Quarter 2 Report for Green Infrastructure Living Laboratory (GILL)
Report Period: **9/1/2018 ~ 11/30/2018**

Grant number: **1620003**	Contract number: **1620003** Period covered: **9/1/2018 ~ 11/30/2018**
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1. Executive Summary

Major activities for the second quarter of FY18/FY19 contract period include further elaboration of the Monitoring and Maintenance App (MMA), further development of the GILL website, winterization of the Boys' Choir Lot (BCL) and comprehensive statistical analysis on the collected data from the BCL, soil moisture sensor installation and data collection at the new rain garden sites, and hydrologic modeling of the Rec. Center RHC. A RESTful API ecosystem using AWS platform was under development to fulfill the real-time service of visualization in MMA and data transferal for IoT device. For the BCL, the outflow measurement systems were collected, carried to the corner of the site, and covered with multiple impermeable layers to ensure safety against freezing during winter. Also, all boxes in BCL containing electrical and sensor equipment were inspected for water leakage and the pressure sensors were removed or protected from the weather. The new paired monitoring rain gardens were equipped with soil moisture sensors and continuous data were collected and analyzed from these sites. To study the impact of precipitation and local site irrigation on the soil moisture data at the new rain garden sites, precipitation data from PWD gages in proximity of the sites and the watering schedules of the PWD contractors were analyzed. For the Rec. Center RHC, a new hydrologic model was built, calibrated, and validated using the monitoring data. Then the hydrologic model was used to simulate the water level inside the RHC during a 10-year simulation period (2007-2017) to evaluate the performance of Real-time Control (RTC) systems in decreasing the cumulative slow release and over flow volumes to the sewer system.

Meetings between the project team and PWD team were held throughout the reporting period, from September 4, 2018 to November 29, 2018. During these meetings, technical issues associated with the monitoring sites were discussed and resolved. These discussions helped the GILL team to better understand the monitoring results and to develop future research directions.

Major goals of the project for the third quarter of the FY18/FY19 contract period:

- Further analysis of the data collected from the new rain garden sites.
- Further analysis of the data collected from the BCL and preparing draft of a journal paper from the results (deliverable #26)
- Further analysis and modeling of the data collected from Rec. Center RHC and preparing draft of a journal paper from the results (deliverable #28).
- Update, revise, and evaluate the Web app.

- Develop multiple APIs to enable visualization and data export platforms for the MMA.

2. Project Updates

a. Existing Monitoring Sites

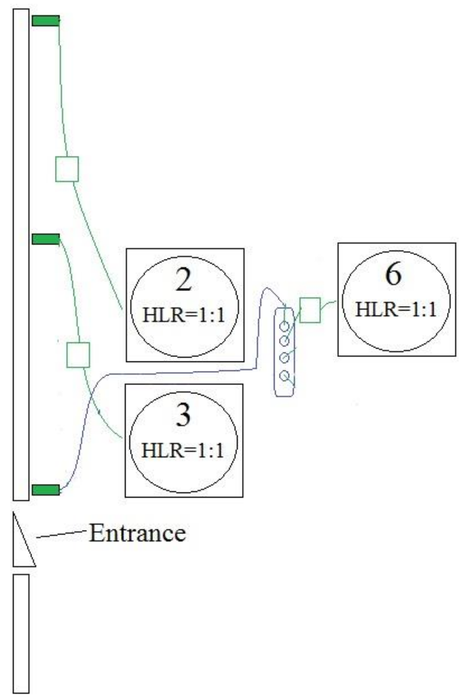
i. BCL

Major field activities at the BCL over the second quarter of FY18/FY19 include statistical analysis on the collected monitoring data and site winterization (Table 1 and Figure 1). Statistical correlation among different precipitation characteristic parameters (e.g. depth, duration, etc.) and soil moisture (e.g. volumetric water content, time to peak, travel time in the soil, etc.) for 1:1 prototypes (e.g. barrels #2, 3, and 6 in Figure 1) were analyzed. The GILL team decided to table the BCL site over the winter months and restart data collection on Spring 2019. Therefore, outflow measurement systems were collected, moved to the corner of the site, and covered with multiple impermeable layers to ensure their safety during winter. A summary of past and future activities are presented in Table 1.

Table 1. Summary of current and future site activities for the BCL

Fieldwork activity summary over this quarter (September 1-November 30, 2018)	**Summary of next steps**
1- Outflow measurement boxes were collected and moved to the corner of the site. 2- Sensor containers were inspected for impermeability against rain. 3- Statistical analysis was performed between precipitation and soil moisture parameters.	1- Data collection will continue. 2- Further analysis of the collected data over previous monitoring cycles and summarize them as a draft of a journal paper (deliverable # 26).

a)



b)

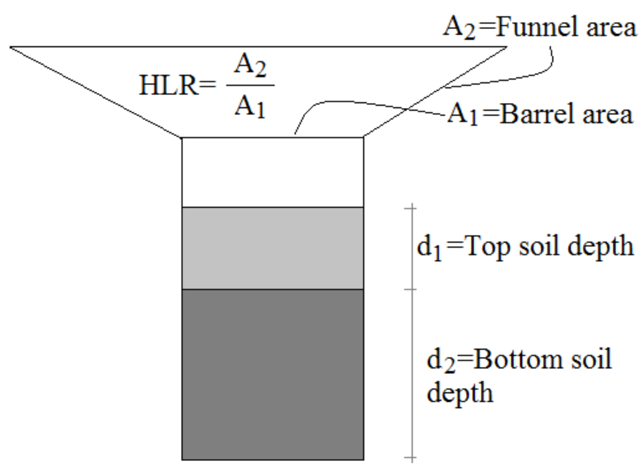


Figure 1. Design configurations for prototypes and power supply distribution at the BCL (Figure 1a) and cross section of funneled prototypes (Figure 1b). The bottom layer soil in all prototypes includes 18 inches of gravel AASHTO #57. The top layer soil for prototypes is 12 inches of high sand soil (prototypes 2 and 6,) and standard stormwater infrastructure soil (prototype 3). HLR values represent the Hydraulic Loading Ratio (HLR) for the prototypes as defined on the diagram.

ii. PISB

Major activities at PISB (Figure 2 and Table 2) over the second quarter of FY18/FY19 contract period include continuous real-time soil moisture data collection using Decagon and Sensoterra sensors (Figures 3, 4, and 5).

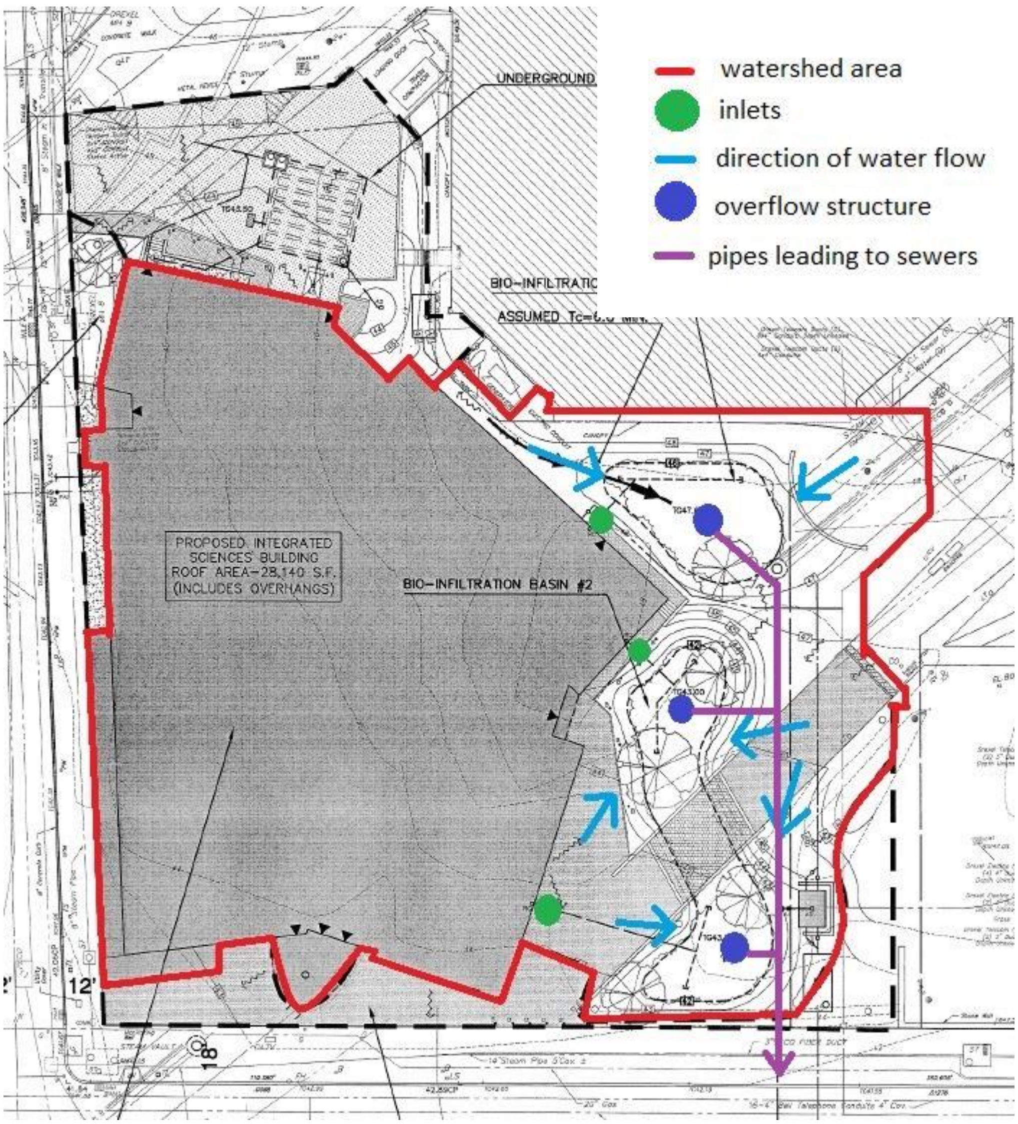


Figure 2. PISB drawing

Table 2. Summary of current and future site activities for PISB.

Fieldwork activity summary over this quarter (September 1-November 30, 2018)	**Summary of next steps**
Continuous real-time soil moisture data collection	Integrate with off-campus rain garden sites

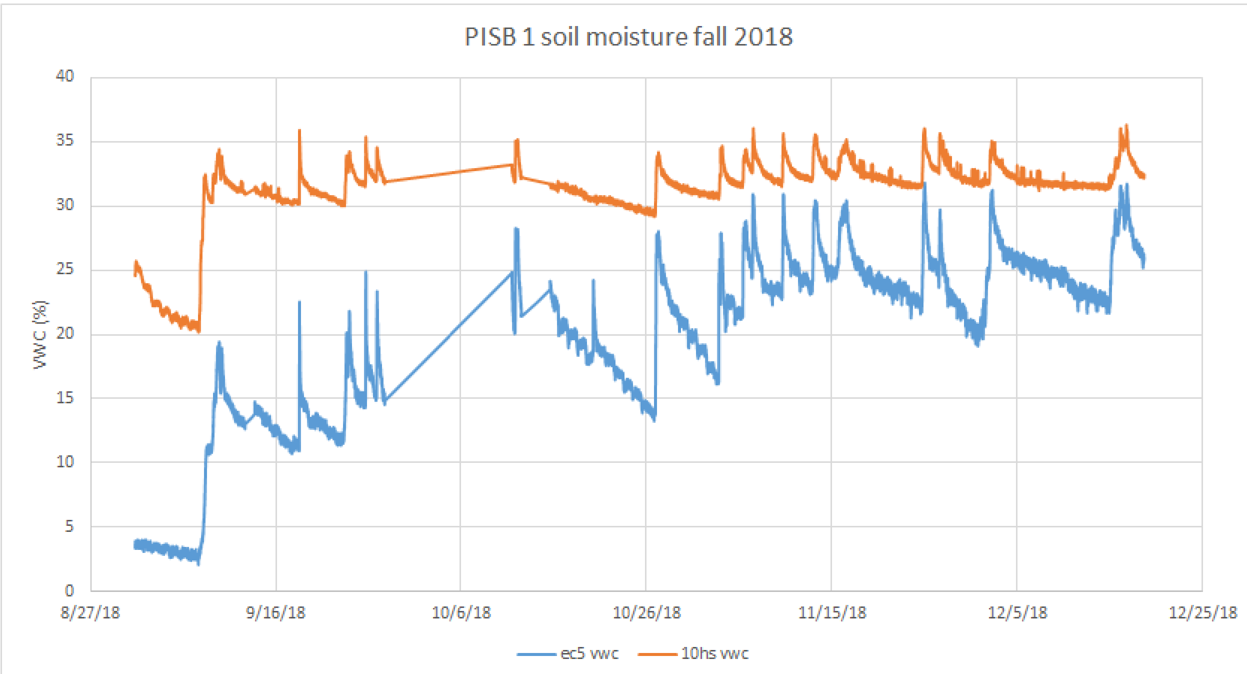


Figure 3. Soil moisture data from PISB 1 between September 1, 2018 and December 17, 2018.

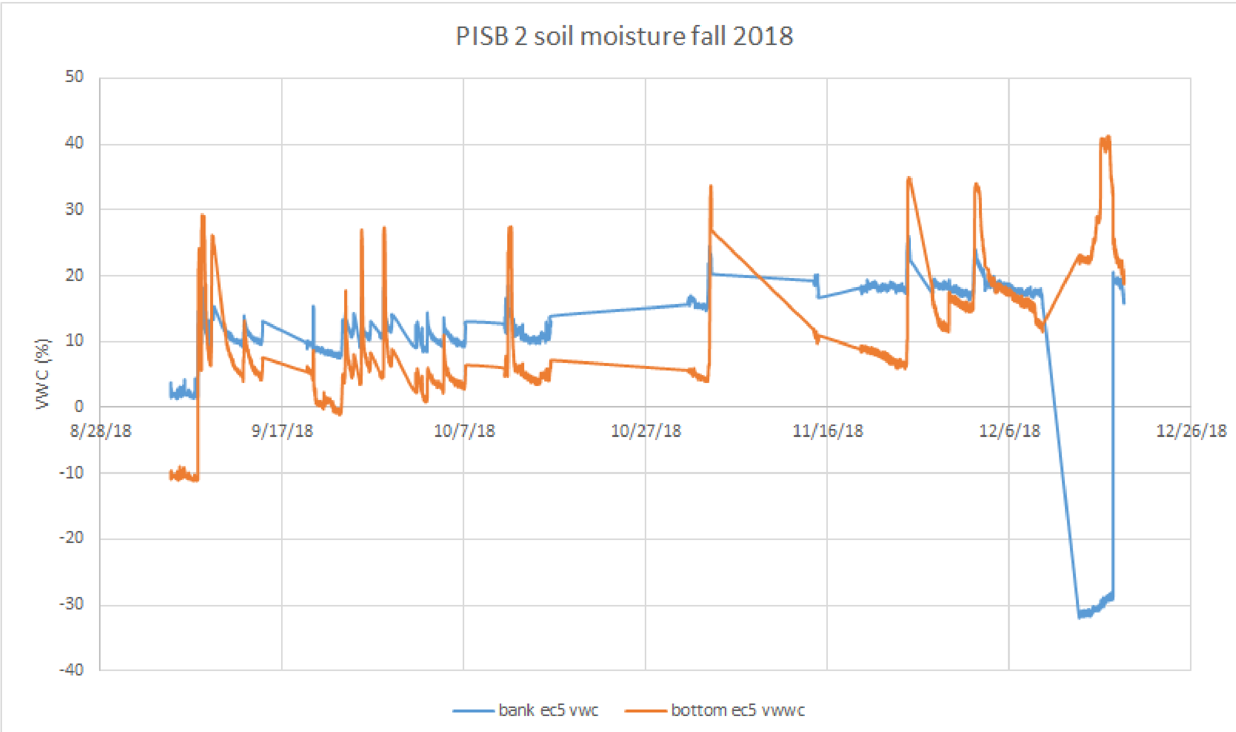


Figure 4. Soil moisture data from PISB 2 between September 1, 2018 and December 17, 2018.

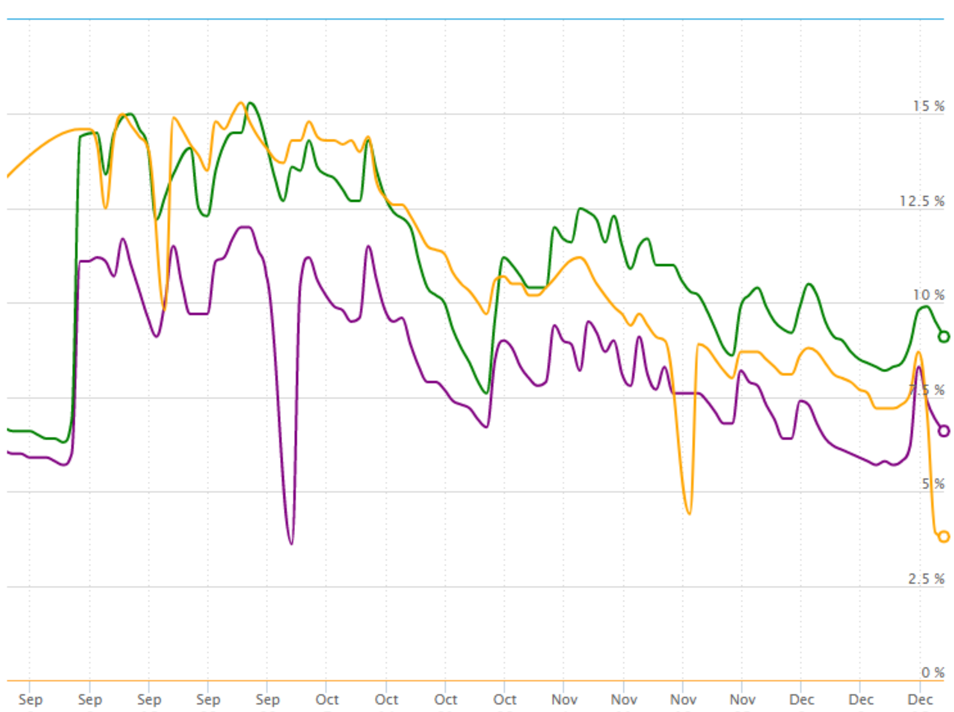


Figure 5. Soil moisture data from Sensoterra sensors at PISB as presented on the Sensoterra web portal between September 1, 2018 and December 17, 2018. The east bank is in purple, the trough is in green, and the west bank is in yellow

iii. Rec Center

Research activities for the Rec Center site over the second quarter of FY18/FY19 contract period (Table 3) include hydrologic modeling of the RHC.

Table 3. Summary of current and future site activities for the Rec Center

Research activity summary over this quarter (September 1-November 30, 2018)	**Summary of next steps**
1- Building a hydrologic model in R to simulate water level in Rec Center RHC. 2- calibrating and validating the developed model for the past monitoring cycles.	1- Use the calibrated model to simulate water level in the Rec Center RHC over a 10-year period (2007-2017). 2- Generating contour plots of percentage reduction in slow release + over flow volume as a function of drainage area and cistern volume.

A hydrologic model was developed in R programming language to simulate continuous water level changes in the Rec. Center RHC over a 10-year period (Figure 6). The model receives hourly precipitation inputs from Philadelphia International Airport and calculates water level in the Rec. Center RHC. First, the roof runoff is calculated as follows:

$$Q = C \times P \times A \quad \text{[Eq. 1]}$$

Where, Q: the inflow runoff volume (m^3), C: runoff coefficient (dimensionless), P: precipitation depth during an individual event (m), and A: drainage area of the Rec. Center RHC which equals 5020 m^2

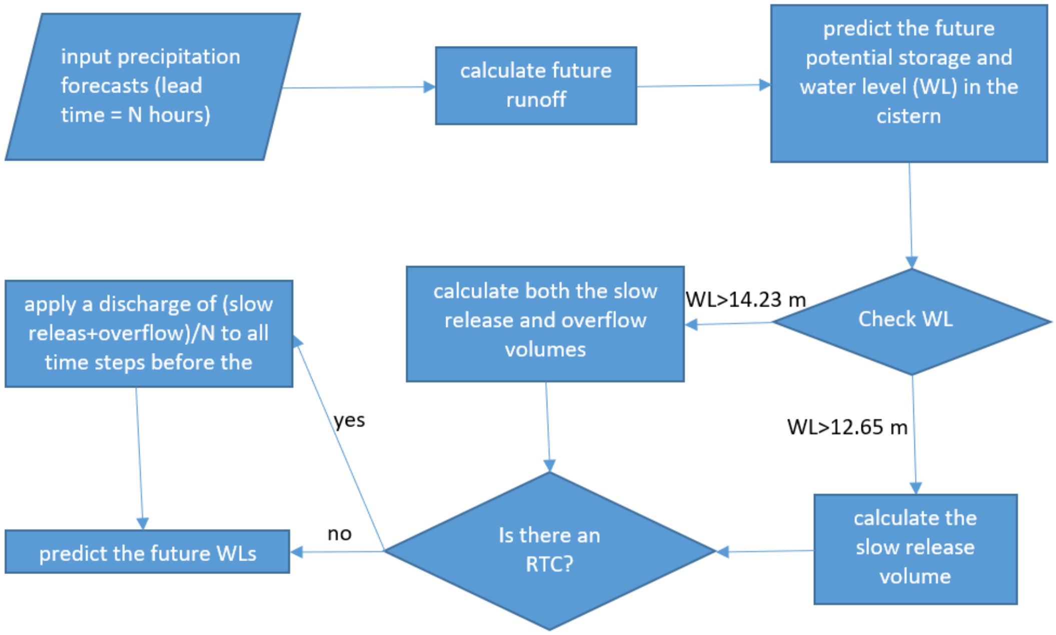


Figure 6. Structure of the hydrologic model used for simulating water level at the Rec. Center RHC. Elevations 12.53 m and 14.23 m correspond to the invert elevations of the slow release and the overflow pipes, respectively.

The predicted event runoff volume and potential water level in the cistern are then calculated using the geometry of the cistern. Next, the potential water level in the RHC is compared with the slow release and overflow pipe invert elevations to figure if the storm event will be followed by a slow release and/or an overflow event. Next, for the RTC-based scenarios, a uniform discharge is applied to empty a fraction of available storage before the event start time. The uniform RTC discharge aims to reduce or eliminate the chance of discharge to the sewer system during and after the event which may potentially contribute to CSO events. It is assumed that the uniform discharge to sewer is always less than the PWD maximum allowed discharge (6.8 lit/s/acre). Finally, the future water level in the RHC is predicted by closing the water budget.

The model was calibrated and validated over three monitoring cycles to include the impact of season change on model parameters. For each cycle, two third of the data was used for calibration and the remaining one-third was used for model validation. Calibration parameters include the runoff coefficient (C in equation 1), leakage outflow rate (cms), and the toilet flush rate (cms). Relative mean squared error between observed and modeled values was used for calibration as follows:

$$RMSE = \frac{\sum_{i=1}^{n}\left(\frac{Q_i^m - Q_i^o}{Q_i^o}\right)^2}{n} \qquad \text{[Eq. 2]}$$

Where Q_i^m and Q_i^o are the ith modeled and observed water levels, respectively.

To study the impact of different hydraulic parameters such as cistern evacuation lead time, water demand, and maximum allowed discharge to the sewer system on the performance of RTC systems, the calibrated model is used to analyze the three following scenarios over a 10-year period (2007-2017) (Table 4):

Scenario 1- the RHC evacuation lead time increases from 3 to 24 hours while all other parameters remain constant.

Scenario 2- The toilet flush demand increases from 1 to 10 m^3/day while all other parameters remain constant.

Scenario 3- The maximum allowed discharge to the sewer system increases from 0.3 to 14 lit/s/acre while all other parameters remain constant.

Table 4. Analysis assumptions for the three scenarios.

Scenario	runoff coefficient	toilet flush use (m^3/day)	Leakage from the RHC (m^3/day)	maximum allowed discharge to the sewer system (Q_{max}) (lit/s/acre)	Lead time
1	0.9	4	2	6.8	3, 6, 9, 24
2	0.9	1, 2, 5, 10	2	6.8	6
3	0.9	4	2	0.3, 1.5, 7, 14	6

The total difference in the sum of slow release and over flow volumes between the base (RHC with no RTC) and the RTC-equipped RHC for the 10-year simulation period is used as a comparison baseline. Contour plots of percent reduction in the sum of slow release and over flow volumes is plotted against drainage area and cistern volume to assess the performance of the RTC in reducing the discharge volume to the sewer system for different site configurations.

Seasonal calibration results indicated a strong agreement between the observed and modeled values (Figure 7). There were only a few short recession periods during which the model underpredicted the observed water levels in the RHC likely due to the clogging of 72-mm slow release orifice (see W1 and W2 in Figure 7). For instance, in W1 window on Figure 10 there is a sudden decrease in the observed drainage rate which is not predicted by the model due to the lack of information about the possible clogging in the cistern's drainage system. In overall, the calibrated parameters varied within a similar narrow range for all seasons (Table 5). Winter had had slightly larger RMSE compared to other seasons due to the lack of snowmelt component in the model. Note that the accuracy of the winter simulations does not greatly impact results of this study due to very small number of slow release events over the winter.

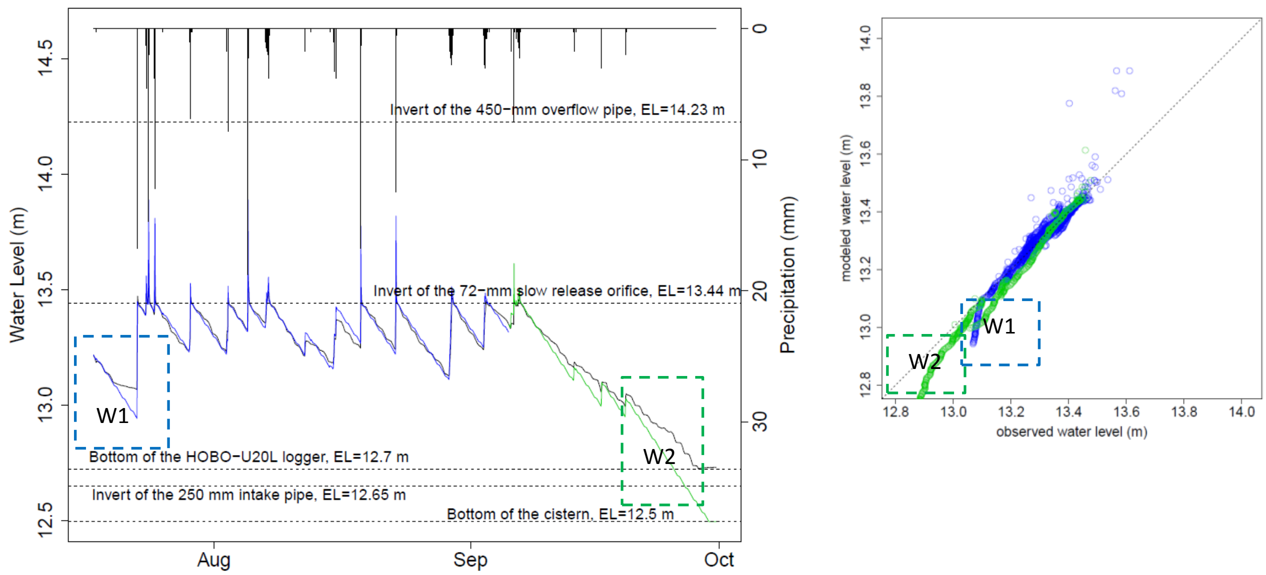


Figure 7. Model calibration/validation results in Rec Center RHC for cycle 3 (July 17, 2017 to September 30, 2017).

Table 5. seasonal calibration results for the Rec. Center RHC

Monitoring cycle	Season	calibrated parameters			RMSE
		C (runoff coefficient)	Leakage rate (l/s)	Flush rate (l/s)	
Cycle 3	Summer/Fall	0.9	1.35	2.65	3.42×10^{-10}
Cycle 4	Winter	0.89	2.19	2.24	7.08×10^{-4}
Cycle 5	Spring	0.89	2.09	2.33	1.62×10^{-7}

b. New Monitoring Sites

After using PWD's Big Green Map tool and many deployments, the new sites for the third year of the GILL project were chosen (Table 6 and Figure 8). The main goal for these sites is to develop an experiment that applies real-time soil moisture and microclimate data to create a data-driven watering schedule. The new sites include seven rain gardens, four of which are on the list of gardens that will receive watering from the PWD maintenance team. The eighth rain garden is PISB, which is an existing GILL site. Each watered garden is paired with a nearby established rain garden. Table 6 summarizes current and future activities for the new rain garden sites.

Table 6- New paired rain garden sites for Year 3 of the GILL project

Final Site Pairings	
Zoo—Parkside	PISB—Mt Vernon
Herron—Weccacoe	Cobbs—Stinger

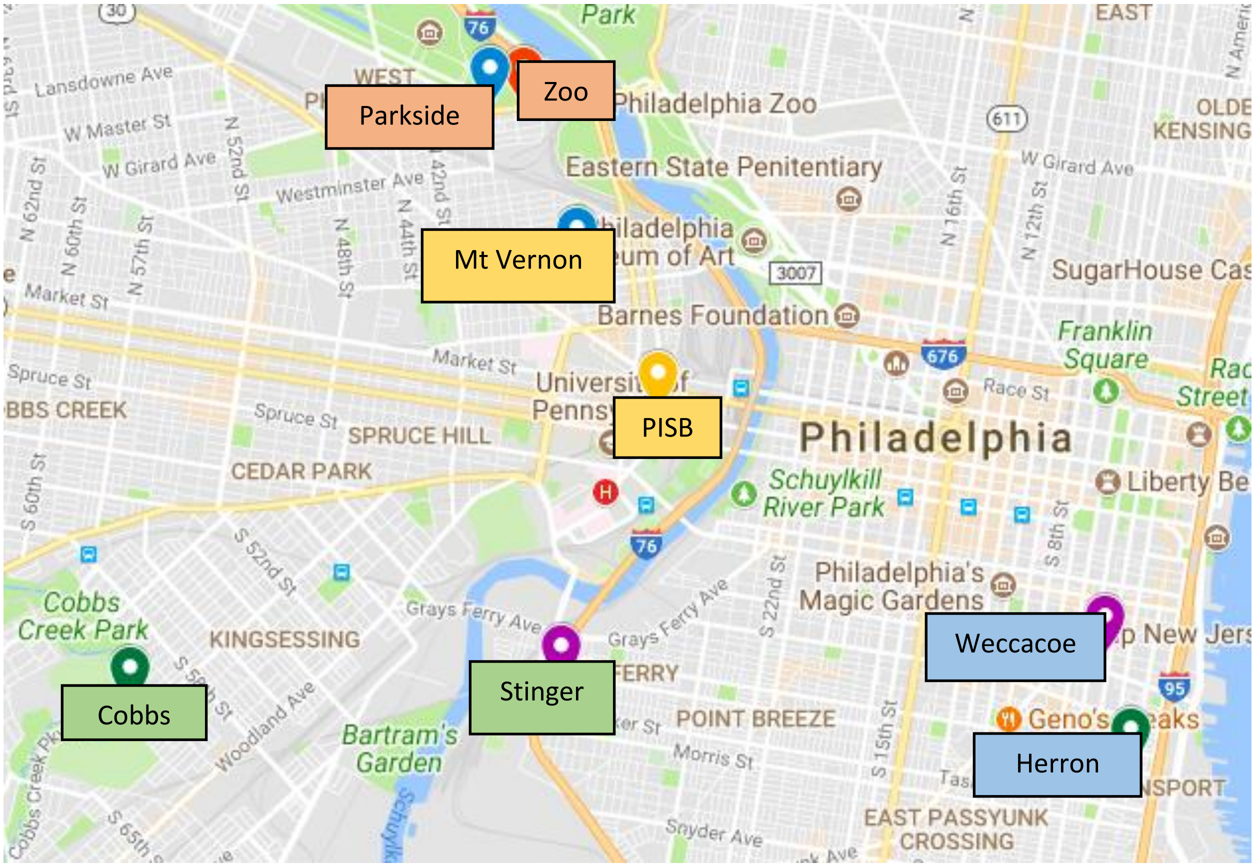


Figure 8. Map of final rain garden pairs

Data was collected at the off-campus rain garden sites until mid-November or later. The monitoring devices were then retrieved. Canopy cover readings and soil samples were collected at the sites.

The original premise of the work was that low-cost soil moisture sensing could help the city to transition from a purely scheduled irrigation regime to one that is data-driven. The custom-built, low-cost IoT monitoring setup performed well, and can be extended to monitor soil moisture on multiple rain garden sites across the city. Significant differences in soil moisture were observed between the bank and the low point of the monitored rain gardens. However, rain garden soil moisture seems to be more closely correlated to climatic conditions during dry spells than to irrigation activities. Additional research is needed to document where and how irrigation water is applied. It is possible that irrigation activities are localized in the rootzones of the plants and thus not detectable by individual soil moisture sensors located below the roots. In that case, additional research would seek to correlate the general soil moisture value with plant health during water stressed conditions.

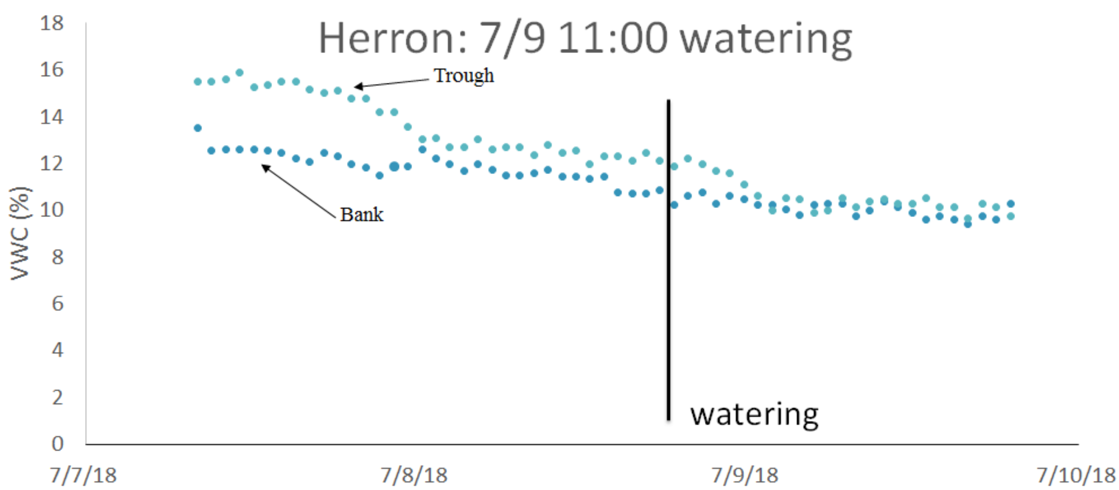


Figure 9. Soil irrigation activities help new vegetation persist through extended dry spells (> 4 days of no rain). However, onsite monitoring of VWC does clearly show a response to irrigation activities.

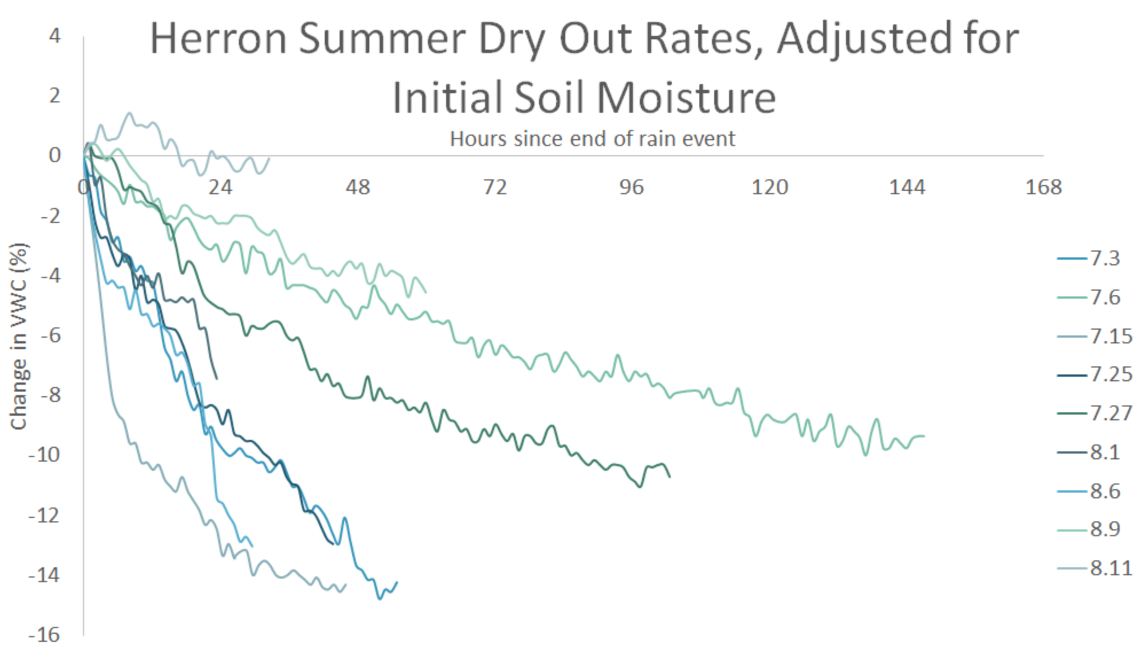


Figure 10. Observed post-rain drying of rain garden bank for nine different events with initial soil moisture removed

Table 7. Summary of current and future site activities for the new monitoring sites

Fieldwork activity summary over this quarter (September 1-November 30, 2018)	**Summary of next steps**
1. Soil moisture, rainfall, irrigation, temperature, humidity, and canopy data collected 2. Devices retrieved from gardens	Continue plotting and analyzing sites data Collect information about irrigation methods

c. Monitoring and Maintenance App (MMA)

Over the first quarter of FY18/FY19, the MMA has been revised to use AWS-based RESTful APIs (Figure 11 and Table 8) for data transferring from all IoT device. The development has been completed and tested for logging data from IoT devices to AWS RDS MySQL database on real time. The data exporting API encountered the data size limits of API in AWS APIGateway. To continue the visualization and data sharing service on GILL website, direct data connection has been made to the MySQL database temporarily. But this process will eventually switch to API for security purpose

The API was developed within AWS platform. The RDS MySQL database was used for data storage for all monitoring information (Figure 11). Data insertion and extraction functions were developed in Python and encoded in AWS Lambda functions which were combined with AWS RDS as an AWS Virtual Private Cloud (VPC). Outside of VPC, AWS API Gateway was used to establish an API portal to execute the AWS Lambda functions with an external triggering event.

The data insertion API has been completed in AWS and implemented in PISB sites. However, AWS API Gateway has a size limit of data exporting of 60KB, which is not sufficient for the visualization and data exporting service in the GILL website development. We have temporarily used direct connections to the database to continue the website development. For the next quarter, this process will be updated using the combination of AWS S3, Lambda function and API Gateway services. Specifically, the Lambda function will extract data from database and save it as a file in S3 with public access for 1 minutes. Then redirect the external API request to the download link of this S3 file. Then the data size of the API function is the URL address which is less than 60 kB. We will also document all the development progress in the next quarter.

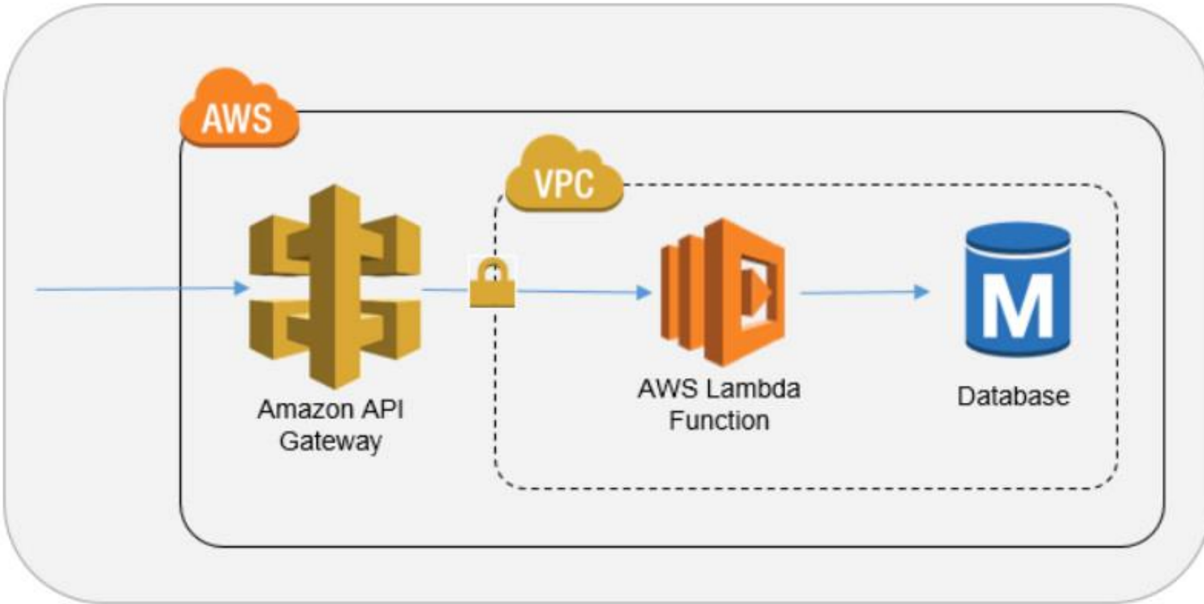


Figure 11. Schematic view of the developed AWS database

Table 8. Summary of current and future site activities for the MMA

Activity summary over this quarter (September 1-November 30, 2018)	**Summary of next steps**
The data transferring process from IoT devices to AWS MySQL database has been updated using AWS API Gateway service.	1- Develop the visualization and data exporting function in GILL website. 2- Update data exporting API using AWS S3. 3- Document all development progress.

3. Summary of Meetings

A summary of meetings over the second quarter of FY18/FY19 contract period, including key meeting topics and action items for each meeting is provided in Table 9.

Table 9. Summary of all meetings in the second quarter of FY18/FY19.

Date	Key Meeting Topic	Action items
9/4/2018	MS advertisement for BCL and new sites	1- Drexel should draft an advertisement for hiring a new BS or MS student to help for BCL and new rain garden sites. 2- Drexel should add the Jefferson green roof to the new sites report and send the edited document to PWD for review. 3- Drexel should develop a hydrologic model for the Rec. Center.
10/02/2018	GILL contract renewal/GILL meeting time reschedule	1- PWD team will follow up with the contract renewal. 2- The next GILL meeting will remain on the same schedule. Meeting time reschedule will start from Oct. 1, 2018. 3- Deliverable review table should be included in all future GILL meeting agendas. 4- Drexel should accomplish new analysis options for the Rec. Center modeling project. 5- Drexel should fit the Horton infiltration equation to the soil moisture data collected from the new rain gardens.
10/16/2018	Chestnut square SRT memorandum/BCL winterization plans	1- Drexel should draft a brief memorandum for the SRT at Chestnut square site and send it to PWD for review. 2- Drexel should address PWD comments for deliverables #23&24. 3- Drexel should prepare a winterization plan for BCL. 4- Drexel should calculate the maximum slow release and overflow discharge values for the Rec. Center modeling project. 5- Drexel should analyze the impact of PWD maximum allowed discharge = 0.05 cfs/acre on the RTC performance.
11/01/2018	BCL sensor winterization plan/lab-scale prototype	1- Drexel should improve the GILL website for faster loading time. 2- Drexel should prepare a plan for sensor winterization at the BCL. 3- Drexel should prepare a plan for a lab-scale BCL prototype. 4- Drexel should prepare on outline for a journal paper from Rec. Center modeling results.
11/15/2018	MetroLab Innovation of the Month-December	1- Drexel should prepare a draft of answers to Metrolab questions and send it tp PWD for review. 2- Drexel should develop a relationship between the initial moisture condition and the recession part of the curve for PISB site. 3- PWD should follow up with the watering team to get the watering schedules for new rain garden sites.
11/29/2018	Database management plan	1- Drexel should prepare a database management plan for GILL. 2- The BCL site should be tabled until next Spring. 3- Drexel should send Metrolab answers to PWD for review.

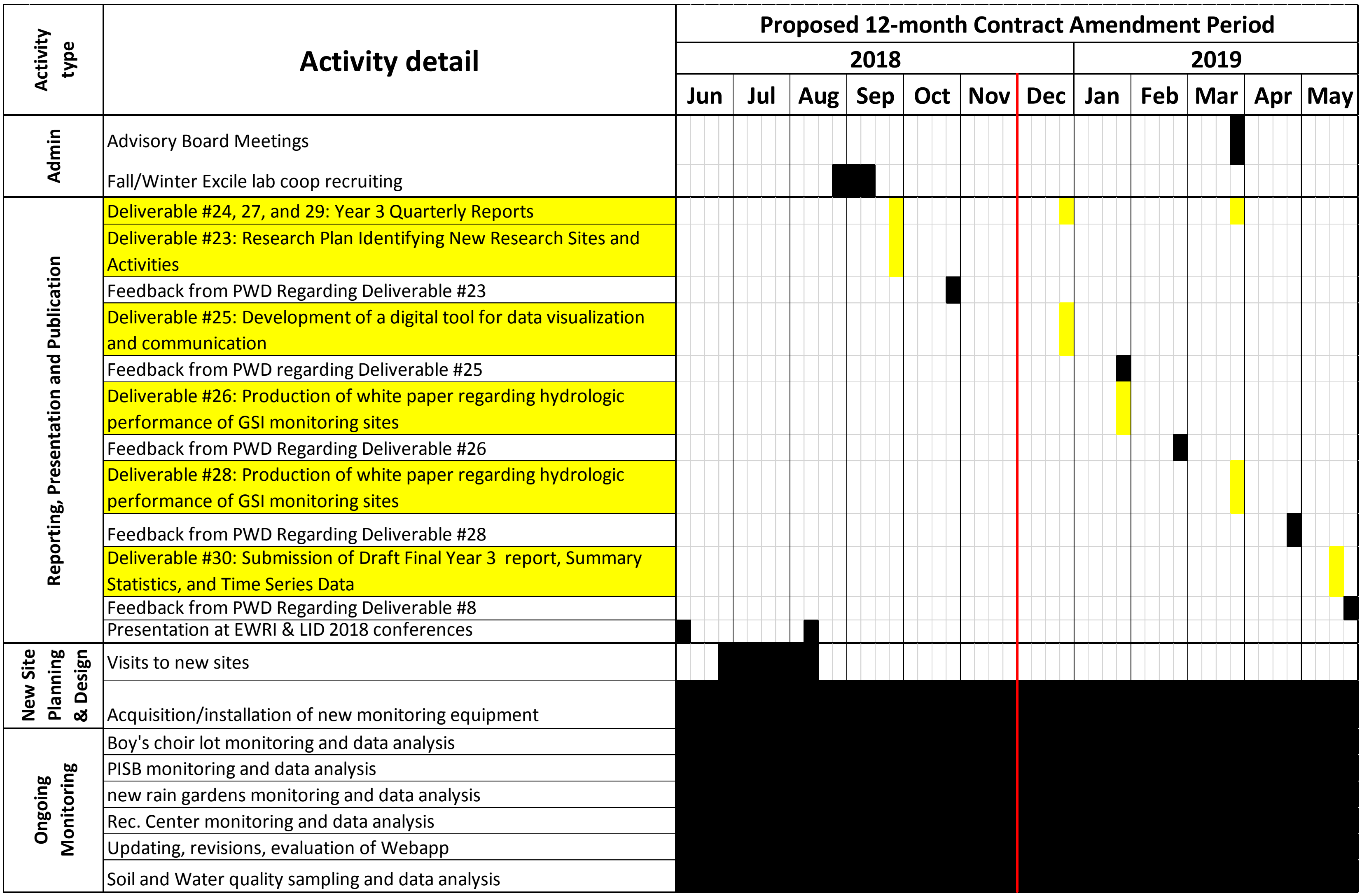
4. Presentations, Communications, and/or Papers

There were no presentations, communications, and conference abstract submission over the second quarter of 2018.

5-Revised timeline and status on deliverable completion

An updated project timeline is shown in Figure 12. The red line separate the second quarter of FY18/FY19 from the remaining period of the project. There were two deliverables due in the second quarter (#23 and 24) which were submitted to PWD on time. Based on this timeline, Drexel research team has met all the project deadlines for the second quarter of FY18/FY19.

Figure 12. Revised timeline for the third year of the GILL project.



A summary of the GILL project deliverables current status for the FY18/FY19 contract period is provided in Table 10.

Table 10. Summary of the project deliverables status for the third year of the GILL project.

Deliverable	Due date	Status
Deliverable #23: Research Plan Identifying New Research Sites and Activities	9/30/2018	Submitted Nov. 1
Deliverable #24: Quarter 1 update report	9/30/2018	Submitted Nov.1
Deliverable #25: Development plan for GILL website	12/31/2018	In progress
Deliverable #26: Production of white paper regarding hydrologic performance of GSI monitoring sites	1/31/2019	In progress
Deliverable #27: Quarter 2 update report	12/31/2018	In progress
Deliverable #28: Production of white paper regarding hydrologic performance of GSI monitoring sites	3/31/2019	In progress
Deliverable #29: Quarter 3 update report	3/31/2019	NA
Deliverable #30: Submission of Draft Final Year 3 report, Summary Statistics, and Time Series Data	5/31/2019	NA