# INFLUENCE OF PLANT COMMUNITY AND MEDIA COMPOSITION ON THE WATER BUDGETS OF COASTAL RAIN GARDENS

*2014 Hixon Fellowship Final Report*

*Selena Pang*
*Master of Environmental Science Candidate, Hixon Fellow 2014-2015*
*Yale School of Forestry and Environmental Studies*

*Advisors: Dr. Gaboury Benoit and Dr. Alexander J. Felson*

INTRODUCTION: Future global and local sea level rise can be expected to stress coastal communities in the northeast United States (Boon 2012, Joughin 2014), particularly those still recovering from past storms. This stress will be exacerbated by regions projected to experience regional precipitation increases. In 2012 and 2013, the state of Connecticut suffered $7.02M and $5.6M in property damage from hazardous weather, respectively. (NOAA 2012, 2013) Implementation of green stormwater infrastructure (GSI) is on the rise, driven by its ability to provide flooding and water quality amendment, as well as added social and economic value. There has been a recent shift towards the use of rain gardens in small-scale flood mitigation, stormwater infiltration and groundwater recharge. (Davis 2009) It has been suggested that sand:compost ratios are particularly influential for infiltration rates. (Thompson 2008) Similarly, it has been observed that organic material tends to create surface clogging. (Archer 2002, Gonzalez-Merchan 2012, Hatt 2007a) Climate can play a role, as well: wetting and drying has been shown to affect infiltration, attributable to swelling and shrinking of organic sediment. (Hatt 2007b) The scalability of such infrastructure allows it to accommodate the time, money and space constraints of the human city, while improving quality of life for city dwellers. However, because green infrastructure is an emerging field, it is critical to study and adaptively manage pilot projects, in order to develop an approach that can encompass the moving targets of ecological restoration and community needs.

*Study Area and Project Context*

Like many post-industrial cities in the US, the city of Bridgeport has ubiquitous vacant and under-used space, which could be reclaimed for GSI projects. (Schilling 2008) However, financial and spatial constraints limit options in terms of size and location of green infrastructure projects, and they are often consigned to small pieces of land and with sub-optimal geologic and hydrologic conditions. While it may be argued that construction on such a site is preferable to doing nothing at all, many of the ecological experiments that underpin GSI design guidelines are based on studies conducted either in the laboratory or at field sites with ideal drainage conditions. Therefore, a critical contribution needed from the scientific community is the installation of urban research projects in the kind of provisional space today's coastal city has to offer. The research projects themselves should be scalable and reproducible in other parts of the city, but study results should be produced at the project scale.

Located in Bridgeport's South End, the Seaside Village Historic District is a coastal residential co-op on the U.S. National Register of Historic Places. The property is located within a quarter mile of the present coastline, and experiences flooding from both hurricanes and regular rain events. (The average monthly precipitation range in Bridgeport is 68-124 mm, occurring over an average of 12-17 days.) (WWO 2013) Over half of the homes were recently fitted with resilience infrastructure, including storm-proof electrical panels or basement sump pumps to control seepage. (City of Bridgeport 2013) Hurricanes Sandy and Irene flooded residents' basements with over five feet of brackish water (personal communication with residents, October 2013), and the neighborhood field was inundated for several weeks, killing the upland plant community. Despite the challenges, residents remain dedicated to the neighborhood and engaged in its development.

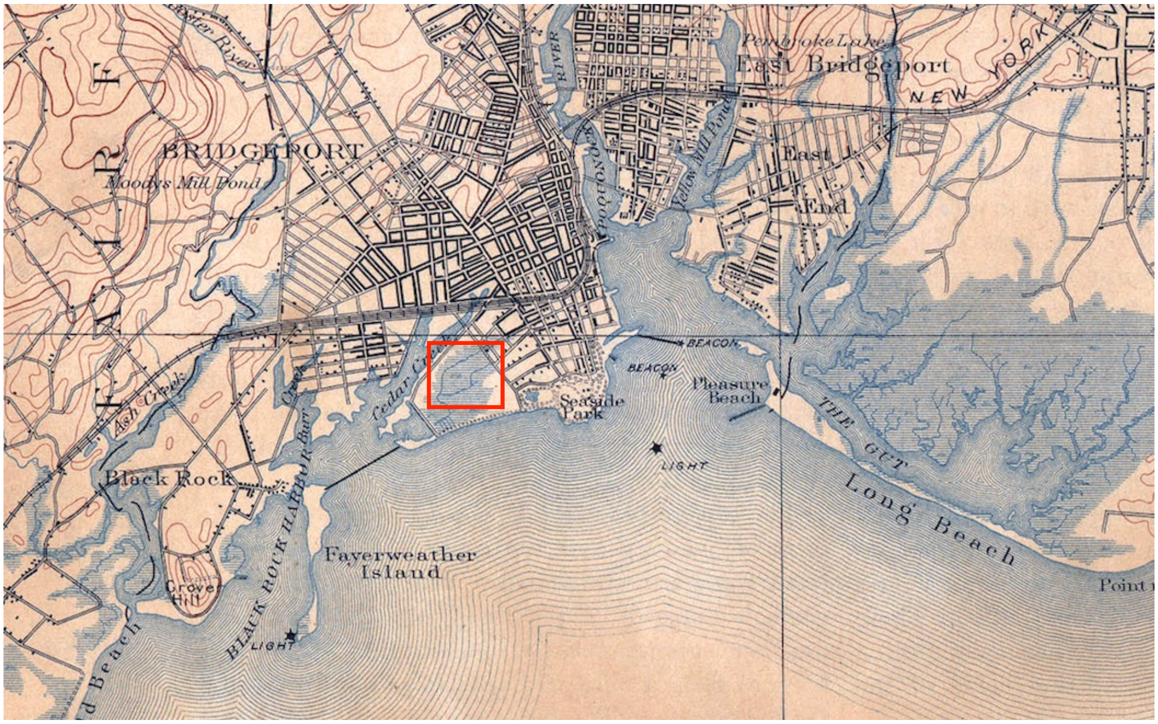

Figure 1: 1893 historical map of the study site. (USGS 1893) Site is marked by a red box.


Figure 2: 2014 satellite image of the study site. (*Image source: Google Earth*) Site is marked by a red box.

A defining characteristic of the study site is the fact that is integrated within a public urban recreational space, The Bridgeport Coastal Bioretention Garden. The 0.25-acre project was planned and constructed in 2011 by a collaboration of stakeholders including

Yale, Seaside Village, the City of Bridgeport, and various agencies and community groups. It was inspired by a neighborhood master plan created by Yale Urban Design Workshop and the Yale Urban Ecology and Design LaboratoryA major focus of the master plan was the potential for GSI to manage stormwater runoff and reduce neighborhood flooding, and the site was constructed to demonstrate how Seaside Village residents can address the source of flooding by managing stormwater across property lines. The site therefore features multiple stormwater management designs that small groups of homeowners might build, to address ponding water throughout the neighborhood.

In addition, the space functions as a designed experiment (DEX). Unlike traditional field experiments and most observational studies of urban environments, DEXs are developed during the site design and planning process, with the goal of improving scientific understanding and adding value to the site. (Felson 2005) Designed experiments provide a platform for communities, practitioners and academics to collaborate on adaptive management of soft GI (GSI) solutions to coastal risk—where stakeholders can both study and shape real world projects at a community scale. A combination of flood vulnerability and community engagement makes Seaside Village an ideal setting for taking a DEX approach. A research landscape sited within a public amenity can provide a city with benefits including the incorporation of ecological processes into urban life, raising the profile of urban ecology, and integrating analysis with aesthetic features. (Felson 2005) Neighborhood residents, community board and management all contributed to selection of the layout of the Bridgeport Bioretention Garden. Only a portion of the bioretention cells are intended for experimentation. A curving peastone walkway helps to break down their modular structure, creating a sense of play on a rigid experimental layout. The DEX also includes non-experimental wetlands which residents are welcome to modify. Other features are strictly for aesthetics, including blue stone paving, stone benches and boulders. During organized group work days, equal priority is placed on research goals, performance goals and aesthetic goals—for example, tasks at a recent workday included reinforcing landscape edging on experimental cells, re-digging a drainage channel and grooming the walkway. (Sometimes, maintenance and research goals would overlap as well—for example, clearing leaves out of a pipe inlet area achieved both goals.) The majority of maintenance occurs on these work days, with a few dedicated residents regularly checking up on the site, weeding and planting in non-experimental areas.

The study area consists of six experimental rain gardens, approximately 8’ x 22’, which receive runoff from the community parking lot via a series of pipes. A few feet below the ground surface, an impermeable clay layer confines underlying groundwater—but in each rain garden, a permeable sand wick perforates the clay. (Following the initial construction phase, the design was modified by breaking through the layer of lowest conductivity (the clay) and filling the perforation with sand.) The wicks are for drainage purposes, but may also cause the rain gardens to behave unpredictably or inefficiently when groundwater pressure is high (for example, during flow tides or large storms).

Figure 3: Study site in May 2014. While still flooded during large storms and in the fall (when evapotranspiration rate declines), the rain gardens have address stormwater ponding in the adjacent parking lot. Following storms, the standing water attracts local and migratory birds including ducks, starlings, turkeys and wild parakeets.

The selection of planting media can markedly affect hydraulic behavior. For example, loam-filled biofilters have shown a six-fold increase in water retention time, compared to biofilters filled with sand. (Lucas 2006) At the study site, rain gardens were manipulated with a combination of soil composition and plant community treatments. The soil treatments lined the rain gardens, and consisted of varying compositions of sand, soil and compost. (Each rain garden was topped with a high-conductivity, high sand topsoil.) There were three soil treatments. Media A, the coarsest media, had a sand/soil compost ratio 90/5/5. Media B had a ratio of of 85/5/10. Media C, highest in fine organic material, had a ratio of 70/15/15.

The initial (2011, 2012) wetland plant community failed due to inundation with storm surge from Long Island Sound, brought by Hurricane Sandy in 2012. The most recent re-planting event (in 2013) used only salt-tolerant native New England marsh species. Due to the extreme sensitivity of wetland plants to elevation gradients, combined with frequent introduction of foreign seeds into the rain gardens, there were only two plant treatments. Treatment 1 consisted of wetland grasses and shrubs, as well as any self-starting species the residents found attractive. Treatment 2 consisted of no plants. (Any seedlings that appeared in Treatment 2 plots were either transplanted to Treatment 1 plots, or removed.)

There are several convenient, feasible options for characterizing the hydraulic performance of rain gardens: visual assessment, infiltration rate testing, and synthetic drawdown time. (Asleson 2009) Visual assessment is time-intensive and non-quantitative, and for these purposes will be done as an enhancement to collection of other data. Drawdown time is determined by filling the rain garden up to capacity, then timing its drainage. While this may give a good relative comparison of performance (especially since the rain gardens are of identical shape), it would inundate the rain gardens with a volume of water atypical of most storms, leading to the question of how applicable such data would be. Additionally, the quantity of water required for this test would require use of a truck with a water tank. Because ths gardens are sited adjacent to the neighborhood parking lot, repeated trials would present the logistical challenge of finding another place for residents' vehicles. The most common assessment method is infiltration rate, often quantified by tests for saturated soil hydraulic conductivity ($K_{sat}$). (Dussaillant 2005) (Each rain garden contains a sand wick (high permeability) at one end that, overlain by the planting media. This wick, together with local geology (discussed later) creates spatial heterogeneity and $K_{sat}$ which assumes homogeneity, is not an appropriate metric for this system. (Asleson 2009) Furthermore, $K_{sat}$ describes a saturated media, and not every rainstorm will contain sufficient precipitation to saturate the soils.

Water budgets have been used in previous studies evaluating rain garden performance. (Dussaillant 2004, Li 2009) While the rain gardens are inundated during a normal storm event, evaporation should dominate the process. However, studies do show that *total* evapotranspiration (i.e. including dry weather) can contribute a fifth to a third of rain bioretention loss, so this contributes substantially to the overall budget. (Brown 2011, Li 2009)

METHODS: This research project investigated the performance of six experimental cells, in order to gain a better understanding of how the site's performance relates to the local landscape, climate and geology. The majority of monitoring instruments were installed at the site in spring-summer 2014, and include: 6 Solinst water level loggers (1 per rain garden), 1 Solinst logger secured to a tree to monitor changes in atmospheric pressure, 1 Rainwise Rainlog rain gauge installed adjacent to a community garden in open space, 1 Onset Comp wind speed gauge (average speed and maximum gust) and pyranometer attached to a utility pole in open space and 2 Hobo pendant event loggers (1 per catchment basin) to monitor water being conducted to the system from the parking lot.

The barologger and water level loggers collected pressure information at 5-minute intervals. The dataset was later downsized to 1-hour intervals due to file size. Rain and catch basin events were reported as they occurred. Measurements will continue through June 2015. Data for July 1 – September 30, 2014 are discussed in this report.

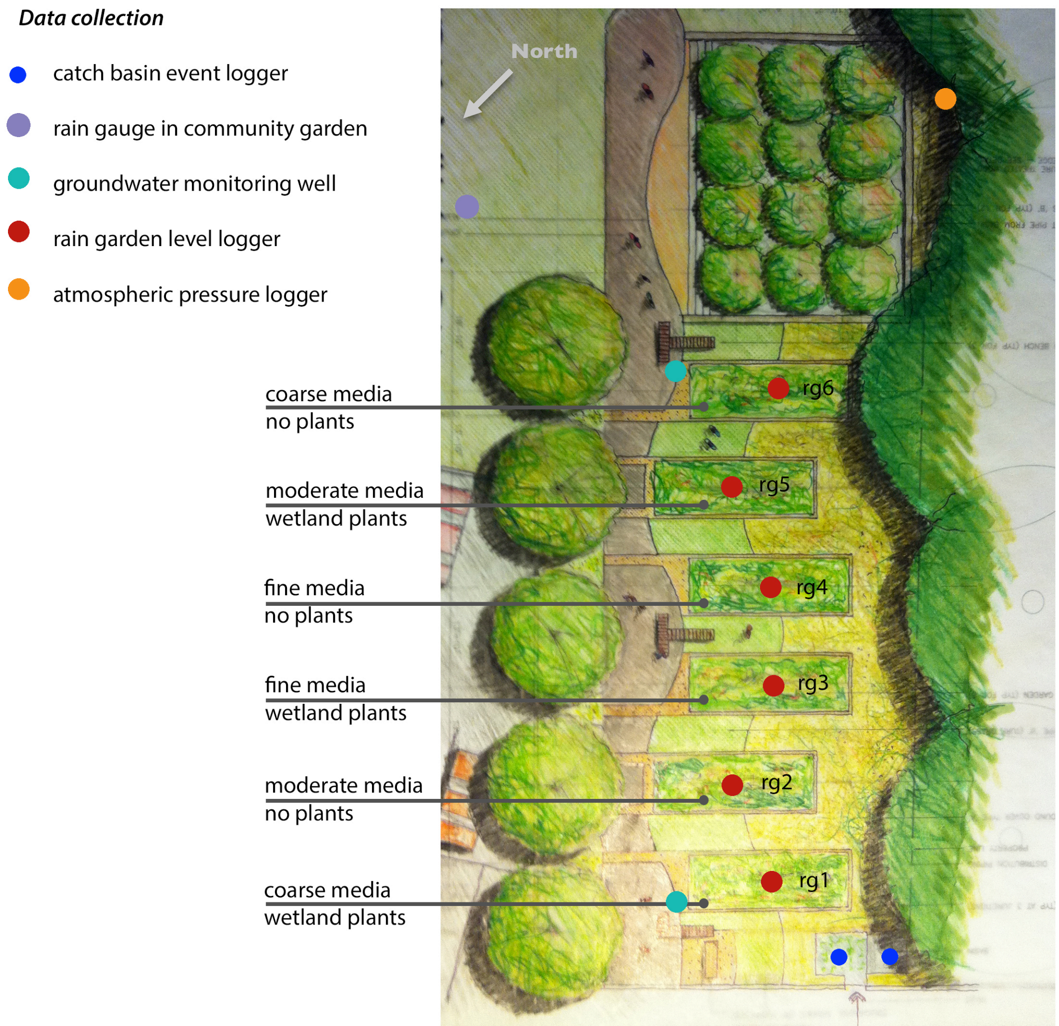


Figure 4: Study design at Seaside Village Bioretention Garden.

Rain garden performance was quantified by calculating a water budget for each rain garden, using the equation:

***INFLOW + PRECIPITATION –EVAPOTRANSPIRATION - STORAGE = GROUNDWATER EXCHANGE***

Inflow from the parking lot was measured using a tipping bucket connected to an event logger, placed in each of 2 catchment basins which distributed water evenly to the gardens. Inflow was calculated by converting tipping bucket events to gallons of water. (1 tip = 1 gallon per catchment basin = 1/3 gallon per rain garden.) Catch basin events were also totaled for every hourly time step.

Precipitation was measured onsite using a tipping bucket rain gauge, and events were summed per hour. Due to equipment damage by animals, onsite measurements of solar radiation and wind speeds are not available for this time period. It was also discovered that Sikorsky Airport no longer possesses a functioning weather station, and instead reports weather data from another station located on the other side of Long Island Sound. Solar, wind, humidity and other raw data for evapotranspiration estimates were taken from the Connecticut Department of Energy and Environmental Protection environmental quality monitoring station at Criscuolo Park, New Haven. (DEEP 2014) This was the nearest weather station reporting solar and weather data from an open field. Evapotranspiration was estimated using the Shuttleworth method. (Benoit)

Rain garden storage was monitored in each rain garden using water level loggers, and groundwater exchange was calculated by difference. Infiltration rates were inferred from temporal storage changes and rain garden geometry. A close approximation of the rain garden dimensions is:

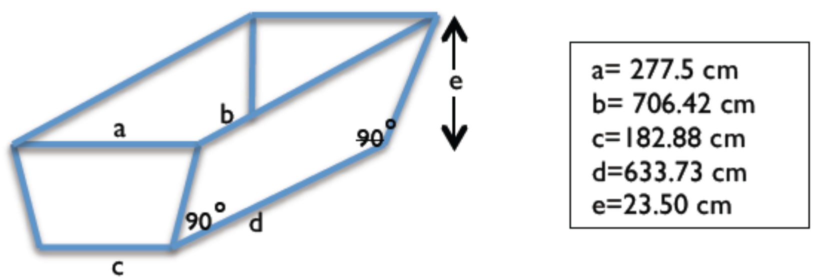


Figure 5: Approximate rain garden dimensions. (Diagram is exaggerated for clarity.)

where one of the short sides is vertical, and one is not (so that $d \neq b$). The volume equation for a trapezoidal prism is $V = ½ (a + c)\, d\, e$, but accounting for the asymmetrical shape, we get $V = [½ (a + c)\, d\, e] + \{ [ ½ (b-d)\, c\, e] + 2 [ (b-d)( ½ ( a-c))\, e] \}$ so that the maximum potential volume of each rain garden is $[½ (277.5 + 182.88) * 633.73 * 23.50] + \{ [ ½ (706.42 - 633.73)\, 182.88 * 23.50] + 2 [ (706.42-633.73)( ½ (277.5 -182.88)) * 23.50] \}$, which translates to a maximum theoretical storage capacity of 3.75 $m^3$ or 3,750L per rain garden. This theoretical shape was also used to calculate storage volume at different water levels.

Hourly water level data were compensated using the closest atmospheric pressure recording. Data reported by water level loggers were adjusted using manual measurements of water level and a digital elevation level, and converted to storage using the equation described above. Rain gauge events were converted into volume in liters (1 tip = 0.01 inch of rain = 25.4 $l/m^2$), by distributing over the footprint of the rain garden. Each catch basin drained to three rain gardens, so that each rain garden should be associated with only 1 set of catch basin events. Catch basin events were associated with the appropriate rain garden, and events converted to a volume which was then divided equally among the 3 rain gardens. Time-independent variables (rain garden number, soil treatment, plant treatment, elevation) were also matched up with the appropriate rain garden records. The multiple least squares regression model below accounts for variability in groundwater exchange, i.e. infiltration, due to soil and plant treatments.

RESULTS: Water levels in the rain garden plots (Figure 9) ranged from 0 to 30.0 centimeters. Rainfall (Figure 6) ranged from 0 to 278.8 liters per rain garden per hour (or 0 to 0.56 inches per hour). Evapotranspiration (Figure 8) ranged from 0 to 91 liters per rain garden per hour (or 0 to 1.41 mm per hour, with a mean value of 0.29 mm per hour).

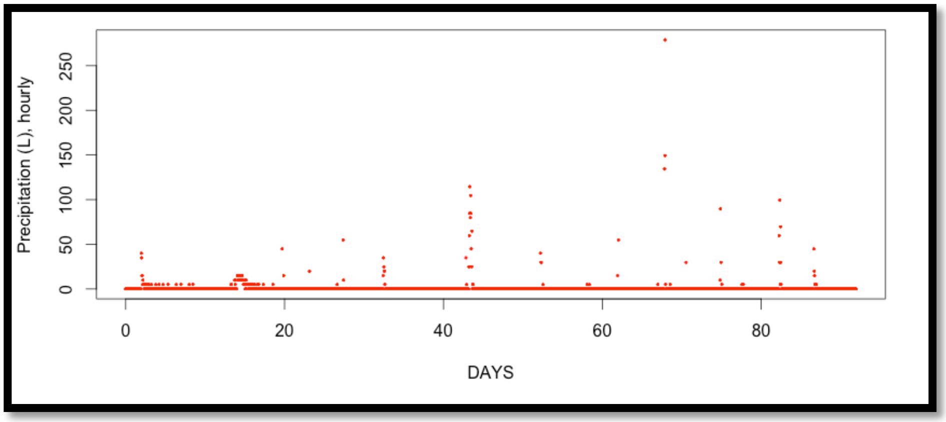


Figure 6: Precipitation (liters). Hourly time step. Data shown: July 1-September 30, 2014.

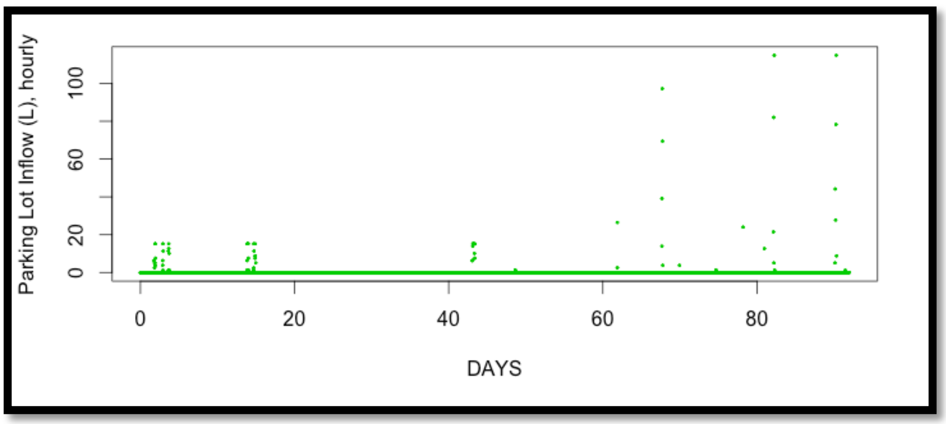


Figure 7: Inflow volume from the parking lot into each rain garden (liters). Catch basin events were converted into liters. Hourly time step. Data shown: July 1-September 30, 2014.

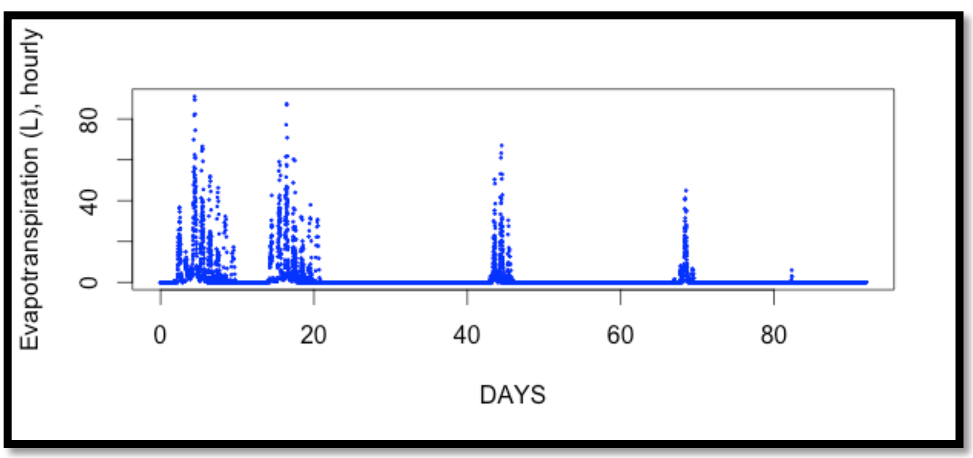


Figure 8: Evapotranspiration in each rain garden (liters). Hourly time step. Data shown: July 1-September 30, 2014.

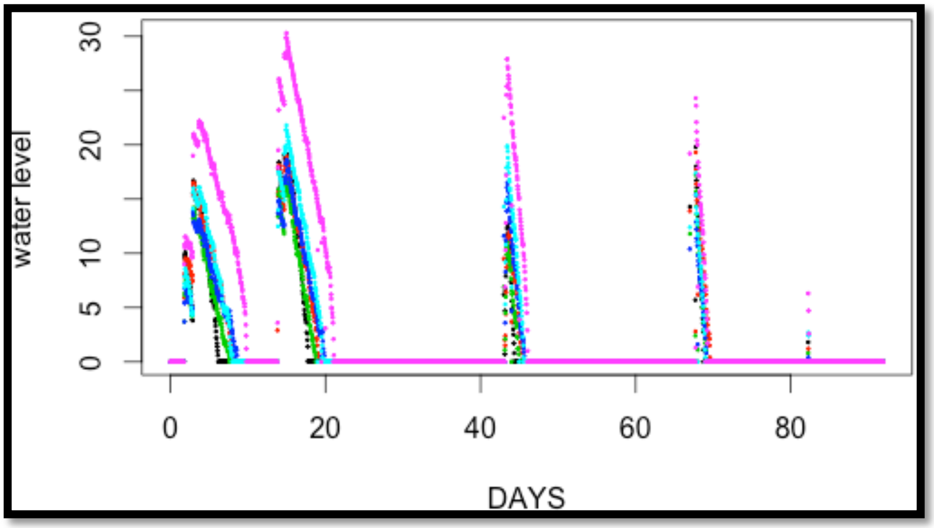


Figure 9: Rain garden water level (cm), constrained to 0. Rain garden water levels reveal five distinct filling and draining events, with rain garden 6 (pink) exhibiting noticeably higher water levels than the other plots. Hourly time step. Data shown: July 1-September 30, 2014.

DISCUSSION: Each rain garden exhibited a unique level-storage curve, Typically, rain garden 5 exhibits the highest adjusted water level and takes the longest to empty, whereas rain garden 1 tends to empty first. Whether these behaviors are seasonally affected will be examined in the future using data from non-growing seasons. Figure 9 shows the relationship between rainfall events and rain garden storage (represented as water level). Not every rain event resulted in a noticeable change in storage. Two types of rain events resulted in storage—intense rainstorms and sustained, lower-volume rain events. The relatively large spike in storage around Hour 73 does not appear to be associated with any change in rainfall, suggesting that water may be entering the system without being accounted for.

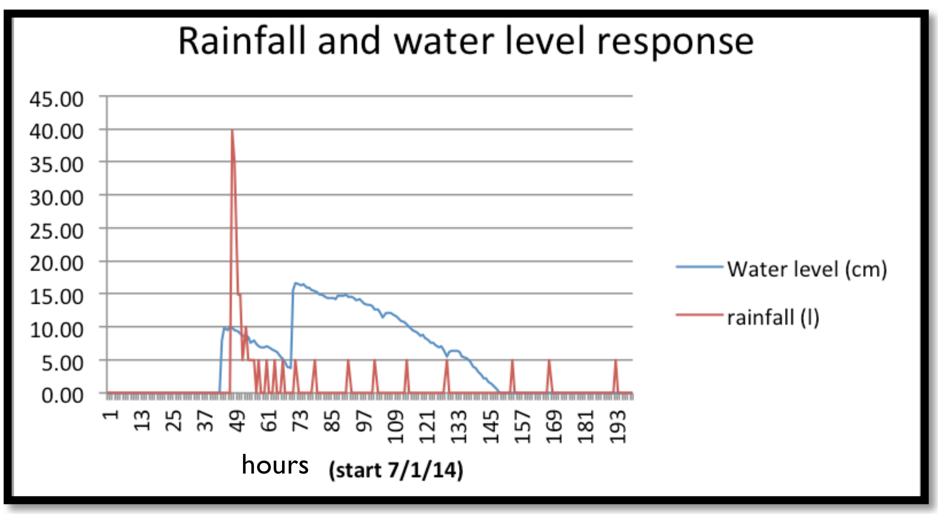


Figure 10: Rain fall (liters) and water level response (cm). Hourly time step. Data shown: Hour 1-197 (July 1-8, 2014).

Figure 10 shows a conceptual respresentation of the water budget of rain garden plot 1 (farthest from Long Island Sound). The water level is shown in centimeters for scale purposes. Groundwater exchange was calculated based on water volume gained by precipitation and parking lot runoff, subtracting volume lost to evapotranspiration, and accounting for storage remaining in the rain garden. As discussed above, not every rain event resulted in the filling of the rain gardens. Groundwater exchange estimates are constrained to non-negative values here. However, Figure 11 shows groundwater exchange estimates as they were calculated, including negative values. (A negative value would imply loss of groundwater to the rain garden—water flowing upwards into the rain garden via the sand wick). While this type of event is definitely possible given Seaside Village's position on the coast above a confining clay layer, the magnitude of the estimates (less than -1000, in some cases) suggest that this budget undersestimates precipitation and inflow, overestimates evapotranspiration and storage, or some combination thereof.

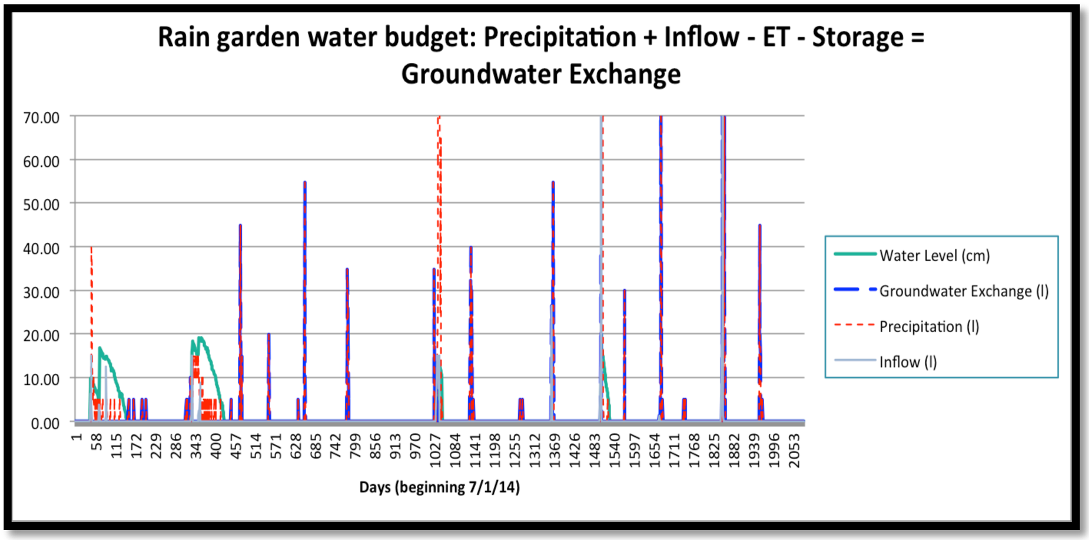


Figure 11: Water level, parking lot inflow, precipitation and groundwater exchange, constrained to 0. Hourly time step. Data shown: July 1-September 30, 2014.

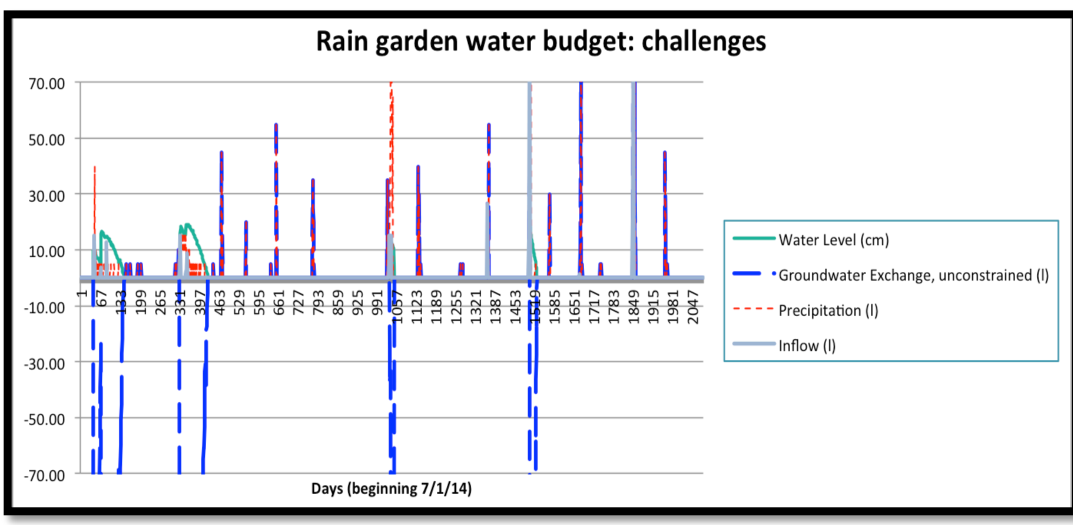


Figure 12: Water level, parking lot inflow, precipitation and groundwater exchange, *not* constrained to 0. Hourly time step. Data shown: July 1-September 30, 2014.

Drainage rates were modeled as a function of rain garden plot treatment. Here, "drainage rates" were taken to mean change in storage per hour, from the hour following a rain event until the rain garden was empty. Due to uncertainty about system inflow described above, during-rain storage and incomplete drainage events were disregarded in the model. Drainage rates were modeled using a generalized least squares regression, with a continuous autocorrelation structure accounting for dependence in time and plot:
*gls(d.STG~LEVEL+soil +plant,corr=corCAR1(form=~DAYS | RG))*

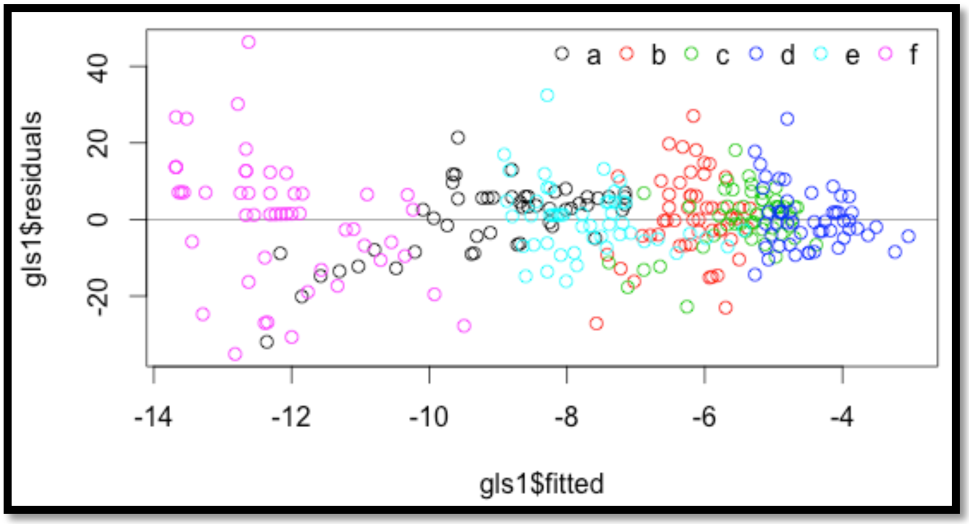


Figure 13: Generalized least squares regression residual plots show that Media A (high sand content, plots a and f) is associated with higher infiltration rates, and Media C (high organic content, plots c and d) is associated with lower infiltration rates. Data shown: July 1-September 30, 2014.

| | Value | Std.Error | t-value | p-value |
|---|---|---|---|---|
| LEVEL | -0.391104 | 0.225038 | -1.7379434 | 0.0832 |
| soilb | 3.173226 | 1.945015 | 1.6314660 | 0.1038 |
| soilc | 4.184624 | 2.103727 | 1.9891479 | **0.0476** |
| plant1 | -1.535024 | 1.869414 | -0.8211258 | 0.4122 |

*Implications for management of coastal rain gardens:* These statistics show that the effect of soil treatment c is significant (p=0.0475), but only when the model includes soil treatment b—indicating that the soil effect, though significant, is not particularly strong. The plant effect is insignificant.

Furthermore, by looking at the magnitude of the residuals vs. the fitted values, one can conclude that the model as it stands explains relatively little of the observed drainage behavior. The statistical results, together with the water budget shown in Figures 10 and 11 provide evidence of the complexity of coastal rain gardens as a subject of study, and suggest that there are major factors outside this model which are controlling the water budget. These are likely related to the instrumentation at the site, as well as precautions taken to the control the experiment as well as the environmental setting. There is reason to believe that the catch basin tipping buckets may become overwhelmed during large storms, when parking lot runoff becomes great enough to overwhelm the rain garden inlet system and the catch basins themselves begin to fill with water. During particularly intense rain, the catch basins may also remain in a tipped position, which would underestimate the number of tips and produce a falsely low estimate of runoff. Another potential source of uncertainty is some metal landscape edging around each rain garden plot, intended to prevent unmeasured runoff from entering the rain gardens. These may not be performing as expected. It also remains possible that, accounting for these errors, confined groundwater is indeed entering the rain gardens from below during high-pressure conditions brought about by tidal conditions and/or heavy rain farther inland.

*Implications for coastal adaptation dialogue*: The addition of aesthetic features brings focus to water at this DEX, recreating the historical wetland landscape in a way that is still recognizable as an urban amenity. Retaining non-experimental features around the DEX allows residents and volunteers to work freely on the site, hold agency and engage with the habitat being created. Ecologists can further urban research by acknowledging and supporting the real need for urban ecology research sites to be visually engaging, and create non-experimental bioretention features which users can nurture and modify, thus remaining actively invested in the project.

The site has shown to be resilient through a series of unforeseen challenges. Despite design alterations, it continues to avert parking lot flooding and retains flexibility as a series of experimental bioretention cells. The community remains engaged throughout the adaptive management process of dealing with hurricane disturbances and intense rainstorms. The process has also facilitated a succession of community-driven public space projects unrelated to the DEX, including an adjacent community garden and dog park. These projects progressed fairly rapidly; both were started and completed this year. These community achievements, which reflect a recognition of agency and a desire to take ownership of underutilized public space, were likely prompted by the most recent (successful) round of planting and instrumentation of the DEX site. Ecologists can encourage further introduction of research sites in urban spaces by remaining committed to individual communities as designed experiments inevitably adapt to complex urban fabrics, and by explicitly recognizing the diverse needs of all involved parties.

CONCLUSION: This experiment provides highly local performance data on green stormwater infrastructure with respect to flooding, and has implications for site management. This research is also yielding qualitative data on plant survival and succession patterns, as well as obvious opportunities for social-ecological research. These data hold relevance for other areas that experience periodic storm surge inundation, impermeable native soils, flat grade and near-wetland growing conditions. Raw data reveal that the rain gardens at the Bridgeport Bioretention Garden receive and infiltrate both rainwater and stormwater runoff, and not all rain events result in rain garden storage. High-sand, low-organic soil treatments are associated with faster drainage rates, and the effect of the effect of the soil treatment is significant. Contrary to what is suggested in the literature, the plant treatment was not significant over these months—suggesting that a sparse planting palette would be for aesthetic value only. Much of the rain gardens' behavior remains unexplained by statistical models, testifying to the complexity of coastal, urban ecological research and suggesting many avenues for future study.

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