section of 3 inches (O.D.) aluminum irrigation pipe (1.3 mm wall thickness) down to the depth of the pre-determined depth of the water table. Our vibracore apparatus consisted of a Wacker Corporation high frequency internal vibrator (Wacker Model H55), attached to a 16.5 ft flexible shaft (Wacker model SM5-S), which was powered by Briggs & Stratton gasoline engine, designed to energize the vibrator unit (Wacker B3000).

Sand Surface samples:

For microbiological analysis: Samples were collected with a spatula and placed in individual Falcon tubes for each sample location (beach) and site (backshore, berm, submerged, water). When collection was carried out this way, then DNA was extracted separately. Alternatively, samples from multiple sites were collected in the same tube and marked as composite. Samples were mixed well before taking aliquot for DNA extraction.

For physical analysis: Sand samples were collected with a spatula and placed in 1-quart plastic zip-lock freezer bags and transported to the University of Wisconsin-Milwaukee Soils Laboratory.

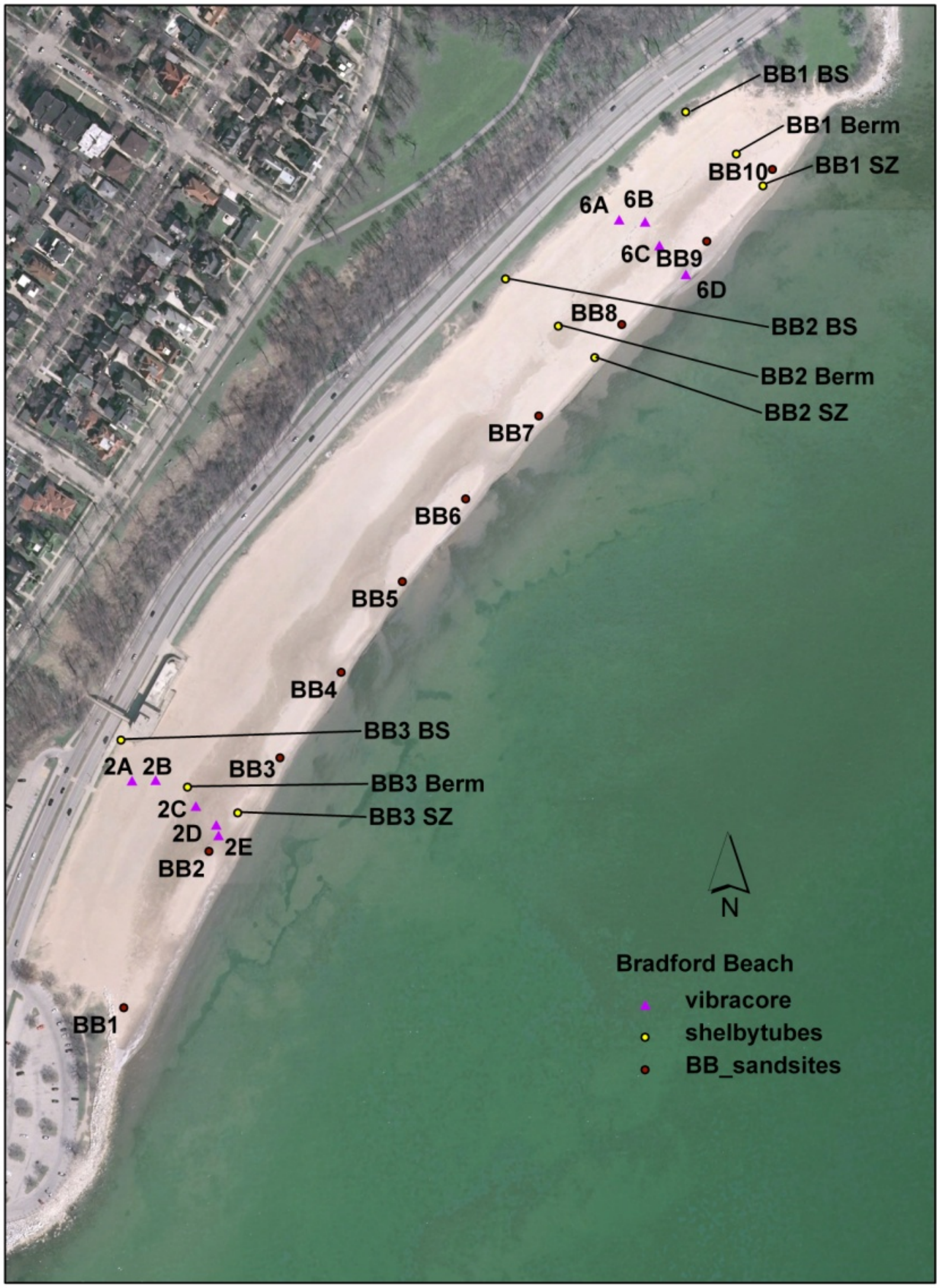


Figure 3-Sampling sites of sand samples (surface sand and core samples collected by Shelby tubes and vibracore)

2.2.3 Stormwater outfall samples

Water samples were collected directly from the stormwater outfall into a 500-ml bottle, and stored on ice and in darkness until filtering in the lab.

2.2.4 Standing water samples

Water samples were collected from the standing water directly into sterile Whirl-Pak™ bags and transferred to 500-ml bottle, and stored on ice and in darkness until filtering in the lab.

2.2.5 Groundwater samples

Piezometers were manufactured at the WATER Institute machine shop and they were made of 4-ft-long, 2-inches-ID-PVC pipe, with holes from 12 inches to 42 inches from top, and had two caps (one removable on the top and one sealed on the bottom). They were wrapped on a 100 µm polyester filter felt. The filter was secured with stainless steel hose clamps and stainless steel wires, as can be seen in Figure 4.

Figure 4-Piezometer at Bradford Beach

Groundwater samples were collected using a battery-powered portable sampling system (Model number 7577-00) Barnant Company. Deionized water was first pumped to clean the tubing line before pumping the groundwater sample. Piezometers were purged with a bailer as needed until clearwater was observed. Samples of groundwater (total volume 500 ml) were then pumped directly into a clean 500 ml bottles and placed on ice and analyzed the same day.

Depth to water was measured in piezometers to the nearest 0.3 cm using an electronic water level sounder (Solinst Model 101). The groundwater elevation was calculated by subtracting the depth to water measurement from the top-of-casing (TOC) elevation. TOC was surveyed four times during the extent of this study: when they were installed and when one or more piezometers were removed, stolen, or leaning. Modeling of groundwater table was performed in ArcGIS using the Inverse Weight Distance (IWD) Interpolator.

2.2.6 Samples of runoff infiltrating through the sand

Ten pan lysimeters were installed at Bradford Beach on July 7, 2011 three feet south of 10 selected piezometers (#3, 4,6,7,8,10,11,12,14, and 15), as can be seen in Figure 5. The sample access tube was attached to the collection flask, and the arm of the flask was attached to the hand pump. As the pump was pulled the sample was collected in the flask and transferred to a clean bottle, and stored on ice and in darkness until filtering in the lab.

2.3 *E. coli,* enterococci, and total coliforms enumeration

All water samples are analyzed within 12 hours using the appropriate USEPA method. Each environmental water sample was filtered through a 0.45-µm-pore-size 47 mm nitrocellulose filter and placed on modified m-TEC (Difco, Sparkes, MD) agar according to the EPA method for *E. coli* enumeration [3], on mEI agar (Difco, Sparkes, MD) for enterococci enumeration [4], and on MI (Difco, Sparkes, MD) for total coliforms enumeration [5]. The volumes filtered varied according to expected contamination, where 10 ml and 100 ml volumes were analyzed for water beach samples, and 1 ml and 10 ml volumes were analyzed for outfalls at the beaches, and the remaining beach samples. The plates were incubated at 44.5°C for 24 h for *E. coli* enumeration, at 41°C for 24 h for enterococci enumeration, and at 37°C for 24 h for total coliforms enumeration. MI plates were exposed to longwave ultraviolet light (366 nm), all fluorescent colonies were counted.

2.4 DNA extraction

All water samples were filtered within 12 hours for DNA extraction. For beach water samples or outfall samples, a volume of 100 to 200 ml of sample was filtered onto a 0.22 µm pore size 47 mm nitrocellulose filter and stored at -80°C. For groundwater samples, the highest possible volume was filtered. Extraction of DNA for stormwater outfall samples were performed as described in [6, 7]. Extraction of DNA of samples of groundwater, runoff infiltrating through the sand samples, and lake water were performed using crude bead-beating method as described in [8].

Figure 5- Sampling sites of subsurface water (groundwater sampled at the piezometers and runoff infiltrating through the sand sampled at the pan lysimeters)

2.5 PCR and qPCR

PCR and qPCR analysis for all samples were performed as described in [6, 7]. Samples were tested for human *Bacteroides* genetic marker.

2.6 Measurement of bacteria in the beach sand

Sand (20g) was vortexed with 30 ml of sterile water. *E. coli* and enterococci were determined as described in[9].

2.7 Determination of physical properties of sand

Moisture content, organic content, hydraulic conductivity, and sieve analysis. For determination of water content, the oven-drying method was used with a drying temperature of 105°C, according to ASTM D 2216-90.

Determination of organic content was performed according to ASTM D 2974. Mass of an empty, clean, and dry porcelain dish was recorded. Oven-dried sand from the moisture content analysis was placed in the porcelain dish and mass of the dish and sand specimen was recorded. Dish was placed in a muffle furnace at 440°C overnight. Dish was removed from the furnace and let it cool down in a dessicator to room temperature. Mass of the dish containing the burned sand was recorded and % of organic matter was computed.

Determination of hydraulic conductivity (K) was performed using the constant head permeability method, according to ASTM D 2434-68.Sand sample was mixed with a sufficient amount of distilled water to prevent segregation of particles during placement into the permeameter. Sample was compacted to a reasonably high density without damage to the filter screen. Sample was saturated with upward flow of water. Water was allowed to flow through sample and exited across the overflow weir and was collected from the output tube into a beaker so Q in some time t could be measured. This process was performed in triplicate.

Grain size analyses were conducted using method ASTM C 136-05. Samples were placed in aluminum tins and oven dried for 24 h at 110 °C, the oven dried samples were place in a stack of sieves (75-µm, 106-µm, 150-µm, 250-µm, 425-µm, 850-µm, 2-mm, and 4.75-mm), the stack was placed in a mechanical shaker for 10 min, and the fraction of sample retained on each sieve was weighed on an electronic scale (Ohaus Explorer Pro Model EP2102C) to nearest 0.01 grams. The cumulative weight retained was calculated starting from the largest sieve size and adding subsequent sediment weights from the smaller size sieves.

2.8 Measurement of conductivity in water samples

A multiparameter sonde with sensors for conductivity, temperature, pressure (depth), turbidity, chlorophyll A, and DO (model 6600 EDS V2, YSI, Yellow Spring, OH) was dipped into the sample after all the micro analyses were performed. Reading was performed at the same time and recorded on a log notebook.

2.9 Measurement of turbidity in water samples

Turbidity was measured with a 2020 turbiditimeter, which is a portable, microprocessor controlled nephelometer, calibrated in Nephelometric Turbidity Units - NTU. Instrument was calibrated for two standard solutions in the range of the samples to be tested.

2.10 Topographical surveys

2.10.1 Data acquisition

Three comprehensive topographical surveys were conducted at the Bradford Beach Project Site in November 2009, April 2010, and July 2010. Figure A- 2 to Figure A- 4 in Appendix A show the three surveys. The accuracy parameters were predetermined with the intention of capturing the topographic relief of the site within 0.1 U.S. Survey Feet (3.048 cm). Two types of technology were utilized in these surveys. Real Time Kinematic (RTK) Global Positioning System (GPS) technology with a Virtual Reference Station (VRS) network base correction was used to establish primary control and to capture XYZ data on the ground. This equipment consisted of a Trimble R8 Rover antenna on a fixed 2-meter rod with an integrated level vial and a cellular phone modem. The second type of technology involved a robotic total station with reflector-less scanning capabilities, which was used to capture XYZ data on the ground. This equipment consisted of a Trimble S6 Robotic Total Station on a standard tribrach/tripod setup and a 360-degree prism on a variable height rod with an integrated level vial. The tips of both rods were modified with a blunt face to mitigate penetration into the sand. A Trimble TSC2 Data Collector with the trademarked Survey Controller software provided the field software link to both technologies.

The VRS network is operated by the Wisconsin Department of Transportation (WisDOT) Geodetic Survey Unit. This network, called the Wisconsin Continuously Operating Reference Stations (WISCORS) Network, consists of permanent GPS sites, which provide real-time corrections to mobile users. The WISCORS is on the North American Datum of 1983 (NAD 83) (2007) horizontal datum with height above the ellipsoid (HAE) as its vertical component. This presents a unique challenge in the Greater Milwaukee Area, where the primary horizontal and vertical control datums observed by the Southeastern Wisconsin Regional Planning Commission (SEWRPC) are the North American Datum of 1927 (NAD 27) and the National Geodetic Vertical Datum of 1929 (NGVD 29), respectively. SEWRPC maintains a network of monuments on a half-mile grid referenced to these datums, which meet the horizontal control accuracy of Third Order, Class I and the vertical control accuracy of Second Order, Class II of the National Geodetic Survey's "Bluebook" standards.

Unfortunately, NAD 83 (2007) and NAD 27 are state plane coordinate system datum modeled on completely different ellipsoids. Therefore, it was necessary to perform a site calibration for the Bradford Beach project area to correct the broadcasted data to the published data on the aforementioned SEWRPC monuments surrounding the site. A multi-parameter adjustment algorithm was performed within the Survey Controller software, effectively calibrating to the NAD 27 horizontal datum through translation, rotation, and scale factor algorithms. In order to predict an NGVD 29 elevation, a geoid model (Geoid03) was applied to the HAE to come up with the vertical component.

The terrain encompassing the extent of the project area is relatively mild in terms of slope. In order to create an accurate topographic representation of the terrain surface, a maximum spatial threshold was established by which to collect the XYZ data. The space between data points did not exceed an arbitrary limit of ten feet. In the case of areas with highly-variable microtopography, the space between data points was reduced accordingly so as to accurately capture these features.

The project survey area was bounded in the following manner. The easterly limits included the Lake Michigan edge of water. The westerly limits were defined by the westerly edge of asphalt of the pedestrian path parallel with the north-bound lane of Lincoln Memorial Drive. The northerly limit was delineated immediately north of the rain garden at the northerly end of the beach. The southerly limit was established immediately south of the extent of the sand. Unfortunately, the survey conducted in November 2009 was prematurely terminated due to seasonal inclement weather. Therefore, it is incomplete in comparison to the two remaining surveys. In particular, the westerly area longitudinal to the beach north of the beach house along with the most northerly extent was not captured. However, the surveys completed in April and July of 2010 were comprehensive within the established bounds. Although the November 2009 survey could not be used in the volumetric differential calculations due to its extents being incongruent with those of the April and July 2010 surveys, there is still observational value to be gained.

2.10.2 Data processing and analysis

All of the collected field data was downloaded and consolidated in the Trimble Geomatics Office software. Subsequent to this, the data was transferred to survey software, Carlson 2010 Civil Suite, for processing and analysis. The data points from each survey were used to construct a Triangular Irregular Network (TIN) model for each surface. These models form the foundation of the topographic contour maps created for each of the three surveys. They also allows for efficient quality control, as erroneous data is conspicuously identified in anomalous contour lines.

In order to present the topographical surveys in the most aesthetic and efficient manner, the contour intervals were arbitrarily established at 0.25 feet (7.62 cm), even though predetermined accuracy standards allowed for a finer resolution. When a test plot was created with 0.1 foot (3.048cm) contours, the map was too cluttered for the size and scale of the drawings. The scale of each of the topographic maps was maintained at 1” = 100’ for consistency. Furthermore, a geo-referenced 2007 aerial photograph was included as a background overlay and a landscape perspective. It is interesting to note the discrepancy of the Lake Michigan shoreline due to expected periodic differences in lake water elevation. It should also be noted that the April 2010 topography included part of the surf zone in its surveyed extent. This area appears as a solid blue color on the map.

2.11 Lake water levels

Daily lake water levels were obtained from electronic data available on NOAA website – Tides & currents (http://tidesandcurrents.noaa.gov/station_info.shtml?stn=9087057). The station ID is 9087057. Its coordinates are 43°0.1'N and 87°53.2W. It is located in the U.S. Naval and Marine Corp Reserve Training center, in Milwaukee, as can be seen in Figure 6.

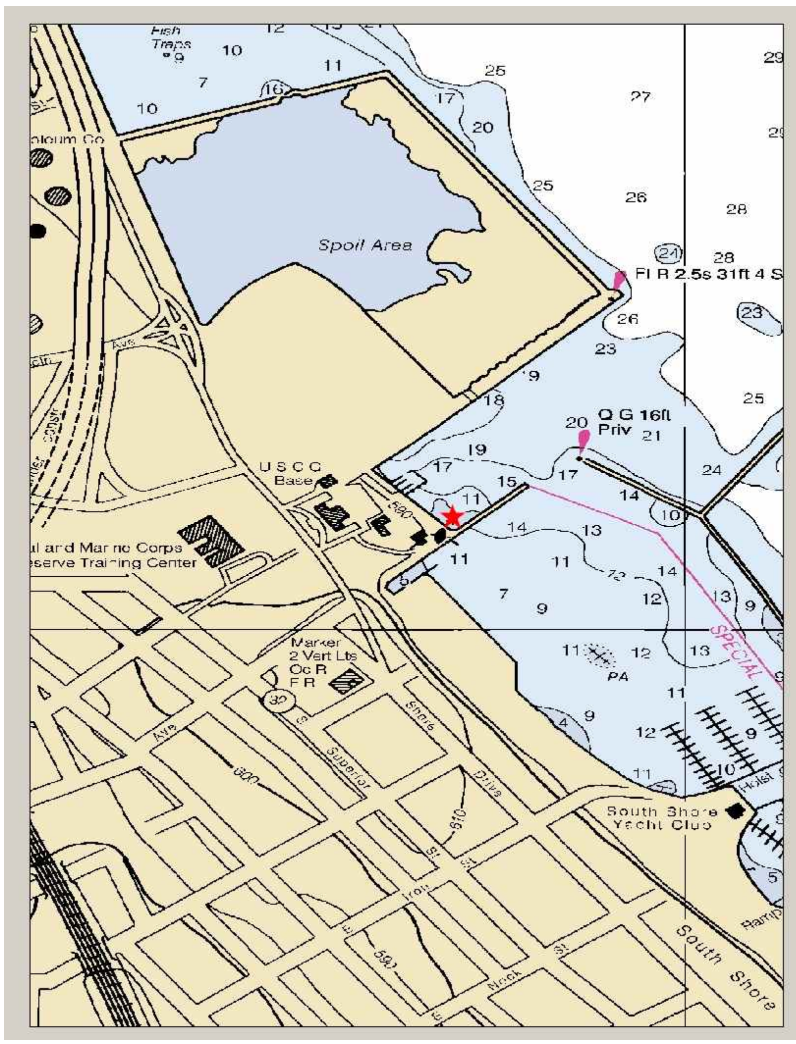


Figure 6- Lake water levels gage is located just south of the Milwaukee harbor (red star)

2.12 Precipitation

Daily precipitation data were obtained from the weather station operated by NOAA at the Milwaukee Mitchell Airport, located 10.4 miles south of Bradford Beach. Although not as conveniently located, the station was sufficiently close to provide useful precipitation data for the study. In December 2009, a weather station was installed at Bradford Beach, on the top of the beach house. However, this data was not used because this study covers the time frame from 2006 to 2010, and no historical weather data is available at that location before 2009.

2.13 Currents and wave data

Currents and wave data was kindly provided by Dr. David Schwab and Gregory Lang from NOAA, obtained through hydrodynamic modeling.

2.14 Geophysical surveys

A variety of geoelectrical techniques were used in an attempt to understand the subsurface lithologies of the site. There appears to be very little historical data to help define the sub-sand surface on which the present beach was built. The geoelectrical techniques included D.C resistivity soundings and profiles, EM conductivity studies and limited ground penetrating radar (GPR).

2.14.1 Electromagnetic

Electromagnetic studies were conducted with a Geonics EM31-MK2 Ground Conductivity Meter that detects subsurface conductivity changes to a depth of about 6 meters. These conductivity changes can be due to lithologic changes, changes in water saturation and/or changes in pore fluid conductivity. Detailed survey lines were marked and measured in a grid running in both North/South and East/West directions to target horizontal and lateral changes in subsurface conditions. The conductivity meter was carried parallel to the survey line direction. Data was collected automatically at 2 second intervals while the operator moved at a slow walking pace. Absolute tie in data was recorded at 50 and 100 meter points. All data were processed with Geonics DAT 31 software where corrections to survey line distances and measurement directions were also made.

2.14.2 Electrical Resistivity

Both DC resistivity sounding and DC resistivity profiles were conducted on site. The locations are noted in Figure 7. Soundings were conducted at 2 points approximately 70 meters apart along a line centered in the middle of the beach parallel to the shore. The sounding used an ABEM Terrameter SAS 1,000/VES resistivity meter in a Wenner configuration with “a’ spacings ranging from 0.47 meter to 67 meters. All sounding data were modeled with Interpex 1X1D resistivity inversion software.

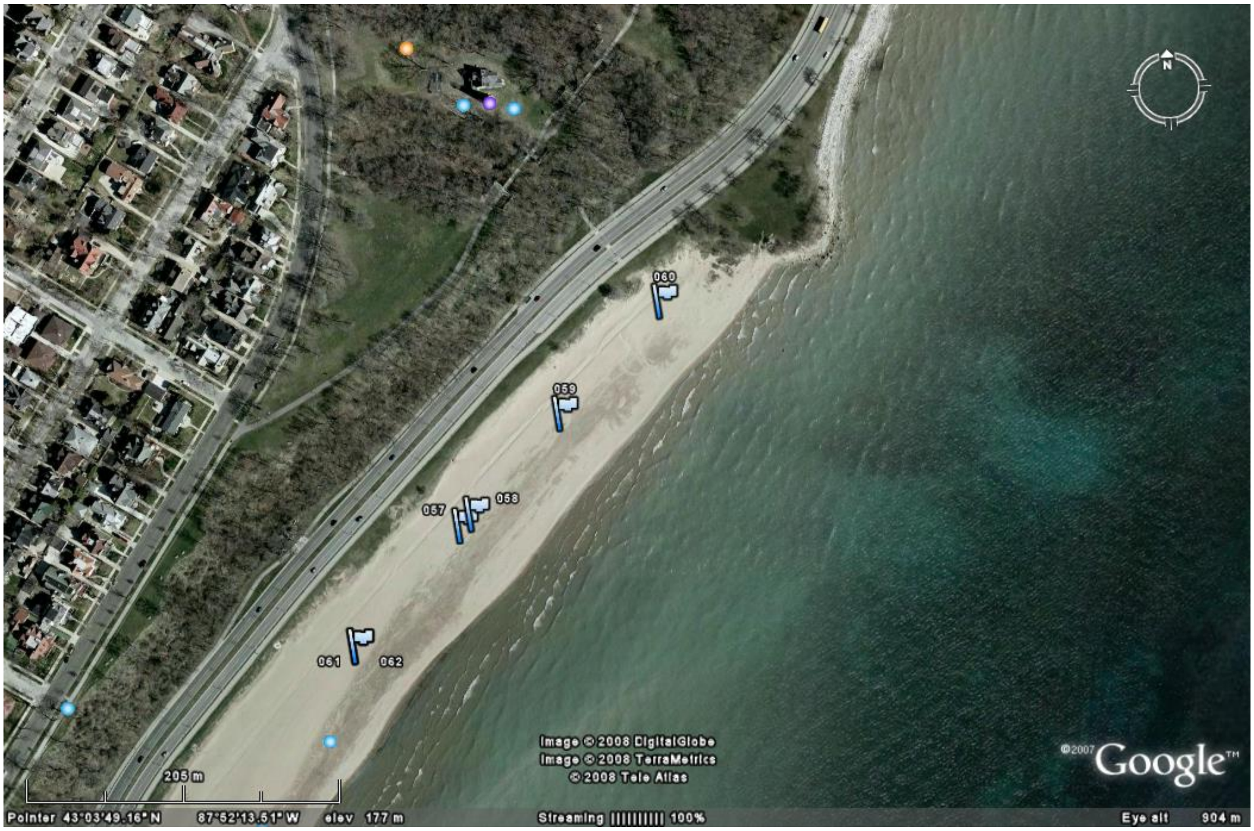


Figure 7- Field site location: north end of Bradford Beach

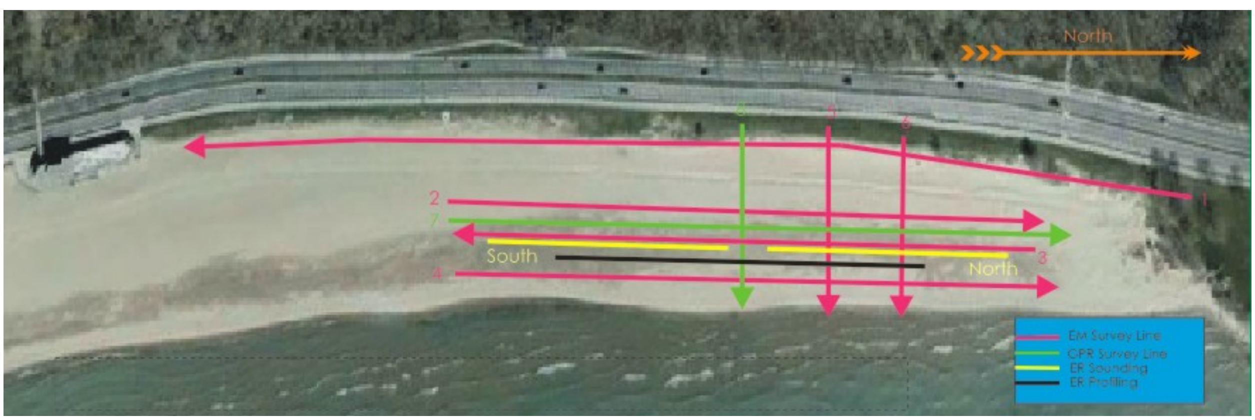


Figure 8-Electrical line locations.

2.14.3 Resistivity Soundings

The Resistivity soundings produced well defined vertical information on electrical properties with depth. Electrical properties can relate to both changes in geologic lithologies (changes in material) as well as changes in pore fluid content and pore fluid conductivity.

2.14.4 Resistivity profiles

Resistivity profiles were performed using a 16 electrode GF Instruments ARES-Automatic Resistivity System in dipole-dipole configuration. Both 2 meter and 5 meter spacing profiles were collected in between the two centers of the sounding (Figure 8). Data were modeled with RESISTIX 2D inversion software.

2.14.5 Ground Penetrating Radar

GPR data was collected with a Geophysical Survey Systems Inc. SIR 3000 GPR unit. A total of 4 survey lines were run. Survey lines were marked every 1 meter to use for tie points for the GPR distance data. Data was collected on each line with both a 120 MHz and a 400 MHz antenna. Survey lines spanned from Lincoln Memorial Drive to the water's edge (West/East), and along the North center of the beach (South/North). These were the same lines sampled with Resistivity and EM techniques.

2.15 Base data station at Bradford Beach

Camera Hardware The network camera installed at the base station is an Axis 213-R (Axis Communications, Inc., Chelmsford, MA; http://www.axis.com/). It is controlled by scripts written in the open-source PHP language (The PHP Group; http://www.php.net/) and run on a Technologic Systems TS-7260 board (Technologic Systems, Fountain Hills, AZ; http://www.embeddedarm.com/).

3 RESULTS AND DISCUSSION

3.1 Topographical surveys

The first objective of performing topographical surveys at Bradford Beach was to measure the elevation of the beach to assess flooding conditions, and also to measure the depth of a swale along the beach (coinciding with the wet area) that had already been noticed by observation. Figure 9 shows details of the topographical survey performed in November 2009. It is possible to observe that the southern part has higher elevations than the northern part of the beach. Also, there is a depression that is observed along the beach (swale), where the deepest depressions are identified, coinciding with the wet area - 581.50 ft on the southern part of the beach and 581.00 ft on the northern part of the beach.

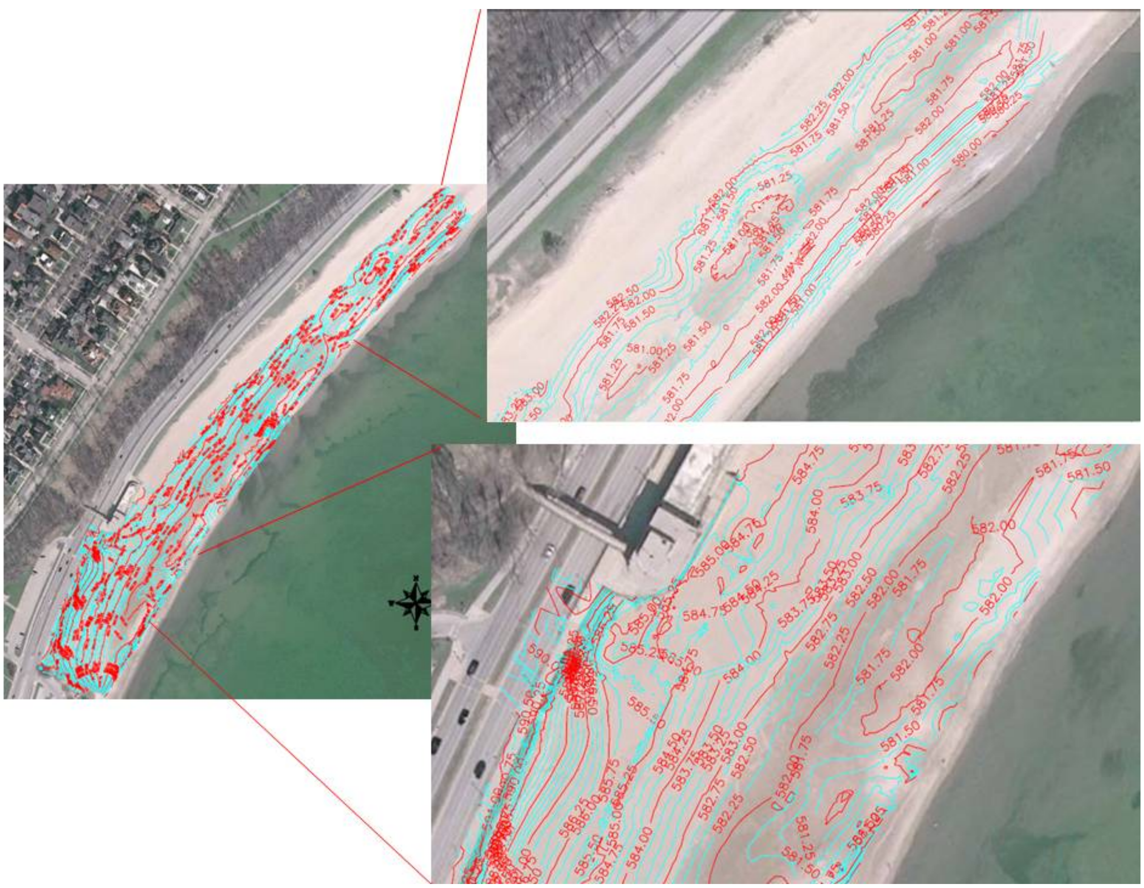


Figure 9-Topographical survey of Bradford Beach in November 2009. Note that a) the overall southern part has higher ground elevation than the northern part and b) the deepest depressions (swale) are located on the wet area that is observed along the beach (581.50 ft on the southern part and 581.00 ft on the northern part).

Another topographical survey was performed in April 2010 (Figure 10). Again, the larger region with deepest depression is located on the northern part of the beach (581.0 ft). The swash zone was also surveyed in April (dark blue area). The slope of the beach is approximately 1:32 on the southern part of the beach (gentle slope) and on the northern part of the beach the slope is either mild (1:65) or flat on the north end. This mild to flat beach face on the northern part of the beach allows washing from high waves to crash onto the beach and be trapped on the shoreward side of the berm (swales).This process is facilitated if the berm is mild to flat, mostly common on the northern part of the beach. The beach face slope is expressed in a ratio of feet. Slope is expressed in a ratio indicating the unit of rise to the unit of horizontal distance (rise over run). Other objectives of topographical surveys are discussed in Appendix A. More information on impact of storms at Bradford Beach is presented in Appendix B.

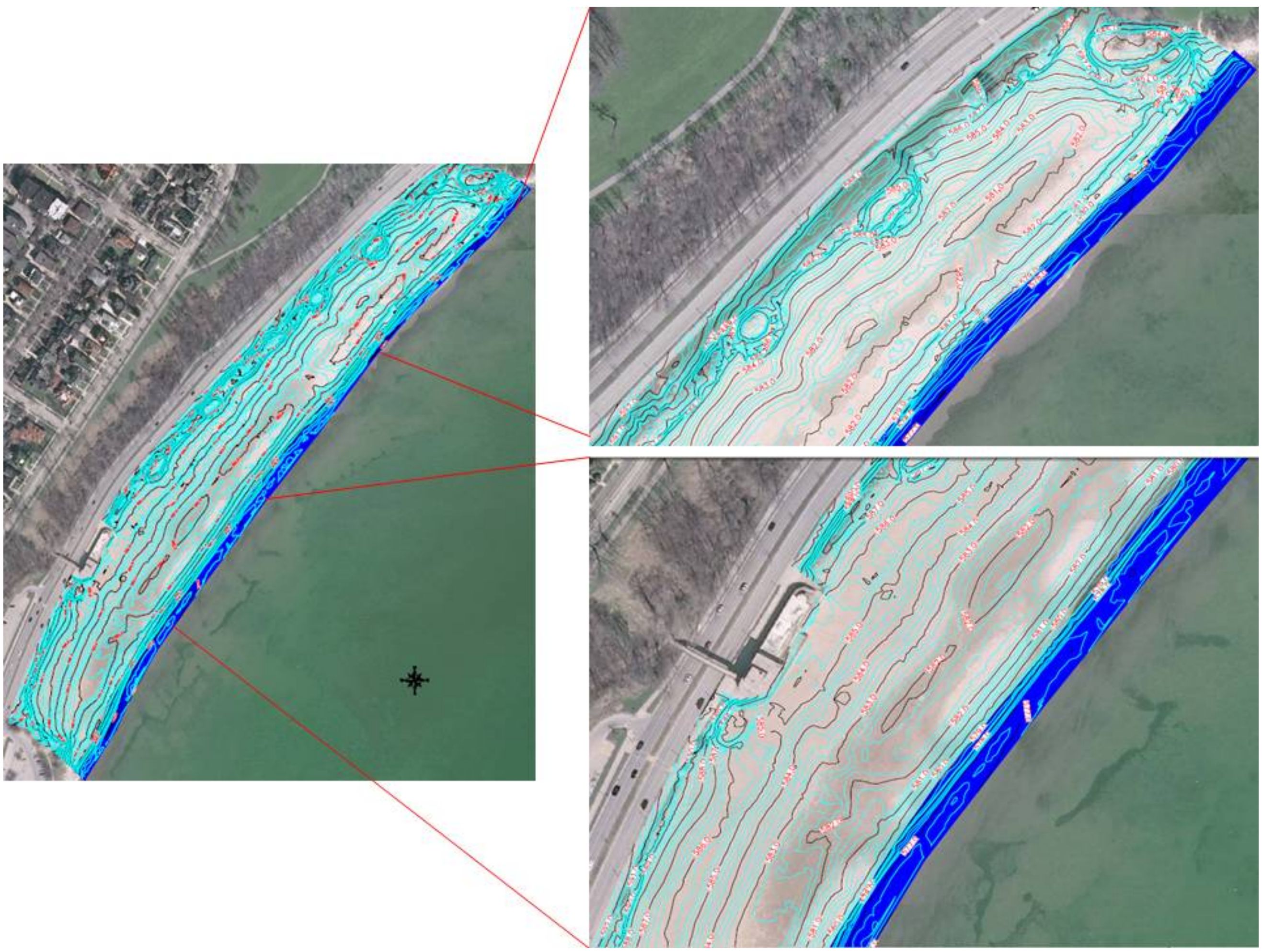


Figure 10-Topographical survey of Bradford Beach in April 2010. Note that after the winter time and beginning of Spring; again the region with the largest deepest depression (581 ft) is located on the northern part of the beach. Note that the swash zone (dark blue area) was also surveyed in April.

3.2 Water levels

3.2.1 Groundwater levels

Statistical analyses were performed on groundwater levels and are presented in Table 1. Measure of variability was calculated according to Equation 1. Full hydrographs of groundwater levels measured from October 2009 to December 2010 are presented in Appendix C. Seasonal effects are observable on most of the hydrographs, although not as strongly at observation sites very close to the lake. Minimum groundwater elevations ranged from 176.210 m to 177.173 m. Maximum groundwater elevations ranged from 176.791 m to 178.153 m. Therefore, groundwater changes (Δm) were up to 1.060 m. Maximum and minimum levels and range of measured levels at each site are summarized in Table 1. The range of measured levels varied from a minimum of 176.210 m at PZ-10 and PZ-11on the northern part of the beach to a maximum of 178.153 m at PZ-1 on the southern part of the beach.

$$Measure of variability = \frac{(xi - meanx)^2}{fullrange}$$ Equation 1 – Measure of variability

where:

xi– a measurement of groundwater level of a given well (m)
Mean x – mean of all measurements for a given well (m)
Full range – full range of groundwater levels for all the 15 wells, in this case 1.943 m.

Piezometers PZ-1, PZ-3, and PZ-4 had the highest variability (20 cm, 20.9 cm, and 21.6 cm, respectively), followed by PZ-7 and PZ-8 (14.9 cm and 16.7cm, respectively) and by PZ-6 (8.7 cm) and PZ-9 and PZ-14 (7.9 cm). The variability of the other wells ranged from 4.8 to 6.9 cm. The well with the least variability was PZ-5, with 3.2 cm.

Table 1-Statistics of groundwater level at monitoring sites from October 2009 to December 2010[1]

	N	Mean (m)	Median (m)	Max (m)	Min (m)	Δ (m) = Max-Min	Variability (m)
PZ-1	115	177.380	177.320	178.153	177.093	1.060	0.0200
PZ-2	79	177.174	177.153	177.513	176.956	0.557	0.0069
PZ-3	121	177.121	177.069	177.592	176.894	0.698	0.0209
PZ-4	122	176.814	176.780	177.322	176.54	0.782	0.0216
PZ-5	115	177.216	177.173	177.747	177.173	0.574	0.0032
PZ-6	122	176.800	176.782	177.238	176.564	0.674	0.0087
PZ-7	97	176.767	176.712	177.128	176.536	0.592	0.0149
PZ-8	120	176.680	176.629	177.256	176.369	0.887	0.0167
PZ-9	91	176.655	176.641	177.202	176.378	0.824	0.0079
PZ-10	122	176.609	176.590	177.064	176.21	0.854	0.0048
PZ-11	120	176.574	176.561	176.954	176.21	0.744	0.0068
PZ-12	122	176.590	176.574	177.038	176.244	0.794	0.0065
PZ-13	117	176.636	176.602	177.275	176.459	0.816	0.0065
PZ-14	121	176.567	176.558	177.023	176.27	0.753	0.0079
PZ-15	47	176.538	176.543	176.791	176.315	0.476	0.0057

Histograms of the number of measurements of specific groundwater levels per piezometer are shown in Figure 11. PZ-5 was dry most of the time throughtout this study. The region where this piezometer was installed has harder sand material compared to the sand material surrounding any other piezometer. Its installation was more difficult and it is located underground where groundwater table was barely reached. We decided to keep this piezometer there as a control site on that transect, not with the purpose of monitoring groundwater variability.

PZ-8, PZ-9, PZ-10, PZ-11, PZ-12, and PZ-15 were dry at least once throughout this study. Therefore they are all truncated at the low end of the histogram because their lowest level was considered the bottom of the piezometer. These piezometers are all located on the northern part of the beach, where groundwater table is lower. None of the piezometers located on the southern part of the beach were dry throughout this study.

[1] Readings that are below the bottom of the well: level was truncated on the bottom of the well. Readings that are above the ground surface: level was considered as any other reading.

Table 2-Observed maximum and minimum groundwater stage from October 2009 to December 2010

	Minimum (m)	Date	Maximum (m)	Date
PZ-1	177.093	3/6/2010	178.153	7/23/2010
PZ-2	176.956	2/12/2010	177.513	10/27/2009
PZ-3	176.894	11/22/2010	177.592	1/29/2010
PZ-4	176.540	11/5/2010	177.322	1/28/2010
PZ-5	dry	Most of the time was dry, except 7/15/10, 7/16/10, and 7/23/10	177.747	7/23/2010
PZ-6	176.564	2/12/2010	177.238	12/15/2009
PZ-7	176.536	4/23/2010	177.128	6/15/2010
PZ-8	dry	10/15/10, 10/16/10, 4/22/10, and 10/23/10	177.256	2/17/2010
PZ-9	dry	2/4/2010	177.202	7/23/2010
PZ-10	dry	2/4/2010	177.064	7/23/2010
PZ-11	dry	2/4/2010	176.954	7/23/2010
PZ-12	dry	2/4/2010	177.038	7/23/2010
PZ-13	176.459	2/4/2010	177.275	7/23/2010
PZ-14	176.270	4/9/2010	177.023	7/15/2010
PZ-15	dry	9/2/2010	176.791	7/23/2010
Lake level	175.807	12/29/2010	176.461	10/29/2010

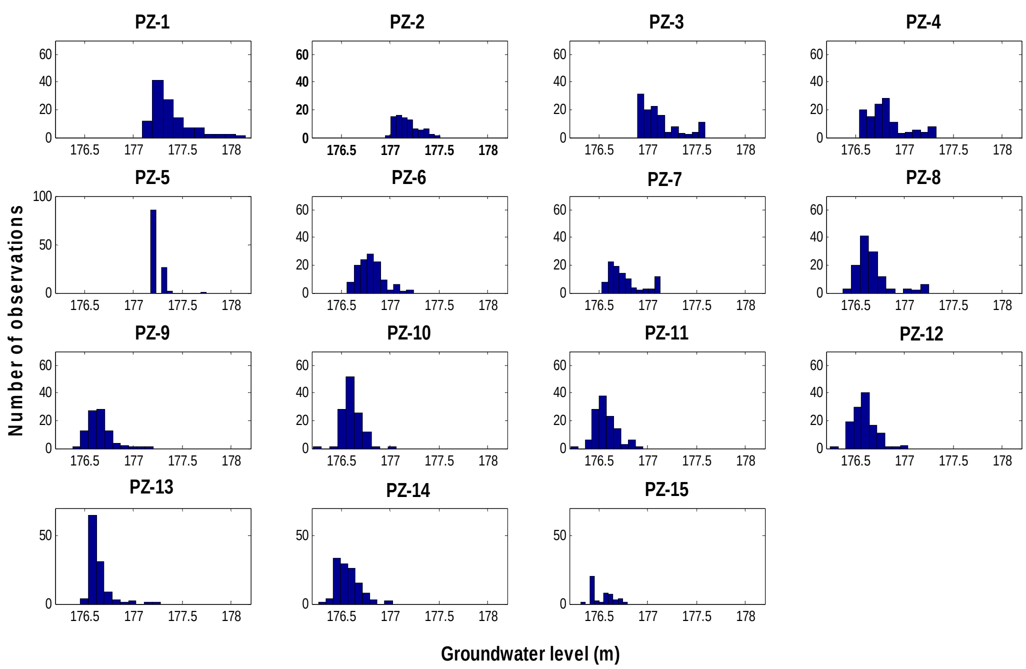


Figure 11- Histogram of all piezometers at Bradford Beach. Data presented is from October 2009 until December 2010.

PZ-1, PZ-9, and PZ-13 are located next to the rain gardens 1, 4, and 6, respectively. Their histogram have skewed distribution, with the high end having a long tail and the low end being truncated (out of these three, only PZ-9 was dry at least once during the study). Watershed of outfall 2 is larger than the watershed of outfall 6, which is larger than the watershed of outfall 4 (see Appendix D). Obviously, watershed of outfall 7 is the largest at Bradford Beach. While it is possible that it impacts the groundwater table in the northern transect of piezometers, it was not subject of this study and not enough data is available to support this hypothesis.

PZ-4, PZ-7, PZ-11, and PZ-15 are located near the lake. Therefore they are more affected by lake level elevation and waves and current action. From these, only PZ-15 was dry at least once during this study and its level is truncated to the low end because it is located in a region with the lowest water table.

PZ-2, PZ-3, PZ-6, PZ-8, PZ-10, PZ-11, PZ-12, and PZ-14 are located in the wet area of the beach. PZ-2 and PZ-3 are located in the southern part of the beach, with more frequent readings in the high end of the histogram. The other piezometers are located on the northern part of the beach, with more frequent readings on the low end of the histogram.

Water level contours drawn from the piezometers data are shown in Figure 12. It is evident from the slope of the water table that groundwater movement is toward the lake, with the gradient being steeper near the rain gardens than near the shore. It is also possible to see that there is a slope from south to north, in which the gradients are steeper on the southern part than on the northern part, although the lower concentration of observation points is on the southern part of the study area.

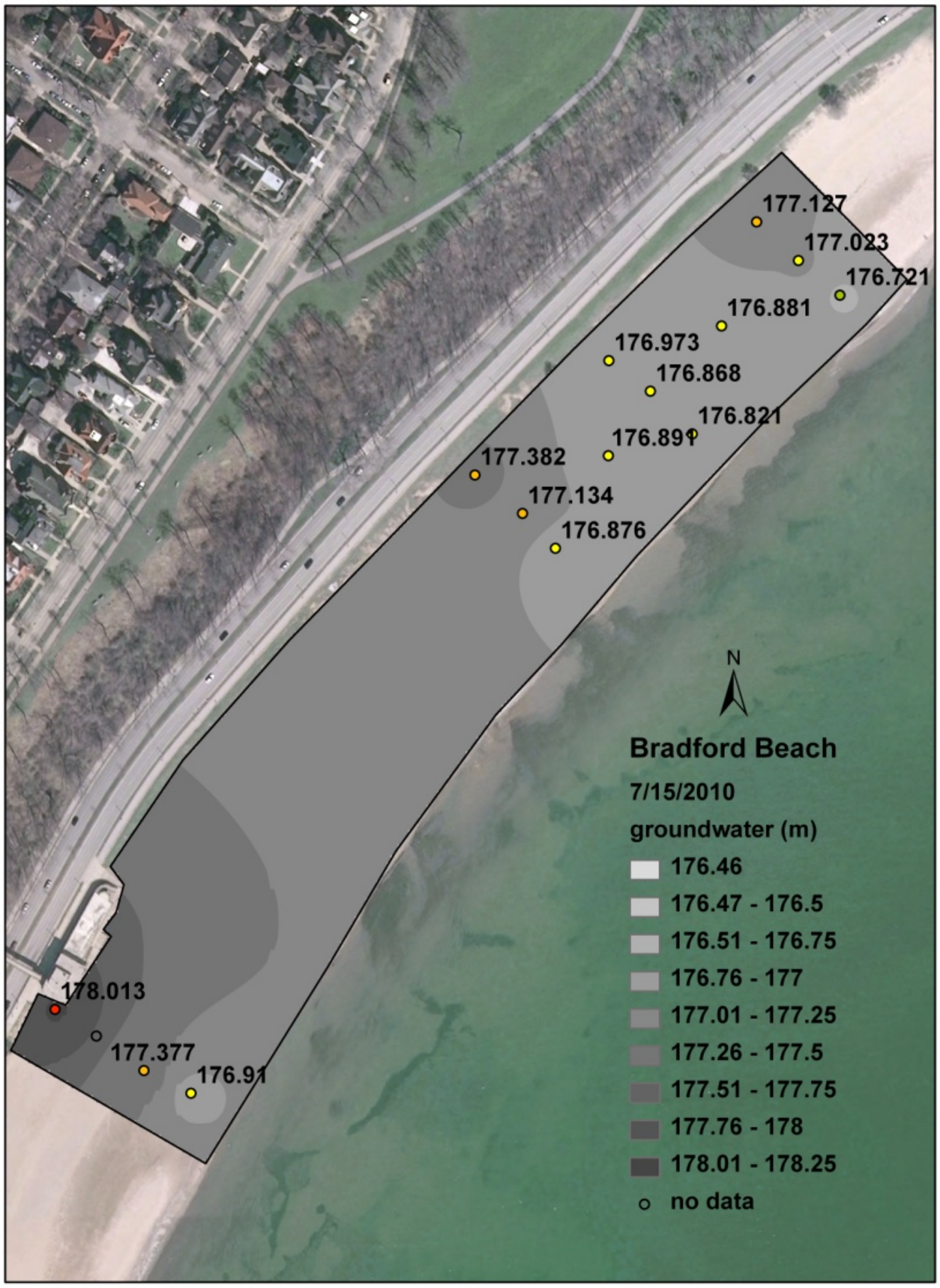


Figure 12-Typical groundwater table at Bradford Beach. Data presented is from 7/15/10.Total rainfall for the past 48 hours was 1.37 in total and piezometers were serviced at 7:30 pm after the storm. Mean lake level was 176.268 m at that time.

3.2.2 Effect of precipitation

Table 3-Average precipitation (in) in Milwaukee from 1981 to 2010

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1.75	1.64	2.27	3.56	3.40	3.90	3.66	3.97	3.17	2.65	2.71	2.03	34.71

Precipitation was measured 10.4 miles (16.7 km) south of Bradford Beach at the Milwaukee Mitchell Airport. The average precipitation from 1981 to 2010 is 34.71 inches per year.

In general, groundwater levels correlate well with the precipitation events. Groundwater levels rise quickly within 24 hours when there is a rainfall event (as can be seen in Figure 13) and they decrease quickly too (as can be seen in Table 4 and Figure 14 and Figure 15. The slower decay happens on the piezometers near the outfalls, since they have closer connection to the water that is being infiltrated on the rain gardens. The quicker decay happens on the piezometers that are closer to the lake. PZ-5 was constantly dry, except for three days from October 2009 to December 2010, in which there were heavy rainfall events, as can be seen in Table 2. Most of the wells reached their maximum level during a storm event. Piezometers1, 5, 9-12 reached their maximum on the 7/22/10 storm. Well 14 reached it maximum the week before, in which there was a heavy rainfall event on 10/15/10. PZ-2 was removed on 5/27/10. Then, its behavior is unknown during the 7/22/10 event, but it reached its maximum on 10/27/09 right after 0.51 in of rain in the day after of the surveying. PZ-3 and PZ-4 reached its maximum in two very wavy events in January (0.77 m and 0.82 m of wave height). PZ-7 reached its maximum on a wavy and rainy day with 0.42 in of rain and 0.43 m of wave height. PZ-7 was out of order from 11/4/09 until 5/31/10. Therefore, its behavior is unknown during that period, as well on 7/23/10 and after 10/1/10.

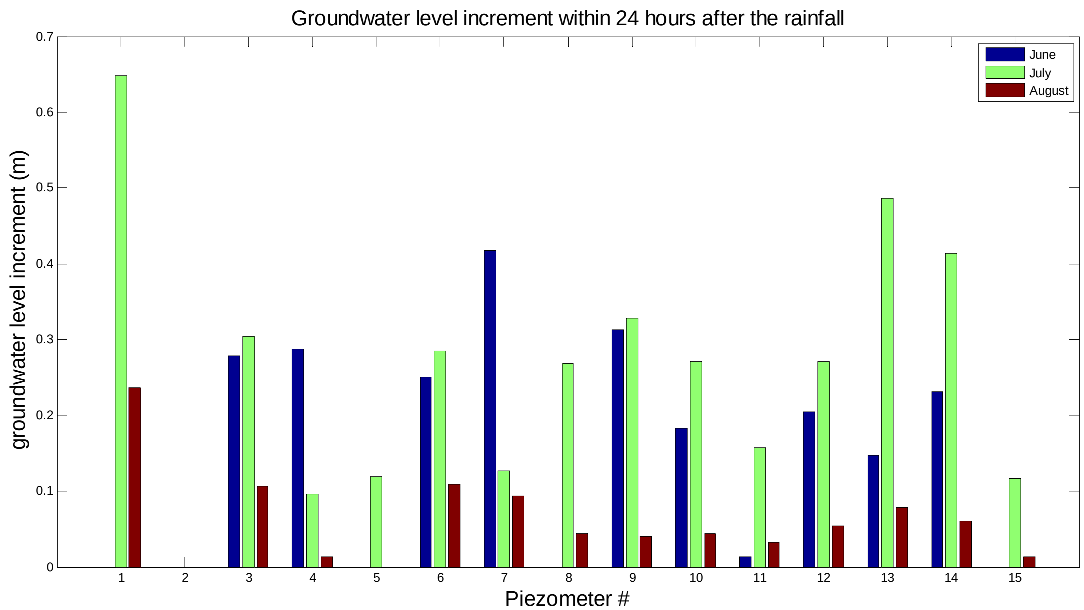


Figure 13- Groundwater level change within 24 hours after the rainfall. Data presented is from June, July, and August 2010.

Table 4-Percent decay of groundwater level within 24 hours after rainfall event. Descriptive statistics is for June, July, and August 2010.

	Mean	Geometric mean
Wells next to the outfalls	**39**	**33**
Wells in the wet area	**48**	**41**
Wells next to the lake	**63**	**58**

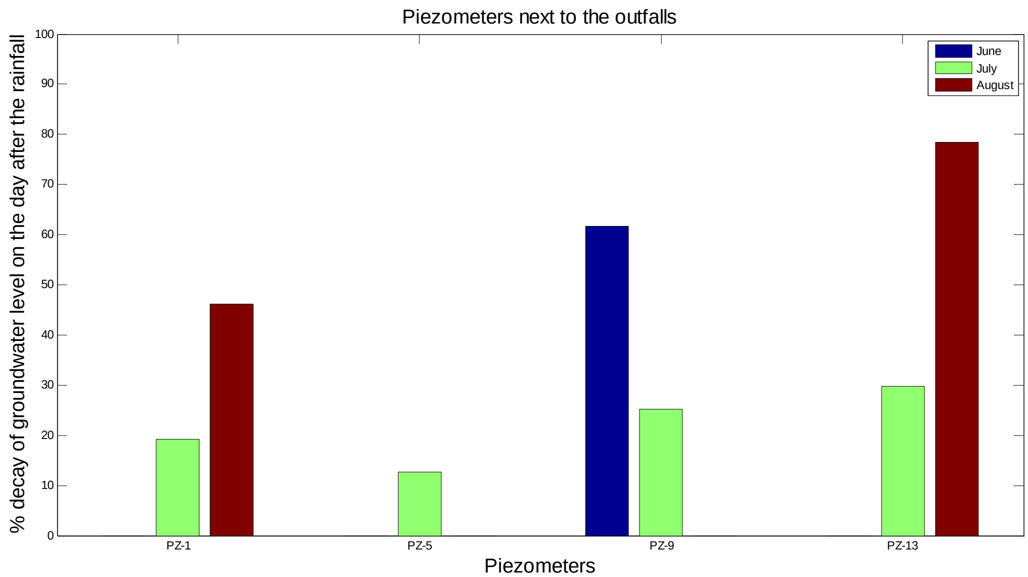


Figure 14– Percent decay of groundwater level within 24 hours after a rainfall event. Piezometers 1, 5, 9, and 14 are next to outfalls. Data presented is from June, July, and August 2010.

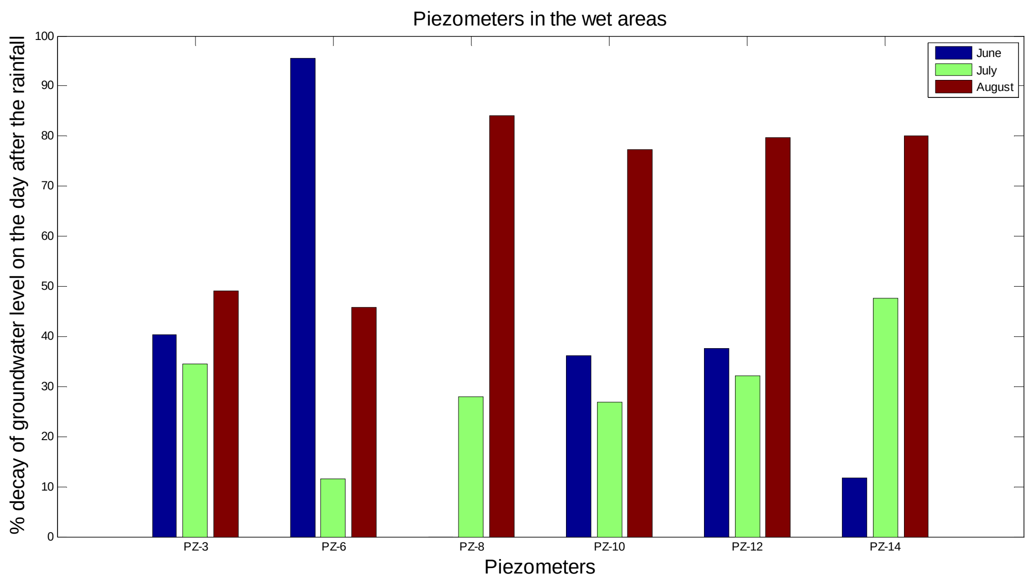


Figure 15–Percent decay of groundwater level within 24 hours after a rainfall event. Piezometers 3, 6, 8, 10, 12, and 14 are located on the wet areas. Data presented is from June, July, and August 2010.

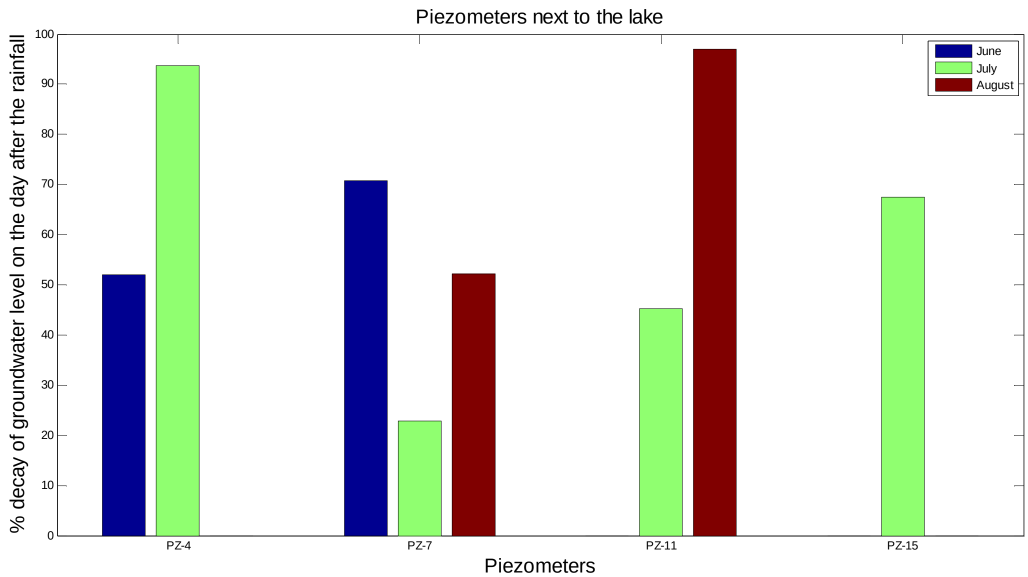


Figure 16– Percent decay of groundwater level within 24 hours after a rainfall event. Piezometers 4, 7, 11, and 15 are close to the lake. Data presented is from June, July, and August 2010.

3.2.3 Effect of Lake Michigan water levels

In general, piezometers on the northern part of the study area correlate really well with daily lake level elevations, especially 6, 9 10, 11, 12, 14, and 15, according to Figure 17. These piezometers are located on a region where the groundwater table is lower and where the gradient is less steep. Therefore, lake effect is more intense. Although PZ-7 and PZ-8 are also on the northern part of the beach, they do not behave the same way, perhaps because they are located in a region where the water table is still high enough and the gradient is steep. PZ-8 correlates well with lake level, rainfall, wind speed and current direction. PZ-7 has little correlation with lake level; its level is more correlated with rainfall, waves, wind, and current speed and direction.

Hourly variation

On April 10, 2010, groundwater levels of all the piezometers were monitored hourly for eight hours, as shown in Figure 17. It was a wavy day (daily average wave height was 0.46 m), no rain for the past 48 hours, and SW wind.PZ-9 and PZ-15 were out of order. The lake level increased 8.4 cm between 9:37am and 17:00 on that day. PZ-3 and PZ-4 showed the highest and immediate response to lake water level increase. PZ-3 abruptly increased 18.1 cm when the lake level increased 4.9 cm from 14:20 to 15:30 and it returned back to where it was when the lake level retracted 1.7 cm.PZ-4 increased 1.5 cm within 14:20 and 17:00, as a response to the increase of elevation of the lake of 5.8 cm at that time.PZ-11, PZ-12, and PZ-14 had an increase of 1.4 cm on their level within the eight hours of the study. PZ-1, PZ-6, and PZ-7 decreased 2 cm, 1.3cm, and 2.1cm, respectively. All the other piezometers remained fairly stable under the conditions of the field experiment.

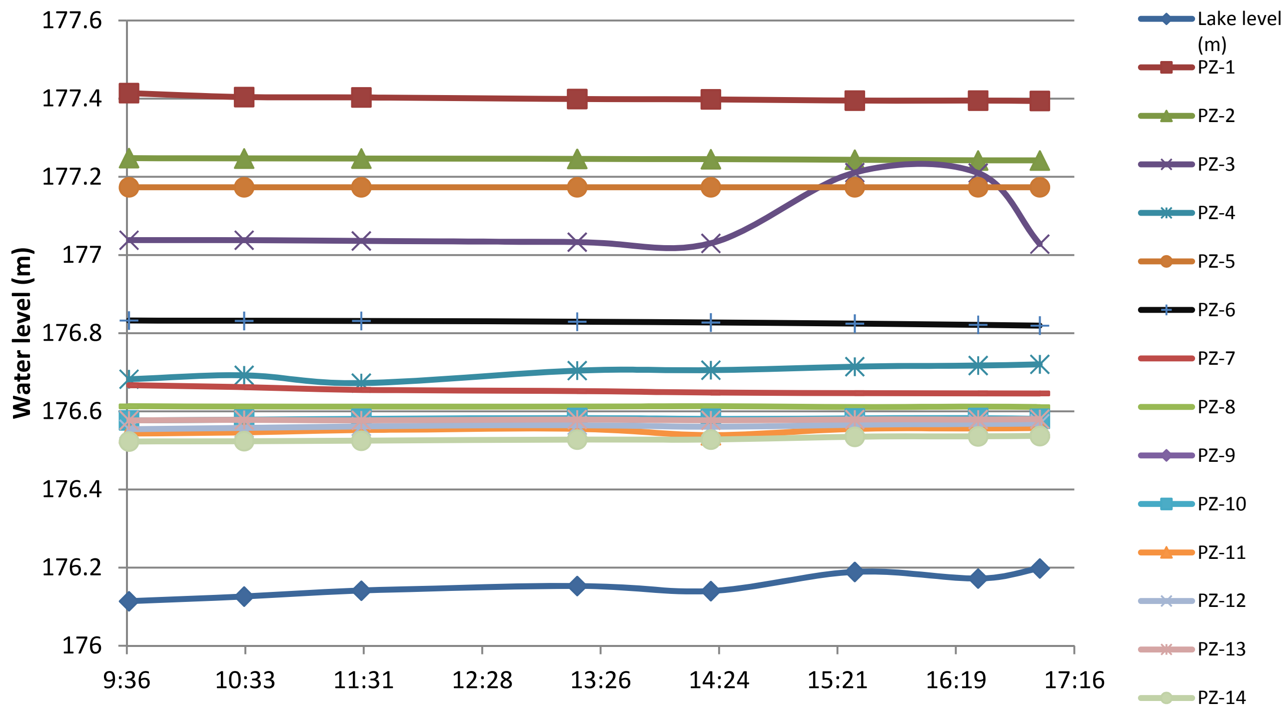


Figure 17-Water levels measured hourly on April 10, 2010.

3.2.4 Statistical analysis correlating groundwater level to lake and meteorological variables

One of the aims of the current study was to gain insight into the relationship between groundwater levels and lake levels, waves, currents, wind, snowfall, and rainfall.

Spearman's rank correlation (ρ) assesses how well the relationship between two variables can be described using a monotonic function and it was used to evaluate the relationship between groundwater level at the piezometers and environmental parameters. Snowfall and wind speed is not presented on the table because none of the piezometers showed correlation at a significant level with them. Groundwater level is correlated with lake level and rainfall events, as can be seen in Table 5. All piezometers presented significant correlation with lake level at $p \leq 0.05$, except PZ-7 although it has low p-value ($p=0.062$).While PZ-2 and PZ-3 do not have significant correlation with rainfall at the 0.05 level, their levels rise following a heavy rainfall. Time series of groundwater level per piezometers, lake level, and rainfall can be found in Appendix C.

All the other environmental parameters that presented any significant correlation with groundwater elevation were tested for synergistic interaction, by using binary logistic regression. Variables were evaluated for interaction with 95% CI when groundwater level in the respective piezometers was above mean level in that particular piezometer (mean level listed in Table 1).

Wind direction was the only variable that showed synergistic interaction on rising groundwater level above mean level in PZ-3 (p=0.01) and PZ-7 (p=0.025).

Table 5- Spearman's rank correlation (ρ) of groundwater levels and environmental variables. Significant correlations at p≤ 0.05 are flagged.[2] PZ-5 is not listed because it was dry most of the time.

	RAINFALL	WIND_2MI	CUR_DIR	CUR_SPEE	WAVE_PER	WAVE_DIR	WAVE_HEI	LAKE_LEV
PZ1 (n=115)	0.250*	0.095	-0.114	-0.114	-0.120	-0.115	-0.095	0.480*
PZ2 (n=79)	0.119	-0.001	-0.037	0.036	0.118	-0.093	0.125	0.564*
PZ3 (n=121)	0.148	0.200*	0.146	-0.113	-0.106	-0.027	-0.122	0.293*
PZ4 (n=122)	0.243*	0.080	0.283*	-0.046	0.118	0.204*	0.080	0.404*
PZ6 (n=122)	0.359*	-0.017	-0.019	-0.153	-0.045	0.092	-0.050	0.739*
PZ7 (n=97)	0.288*	0.295*	0.198	-0.051	-0.021	0.018	-0.046	0.190
PZ8 (n=120)	0.258*	0.064	0.205*	-0.151	-0.026	0.157	-0.069	0.571*
PZ9 (n=91)	0.350*	-0.001	-0.130	-0.143	-0.028	0.105	-0.023	0.674*
PZ10 (n=122)	0.389*	0.030	0.076	-0.043	0.215*	0.114	0.203*	0.657*
PZ11 (n=120)	0.443*	-0.045	0.202*	-0.129	0.133	0.290*	0.112	0.866*
PZ12 (n=122)	0.456*	-0.091	0.160	-0.164	0.137	0.275*	0.106	0.844*
PZ13 (n=117)	0.345*	0.091	0.098	-0.136	0.000	0.074	0.000	0.655*
PZ15 (n=47)	0.272	-0.027	0.136	-0.230	-0.230	0.273	-0.253	0.869*

3.2.5 Ground surface elevation in relation to groundwater table

A topographical survey was performed on July 10, 2010 and ground surface elevation was measured next to the piezometers, as can be seen in Figure 18. It is clear that the ground surface elevation decreases from south to north. It is also evident that the piezometers that are located in the middle of the transects lie on a lower area, where the water from rainfall or lake water coming from the waves that reach that area can get trapped until it gets infiltrated and/or evaporates. An exception to this statement is the PZ-5 to PZ-7 transect has a constant decreasing slope eastward, and PZ-6 is at higher elevations in relation to other piezometers set in the middle of the beach. That helps to explain why the region around PZ-6 does not get easily flooded during rainfall events.

Erosion and/ or accretion observed on the ground surface located near the piezometers are presented in Table 6. Over the winter (November 2009 and April 2010 surveys), it is possible to

[2] **RAINFALL- Rainfall depth (in); WIND_2MIN – Wind direction; CUR_SPEE- Current speed (m/s); WAVE_PER – Wave period; WAVE_DIR- Wave direction; WAVE_HEI- Wave height(m); LAKE_LEV- Lake level (m)**

see that the regions mostly affected by erosion were near the lake on the northern part of the beach (PZ-15, followed by PZ-7 and PZ-11). The regions mostly affected by accretion are PZ-14, followed by PZ-12, PZ-4, and PZ-1. The patterns change between April 2010 and July 2010. The regions mostly affected by erosion are PZ-7 and PZ-14, followed by PZ-13. Significantly accretion was not observed. The regions that were slightly affected by accretion are PZ-5, PZ-12, and PZ-15. More information about surveying and installation of the piezometers can be found in Appendix E.

The mean depth of groundwater table at Bradford Beach in the standing water zones is 0.5 m; in the non-saturated zones is 0.8 m, and in the whole beach is 0.7 m. The minimum groundwater depth is 10 cm, creating chronic moist areas, minimizing the infiltration process, and facilitating standing water zones

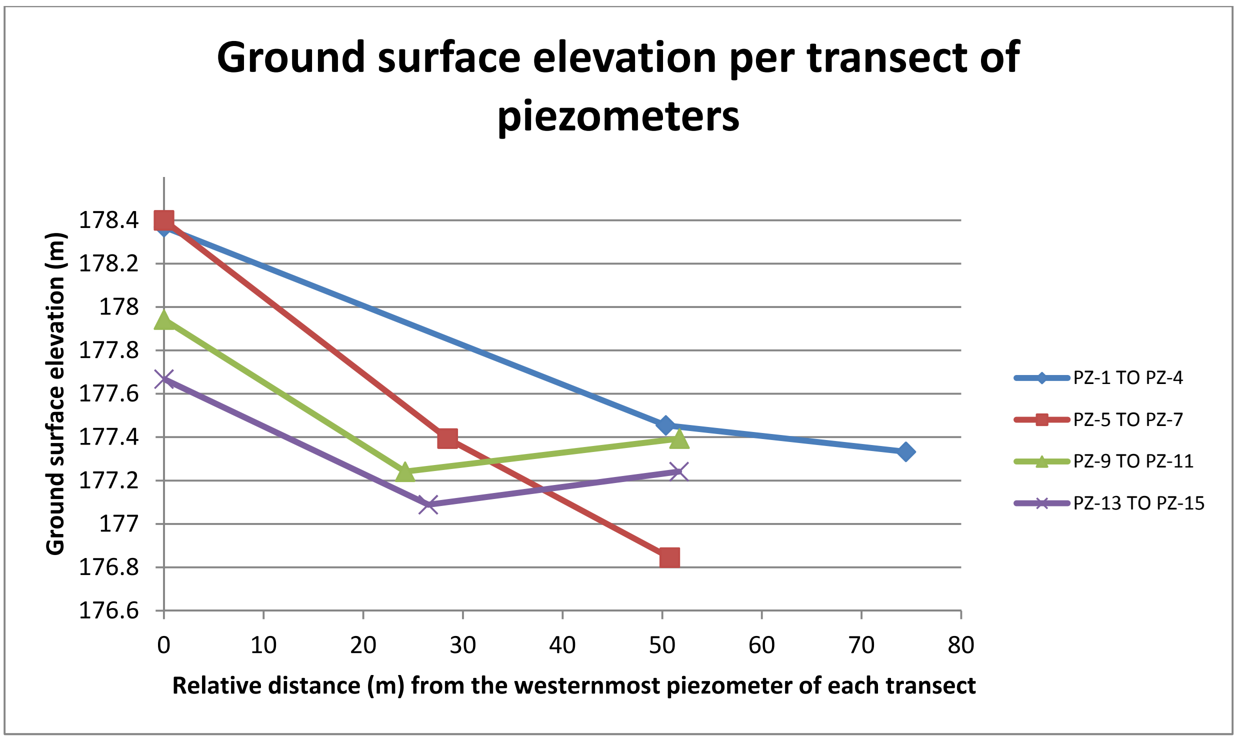


Figure 18-Ground surface elevation measured on July 10, 2010.

Table 6-Erosion and accretion (in m) measured on ground surfaces nearby wells. The topographical surveys considered are listed.

Piezometer	April 2010 - Nov 2009	Jul 2010 - April 2010
PZ-1	0.0914	-0.0305
PZ-2		
PZ-3	0.1524	-0.0914
PZ-4	0.0914	0.0000
PZ-5		0.0610
PZ-6	0.0000	-0.0914
PZ-7	-0.0305	-0.3048
PZ-8	0.0000	0.0305
PZ-9		-0.0305
PZ-10	0.0305	0.0000
PZ-11	-0.0305	0.0000
PZ-12	0.0914	0.0610
PZ-13		-0.1219
PZ-14	0.5182	-0.5486
PZ-15	-0.2743	0.0914

3.2.6 Groundwater table and flow direction

Visualization of groundwater isohypses and flow direction was performed in MATLAB. Cubic interpolation was used. Average hydraulic head measured on the piezometers from October 2009 until December 2010 is presented on Table 7 and visualization of flow direction is presented on Figure 19. More information is provided in Appendix C.

Groundwater gradients ranged from average of 0.008 m/m on the southern part of the beach and average of 0.004 m/m on the northern part of the beach. These shallow groundwater gradients are typically toward Lake Michigan (eastward, with a small component northward); however negative gradients (sloping away from the lake) were measured, mainly around PZ-7, as can be seen in Figure 20. This is in agreement with measurements reported in two Great Lakes beaches in Racine, WI [10].

Table 7-Average hydraulic head (m) measured on piezometers at Bradford –October 2009 to December 2010

PZ-5	PZ-6	PZ-7	PZ-8	PZ-9	PZ-10	PZ-11	PZ-12	PZ-13	PZ-14	PZ-15
177.2160	176.8000	176.7670	176.6800	176.6550	176.6090	176.5740	176.5900	176.6360	176.5670	176.5380

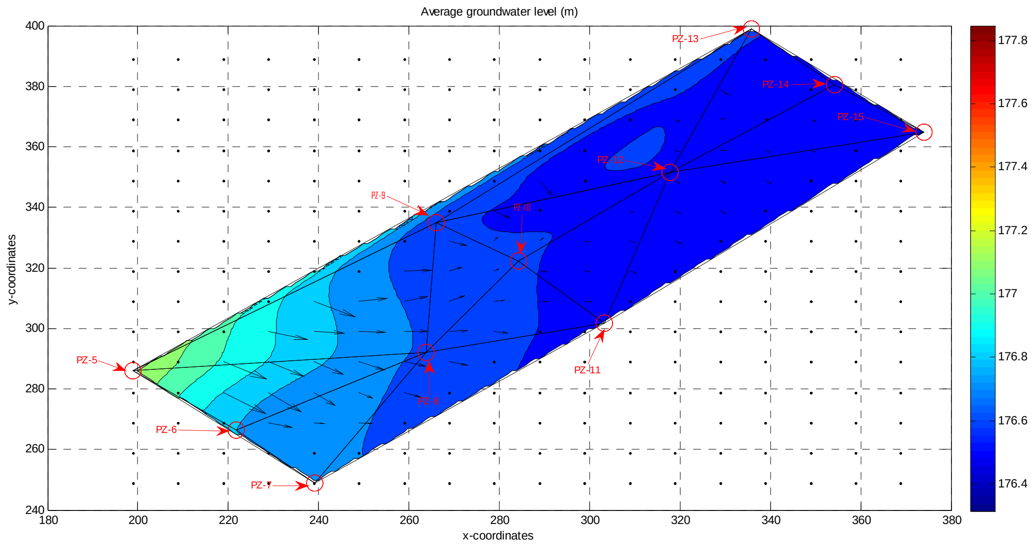


Figure 19- Visualization of groundwater isohypses on the northern part of Bradford Beach. Data presented is average level from October 2009 to December 2010.

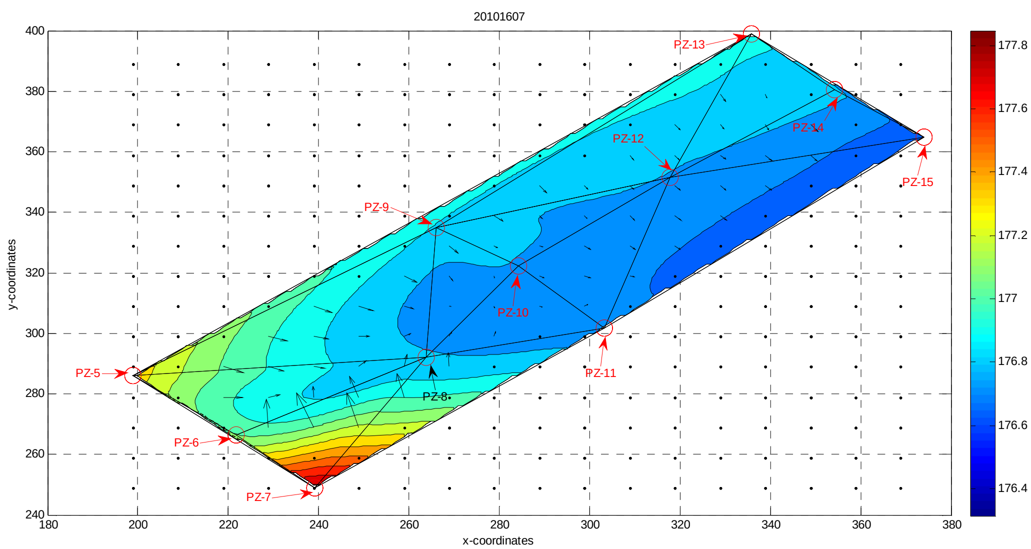


Figure 20-Visualization of groundwater isohypses on July 16, 2010.

3.3 Subsurface water properties

3.3.1 Microbiological properties

Groundwater samples were tested for total coliforms, *E. coli*, and enterococci, as can be seen in Table 8. Total coliforms were present at high levels in all piezometers, except PZ-2. Total coliforms are a group of closely related, mostly harmless bacteria that live in soil and water as well as the gut of animals. The extent to which total coliforms are present in the source water can indicate the general quality of that water, but these organisms are not exclusive to fecal pollution. The sites with higher levels of fecal indicator bacteria (FIB), e.g. *E. coli* and enterococci, were PZ-3 on the southern part of the beach and PZ-7, PZ-8, and PZ-10 on the northern part of the beach. These piezometers are located in regions affected by standing water where bacteria are allowed to grow and standing water will infiltrate through the sand and reach groundwater. These sites may also have experienced wave run-up that introduced FIB into the piezometer.

In regarding to the piezometers that are located next to the rain gardens: PZ-1 presents the least amount of bacteria, even during heavy rainfall events. PZ-1 and PZ-13 have low levels of FIB. These are the two outfalls that have higher watershed area and where concentration of bacteria could be diluted more easily with rain water. The watershed that discharges in outfall 6, next to PZ-9 is smaller and concentration of bacteria can be higher due to a lower dilution factor. All these piezometers are located on regions that do not get easily affected by stormwater runoff allowed to overflow from the rain gardens during heavy rainfall event

In regarding to the piezometers that are located next to the lake: PZ-15 presents similar characteristics to the lake. PZ-4 presents slightly lower concentration of bacteria than lake water sampled on the same day. PZ-7 presents higher concentration of bacteria compared to the others, but these are the piezometers most affected by standing water compared to the others and also mostly exposed to wave action.

Geoestatistical modeling of *E. coli* was performed at Bradford Beach for three consecutive days: July 14, July 15, and July 16, 2010. These models are presented in Figure 21 to Figure 23. It is possible to see that on July 14 there was no rain for the past 24 hours, and the levels of *E. coli* were extremely low, expect in PZ-7, which is more subject to wave action. On July 15, there was a heavy rainfall event, and bacteria levels went up on the northern part of the beach, especially on PZ-8 and PZ-14 which are more affected by standing water, and overflow from the rain gardens. They are also located on regions where the beach face is mild and lake water is able to overcome the mild berm. Once it reaches the middle of the beach where the deeper depressions are located, retention of lake water. On the day after of the rainfall, high levels of bacteria are still present at certain locations. Detailed information about microbiological and physical analysis in groundwater can be found in Appendix F.

Table 8 - Ranges and mean values of microbiological characteristics of groundwater per piezometers. Statistical analysis is for data collected from October 2009 to September 2010.

	E. coli (CFU/100 ml)			*Enterococci (CFU/100 ml)*			*Total Coliforms (CFU/100ml)*		
	Mean	Range	N	Mean	Range	N	Mean	Range	N
PZ-1	3	0-33	16	5	0-35	16	2466	2-26000	14
PZ-2	1	0-4	6	0	0-2	6	7	5-10	2
PZ-3	201	0-2300 *	20	59	0-900	21	3343	0-21000	16
PZ-4	84	0-890	20	1130	0-22400	20	3949	0-26000	15
PZ-5	23	0-100	5	2715	130-5300	2	9500	7600-11400	2
PZ-6	17	0-191	20	11	0-160	20	1485	0-11100	14
PZ-7	5042	0-40000	19	19245	0-345000	19	12311	40-82000	14
PZ-8	818	0-6200	20	1773	0-28500	20	62210	20-570000	16
PZ-9	273	0-3900	15	336	0-4200	15	5096	0-60000	15
PZ-10	1293	0-21000	19	3812	0-47200	19	494503	0-6600000	15
PZ-11	12	0-117	20	28	0-239	20	5392	3-49000	15
PZ-12	9	0-99	20	22	0-239	20	6297	3-49000	15
PZ-13	1	0-6	20	148	0-2630	20	7323	0-69000	15
PZ-14	204	0-1500	17	707	0-3440	17	10732	0-93000	14
PZ-15	172	0-1500	9	308	0-2500	9	2496	28-11600	9
Lake water	276	7-1890	17	197	4-1737	17	2079	40-10800	8

.

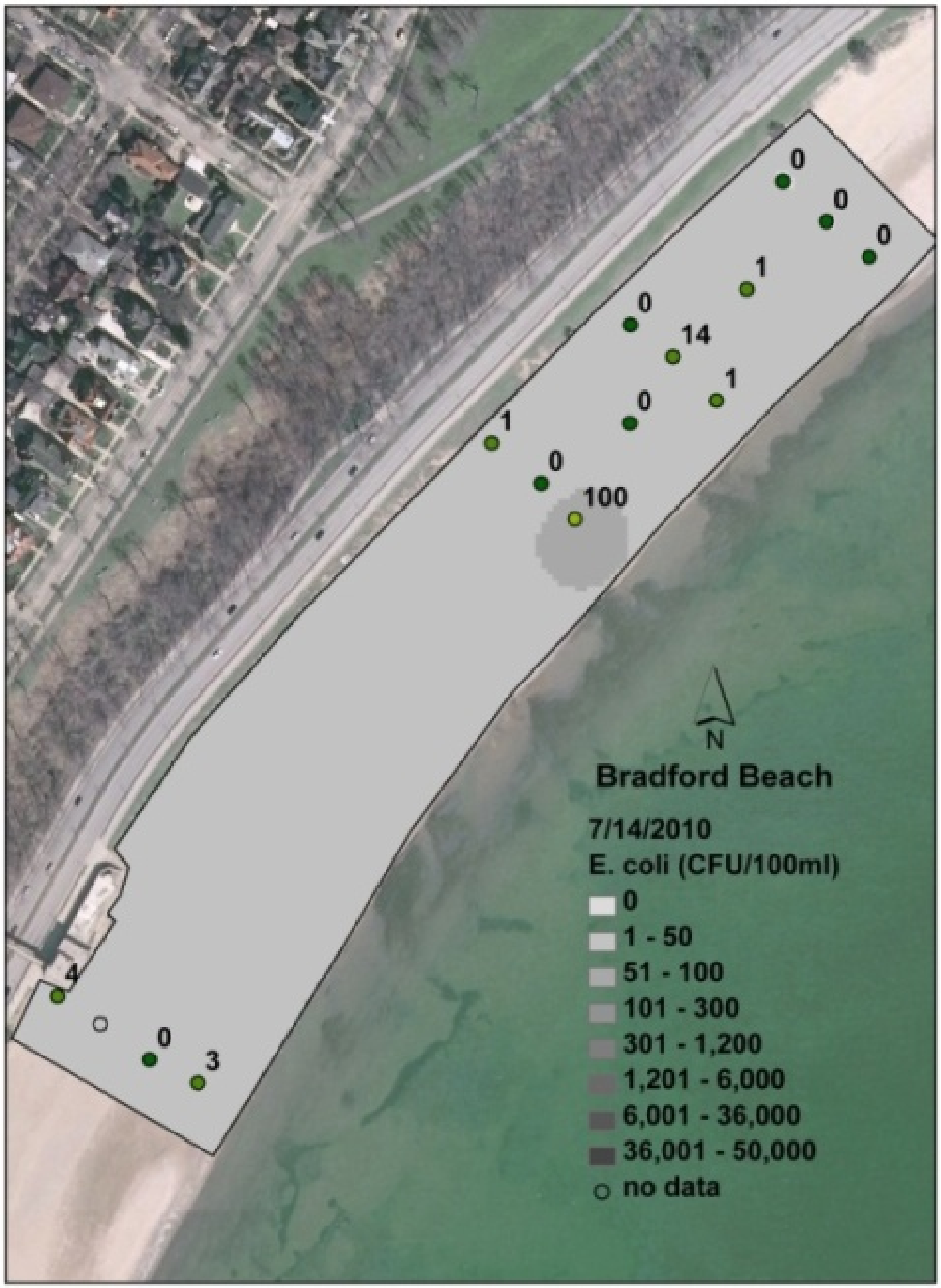


Figure 21-–Geoestatistical modeling of *E. coli* in groundwater at Bradford Beach. Samples were collected on the day before a rainfall event.

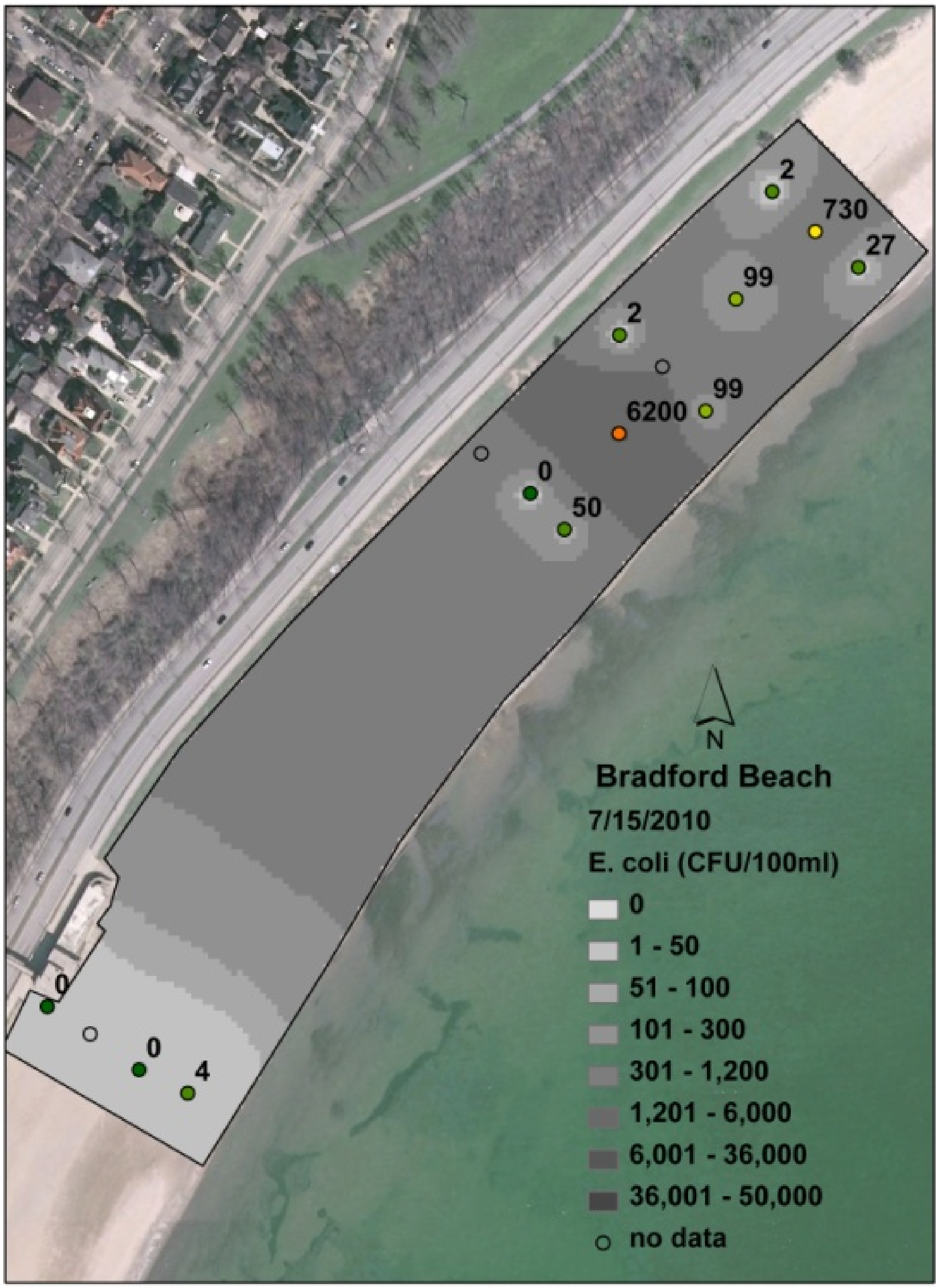


Figure 22 – Geoestatistical modeling of *E. coli* in groundwater at Bradford Beach. Samples were collected on the day of a rainfall event.

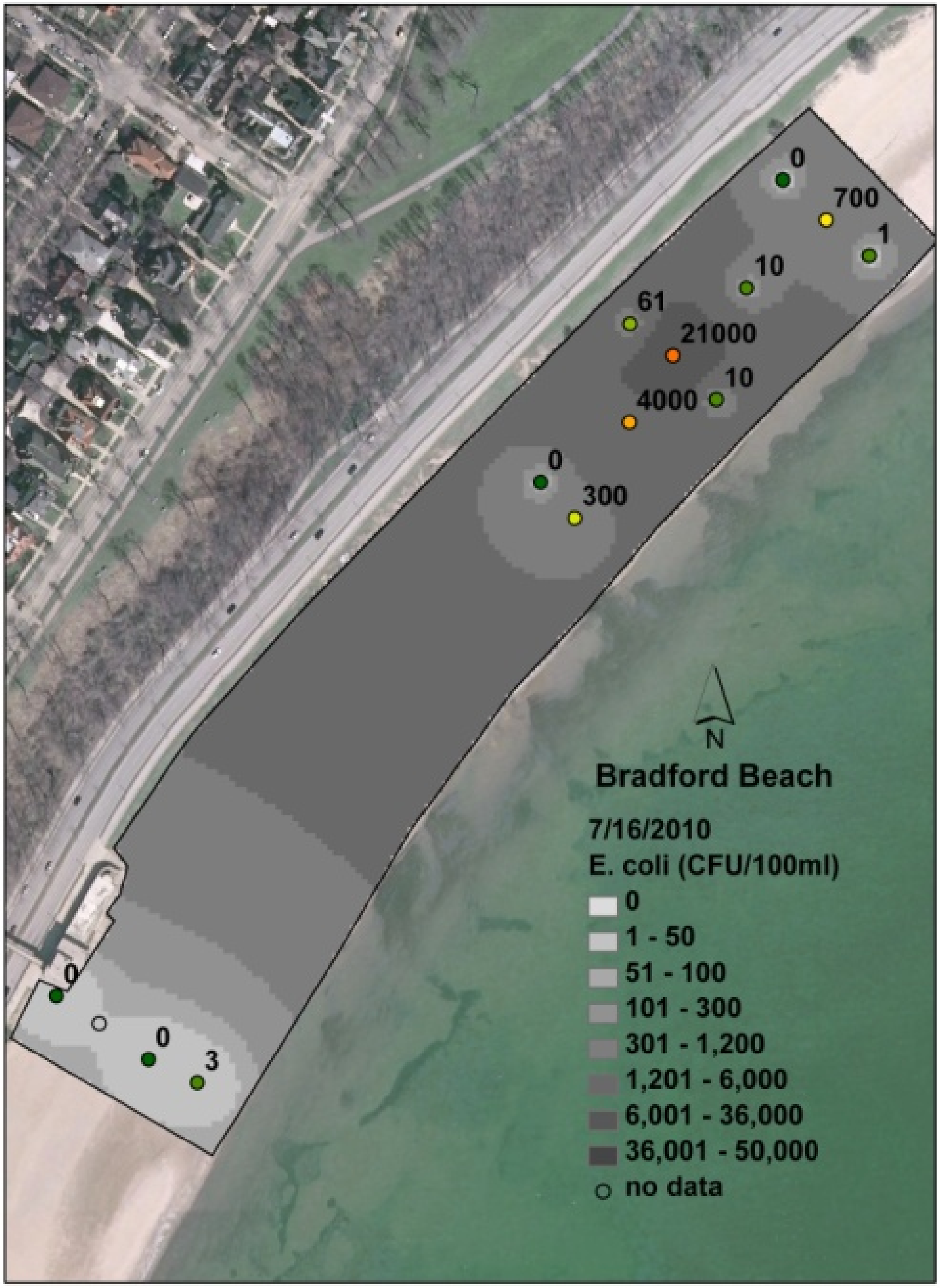


Figure 23 –Geoestatistical modeling of *E. coli* in groundwater at Bradford Beach. Samples were collected on the day after a rainfall event.

3.3.2 Physical properties

In regarding to the physical properties, turbidity increases with rainfall events. However, conductivity is driven by other parameters. Modeling of conductivity for July 14 to16, 2010 are shown in Figure 24 to Figure 26. Conductivity is higher on the southern part of beach than on the northern part. When it rains, it tends to decrease due to dilution of concentration of ions and increases again on the day following the rainfall event.

Table 9-Ranges and mean values of physical characteristics of groundwater per piezometers. Statistical analysis is for data collected from October 2009 to September 2010.

	Turbidity (NTU)			*Conductivity (mS/cm)*		
	Mean	*Range*	*N*	*Mean*	*Range*	*N*
PZ-1	146	2.58-800	12	0.377	0.273-0.460	10
PZ-2	13.95	0.81-50	4	NA	NA	NA
PZ-3	9.23	0.91-45.3	19	0.691	0.45-1.185	13
PZ-4	26.36	1.90-180	18	0.715	0.385-1.390	13
PZ-5	392.5	35-750	2	NA	NA	NA
PZ-6	4.01	0.99-9.71	17	0.282	0.249-0.315	12
PZ-7	36.5	2.30-210	17	0.410	0.194-0.483	12
PZ-8	34.15	0.95-160	18	0.270	0.224-0.308	11
PZ-9	7.2	1.22-49.90	15	0.302	0.176-0.368	13
PZ-10	87.58	1.20-700	18	0.360	0.130-0.901	13
PZ-11	3.3	1.30-12.80	18	0.467	0.368-0.691	13
PZ-12	3.29	1.3-13.5	18	0.475	0.368-0.691	13
PZ-13	3.51	0.86-8.80	18	0.357	0.271-0.547	12
PZ-14	9.89	0.96-75	15	0.436	0.232-0.601	11
PZ-15	15.89	0.69-75	9	0.472	0.270-0.614	7
Lake water	18.14	3.2-39	12	0.293	0.194-0.328	10

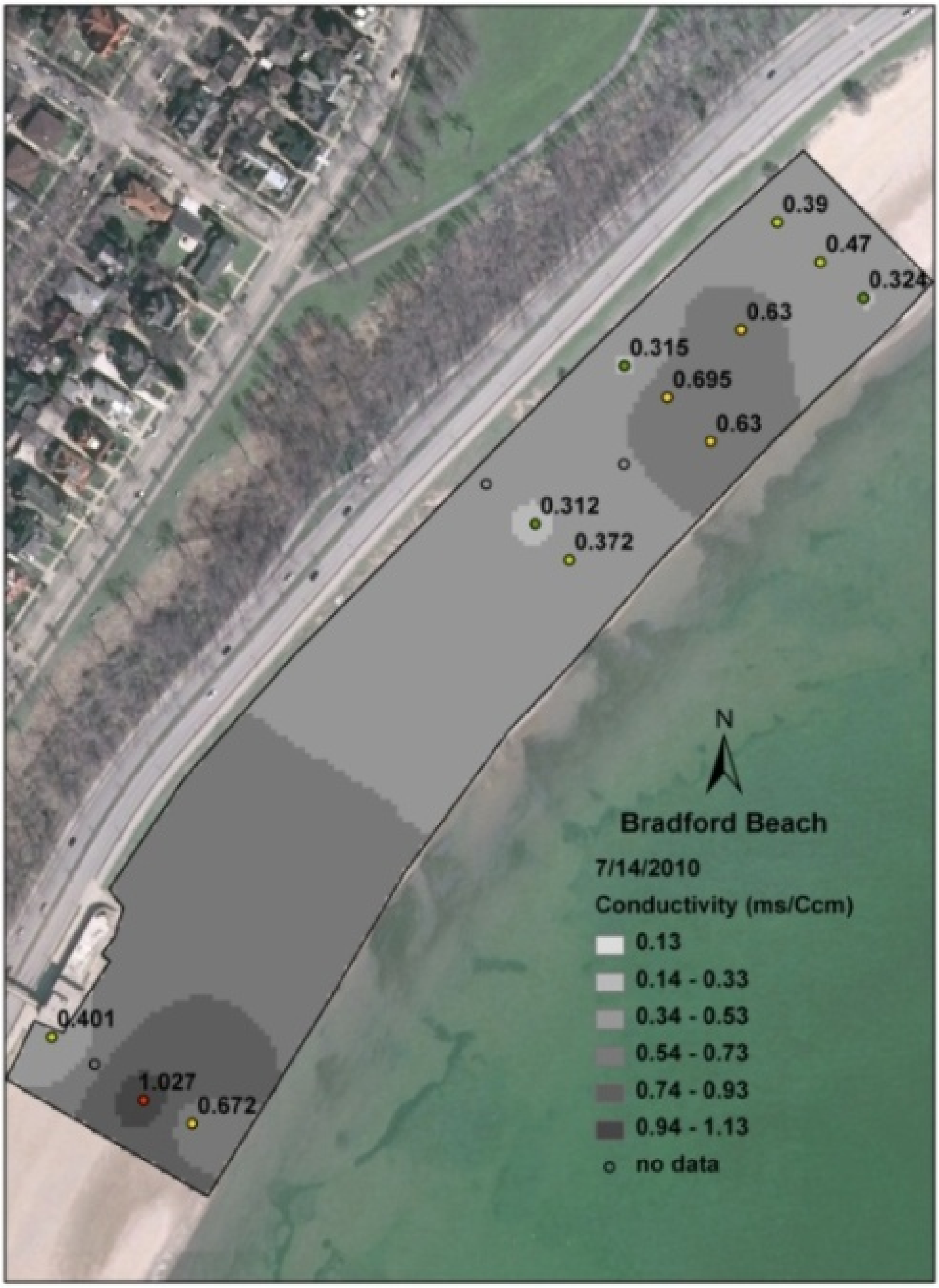


Figure 24- Geoestatistical modeling of conductivity in groundwater at Bradford Beach. Samples were collected on the day before a rainfall event.

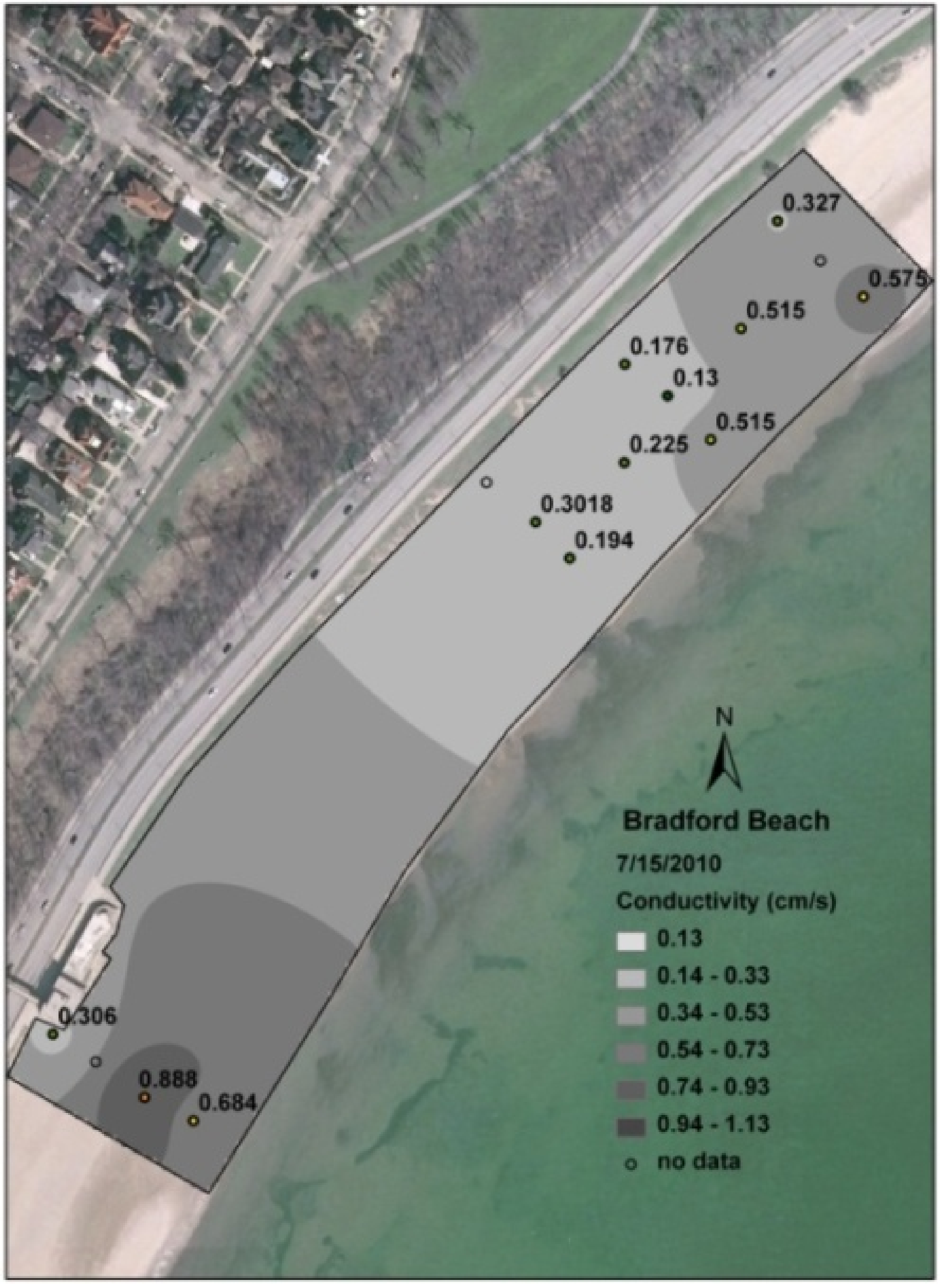


Figure 25 – Geostatistical modeling of conductivity in groundwater at Bradford Beach. Samples were collected on the day of a rainfall event.

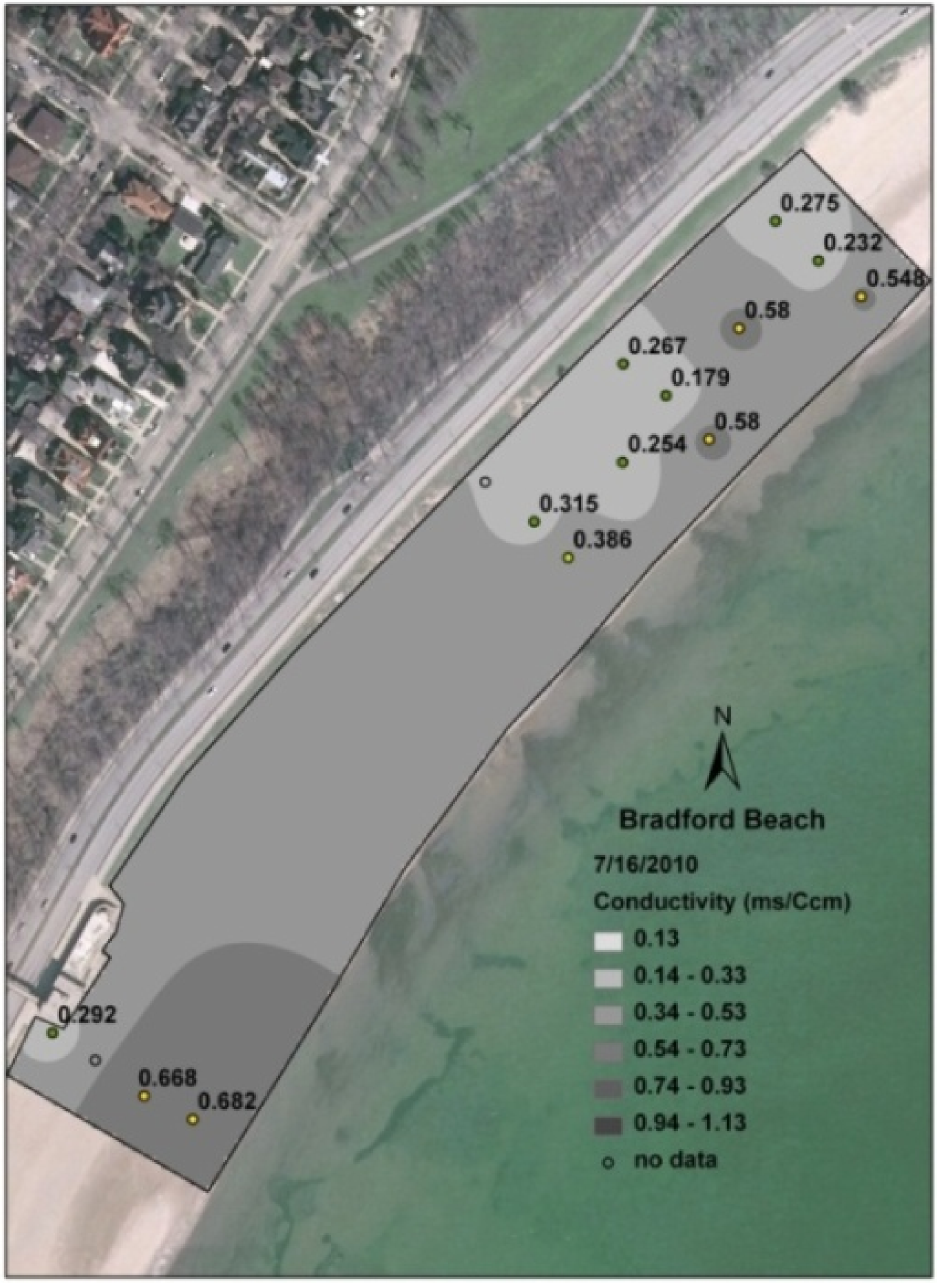


Figure 26 – Geoestatistical modeling of conductivity in groundwater at Bradford Beach. Samples were collected on the day after a rainfall event.

3.3.3 Runoff infiltrating through the sand water quality and relationship to groundwater

Due to the high levels of FIB found in groundwater mainly during rainfall events, samples of runoff infiltrating through the sand were collected in pan lysimeters. More information on installation of pan lysimeters can be found in Appendix G.

Comparison of concentration of FIB in piezometer and correspondent pan lysimeter is shown in Figure 27 and Figure 28. Bacteria concentration in pan lysimeter is higher than the concentration in the piezometers. That suggests that the primary source of bacteria in groundwater is the standing water that infiltrates into the ground, especially considering that the groundwater table is very shallow on those locations.

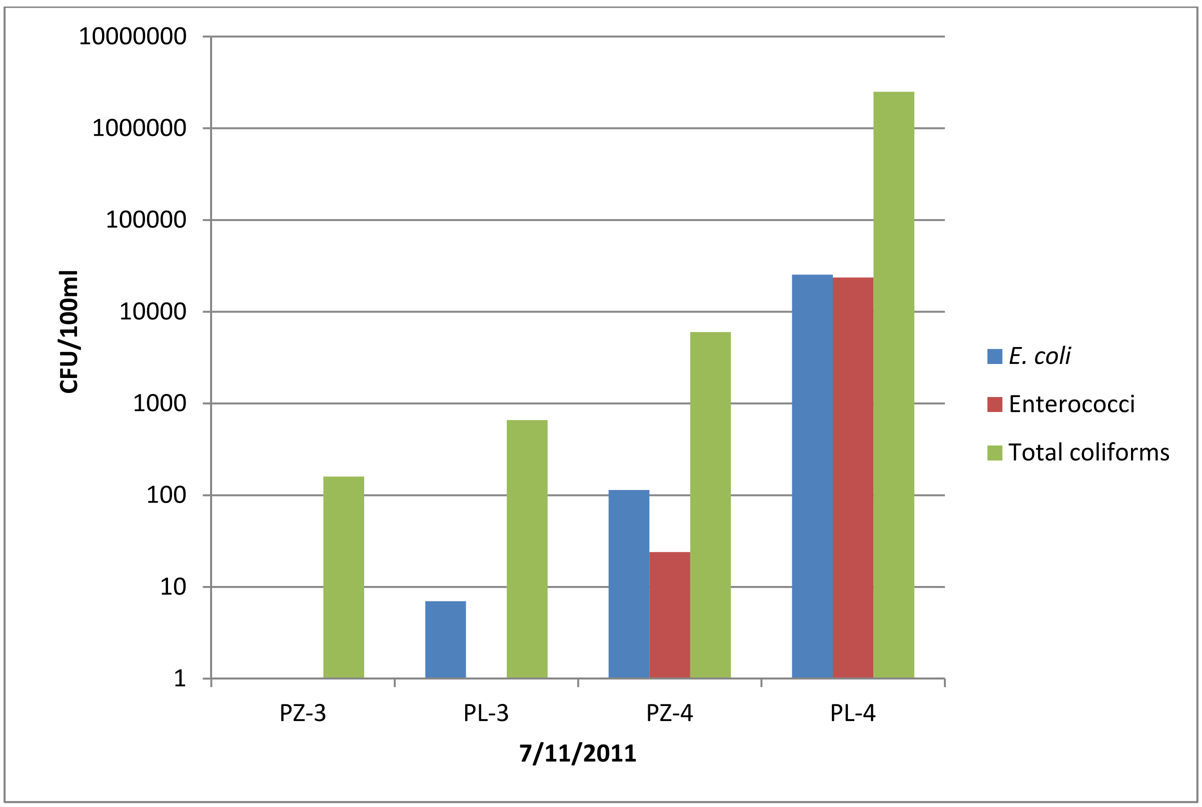


Figure 27- Comparison of FIB in piezometers (PZ) and correspondent pan lysimeter (PL). Samples were collected on 7/11/2011.

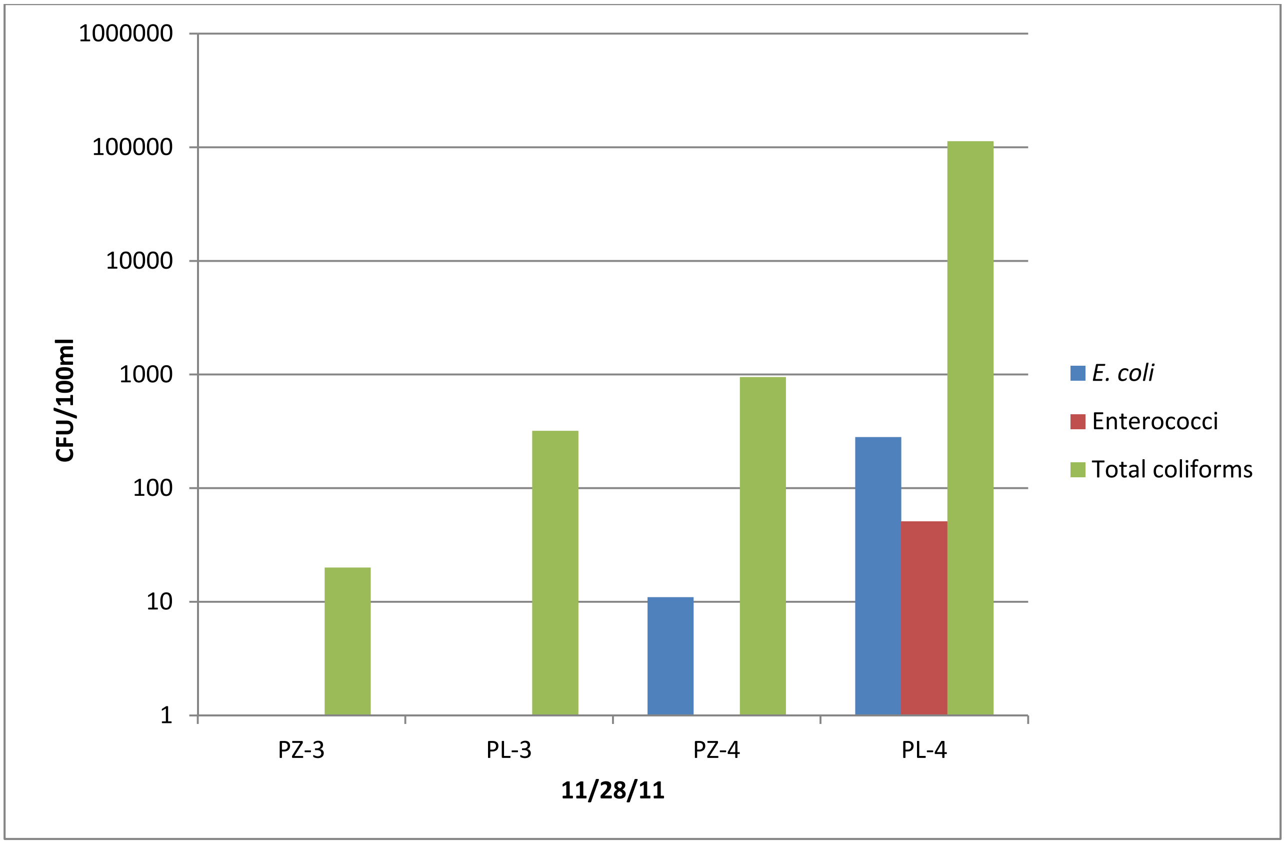


Figure 28- Comparison of FIB in piezometers (PZ) and correspondent pan lysimeter (PL). Samples were collected on 7/28/2011.

3.4 Bacteria dynamics in the beach environment

3.4.1 Beach environment before and after construction of the rain gardens

Previously eight stormwater outfalls (as shown in Figure 2) would discharge stormwater on the sand near the Lincoln Drive boundary. Stormwater runoff would run across the beach and reach lake water eventually. Stormwater outfalls were tested for human *Bacteroides*, which is a sewage indicator and they were found positive. This means that stormwater outfalls are contaminated with sanitary sewage (probably from leaking sewer lines exfiltrating into the stormwater system). This tells us that sewage is released at the beach, but it is very often below the limit of detection in the water. Therefore, it is important to control the sewage source directly.

Rain gardens started operating in mid 2008. Rain gardens filter pollutants from stormwater runoff. During heavy rainfall events, stormwater is allowed to overflow from the rain gardens and run across the sand towards the lake. Six rain gardens were installed at Bradford Beach. Aerial view of each of the rain gardens can be found in Appendix H.

Although overflow volumes reported by MMSD (shown in Figure 29) were higher in 2008, 2009, and 2010 compared to 2006 and 2007, beach water quality has been improving since 2009 (as can be seen in Table 10). Previous research has shown that the major contributor of poor water quality is stormwater discharged near the beach. The improvement in lake water quality was observed in the following years when rain gardens were well established and retaining stormwater. The full table is presented in Appendix I.

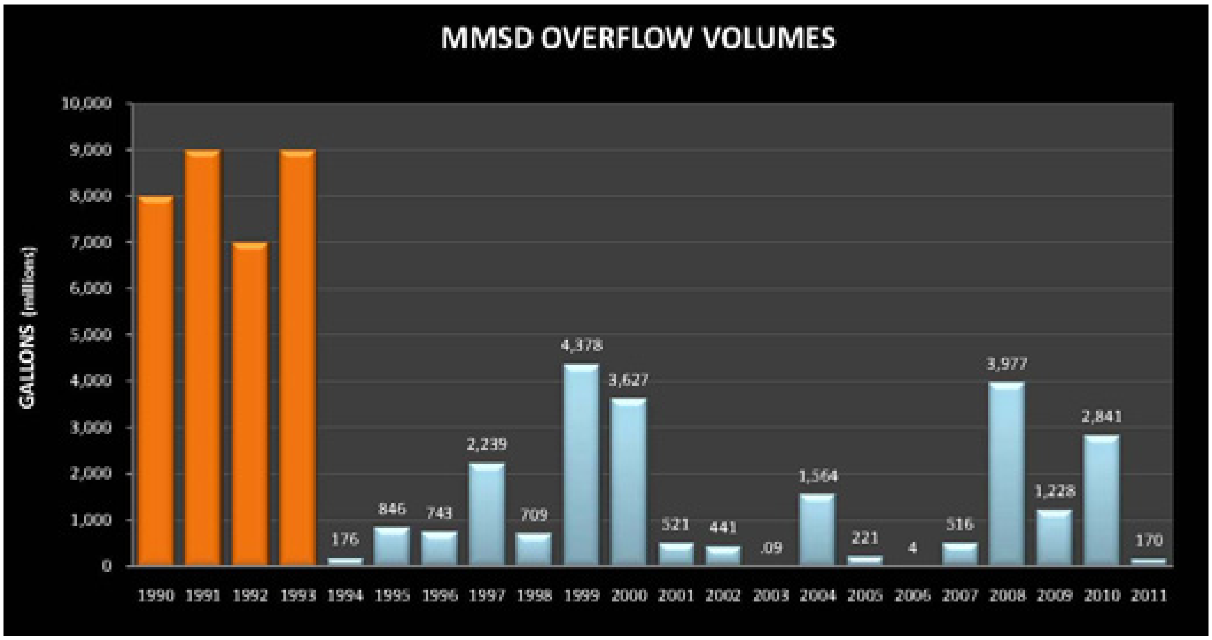


Figure 29- MMSD Overflow volumes. Source: http://v3.mmsd.com/Overflow.aspx

Table 10-Summary of Fecal Indicator Bacteria concentration in beach water from 2006 to 2011

	E. coli			enterococci		
Year	N	Average (CFU/100ml)	Geometric Mean (CFU/100ml)	N	Average (CFU/100ml)	Geometric Mean (CFU/100ml)
2006	61	276	95	61	35	24
2007	63	976	181	57	163	64
2008	53	455	248	56	323	67
2009	86	233	56	86	152	13
2010	64	371	55	65	400	29
2011	74	672	48	75	606	15

Concentration of *E. coli* on surface sand collected on the berm and on the backshore has been reducing since 2008, when the rain gardens were installed. Decreasing trend can be observed over time in Figure 30 and Figure 31). No evident impact has been observed in the submerged sand (Figure 32). Backshore sand location coincides with the region where the deepest depressions are located and where the groundwater table is closer to the ground. It is also the region in which concentration of *E. coli* is higher, which is in agreement with the fact that moisture has been strongly linked to FIB survival. Although the submerged sand is located in a region that is constantly wet (the swash zone), that region is also constantly under shear stress due to the wave action and longshore currents. Therefore, attachment of bacteria to sand grains becomes more challenging in that region.

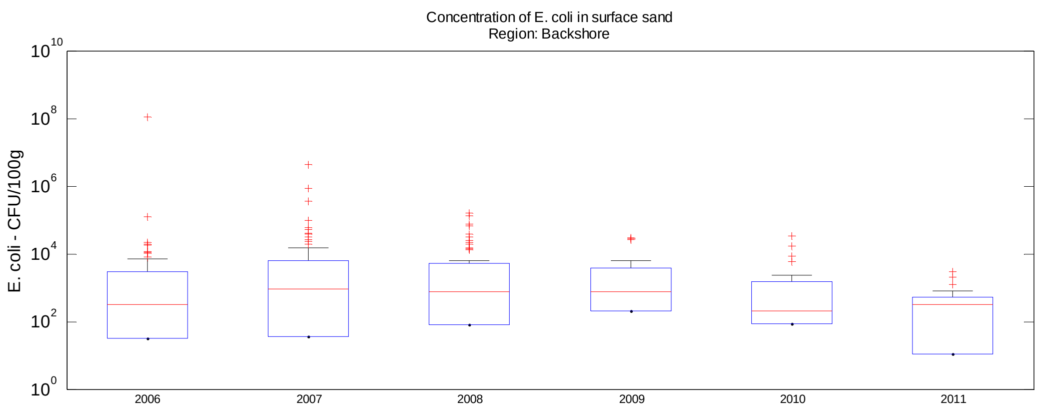


Figure 30- Boxplot of E. coli in surface sand collected on the backshore of the beach from 2006 to 2011. Bacterial contamination has been reducing since 2008, although the median is comparable to previous years.

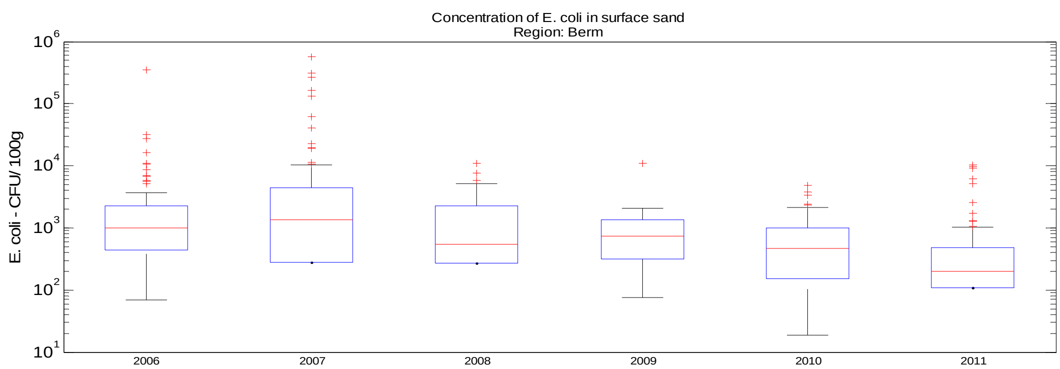


Figure 31- Boxplot of *E. coli* in surface sand collected on the berm of beach from 2006 to 2011. Median of bacterial contamination has been reducing since 2010, when the rain gardens were fully developed.

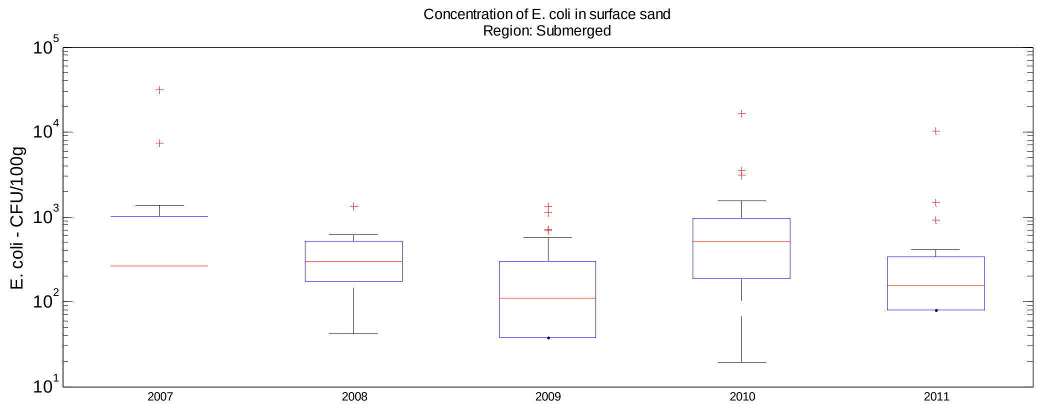


Figure 32- Boxplot of *E. coli* in surface sand collected in the submerged area of the beach from 2006 to 2011. Reduction in bacterial contamination has not been observed so far since installation of the rain gardens.

3.4.2 Investigation of presence of sewage in standing water, groundwater, runoff infiltrating through the sand, and lake water

Standing water was found positive for bacterial markers, indicating sewage contamination, mainly during very heavy rainfall events (see 2009 events on Figure 34 and full dataset on Table A- 8 in Appendix J). Therefore, standing water is a health concern during heavy rainfall events. Groundwater and runoff infiltrated through the sand were also found positive for human *Bacteroides* only during heavy rainfall events.

Sewage contamination continues to be intermittently detected in outfalls along Bradford Beach, and more commonly, in the outfalls north of the beach. The rain gardens retain contaminated water and prevent it from running across the beach, whereas the outfalls located to the north of Bradford Beach discharge directly to the lake, where contamination delivered to the beach in the longshore current is a health concern. Further, standing water has been found to have high enterococci and *E. coli* levels in the absence of sewage bacterial markers. This could indicate fecal pollution from birds. The health risk due to avian fecal pollution is not well quantified, but gulls have been noted to carry pathogens.

Figure 33- Children playing on standing water almost in front of the Beach House, at Bradford Beach. Picture was taken on June 8, 2009.

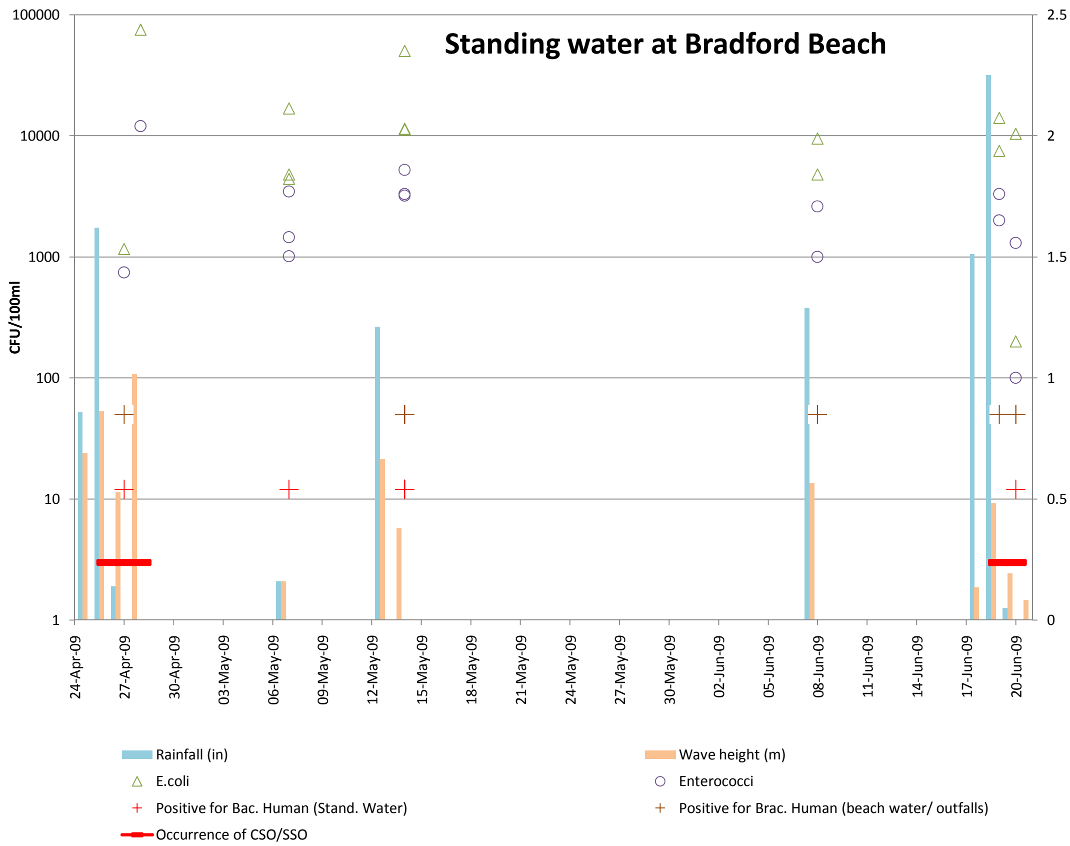


Figure 34-Relationship between presence of sewage indicator in standing water and rainfall and wave height. Positive for human Bacteroides was always related to heavy rainfall events and/or wavy days, except on 5/9/2009.

3.5 Geophysical surveys

Several geophysical surveys were performed on the north end of Bradford Beach: electromagnetic surveys, resistivity soundings, resistivity profiling, and ground penetrating radar. Detailed information can be found in Appendix K.

The resistivity soundings on the southern part of the study area show four well defined electrical layers. Layer 1 which encompasses the first half meter is characteristic of dry sand. Layer 2 (0.5 to 4 m) is interpreted as saturated sand. Layer 3 (4-10 m) is unknown, but it is most conductive. Layer 4 (<10m) is probably less saturated till. The resistivity soundings on the northern part of the study area are slightly more complex. The first 0.5 m is the same, but the layer from 0.5 to 1 meter is much more conductive than the similar depth in the southern sounding. Layer 3 is the same and Layer 4 is thicker.

Resistivity profile calculations produced a stratified model consistent with sounding data. Figure 35 presents the data for the 5 meter spacing survey, which senses to about 6 meters. The resistivity at the surface is higher to the south, and the resistivity is lower at depth toward the south. The low resistivity at depth toward the south may be the results of a water plume from the storm drain to the east of the profile.

All the geophysical surveys suggest a fairly uniform sand surface layer that may be as thick as 3 meters. The electrical sounding and profile results show some lateral variations at a depth of about 3 meters which could be pre-1930 beach material, or different levels of sub–sand saturation, possibly due to the drain outfalls near Lincoln Memorial Drive. However, changes at this depth are unlikely to be affecting the surface sands, or causing the standing water.

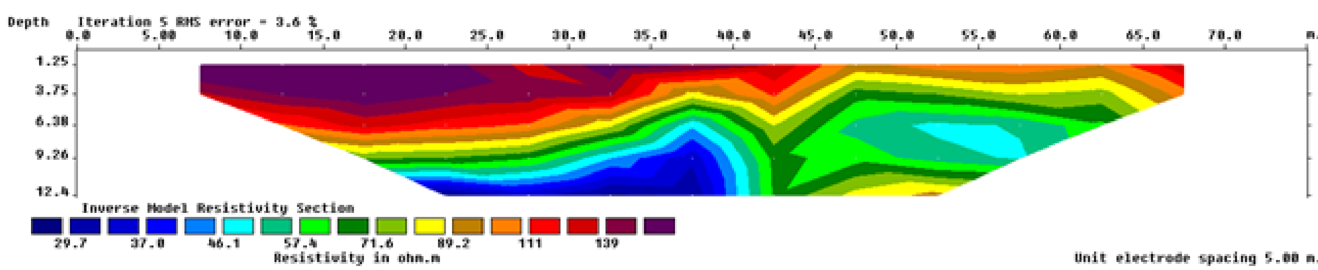


Figure 35-Resistivity profile (pseudosection) with 5 meter spacing. The graph is interpreted layer parameters. It shows higher resistivity to the south and lower resistivity at depth. This profile is sensing to approximately 6 m depth at the center.

3.6 Summary of dynamics of formation and retention of standing water

3.6.1 Mechanisms of formation of standing water

There are two mechanisms of ***formation*** of standing water. The primary mechanism is *precipitation* (and the resulting surface runoff), as shown in Figure ES- 3. The secondary (but not significant at the 0.05 level) is *wave height*. There is a higher correlation between standing water and rainfall (especially within 24 hours of the event) than standing water and wavy days.

3.6.2 Mechanisms of retention of standing water

The main mechanisms of ***retention*** of standing water are discussed next:

Beach erosion and deposition are major factors in the formation/retention of standing water: Beach erosion was observed mainly in the central part of the beach (cross-shore direction, where the wet sand can be observed on Figure ES- 2), with the deeper depressions located mostly on the northern part of the beach. These are the regions where the water table is just below the beach surface (10 cm in the worst case scenario, when there is a maximum groundwater level), creating chronic moist areas and slowing the infiltration process, mainly on the northern part of the beach, thereby contributing to concentration of standing water in that region.

Finer sand on the northern part of the beach implicating in slower infiltration: Bucket samples and sand core samples were analyzed for grain size distribution before and after the rain gardens were built. On the southern part of the beach sand has medium size and is less uniform where d_{50} is 326±83 μm (n=28) whereas on the northern part of the beach sand has fine size where d_{50} is 243±26 μm (n=51). Grain size distribution for all sand samples can be found in Appendix L.

Transient increases in the water table: Rain gardens can augment transient increases in the water table level. Rise of the water table could produce less storage volume in the sand for newly infiltrated water, resulting in more surface runoff once that storage is used up. The groundwater level is very responsive to rainfall, rising within 24hrs of the precipitation.

Concentration of fines in the swales and trapping of water due to lower hydraulic conductivity (K): Finer particles (organic or inorganic) that used to be washed out to the lake before construction of the rain gardens could now be collecting in the swales and could reduce the hydraulic conductivity. This is a reasonable assumption, although no historical data pre construction of rain gardens is available.

Higher horizontal hydraulic conductivity (K_h) on the northern part of the beach would slow down process of infiltration of runoff: K_h is estimated to be one to three orders of magnitude higher than K_v in that region, according to field experiment performed with a pan lysimeter (details in Appendix G). Although this is a reasonable estimation, no field measurements of K_h were performed.

Alterations in drainage patterns: Discharge from the outfalls across the beach may originally have created channels that drained the low elevation area in the middle of the beach. Once the rain gardens were in place, these channels no longer formed and surface runoff or wave runup can accumulate in the middle of the beach. This is a reasonable assumption, although no historical data pre construction of rain gardens is available.

3.7 Management practices recommended to reduce and/ or eliminate presence of standing water

Beach grooming - It may improve conditions, but cannot compensate for lack of sand. Grooming aerates the top layer of sand, allowing it to dry out. Moisture content is strongly linked to *E. coli* survival; therefore, grooming potentially can reduce *E. coli* levels. However, the combination of minimal sand with a high water table creates areas that have standing water or chronic saturation. In addition, grooming should not reduce the berm formation at the water line, as this serves as a barrier to wave run-up.

Channels to drain swales - Building channels through the berms along the beach from swales toward the lake would help to drain the swales.

Beach nourishment – It would eliminate standing water and keep the beach above the mean lake level. A grading plan was prepared with the purpose of simultaneously rectifying the loss of material due to the storms while filling the longitudinal swale running the length of the beach.

Analyses are conclusive in regard to both the existing deficit of beach material and documented erosion between November 2009 and April 2010 (slight erosion, mostly alongshore close to the water) and the large erosion all over the beach from April 2010 to July 2010. The erosion resulting from the July 2010 storms is summarized in Appendix A. The recommended grading for the beach is also in Appendix A. The survey data analysis provided a sample grading plan, which would simultaneously rectify the loss of material due to the storms while filling the longitudinal swale running the length of the beach.

In conclusion addressing the material deficit without also recommending mitigating measures for the erosion mechanism would be remiss. This could be accomplished through the consultation of a coastal engineer. When lake levels were really high in the 70s and waves would crash upon Lincoln Drive in storms, a lot of sand was eroded from the beach (and went offshore). As water levels have subsequently declined, that sand has moved even farther offshore. This sand could be pumped back onto the beach, but a coastal engineer needs to determine how any removal will affect offshore stability.

Topographical surveys show that a total of approximately 5,389.4 yd^3 (8,084.1 tons) of material would need to be imported to execute the design of the grading plan. A cost estimate was prepared, totalizing $235,423 (details in Appendix A).

4 CONCLUSIONS & RECOMMENDATIONS

There are two mechanisms of formation of standing water. The primary mechanisms a rise in groundwater levels caused by the infiltration of precipitation and a secondary mechanism is wash from high waves crashing onto the beach. The main mechanisms of retention of standing water have to do with beach topography resulting from beach erosion and deposition, coarser sand on the southern part of the beach when compared to the northern part, allowing quicker infiltration and less presence of standing water, and transient increases in the water table augmented by the rain gardens. Although it is reasonable to assume that concentration of fines in the swales and trapping of water due to lower hydraulic conductivity (K) and alterations in drainage pattern after construction of rain gardens may play an important role on retention of standing water, no data pre-rain gardens is available to support these hypothesis. It is also reasonable to estimate that K_h is higher on the northern part of the beach, slowing down the infiltration; however no field measurements were performed.

When heavy rainfall events happen, stormwater is allowed to overflow from the rain gardens and run across the beach. Under these circumstances, standing water was found positive for sewage indicator, as well as pore water and groundwater, which is a health concern. Beach nourishment is therefore recommended to eliminate standing water and assure that the beach elevation will remain above lake level, avoiding flooding of the area. Beach grooming is a technique encouraged to continue to be applied at Bradford Beach. In addition, building channels through the berms along the beach from swales toward the lake would help to drain the swales. Consultation of a coastal engineer is encouraged for recommendation of mitigating measures for the erosion mechanism.

5 ACKNOWLEDGMENTS

This project was partially funded by The Park People. Authors thank Elizabeth Sauer, Dr. Patricia Bower, Melinda Bootsma, Victoria Smejkal, Rohan Jadhav, Dr. Ryan Newton, Robert Graziano, Gerard Guerra, Ryan English, Ben Dickinson, Jackson Sorensen, Daniel G. Uphoff, Morgan R. Schroeder, and Anne K. Bruckner for helping with field work and with lab analyses. We also thank Thomas Hansen for providing hourly digital images from Bradford Beach and Greg Barske and Randolf Metzger for building the piezometers. We thank Dr. David Schwab and Gregory Lang for providing current and wave data for Bradford Beach and Dr. Sam Helwany and Dr. Hani Titi for allowing us to use the Soils Lab. We also thank Kim Weckerly for helping with Arc GIS maps. We also show our gratitude to Stevan Keith, P.E., from Milwaukee County DTPW for helping us to choose the locations to install the piezometers. Special thanks to Dave Hart of the Wisconsin Survey for the use of the states SIR 3000 GPR unit and post data corrections and manipulations.

6 REFERENCES

[1] H. R. Bravo, S. L. McLellan, E. Sauer, H. Bootsma, J. Hiller, and W. Weaver, "Ecological study and management plan for Atwater Park Beach," University of Wisconsin-Milwaukee, Milwaukee 2010.

[2] J. A. Patz, S. J. Vavrus, C. K. Uejio, and S. L. McLellan, "Climate change and waterborne disease risk in the Great Lakes region of the U.S.," *American Journal of Preventive Medicine*, vol. 35, pp. 451-458, 2008.

[3] U.S.EPA, "Method 1103.1: *Escherichia coli (E. coli)* in Water by Membrane Filtration Using membrane-Thermotolerant *Escherichia coli* Agar (mTEC)," U. S. Environmental Protection Agency, Washington D. C. EPA 821-R-02-020, 2002.

[4] U.S.EPA, "Method 1600: Enterococci in Water by Membrane Filtration Using membrane-Enterococcus Indoxyl-β-D-Glucoside Agar (mEI)," U. S. Environmental Protection Agency, Washington D. C. EPA 821-R-02-022, 2002.

[5] U.S.EPA, "Method 1604: Total Coliforms and Escherichia coli in Water by Membrane Filtration Using a Simultaneous Detection Technique (MI Medium)," U. S. Environmental Protection Agency, Washington DC EPA 821-R-02-024, 2002.

[6] S. L. McLellan and E. Sauer, "Pathogens in urban stormwater: Identification and mitigation of human sources of fecal pollution.," Great Lakes WATER Institute, Milwaukee 2006-2009 Technical Report for MMSD, 2009.

[7] E. Sauer, J. L. VandeWalle, M. J. Bootsma, and S. L. McLellan, "Detection of the human specific *Bacteroides* genetic marker provides evidence of widespread sewage contamination of stormwater in the urban environment," *Water Research*, vol. 45, pp. 4081-4091, 2011.

[8] J. S. Lavender and J. L. Kinzelman, "A cross comparison of qPCR to agar-based or defined substrate test methods for the determination of *Escherichia coli* and enterococci in municipal water quality monitoring programs," *Water Research*, vol. 43, pp. 4967-4979, 2009.

[9] L. J. Beversdorf, S.M.Bornstein-Forst, and S.L.McLellan, "The potential for beach sand to serve as a reservoir for *Escherichia coli* and the physical influences on cell die-off.," *Journal of Applied Microbiology*, vol. 102, pp. 1372-1381, 2007.

[10] J. D. Skalbeck, J. L. Kinzelman, and G. C. Mayer, "Fecal indicator organism density in beach sands: impact of sediment grain size, uniformity, and hydrologic factors on surface water loading," *Journal of the Great Lakes Research*, vol. 36, pp. 707-714, 2010.

[11] F. H. Kulhawy and P. W. Mayne, "Manual on estimating soil properties for foundation design." California: Eletric Power Research Institute, 1990.