D.C. Water Resources Research Institute
Annual Technical Report
FY 2017

Introduction

The District of Columbia's Water Resources Research Institute, from here on called the Institute, 2017 Annual report provides information on the research, training and information transfer projects funded in 2017 to support the District's efforts to protect and improve water quality. This report is a summary of the Institute's accomplishments for the period of March 1, 2017 through February 28, 2018. The mission of the Institute is to identify the problem and contribute to the solution through applied research and training projects funded through the seed WRRI's grants.

According to the District of Columbia 2018 Integrated report, water quality data collected during 2013 to 2017 showed that the designated uses that directly relate to the human use of the District's waters were generally not supported. Consequently, DC water ways are impaired. The major causes of impairment to the District's rivers, lakes, and estuaries are elevated bacteria and pH and low dissolved oxygen (DO) concentrations. The overall water quality trend shows that the Anacostia River needs attention in DO level, it is actually improving in Fecal Bacteria, Water Clarity, Chlorophyll a, stormwater runoff volume. Toxics, trash, and submerged aquatic vegetation. To address this water quality issue, the DC WASA's combined sewer long-term control plan includes green and gray infrastructure solutions. The green infrastructure solution includes improving tree canopy and construction of green roof, bio retention and rain garden. The gray infrastructure includes construction of large underground tunnels that will serve as a collection and retention system for the combine sewer during rainfall conditions. Supporting the integrated approach of gray and green solutions through applied research is part of the mission of the DC's Water Resources Research Institute.

Housed in the College of Agriculture, Urban Sustainability and Environmental Sciences (CAUSES) of the University of the District of Columbia, the Institute continued building capacity to coordinate water research, training and outreach activities in the District of Columbia in order to enhance the management of quality and quantity of DC waterways. Since 2005, the Institute has provided seed grants for 105 research projects and trained hundreds of graduate and undergraduate students. The seed grants created opportunities for students and new faculties in creating innovative research projects and getting trained in the new water technologies. The seed grant also helped new faculty leverage more extramural funding. As the result of the Institutes effort, the University of the District of Columbia has received about $2 million in financial support over the years to build state-of-the-art research and training laboratories for environmental and water quality testing, as well as modeling and simulation. These laboratories facilitated the establishment of new professional science master's programs, including water resources management, urban sustainability, and urban agriculture.

In 2017, the Institute funded and implemented eight research projects that address key water issues in the District. The overarching goal of these projects includes identifying city water resources and environmental problems and contributing to their solutions. About 30 graduate and undergraduate students were directly involved in the research projects of the reporting period, and many more students were indirectly benefited from the training program associated to the funded research projects in the water quality testing technologies through lab and field experiences.

Partially funded through the administrative project, the Institute also manages two state-of-the-art laboratories: water and environmental quality testing laboratory, and water and environmental quality modeling and simulation laboratory. The water and environmental quality testing laboratory became accredited by the National Environmental Laboratory Accreditation Program (NELAP) with NELAC standard in October 2015 through the State of New Hampshire Environmental Laboratory Accreditation Program. The lab is now nationally accredited for trace metals, minerals and water hardness in potable and non-potable waters. This reporting period, the Institute expanded its national laboratory accreditation two important areas: (1) trace metals and mineral analysis in soil, bio-solids or solid samples, and (2) total coliform and E Coli in potable and non-potable water. The lab is now in the process of expanding its NELAP accreditation for pesticides analysis. This NELAP accreditation is the 1st of its kind in the Washington, DC metropolitan area and has a significant impact in enhancing the research and training capacity as well as community service at UDC.

Research Program Introduction

In FY 2017, the Institute funded eight research projects that address three research areas: hydrology and stormwater management, water quality, and green infrastructure. The progress report of Dr. Sasan Haghani's project introduces the analytical methods to measure runoff quantity from the green infrastructure (GI) such as green roof systems. The proposed analytical method can be applied as a tool for the performance evaluation of the green infrastructure. The proposed tool can help extract key performance parameters, including precipitation hyetographs, runoff hydrographs, runoff volume, peak flow, time base of runoff hydrographs as well as green roof outflow hydrographs.

The progress report of Dr. Kamaran Zendehdel compares the difference between intensive (deep) and extensive (shallow) greenroofs in mitigating stormwater runoff at its source. The incentives policy treats both green roofs the same. In reality, the intensive greenroofs are heavier and require a higher initial investment and more maintenance over the long term than extensive greenroofs. In addition, intensive greenroofs generally require more structural support to accommodate the weight of the additional growing medium and public use. The proposed research compares the effectiveness of intensive and extensive green roofs using in-situ experimental design integrated with sensor technologies.

The progress report of Harris Trobman introduces the importance of developing guidelines for the maintenance of green roofs. There is no city wide maintenance plan or national standards for GI practices maintenance guidelines. This project aims to better inform the design, construction, and maintenance of green infrastructure. UDC is currently working with DC Water to conduct GI trainings for maintenance and operations of Green Infrastructure Practices.

The progress report of Dr. Victoria Connaughton investigates the application of rear zebrafish eggs/larvae to track changes in growth, survival, behavior, and anatomy of fish as an index of overall water quality. The study aims to develop a bioassay, with zebrafish, that can be used to examine the overall health of the Anacostia. The proposed methods complement the use of macroinvertebrates such as clams for tissue accumulation of chemicals in surface waters.

The progress report of Dr. Stephen MacAvoy examines the relation of nutrient and land use patterns in the tidal Anacostia River. The project compares the urban and the suburban areas in terms of organic and in-organic pollutants, including nitrate, poly aromatic hydrocarbons and calcium. The preliminary data indicates calcium and nitrate concentrations are higher in the suburban sites than in the urban sites of the Anacostia River watershed.

The progress report of Dr. Carol Salomon introduced the application of genetic tools in monitoring main water quality indicators such as fecal bacteria, chlorophyll a, and toxins in the Anacostia River. The goal of this study was to use bioinformatics to have a better resolution of "possible contaminants of concern" such as toxic and harmful algae, pathogenic bacteria and viruses and how their abundance is influenced by nutrient loading as the result of installation of gray infrastructure, the Anacostia River Tunnel system.

The progress report of Dr. Leila Farhadi introduces a new integrate state-of- the-art computational and data assimilation techniques that enable the quantification and mapping of the evapotranspiration and recharge flux using spaceborne and airborne remote sensing measurements of land surface state variables. The ultimate goal is to quantify these fluxes over the Chesapeake bay watershed at spatial scales of several hundred meters to several kilometers (order 0.1–10 km) and temporal scales of 1–3 days, relevant to the current and foreseeable range of applications in water resources and operational weather and climate predictions.

Measurement and Performance Analysis of UDC Van-Ness Campus Green Roof System with automated sensors

Basic Information

Title:	Measurement and Performance Analysis of UDC Van-Ness Campus Green Roof System with automated sensors
Project Number:	2017DC186B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Hydrology, Water Quantity, Methods
Descriptors:	None
Principal Investigators:	Sasan Haghani, Pradeep K. Behera, Sassan Aflaki

Publications

There are no publications.

Design and Implementation of Intelligent Green roof system

Progress Report

PI: Sasan Haghani, Ph.D.

Department of Electrical Engineering,

Co-PI: Pradeep K Behera, Ph.D., P.E, D.WRE

Department of Civil Engineering,

School of Engineering and Applied Sciences

University of the District of Columbia

April, 2018

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Executive Summary

Storm water management is one of most important issues the District of Columbia faces. The inadequate capacity of the combined sewer system and the wastewater treatment plant, a large amount of combined storm-water and raw municipal wastewater is discharged into the local receiving waters such as Anacostia River, Potomac River and Rock Creek. The Anacostia River is identified as one of the most polluted water bodies in the nation and there are many efforts going on to reduce the amount of pollution in this water body. The highly urbanized area of the District and associated anthropogenic activities and vehicular pollution results in storm-water is also highly polluted with various toxic organic compounds, metals, nutrients and pathogens. The Chesapeake Bay Program estimates that urban and mixed open areas account for 18 % of nitrogen and 29 % phosphorous loadings to the Chesapeake Bay and the share of nutrient loads from urban areas is growing.

The University of the District of Columbia (UDC) Van Ness campus covers approximately nine acres. Over 75 % of the nine acres is impervious area. It contains eleven buildings and is located directly above a metro red line stop. The site is located along an ultra-urban commercial avenue. The corridor was largely built during early 1980s with the completion of the metro line, however lot level development and redevelopment continues. The site drains to the Municipal Separated Sewer System (MS4) and is the largest single land user contributing to the site's two discharge outfalls. These outfalls discharge to the Rock Creek in 4 the Soapstone Valley Park around Audubon Terrace less than half a mile from the campus. Through the funding from the District of Columbia Department of the Environment (DDOE) UDC campus service is retrofitting approximately 130,000 square feet of new green roofs at the UDC Van Ness campus.

The outcome of the research done was to provide the real world performance of the green roof systems in controlling runoff quantity from the subject green roof systems as well as for any such system within the District of Columbia. For this purpose, a measurement system was implemented so that different measurements from a green roof, such as soil moisture, runoff quantity, temperature, etc. can be measured and sent to a base station.

Introduction

In spite of massive public investments in sewage and drainage infrastructure, water quantity problems (i.e., flooding, erosion and sewer back up) and water quality problems (i.e., pollution loading) from wet-weather flows continues to have significant impacts on receiving waters. Management of urban stormwater has been a major issue for a number of metropolitan cities in the United States. Poorly designed storm water drainage system poses both quality and quantity issues as pollution and waste is transported by stormwater. The transportation of waste and pollution presents problems on public health and environmental quality. Similar to many older cities in the nation, the sewer system in the District of Columbia is serviced by both combined and separate sewer systems. It has recognized that these systems contribute significant pollution to the Anacostia and Potomac Rivers and Rock Creek through Combined Sewer Overflows (CSOs) and Storm Sewer discharges during wet-weather (i.e., rainfall and snowmelt) events. These overflows and associated pollutant loads can adversely impact the quality of the receiving waters. To address these problems, the District of Columbia Water (DC Water) has been implementing a Long Term Control Plan (LTCP) that include underground tunnel system which will capture stormwater runoff during rainfall period and will be treated through treatment system gradually.

As a supplement to expensive LTCP and to address the above mentioned stormwater problems District also focused on reducing peak stormwater runoff, delaying the peak, reducing the runoff volume and reducing the associated pollutant load as much as possible. A low cost and sustainable way of reducing the adverse effects of stormwater is to use Low Impact Development (LID) practices such as but not limited to retention, detention, bioretention ponds, green roof, permeable pavements, and constructed wetlands. The implementation of LID systems has been popular over last decade compare to the end-of-the-pipe treatment system. Moreover, the emphasis on the green infrastructure that includes LID system is gaining traction over last couple of years. As a result, several cities are implementing green roof systems for the large buildings. However, there are limited studies are available for the evaluation of the performance of green roof system in controlling the runoff quantity and quality.

The availability of many flat roofs in the city makes ideal to implement green roofs as a means of quality control. The purpose of this project was to build a device that consists of different sensors and measures the stormwater runoff from the green roof, located at the University of the District of Columbia, Van-Ness campus. The device consists of soil moisture sensor, temperature sensor, water flow sensor, rain sensor and humidity sensor. All the sensors collect data such as soil moisture at different depth and project the data in an organized table.

Different factors such as land availability and cost can make it difficult to implement these stormwater management systems. For this particular reason green roofs have become the main focus for the District. Having an analytical tool for green roof system that is able to predict the performance of runoff volumetric control that can be useful for water resources engineers, planners and regulators.

Research Objectives

The overall goal of the proposed study is to evaluate the performance of green roof systems which will be useful for urban stormwater management analysis. The newly build green roof systems is located in the roof top of building 44 at the UDC campus at the Van-Ness. At this stage the research will focus on the performance evaluation of runoff quantity; the proof of concept by focusing on a small area of the District. The objectives of the research include:

* Development of analytical methods to measure runoff quantity from the green roof systems by installing appropriate equipment.

* Several performance parameters can be extracted from the recorded data and can be calculated (i.e. Precipitation hyetographs, runoff hydrographs, runoff volume, peak flow, time base of runoff hydrographs as well as green roof outflow hydrographs)

Methodologies and Results

To To design the sensor network, different sensors along with a Raspberry PI was used. Design specifications are provided below. An overview of the complete design is given below in Figure 1.

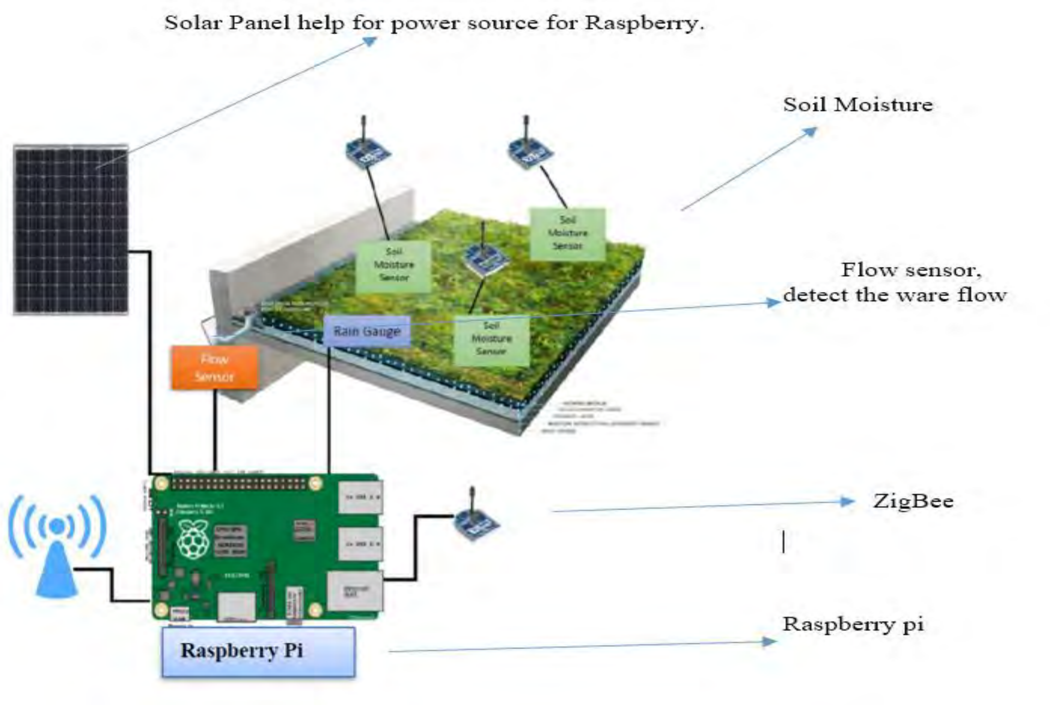

Figure 1: Green roof Sensor System Overview

Following presents a detailed description of the sensors and the connections to the Raspberry PI are given.

Rain Sensor

The rain sensor and raspberry pi 3 are connected as shown in Figure 2.

Figure 2: Rain sensor and Raspberry Pi 3.

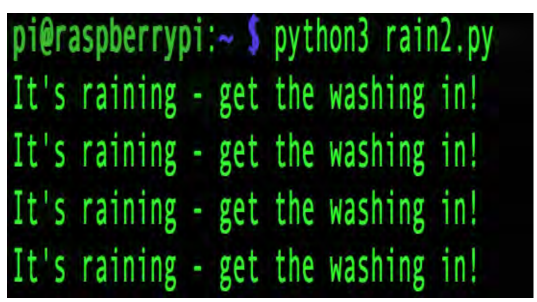

Figure 3: The output of the rain sensor.

The connection shows that raindrop alert sensor kit in use with a Paspberry P 3. The function is to use a simple raindrop sensor and Pi alert when it rains. In that case, the water flow from the tank will stop. When no raindrops are on the sensor, the sensor controller's (digital output) pin in High (3.3V in our case). When raindrops are detected this changes to Low (0V). By connecting digital output to a GPIO port on the Raspberry Pi (GPIO 18) can read the status and set off the buzzer (on GPIO 13) when rain is detected. When rain is detected, the sensor sends the data to the screen which indicates it's raining as shown in Figure 3.

The code implemented on the Raspberry Pi is included below in Figure 4.

```
from time import sleep
from gpiozero import InputDevice
no_rain = InputDevice(18)
def chk_rain(iterations):
for x in range(iterations):
sleep(0.1)
while True:
if not no_rain.is_active:
print("It's raining ")
# insert your other code or functions here
# e.g. tweet, SMS, email, take a photo etc.
sleep(1)
```

Figure 4. The code for the detection of raindrop developed using Python

Soil Moisture Sensor

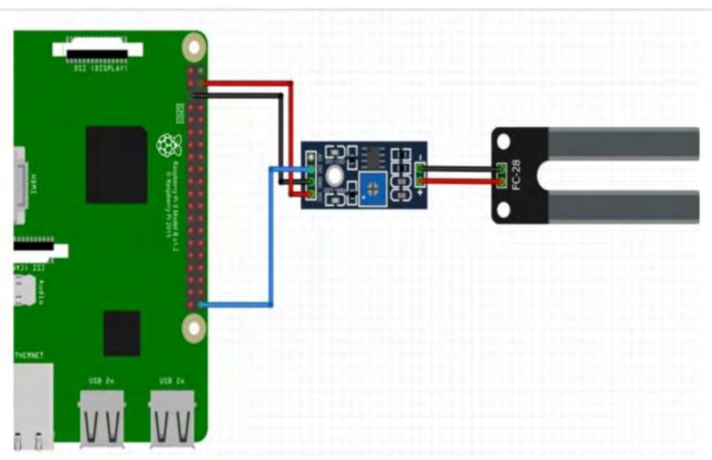

Figure 5: The connection between Soil moisture sensor and Raspberry Pi-3.

The main purpose of this hardware is to let us get soil moisture readings. The function of the soil moisture is sensing the moisture of soil and sending data to the base station. In that case, the greenroof manager will be notified of the level of moisture and can plan accordingyl . The setup of the system is shown on Figure 5. As shown in Figure5, a Raspberry Pi 3, pcs jumper cable, and Soil moisture sensor are connected where the connections are as follows: VCC goes to 5V, GND to GND, SIG to GPIO 21. The following code, shown in Fifure 6, is developed in Python and is downloaded on the Raspberry Pi for the operation of the soil moisture data.

```
#!/usr/bin/python
import RPi.GPIO as GPIO
import time
#GPIO SETUP
channel = 21
GPIO.setmode(GPIO.BCM)
GPIO.setup(channel, GPIO.IN)
def callback(channel):
if GPIO.input(channel):
print ("no Water Detected!")
else:
print ("Water Detected!")

GPIO.add_event_detect(channel, GPIO.BOTH, bouncetime=300) # let us know when the pin goes HIGH or LOW
GPIO.add_event_callback(channel, callback)  # assign function to GPIO PIN, Run function on change

# infinite loop
while True:
callback(21)
time.sleep(1)
```

Figure 6. The code for the detection of soil moisture developed using Python

Humidity and Temperature Sensor

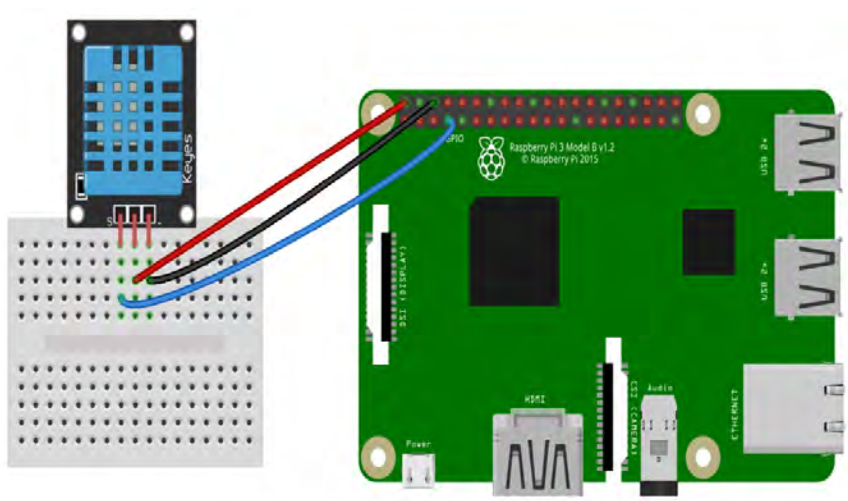

Figure 7: Humidity and Temperature sensor connections with Raspberry Pi-3

The connection of the humidity and temperature sensors to the Raspberry Pi are showin in Figure 7. The DHT11 is used for temperature and humidity sensor to provide digital temperature and humidity reading from the environment of green roof. The selected sensors are also very popular in remote weather station, soil monitors, and home automation system. The following code is used to obtain the data from the temperature and humidity sensors.

```
import sys
import Adafruit_DHT
while True:
humidity, temperature = Adafruit_DHT.read_retry(11, 4)

print 'Temp: {0:0.1f} C  Humidity: {1:0.1f} %'.format(temperature, humidity)
```

Figure 8: Code implemented on Raspberry Pi-3 to read temperature and humidity sensor data

Water Flow Sensor

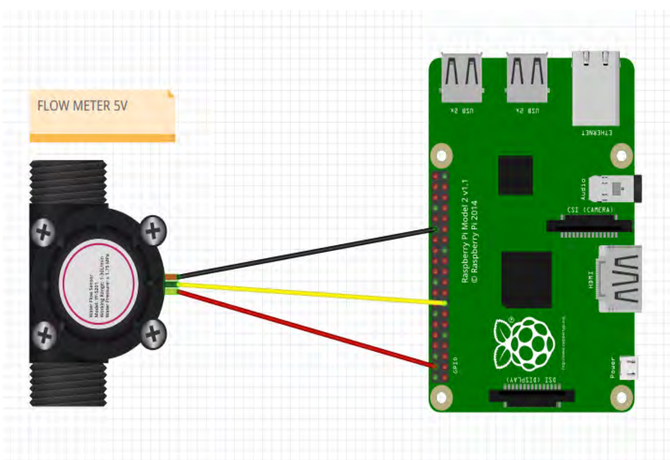

Figure 9: Water flow sensor with Raspberry Pi-3.

The function of water flow sensor is to notify the base station whether water is flowing into the green roof. As we can see from the screenshot, the flow sensor has three wires.

- Red – 5V
- Black > GRDN
- Yellow > Signal.

Red wire is connected into 5V of raspberry GPIO 5V. As we know black wire is connected into GND, and Yellow wire is connected into GPIO 26 of raspberry pi – 3 which is the signal. The following code was developed for the operation of the water flow sensor.

```
import RPi.GPIO as GPIO
import time, sys
FLOW_SENSOR = 22
GPIO.setmode(GPIO.BCM)
GPIO.setup(FLOW_SENSOR, GPIO.IN, pull_up_down = GPIO.PUD_UP)
global countcount = 0
def countPulse(channel):
global countif start_counter == 1:
count = count+1 #print (count)
flow = count / (60 * 7.5) #print(flow)
GPIO.add_event_detect(FLOW_SENSOR, GPIO.FALLING, callback=countPulse)
while True:
try: start_counter = 1
time.sleep(1) start_counter = 0
flow = (count * 60 * 2.25 / 1000)
print ("The flow is: %.3f Liter/min" % (flow))
count = 0 time.sleep(5)
except KeyboardInterrupt:
print ('\nexiting')
GPIO.cleanup()
sys.exit()
```

Figure 10: Code implemented on Raspberry Pi-3 for the flow sensor

Project Outcomes

The outcome of the research is to provide the real world performance of the green roof systems by implementing a wireless sensor monitoring system. The research included the measurement of precipitation at the green roof location, soil moisture, and runoff quantity during and after the storm event with automated sensors. The measured data can be used to develop runoff hydrographs. The outcome of this research can be used in the simulation models for green roof systems. Moreover, the data and knowledge base generated from this research can be useful for the development of green roof design guidelines for the District as well as for similar climatic regions of North-East U.S.

Student Supports and Benefits

Three undergraduate students worked on this project. Zerihun Biru and Kaleb Lambebo from the Computer Science Department and Dilnesa Nukuro from the Electrical and Computer Engineering

Department participated in the design of the green roof wireless sensor monitoring system. Senior student Dilnesa Nukuro also is currently using this project as his senior capstone design project in the department of electrical and computer engineering.

Not only students from various backgrounds worked on this project together, but the project also gave two faculty members from the departments of electrical and computer engineering and civil engineering to work and interact with each other.

External Funding

As a result of the collaboration on this project, the PIs Dr. Haghani and Dr. Behera collaborated together on a Targeted Infusion Project which is under consideration for funding from the National Science Foundation.

Conclusion

In this project a wireless sensor network for green roof monitoring, consisting of various sensors was implemented. The system is capable of measuring several factors such as soil moisture, the presence of rain, humidity and temperature. The system is also capable of detecting whether water is entering the green roof infrastructure or not.

Acknowledgement

The PIs and the undergraduate students are grateful for the support they have received through the DC WRRI for this project.

Reference

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- Hac, Anna. *Wireless sensor network designs*. John Wiley & Sons Ltd, 2003. VanWoert, Nicholaus D., et al. "Green roof stormwater retention." *Journal of environmental quality* 34.3 (2005): 1036-1044.
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In-Situ Comparison of Extensive and Intensive Greenroof Infiltration

Basic Information

Title:	In-Situ Comparison of Extensive and Intensive Greenroof Infiltration
Project Number:	2017DC187B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Education, Methods, Water Quantity
Descriptors:	None
Principal Investigators:	Kamran Zendehdel, Harris Trobman

Publication

1. Zendehdela, Kamran, Paul Avellanb, Tony Fitzgeraldc. 2018. Closing the loop, the UDC community compost project as part of the UDC food hub concept, Poster Presentation, NCR-AWRA Annual Water Symposium.

In-Situ Comparison of Extensive and Intensive Greenroof Infiltration

Kamran Zendehdel (PI)

Harris Trobman (Co-PI)

UDC CAUSES

Center for Sustainable Development

May 10th, 2018

1. Executive Summary

Greenroofs are effective technique in dense cities such as Washington DC, where so much surface area is taken up by roofs. Greenroofs provides an opportunity to mitigate stormwater runoff at its source. Two main greenroof categories are defined based on substrate depth: *intensive* (deep) and *extensive* (shallow). Compared to extensive greenroofs, intensive greenroofs are heavier and require a higher initial investment and more maintenance over the long term than extensive greenroofs. In addition, intensive greenroofs generally require more structural support to accommodate the weight of the additional growing medium and public use.

Despite the large difference in soil volumes among intensive and extensive systems they are generally treated the same for stormwater credits. There has not been a side by side research comparison of the two systems to compare each system's impacts on runoff. In this research we investigate the impact of growing media depth (intensive vs. extensive) in stormwater retention and detention while taking into account various stormwater events. We used the UDC greenroof and its three existing media depths and developed an experimental design to study stormwater retention, detention and associated water quality. We aim to answer the following questions: Does an extensive roof manage just as much stormwater as an intensive roof? How does soil saturation impact this? And do intensive roofs potentially play a larger role in reducing flooding?

2. Introduction

During the last few decades, researchers developed techniques known as green infrastructure practices such as greenroofs, rain gardens and permeable pavers to minimize stormwater problem. Among these technologies vegetated roofs, garden roofs, or greenroofs are becoming more widely used in the United States. A greenroof is a multilayer roof made up of a waterproof layer, protection layer, drainage layer, media layer, and vegetation layer. The system enables water to be detained on the roof during rain events, reducing the flow of runoff from the roof. Greenroofs are an important technique to manage urban runoff. Greenroofs are effective technique in dense cities such as Washington DC, where so much surface area is taken up by roofs. Greenroofs are helping DC minimize its stormwater problem, reduce heat island effect, improve the biological diversity of the city, save energy for cooling and heating buildings and make the city more resilient against storm events. DC leads many large cities in North America in greenroof installed (square feet) over the past few years.

Greenroofs provides an opportunity to mitigate stormwater runoff at its source. Two main greenroof categories are defined based on substrate depth: *intensive* (deep) and *extensive* (shallow). Compared to extensive greenroofs, intensive greenroofs are heavier and require a higher initial investment and more maintenance over the long term than extensive greenroofs. In addition, intensive greenroofs generally require more structural support to accommodate the weight of the additional growing medium and public use.

The thin depth of substrate for an extensive greenroof limits the plant height and species that can be grown without irrigation (Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006), but they are better suited for retrofit applications due to lighter weight requirements compared to their intensive counterparts. The maximum soil depth in extensive greenroofs is 6 inches, which allows shorter plants such as sedum with shallow roots to easily grow. In intensive greenroofs, the soil depth varies between 6 to 15 inches. The extensive greenroofs are cheaper to build than intensive greenroofs ($5 - $25 compare to $25-$40 respectively) and need less maintenance compare to intensive greenroofs.

In this study we focused on the following questions:

1. What is the link between the depth of growing media on a greenroof and stormwater retention under various storm events?
2. What is the link between the depth of growing media on a greenroof and stormwater detention under various storm events?
3. What is the link between the depth of growing media on a greenroof and the water quality leaving a greenroof under various storm events?
4. How should new greenroof regulations and financial incentives consider the depth of growing media depth in stormwater retentions and detention?

3. Methodologies

In this study, we used the UDC greenroof and its three media depth to study stormwater retention, detention and associated water quality. Figure 1 present the experimental design that we will use to collect data.

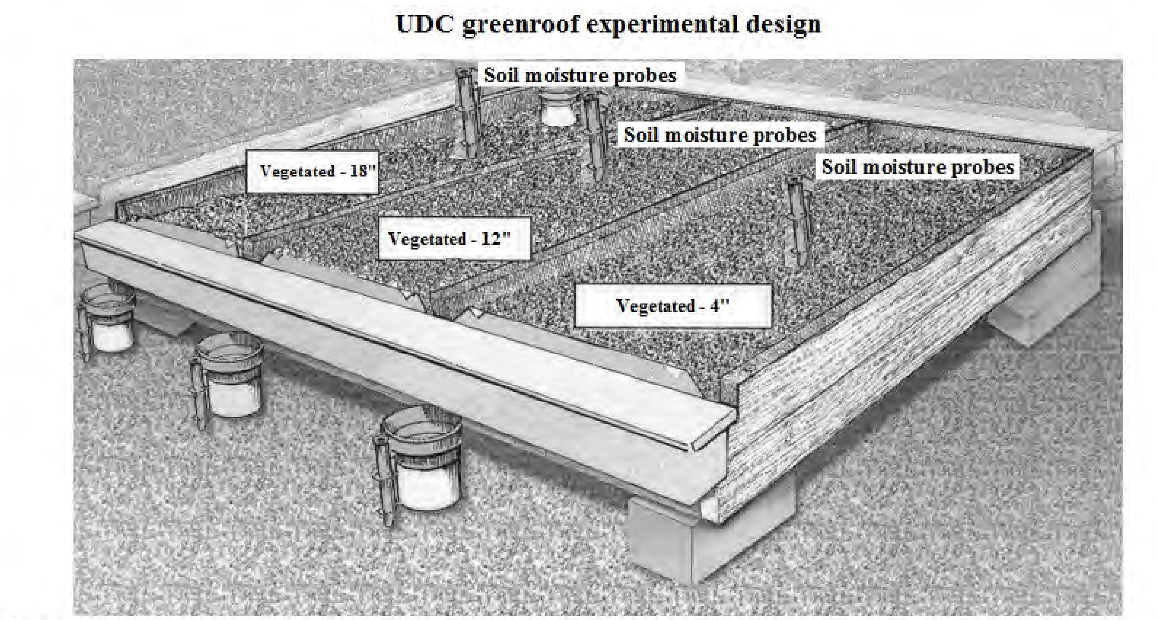

Fig. 1. Graphic representation of the model-scale roof platforms to evaluate stormwater retention anddetention in the roof surface comparison study.

As it is seen in Figure 1, we are collecting stormwater runoff data directly from all three plots with various growing media depth as part the UDC greenroof. The UDC greenroof has three media depths: 4”, 12” and 18”. All these three plots will have similar soil with different plants. The plots will be replicated 4 times on each depth. No changes will be made to the existing greenroof media which is 2 years old. The aim is to have a complete side by side field study which has yet to be completed outside of laboratory conditions. The 4” plot has full cover sedum, the 12” media depth plot has short plants including flowers and the 18” media depth plot has vegetation. Figure 2 presents the location of plots on the actual greeroof. As it is seen, the reasech will take place in North West part of the Greenroof.

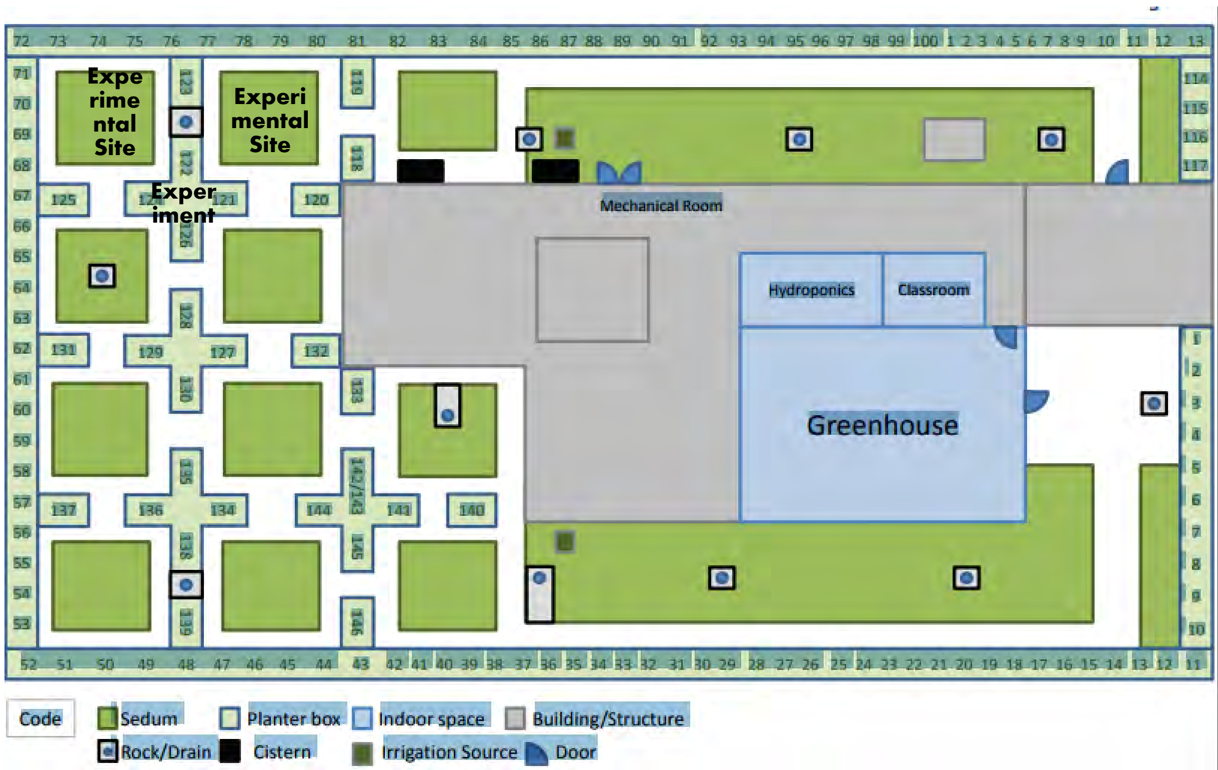

Figure 2: Plot locations on the greenroof.

Nine soil moisture probes are purchased from Cambell Scientific and will be set up by students hired for this project. The 4” plot will be considered extensive and 12” and 18” plots will be considered intensive. The two intensive plots will get probes at 3 depths to understand how much moisture change during various storm events during 5 months of data collection. The probes will be located at different vertical heights to sense if stormwater is infiltrating to the bottom layers. If the bottom sensors in the intensive greenroof alert of moisture change this is an indicator that the depth change matters. The irrigation system is removed from the area that is shown on Figure 2. This enables us to just focus on rainfall. We will correlate the rainfall data with the soil moisture data to understand the potential of an intensive greenroof on storm events less than 1.7”. Additionally, stormwater frequency will be considered for comparison of the soil moisture effect on infiltration capacity.

4. Results and Discussion

Two UDC students have been hired for this project and they went through a series of training to learn about green infrastructure projects and their role in water quality management. The students also completed a comprehensive literature review, which enabled us to tune our methodology. We already ordered all necessary materials and received most of them except the data logger. All research sites on the UDC greenroof were secured and evaluated. Some site preparation was done to make sure that the site meets our need for this research. The students went through an online training on how to install the sensors and connect them to the data logger. All 12 purchased sensors are ready to be in place to enable us to read soil moisture in our greenroof. The weather station is also installed to collect rain data. We also going to meet the Campbell Scientific representative next week to make sure all sensors and data logger is installed in the right way.

5. Project outcomes, presentations, publications or thesis (book chapter journals or conference proceedings)

We have a comprehensive literature review developed by the students. We are waiting to have more results to enable us to develop a peer reviewed publication soon.

6. Student supports

One gradtuate and one undergradtaute student is working on this project. The undergraduate student is working along the graduate student who has more experience. This gives the undergraduate student to learn about doing literature review, experimental design, data collection and developing reports.

7. Extramural funding received or pending

We successfully received $200,000 grant from National Fish and Wildlife Foundauion (NFWF) to work on benefits of using green infrastructure on urban community gardens to minimize their water pollution problem. This grant enabled us to expand our focus and conduct a comprehensive research on the nutrient management of green infrastructure projects.

8. Conclusion

We are working on our research and hopefully will develop our conlusions soon.

9. Acknowledgement

We truly appreciate WRRI to support us through awarding the grant and enable us to work on this project.

10. References (APA style)

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Performance Monitoring of Green Infrastructure Maintenance in the District

Basic Information

Title:	Performance Monitoring of Green Infrastructure Maintenance in the District
Project Number:	2017DC188B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Water Quality, Water Quantity, Education
Descriptors:	None
Principal Investigators:	Harris Trobman, Kamran Zendehdel, Dwane Jones

Publications

There are no publications.

Performance Monitoring of Green Infrastructure Maintenance in the District

UNIVERSITY OF THE DISTRICT OF COLUMBIA
COLLEGE OF AGRICULTURE, URBAN SUSTAINABILITY AND ENVIRONMENTAL SCIENCES

Harris Trobman (PI)

Kamran Zendehdel (Co-PI)

UDC CAUSES

Center for Sustainable Development

April, 2018

1. Executive Summary

Green infrastructure (GI) is still a relatively new approach to managing stormwater, and maintenance remains one of the key obstacles to its widespread implementation. It is well recognized that proper inspection, maintenance, and operations is needed of GI practices in order to ensure long term performance success. Additionally, a critical component of a successful program is to demonstrate the performance of the GI installation. With an immense number of GI projects successfully being installed in DC, their performance (stormwater control function) can be tremendously impacted by lack of proper maintenance.

This project aims to better inform the design, construction, and maintenance of green infrastructure. There is no city wide maintenance plan or national standards for GI practices maintenance guidelines. UDC is currently working with DC Water to conducte GI trainings for maintenance and operations of Green Infrastructure Practices (PMPs). However, there is a lack of guidance and locally based protocols to the actual current state of green infrastructure facilities including challenges and opportunities to inform operations and maintenance (O&M). This study assesses the current state of implemented green infrastructure bmps located in the District. This is essential in developing protocols that guide future design, construction, operation and maintenance of GI practices. Additionally, this information will be disseminated in green infrastructure maintenance trainings at UDC as well as released in a report format. This will be important for key stakeholders implementing GI practices including District Department of Energy and Environment, DC Water, District Department of Transportation, and building owners.

On this research two UDC students are work with the PI and Co-PIs to select a cross section of 30 small to medium sized GI practices to collect design, performance and maintenance data. This included a variety of bmps including bioretention cells, rain gardens, pervious pavements, bayscaping, and rain-barrels/cisterns. Students are working to select the sites and collect data and analyze the systems. The students will make use of the environmental testing laboratory collecting soil samples of each site to measure for buildup of heavy metals, nutrients, and sediment.

2. Introduction

Stormwater runoff is a major cause of water pollution in urban areas. Naturally when rain falls in undeveloped areas, soil and plants absorb and filter the water. However, in urban areas when rain falls on our impervious roofs, streets, and parking lots, the water cannot soak into the ground. In these highly urbanized areas, stormwater is mostly drained rapidly through an engineered collection system (storm sewers) and discharged into nearby water bodies. Along the way the stormwater picks up trash, sediment, bacteria, pathogens heavy metals, and other pollutants from the urban landscape, polluting the receiving waters. Higher flows also can cause erosion and flooding in urban streams, damaging habitat, property, and infrastructure. This is a critical challenge for the District and many other older us cities, where the development causes significant runoff challenges. The runoff threatens the health of rivers and streams, causes severe erosion, threatens human health, pressures the drinking water supply, and can cause damage and flooding to buildings. The District is not immune from these challenges where an estimated 3.2 million gallons of sewage and stormwater overflows into the District's rivers annually.

Green infrastructure practices are increasingly regarded as viable tools to mitigate stormwater runoff. The District has emerged as national leader to install GI projects across the city leading the nation in trees planted and green roofs per capita. The city has been initiating a wide range of financial and technical incentives and rebates to communities in the District through their cost-share programs, providing Riversmart rebates and technical advice to use GI practices. As the result, the District has become recognized as one the nation's leaders to use GI practices to manage stormwater. During the last few years, the city has invested billions of dollars in stormwater management projects in public and private properties. The wave of GI projects performance is to improving the Districts urban waterways and the Chesapeake Bay. Despite this strong progress there is uncertainty in regards to the current monitoring and performance of these pilot projects. More energy and time must be spent understand the current state of these pilot systems so that they can perform long term. This must be integrated into the current training of a workforce that will maintain these living- systems.

3. Methodologies

In this research two UDC student interns are working with the principal investigators. As we received the grant funding recently, the project started a few months late. The students completed a literature review for the study. Based on the literature review, an experimental design is developd. We currently working with Department of Energty and Environment (DOEE) to establish 25-30 GI BMPs for tthsi research. This will include a variety of bmps including bioretention cells, rain gardens, pervious pavements, bayscaping, and rainbarrels/cisterns. Students will collect data including picture of BMPs, soil samples, list of plant, sign of damage to each BMP and will analyze the systems. The students will make use of the UDC environmental testing laboratory and will collect soil samples of each site to measure the presence of heavy metals and nutrients. Additionally, we will analyze each PMP's performance. A list of criteria is under development to eable us to evaluate PMPs performance. Lastly, an analysis will be conducted for any noticeable maintenance, construction, and design challenges across the different systems.

4. Results and Discussion

Two UDC students have been hired for this project and they went through a educational process to learn about about green infrastructure projects and their role in water quality management. The students also completed a comprehensive literature review, which enabled us to develop our methodology and necessary criteria to to select 30 Green Infrastructure through working with Department of Park and Recreation (DPR). The selected GI projects are classified based on the list of criteria established. We already ordered all necessary materials that we need for this research and are waiting to receive the materials and be able to collect data. We established a close collaboration with our partner and we hope that the result will be instrumental for both of us.

5. **Project outcomes, presentations, publications or thesis (book chapter journals or conference proceedings)**

We have a comprehensive literature review developed by the students. We are waiting to have more results to enable us to develop a peer reviewed publication soon.

6. **Student supports**

One gradtuate and one undergradtaute student is working on this project. The undergraduate student is working along the graduate student who has more experience. This gives the undergraduate student to learn about doing literature review, experimental design, data collection and developing reports.

7. **Extramural funding received or pending**

We successfully received $200,000 grant from National Fish and Wildlife Foundauion (NFWF) to work on benefits of using green infrastructure on urban community gardens to minimize their water pollution problem. This grant enabled us to expand our focus and conduct a comprehensive research on the nutrient management of green infrastructure projects.

8. **Conclusion**

We are working on our research and hopefully will develop our conlusions soon.

Acknowledgement

We truly appreciate WRRI to support us through awarding the grant and enable us to work on this project.

9. **References (APA style)**

- Berndtsson J. C., 2010. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering, Volume 36, Issue 4, Pages 351-360.

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Anatomical and Behavioral Outcomes of Toxicant Exposure in the Anacostia River: Building a Zebrafish (Danio rerio) Model of Biological River Health

Basic Information

Title:	Anatomical and Behavioral Outcomes of Toxicant Exposure in the Anacostia River: Building a Zebrafish (Danio rerio) Model of Biological River Health
Project Number:	2017DC189B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Biological Sciences
Focus Categories:	Ecology, Toxic Substances, Water Quality
Descriptors:	None
Principal Investigators:	Victoria P Connaughton

Publications

1. Wilken, R. 2017. Anatomical and behavioral outcomes of toxicant exposure in the Anacostia River: building a zebrafish (Danio rerio) model of biological river health. MS. Thesis. American University.
2. Wilken, R and VP Connaughton. Anatomical and behavioral outcomes of toxicant exposure in the Anacostia River: building a zebrafish (Danio rerio) model of biological river health. Poster Presentation. CAS Mathias Student Research Conference, American University

Anatomical and Behavioral Outcomes of Toxicant Exposure in the Anacostia River: Building a Zebrafish (*Danio rerio)* Model of Biological River Health: Progress Report

Victoria P. Connaughton
Department of Biology, American University

Submitted to DC Water Resources Research Institute, University of the District of Columbia

April 20, 2018

1. Executive Summary

This progress report describes the status of the project "Anatomical and Behavioral Outcomes of Toxicant Exposure in the Anacostia River: Building a Zebrafish (*Danio rerio)* Model of Biological River Health". The study aims to develop a bioassay, with zebrafish, that can be used to examine the overall health of the Anacostia. Using water sampled from the Washington Navy Yard, a 3-phase project was proposed: (1) water quality analysis of water samples from the Navy Yard to identify major contaminants in those samples, (2) rearing zebrafish eggs/larvae/juveniles in these filtered water samples to assess changes in growth, survival, behavior, and anatomy, and (3) controlled experiments that directly exposed zebrafish to an identified major contaminant.

To date, we have collected and analyzed water samples from the Navy Yard (Phase 1) and reared zebrafish in these filtered water samples (Phase 2). We are continuing to analyze the data from Phase 2. Phase 3, in which the fish are being reared in an identified major contaminant, is currently being performed. These experiments and the project will continue as planned through summer 2018.

2. Introduction

The Anacostia River was once a popular waterfront for fisherman and recreational fishing. However, with the increase in pollution and subsequent contamination, the waterway has become less suitable for recreational activity. DC law strictly prohibits swimming in the waterway, and fish from the River are not fit for human consumption (AWS, 2015). Fish within the River display lesions and other obvious signs of poor health. Though legal fishing regulations in both D.C. and the state of Maryland promote catch-and-release fishing along the Anacostia watershed and discourage subsistence fishing (DDOE, 2016; MDE, 2016), 2012 estimates showed some 17,000 D.C. residents still rely on the Anacostia for food (AWS, 2015; Schlyer, 2012). Thus, the overall health of the River not only impacts the different aquatic animals, but local human populations as well.

These concerns beg immediate attention toward the River's health and the need to improve water quality. This study aims to take an ecosystem approach to improving water quality by identifying likely bioactive contaminants with negative consequences for fish residing in the Anacostia and tracking their anatomical and behavioral impacts across a developmental time frame. We will assess these consequences in zebrafish (*Danio rerio*), a well-understood aquatic model organism. While chemical analysis of Anacostia River water has identified compounds that are EPA Priority Pollutants, there are a wealth of other chemicals present (DCWater, 2015; NOAA, 2007) whose impact is unknown. Further, it is also not known if it is the combination of chemicals that are deleterious or if it is only a few major chemicals that cause the adverse effects. While lesions on Anacostia fish are a clear sign of poor health and exposure to pollutants, exposure to some contaminants can cause more sub-lethal physiological or behavioral changes, without necessarily obvious wounds. This latter group of contaminants is most problematic as it suggests normal-appearing fish are actually contaminated.

We propose to rear zebrafish eggs/larvae in filtered Anacostia River water to track changes in growth, survival, behavior, and anatomy. We are tracking anatomical and behavioral traits, specifically, because anatomical and behavioral health of fish and macroinvertebrates has been used as one index of overall water quality, including in the Anacostia (AnacostiaWatershedRestorationPartnership, 2010). In fact, biomonitoring studies using clams have shown significant, and differential, tissue accumulation of chemicals in various regions of the River (Phelps, 2002, 2015). We propose a bioassay using fish to assess one of the Anacostia's historically most contaminated sites, Washington Navy Yard.

This document is a progress report on our project to develop zebrafish as a model to assess the biological health of the Anacostia River. Our project involves 3 sets of correlated experiments/phases: (1) water quality analysis of water samples from the Navy Yard to identify major contaminants in those samples, (2) rearing zebrafish eggs/larvae/juveniles in these filtered water samples to assess changes in growth, survival, behavior, and anatomy, and (3) controlled experiments that directly exposed zebrafish to an identified major contaminant.

To date, we have collected water from the Washington Navy Yard and performed water quality analysis. We have also reared zebrafish larvae in these filtered water samples and are continuing to analyze that data. We are currently performing the controlled experiments with a single bioactive compound.

3. Methodologies

Methods for Phases 1 and 2 are taken from Wilken (2017) and were performed as part of an MS Biology thesis at American University (see section 5 below).

Phase 1: water collection and analysis

Water samples were collected from the Anacostia River from a site opposite the Washington Navy Yard. Samples were filtered through 45 μm Whatman glass fiber filters and stored in 1-liter aliquots in Nalgene containers until used in zebrafish exposure experiments. Filters collected during the filtration process were used to complete analysis of organic compounds present in Anacostia samples. Following filtration, glass fiber filters containing sample material were dried at 60°C for two hours to remove excess water. Dried filters were placed in a glass thimble and run through Soxhlet extraction.

Following Soxhlet extractions, rotary evaporation was used to concentrate the products. Samples were then treated with potassium hydroxide for 3 hr under low heat, stirring occasionally, to saponify the sample and allow for separation of polar fatty acids, lipids and polycyclic aromatic hydrocarbons (PAH's). Following saponification, samples were again rotary evaporated to remove excess solvent. Lipids, PAH's and fatty acids were then separated using a separatory funnel. Round bottom flasks containing lipids extracted from the River samples were rinsed with 20 mL 99.9% hexane. PAH's and lipids (neutral) were collected and stored separately from saponified fatty acids (basic). Subsequent processing of these samples further separated fatty acids (lipids) and PAHs.

Fatty acids were neutralized using HCl (33-38%) and brought to a pH of 5.0 to 6.0. In a final separation, hexane was used to separate neutral lipids from the remaining ethanol solution. The final lipid and fatty acid samples were labeled and stored in 5 mL vials at $4^{o}C$ prior to identification of pollutants in each sample portion using gas chromatography-mass spectrometry (GC-MS). All fatty acid samples were analyzed using GC-MS. For all GC-MS runs, 8 μL of sample was injected into the sample port. Analysis began at 50°C, with a constant ramp in temperature of 10°C per minute for a period of 20 minutes, completing the sample run at 250°C. PAH and alkane portions were separated following the methods outlined in Ballentine et al. (Ballentine, Macko, Turekian, Gilhooly, & Martincigh, 1996). In brief, using low-pressure liquid chromatography on a vertical column containing an activated 2.5 g silica (SiO_2)/1.6 g alumina (Al_2O_3) gel, samples were further separated and prepared for analysis using GC-MS. Samples were added directly to activated columns and washed through the column with a hexane solvent, first yielding alkanes. Columns were then washed a second time with a 2:1 hexane/toluene mixture, yielding PAHs.

Phase 2: rearing zebrafish in filtered Anacostia water

Fertilized zebrafish embryos, obtained from in-house spawning of adult animals, were placed into either control Deer Park water or filtered Anacostia water from the Washington Navy Yard. Eggs were reared in these conditions until 30 days postfertilization (dpf), with behavioral testing and anatomical observation occurring on days 7, 15, 20 and 30. Hatching rate and overall survival were also noted. Changes in anatomy were assessed by measuring length, width/girth, eye diameter, and inter-eye distance from photographs of preserved larvae taken with an Olympus SZ-16 stereomicroscope and MetaMorph software; measurements were made using Image J. Changes in behavior were determined using EthoVision motion-tracking software; turn angle, number of directional changes, swim speed, velocity, and activity/inactivity were measured.

Phase 3: rearing zebrafish in a single, major contaminant

Using the above procedure, zebrafish larvae are being reared in 2, 4, 6, 8-tetramethylcyclotetrasiloxane in concentrations ranging up to 1 mM. We chose to use a siloxane compound in these experiments because water quality analysis identified siloxanes (silicon-based compounds present in personal care products) as a contaminant in Anacostia water samples from the Washington Navy Yard. The concentration range was selected because it encompasses the range of concentrations reported for other aquatic contaminants that are pharmaceuticals and personal care products (Daughton & Ternes, 1999). Overall survival and growth, hatching success, behavioral and anatomical changes are being assessed at 7, 15, 20, and 30 dpf, as in the Phase 2 experiments.

4. Results and Discussion

Results presented below are taken from Wilken (2017) and were completed as part of an MS Biology thesis at American University (see section 5 below).

Phase1:

GC-MS analysis of water samples from the Washington Navy Yard (Figure 1) identified ~40 compounds with > 30% accuracy (Table 1). These compounds include hormones, pesticides, and volatile organic silicone compounds (siloxanes). Siloxanes were also found in the hexane control samples; however, the siloxane signal was much higher in the Anacostia water samples, suggesting these compounds are present in the River.

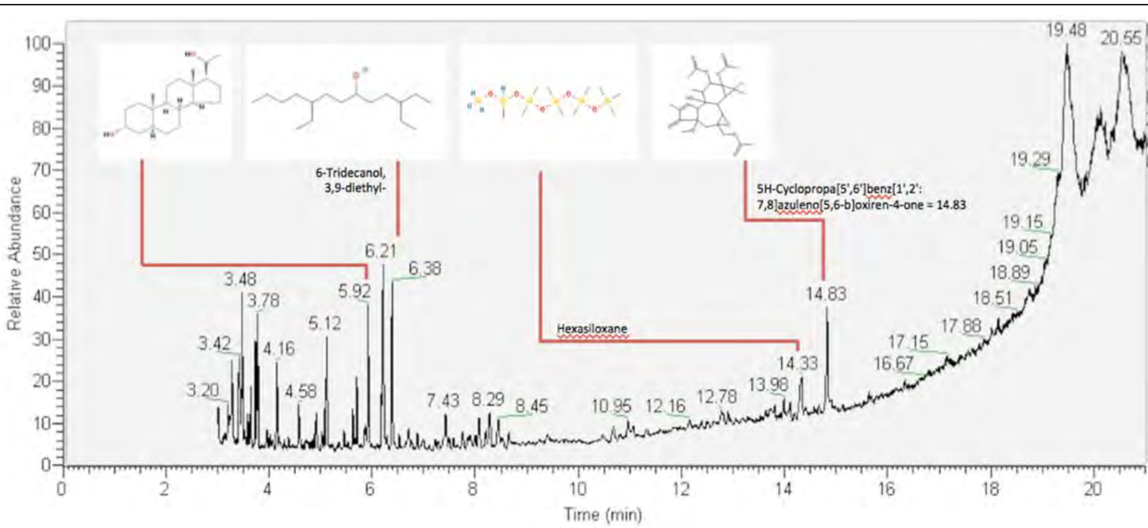


Figure 1. Example GC-MS results showing some compounds identified in the samples, including hexasiloxanes (From Wilken, 2017).

Table 1. Organic compounds identified with > 30% accuracy in hexane control and Anacostia River water samples collected from the Washington Navy Yard. Siloxanes are highlighted yellow (from Wilken, 2017).

Peak Time	Percent Likelihood	Compound Name	Chemical Formula
5.12	55.12	(5β)Pregnane-3,20α-diol, 14α,18α-[4-methyl-3-oxo(1-oxa-4-azabutane-1,4-diyl)]-, diacetate	$C_{28}H_{43}NO_6$
10.91	45.22	(5β)Pregnane-3,20α-diol, 14α,18α-[4-methyl-3-oxo(1-oxa-4-azabutane-1,4-diyl)]-, diacetate	$C_{28}H_{43}NO_6$
13.31	35.26	(5β)Pregnane-3,20α-diol, 14α,18α-[4-methyl-3-oxo(1-oxa-4-azabutane-1,4-diyl)]-, diacetate	$C_{28}H_{43}NO_6$
13.5	35.2	(5β)Pregnane-3,20α-diol, 14α,18α-[4-methyl-3-oxo(1-oxa-4-azabutane-1,4-diyl)]-, diacetate	$C_{28}H_{43}NO_6$
15.95	46.81	1-Heptatriacotanol	$C_{37}H_{76}O$
16.97	53.26	1-Heptatriacotanol	$C_{37}H_{76}O$
17.24	38.04	1-Heptatriacotanol	$C_{37}H_{76}O$
6.21	61.55	2-Cyclohexen-1-one,3,5,5-trimethyl-	$C_3H_{36}O$
6.21	45.31	2-Cyclohexen-1-one,3,5,5-trimethyl-	$C_9H_{14}O$
17.15	49.41	4H-Cyclopropa[5',6']benz[1',2':7,8]azuleno[5,6-b]oxiren-4-one	$C_{26}H_{34}O_7$
21	30.97	4H-Cyclopropa[5',6']benz[1',2':7,8]azuleno[5,6-b]oxiren-4-one	$C_{27}H_{36}O_{10}$
15.9	31.19	4H-Cyclopropa[5',6']benz[1',2':7,8]azuleno[5,6-b]oxiren-4-one	$C_{27}H_{36}O_{10}$
13.98	49.72	5H-Cyclopropa[5',6']benz[1',2':7,8]azuleno[5,6-b]oxiren-4-one	$C_{24}H_{32}O_9$
14.33	35.01	5H-Cyclopropa[5',6']benz[1',2':7,8]azuleno[5,6-b]oxiren-4-one	$C_{24}H_{32}O_9$
14.83	37.4	5H-Cyclopropa[5',6']benz[1',2':7,8]azuleno[5,6-b]oxiren-4-one	$C_{24}H_{32}O_9$
6.39	36.93	6-Tridecanol,3,3-diethyl-	$C_{17}H_{36}O$
6.38	35.97	6-Tridecanol,3,9-diethyl-	$C_{17}H_{36}O$
18.51	36.33	6α,11α,21-Trihydroxy-16α,17α-propylmethylenedioxypregna-1,4-diene-3,20-dione	$C_{25}H_{34}O_7$
18.02	33.47	7aH-Cyclopenta[a]cyclopropa[f]cycloundecane-2,4,7,7a,10,11-hexol,1,1a,2,3,4,4a,5,6,7,10,11,11a-dodecahydro-1,1,3,6,9-pentamethyl-2,4,7,10,11-pentaacetate	$C_{30}H_{44}O_{11}$
20.25	31.1	7aH-Cyclopenta[a]cyclopropa[f]cycloundecane-2,4,7,7a,10,11-hexol,1,1a,2,3,4,4a,5,6,7,10,11,11a-dodecahydro-1,1,3,6,9-pentamethyl-2,4,7,10,11-pentaacetate	$C_{30}H_{44}O_{11}$
19.25	54.45	7aH-Cyclopenta[a]cyclopropa[f]cycloundecane-2,4,7,7a,10,11-hexol,1,1a,2,3,4,4a,5,6,7,10,11,11a-dodecahydro-1,1,3,6,9-pentamethyl-2,4,7,10,11-pentaacetate	$C_{30}H_{44}O_{11}$
19.48	31.15	9-Desoxo-9-x-acetoxy-3,8,12-tri-O-acetylingol	$C_{28}H_{40}O_{10}$
3.05	34.11	Chloroacetic acid, cyclohexyl ester	$C_8H_{18}ClO_2$
6.59	32.47	Corynan-17-ol, 18,19-didehydro-10-methoxy-, acetate (ester)	$C_{22}H_{28}N_2O_3$
8.76	*61.37*	*cyclohexasiloxane, dodecamethyl-*	$C_{12}H_{36}O_6Si_6$
12.78	50.93	Cyclopropa[3,4]benz[1,2-e]azulene-5-one,9,9a-bis(acetoxy)-1	$C_{24}H_{32}O_9$
5.72	49.3	Cyclopropanecarboxylic acid	$C_6H_7Cl_3O_2$
5.71	32.16	Cyclopropanecarboxylic acid	$C_6H_7Cl_3O_2$
4.32	*42.26*	*Cyclotetrasiloxane*	$C_8H_{24}O_4Si_4$
9.41	66.49	Ethyl iso-allocholate	$C_{26}H_{44}O_6$
3.23	55.81	Ethylbenzene	C_8H_{10}
3.23	55.81	Ethylbenzene	C_8H_{10}
6.8	58.49	Morphinan-4,5-epoxy-3,6-di-ol, 6-[7-nitrobenzofurazan-4-yl]amino-	$C_{26}H_{27}N_5O_6$
10.93	*42.31*	*Octasiloxane*	$C_{16}H_{50}O_7Si_8$
10.98	*53.85*	*Octasiloxane*	$C_{16}H_{50}O_7Si_8$
18.68	34.38	Propanoic acid, 2-(3-acetoxy-4,4,14-trimethylandrost-8-en-17-yl)-	$C_{27}H_{42}O_4$
12.16	45.03	Pseduosorsasapogenin-5,20-dien	$C_{27}H_{42}O_3$
8.82	52.11	Spirost-8-en-11-one, 3-hydroxy-, (3α,5α,14α,20α,22α,25R)	$C_{27}H_{40}O_4$
18.58	35.07	Ursodeoxycholic acid	$C_{24}H_{40}O_4$

Phase 2:

We have reared zebrafish in filtered water from the Washington Navy Yard until 30 dpf. We are still analyzing the data, but the results we have suggest larvae reared in filtered Navy Yard water hatched earlier than controls (Fig. 2), with all larvae hatching by 4 dpf. There was no difference in survival between treatment groups.

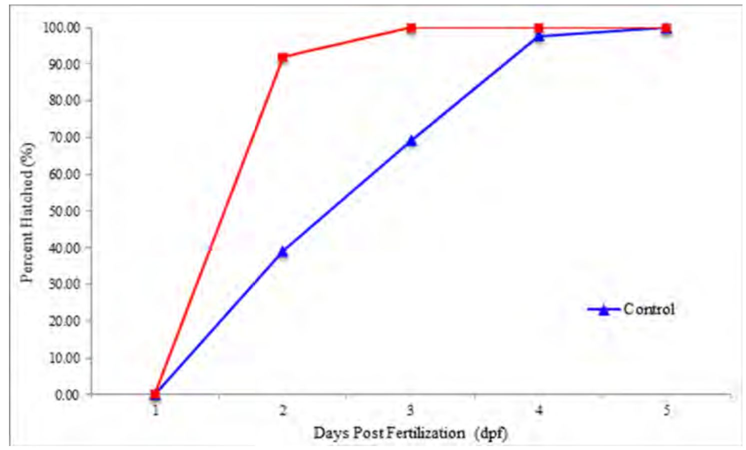
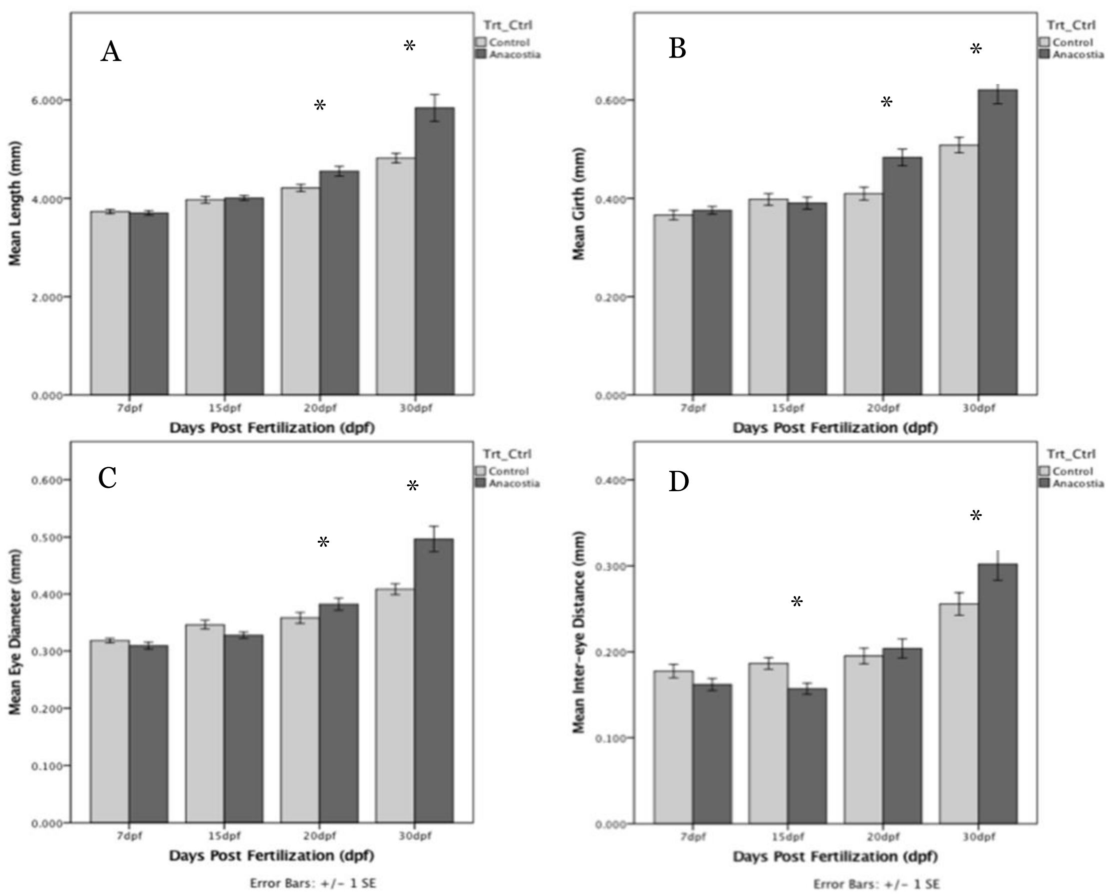


Figure 2. Zebrafish embryos reared in Anacostia River water samples from the Washington Navy Yard (red) hatched earlier than control embryos reared in Deer Park water (blue) (from Wilken, 2017).

Morphological measurements of larvae identified significant differences in length (Fig. 3A), girth (Fig. 3B), and eye diameter (Fig. 3C) at the two oldest ages tested (20 and 30 dpf), with larger measurements recorded for fish reared in filtered Anacostia water. Inter-eye distance (Fig. 3D), however, was significantly larger in Anacostia-reared fish only at 30 dpf; in larvae aged 15 dpf, inter-eye distance was significantly smaller than controls (Fig. 3). We are continuing to analyze the behavioral data, but results to date indicate Anacostia-exposed larvae behaved differently than controls, including increased thigmotaxis, suggesting a stress response.

Figure 3. Morphological measurements of zebrafish larvae reared in either filtered water from the Washington Navy Yard (dark bars) or control Deer Park water (light bars). Measurements were made at 4 ages: 7, 15, 30, and 30 dpf. (A) length, (B) girth, (C) eye diameter, (D) inter-eye distance. Values are mean ± SE. Asterisks indicate significant differences (from Wilken, 2017).



Phase 3:

Experiments exposing zebrafish to different siloxane concentrations are on-going. At this time, we have no data to report.

5. Project outcomes, presentations, publications or thesis

Part of this project served as the basis of a MS Biology Thesis completed by Rebecca Wilken (2017). The methods, results, and figures presented here are taken from that document.

Wilken, R. 2017. Anatomical and behavioral outcomes of toxicant exposure in the Anacostia River: building a zebrafish (D*anio rerio*) model of biological river health. MS. Thesis. American University.

Part of this work was also presented at the College of Arts and Sciences Research Conference in 2017.

Wilken, R and VP Connaughton. Anatomical and behavioral outcomes of toxicant exposure in the Anacostia River: building a zebrafish (*Danio rerio*) model of biological river health. Poster Presentation. CAS Mathias Student Research Conference, American University.

A project building on, and referencing, this research was presented at the recent NASA DC Space Consortium annual meeting.

Jessup, W, J. Wiegand, S. MacAvoy, and VP Connaughton. 2018. Laboratory assessment of Anacostia River Contaminants. NASA DC Consortium Affiliates Meeting, American University.

6. Student support

Graduate (1) and undergraduate (2) students were trained on this project. More specifically, part of this project formed the basis for the MS Biology thesis of one graduate student. An undergraduate student assisted on this project, including anatomical analysis, fish care, and sectioning. Phase 3 of the project is being completed by a second undergraduate student.

7. Extramural funding received or pending

Building on this work, we are interested in using zebrafish to assess water samples collected from other areas of the Anacostia River. To that end, a project using the same methods as this one, but water collected from a different region of the Anacostia, began in Summer 2017 and was supported by funding from the NASA DC Space Grant Consortium (May – August 2017).

8. Conclusion

Anacostia River water collected from the Washington Navy Yard contains a large number of different compounds. Siloxanes are one class of compound found in these samples, at a greater abundance than in the controls. Zebrafish reared in filtered Navy Yard water display differences in hatching rates and anatomical measurements. Larvae reared in Anacostia water hatched earlier and, following 30 days of exposure, were larger in size and displayed stressful behavior. Significant morphological differences at the longest exposure age suggests prolonged exposure is needed for differences to occur. We cannot make conclusions about siloxane-exposed fish, as these experiments/analyses are on-going. We anticipate completing our experiments in the next few months, by the end of summer 2018.

9. Acknowledgement

This work was supported by a seed grant from DC-WRRI/USGS. Dr. Stephen MacAvoy assisted with water quality analysis. Part of this worked formed the basis of an MS Biology thesis (R Wilken). Kim Imanalieva assisted with water analysis, fish care, and anatomical analysis; Jenna Wiegand performed the Phase 3 experiments.

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Examination of nutrient and land use patterns in the tidal Anacostia River

Basic Information

Title:	Examination of nutrient and land use patterns in the tidal Anacostia River
Project Number:	2017DC190B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Water Quality
Focus Categories:	Hydrology, Water Quality, Conservation
Descriptors:	None
Principal Investigators:	Stephen E. MacAvoy

Publications

There are no publications.

Examination of nutrient and land use patterns in the tidal Anacostia River

AMERICAN UNIVERSITY

Department of Environmental

Stephen MacAvoy, Principal Investigator

Department of Environmental Science, American University

April, 2018

1. Executive Summary

Six field excursions have been made to six field stations (3 urban, and 3 suburban) to collect water and sediments for organic geochemical analysis and inorganic ion determination. Findings at this point are preliminary however we have detected enzyme and hormone disrupting polycyclic aromatic hydrocarbons (PAHs) at several sites. We are continuing to collect and analyze sediment samples for organic contaminants and fatty acids.

Inorganic chemistry shows that highest calcium concentrations and highest pH occurs in the suburban sites (our hypothesis was that these would be highest at more urban sites). Interestingly, the highest calcium areas also show low Sr/Ca ratios, suggesting that dissolving concrete is not the calcium source. At the more urban sites, Ca is likely controlled by dissolving concrete, however these trends are still being tested. The smallest suburban stream (Long Branch Creek) shows nitrate concentrations 2 to 3 times higher than other sites, which suggests leaking sewer pipes and concentration of pollutants by low flow conditions. The project is proceeding as expected and the only component that has not be started is the GIS based land use analysis. That analysis starts when the chemistry data has been collected. There will be several months of additional data collection which will help support our final analysis.

2. Introduction

The United Nations Habitat Committee estimates that 70% of the world's population will live in urban areas by 2050. This worldwide trend will also be reflected close to home here in Washington DC. Increasingly growing cities are facing issues with the water quality of local streams that have been historically been ignored but are increasingly being seen as treasures that can enhance quality of life and city economies (Washington Post 2012). Urban areas are therefore focusing on the quality of freshwater resources within the metropolitan areas. Recent attention to urban waterways has lead researchers to recognize that there are a set of characteristics these waters have in common, including: a flashy response to precipitation, altered channel morphology, high concentrations of biologically active hydrocarbons (i.e. hormones and hormone mimickers), low biodiversity, elevated sodium, calcium and other ions, plus elevated nitrogen and phosphorus (Walsh et al., 2005). These different characteristics are not an exhaustive list, nor do they occur in all urban streams. However, it is now widely recognized that they commonly appear in some combination, now referred to as "urban stream syndrome" (Paul and Meyer, 2001). The Anacostia River in Washington DC can almost be characterized as the "poster child" for urban stream syndrome. It is contaminated by metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and sewage (Velinsky et al., 1994; Wade et al., 1994; Foster et al., 2000; Hwang and Foster, 2008; Shala and Foster, 2010; Velinsky et al., 2011). Its ionic strength (conductivity) is high and driven by Na, Mg, and Ca, which are not normally associated with the natural bedrock of the area (Connor et al. 2014), and its biologically "impaired" (Maryland DOE, 2012a). Additionally, 75% of the river's watershed is urban or impervious, 20% is forested and 5% is agricultural (Maryland DOE, 2012b).

While there are great challenges to improving the water quality of the Anacostia, there has been great interest in decreasing the amount of impervious surface through various greenscapes and roofs. This proposal is aimed at determining how land use is correlated with water chemistry, variation in nutrient sources and organic contaminants. The hypothesis is fairly straightforward; sections of the watershed (in Maryland for instance) that have less impervious cover will have less altered water chemistry and petroleum related chemical compounds (such as PAHs). Areas that are heavily impacted by sewage should show a different suite of organic compounds than less impacted sites. Bacterial fatty acids Bacterial fatty acids (including those associated with sewage) have odd and branched fatty acids, whereas algae do not (Lechevalier 1982). Bacteria also do not have fatty acids larger than 18 carbon atoms, which is sharply different from fatty acid profiles of the eukaryotic freshwater algae (Delong and Yayanos 1986). These and other characteristics make fatty acid analysis a robust tool for differentiating carbon sources in freshwater. Fatty acids and bacterial related compounds may correlate with urban land use, but this is not necessarily so. Our initial work shows that nitrate in one suburban stream is regularly 3x higher than the Anacostia main stem, suggesting sewage impacts (see initial results below).

Inorganic chemistry of the stream was also monitored with the organics. High concentrations of calcium, magnesium and other cations have been associated with urban streams and should have an impact on bacteria vs. freshwater algae. Therefor inorganic ions were monitored along with the samples for organic characterization.

If improving the Anacostia's water quality is one of the objectives of greenscaping the city, then the assumption that "greener" sections of the watershed have better water quality should be tested. Since rivers are all strongly influenced by the landscape upstream, the pattern of land use and water quality is very important. If Washington DC wants to make the Anacostia Fishable and Swimmable by 2032, studies like the one proposed would be advisable.

The objectives of this project are 1) to determine the sources of nutrients in the tidal and non-tidal Anacostia, 2) characterize bacterial or algal communities using fatty acids distributions in the river, and 3) to assess variation in bacteria and nutrients as a function of land use along the river.

3. Methods

Towards accomplishing these objectives, we have obtained sediment and water samples from 6 field excursions since May 2017. Each excursion was to 6 different field sties (3 urban and 3 suburban). Sites have been chosen from upstream branches (four in Maryland, two in the District) through downstream locations.

Organic Characterization. Fatty Acids and PAHs- Sediments from the three sites collected during July and November 2006 were dried at 60°C for three days and Soxlet extracted for 16 hours. Fatty acids and PAHs were extracted from the lipids using a modified method of Ballentine *et al*.. All extractions are to be characterized by using a Thermo Trace GC coupled to a Polaris Q ion trap mass spectrometer (GC/MS). All organics are to be identified using NIST mass spectral databases. A variety of GC oven program are being used. The most common being 40°C for 3 minutes, ramp at 10°C/min. to 240°C, hold for 11 min. 30 seconds.

Inorganic Characterization: Water column samples were collected in triplicate using 500 ml acid washed HDPE bottles. All samples were placed on ice for transport. Water column samples were immediately filtered onto glass fiber filters (45um GFF) once they reached the lab, while replicate samples were sent to Cornell's Nutrient Analysis Lab for analysis of water nutrients and inorganics (pH, hardness, SAR, alkalinity, Ca, Mg, Na, K, Fe, Mn, Zn, Al, Ba, Ni, total P, S, Sr,

NO_3^-, NH_4^+, PO_4^{3-}). Methodology for nutrient and inorganic ion analysis was based on EPA requirements (Standard Methods for the Examination of Water and Wastewater, http://www.standardmethods.org/). Colorimetric Bran-Luebbe Automated Ion Analyzer was used for NH_4^+, PO_4^{3-}), and NO_3^-. Elements were analyzed by plasma-atomic emission spectrometry (ICP-AES), which determines trace elements, including metals, in solution.

Land use analysis: Geospatial data on land uses in the Anacostia watershed will be acquired from the National Land Cover Database (NLCD) which provides publicly available data on land cover for Washington D.C. and Maryland.

Chemistry and Land Use Analysis

This study will involve statistical and geospatial analysis. Using the statistical software SPSS, the water chemistry data will be analyzed in order to determine if there are differences among the six sites and to determine. The analysis of variance (ANOVA) will be used to determine whether there is a significant difference between the sampling sites. The ANOVA test will need to be performed for each ion and nutrient. Principle Components Analysis (PCA) will also be used to look for co-variance at each site and the suburban vs. urban sites.

After the data analysis is complete, the chemistry data and land use data will be combined into a GIS overlay map. By creating multiple layers for each type of data in the Anacostia watershed, it can be determined if land use is correlated with water chemistry. The first layer will be the shapefile of the Anacostia watershed, followed by land use, and concrete. After that points will be placed on the map for each sampling site. Included in these points with the chemistry data. Once the map is created and the data inserted, a geographically weighted regression test will be used to determine if there is a correlation between land use, concrete, and water geochemistry. The test is performed for each variable in the dataset. In this analysis this would include the nutrients and other readings taken from the Anacostia River, land uses in the Anacostia watershed, and the types of concrete used in the area. The test with result in a table on the statistics and additional layers for each feature on the map which will show where a correlation occurs. This additional layers will show where the geochemical data is correlated. For example, one layer will show land uses which are correlated with one of the geochemical factors.

4. Results and Discussion:

Although a large amount of data has been collected thus far, we are not yet in the analysis stage of the project. Interpretation of the results would be premature. However, a few items can be included to show progress.

A summary of the inorganic ion data for the 3 urban sites shown in Table 1. This data will be compiled with the organics and the land use from all data (the 6 sites) when the project is complete. The inorganic work is ongoing.

Table 1. Inorganic chemistry data for 3 urban Anacostia River locations											
TDS (total dissolved solids)											
		pH	TDS	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	NO3 (mg/l)	NH4 (mg/l)	Total P (mg/l)	Ca/Sr
Urban											
	Bladensburg	7.4 ± 0.4	425 ± 358	33.7 ± 5.1	9.3 ± 1.6	178.4 ± 165.9	5.4 ± 1.4	0.5 ± 0.3	0.1 ± 0.1	.02 ± .01	224 ± 20
	Kenilworth	7.0 ± 0.1	325 ± 284	27.9 ± 7.7	7.6 ± 2.1	141.2 ± 208.3	4.8 ± 1.4	0.4 ± 0.2	0.2 ± 0.1	.02 ± .01	215 ± 23
	Navy Yard	7.0 ± 0.0	281 ± 152	29.2 ± 6.6	7.5 ± 1.6	103 ± 101	4.5 ± 0.7	0.6 ± 0.3	0.3 ± 0.2	.06 ± .01	222 ± 8

An example of a GC/MS chromatogram is shown in Figure 1. A sample list of organics isolated from the sediments is shown in Table 2. Fluoranthene and pyrene are PAHs and have been implicated in interfering with hormones (fluoranthene) and enzymes (pyrene) (Table 2). As of this writing, only 10% of the samples had been fully characterized. Processing and analysis of these sediments is labor intensive, but the graduate students working on the project are making significant progress.

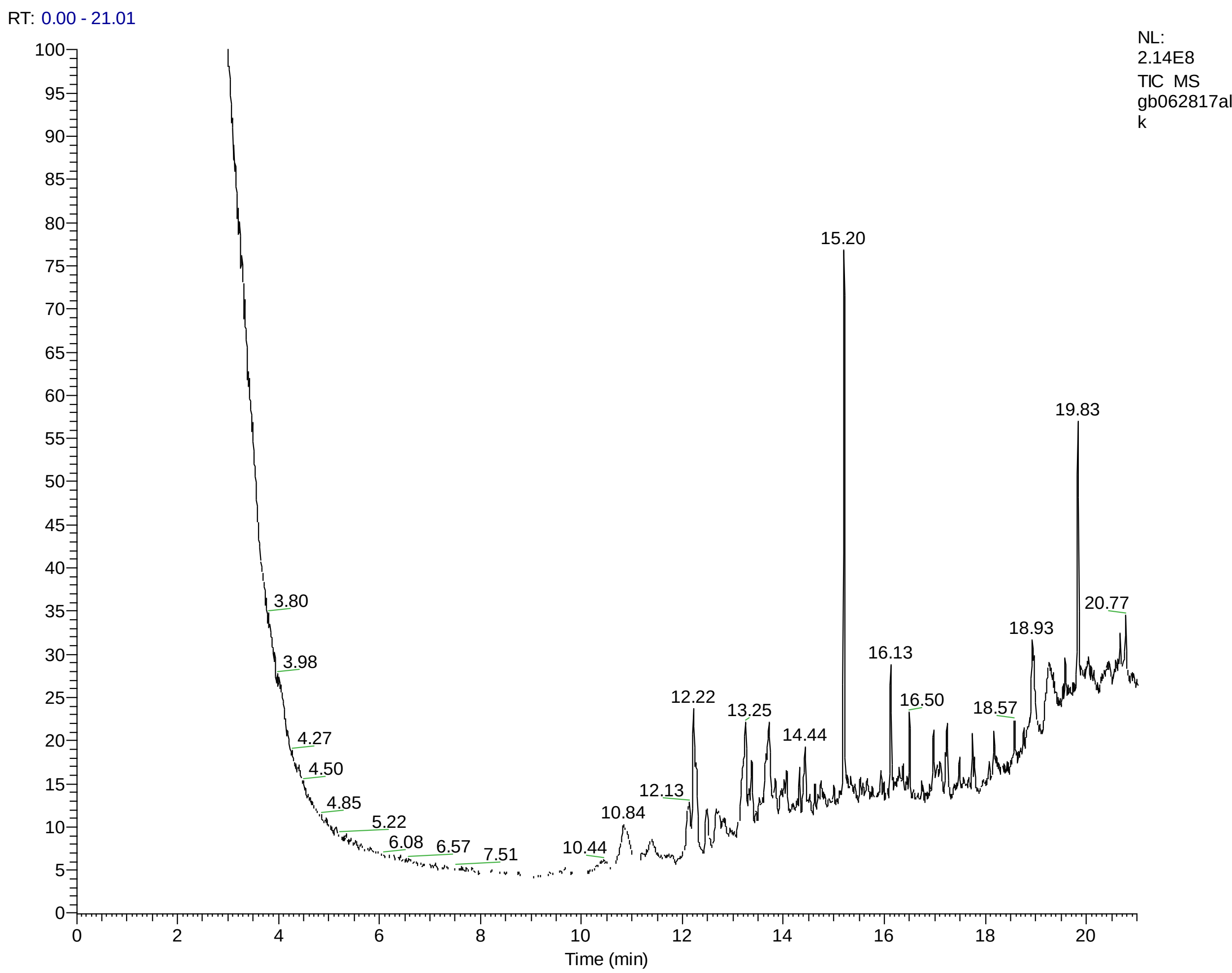

Figure 1. GC/MS chromatogram from Greenbelt Park, MD (June 28, 2017). The large slope on the left is the tail of the solvent peak.

Table 2. Organic compounds of interest from 4 sites. Analysis is ongoing.

Location	Date	Compound
Kenilworth	1/26/18	Fluoranthene
Kenilworth	1/26/18	Bibenzyl
Kenilworth	3/1/18	Bibenzyl
Kenilworth	1/26/18	Pyrene
Green Belt	3/1/18	2,6-Diisopropylnaphthalene
Green Belt	3/1/18	Bibenzyl
Green Belt	6/28/17	10,18-Bisnorabieta-5,7,9(10),11,13-pentene
Green Belt	1/26/18	Bibenzyl
Bladensburg	1/26/18	9-9'Biphenanthrene
Bladensburg	1/26/18	Bibenzyl
Bladensburg	3/1/18	Bibenzyl
Paint Branch	1/26/18	Bibenzyl

5. Project Outcomes:

Peer-reviewed papers:

Connor, N.C., S. Sarraino, D. Frantz, K. Bushaw-Newton, SE MacAvoy. 2014. Geochemical characteristics of an urban river: influences of an anthropogenic landscape. **Applied Geochemistry** 47:209-216.

Bushaw-Newton, K.L., E. Ewers, C.S. Fortunato, J.T. Ashley, D.J. Velinsky, S.E. MacAvoy. 2012. Bacterial community profiles from sediments of the Anacostia River using metabolic and molecular analyses. **Environmental Science and Pollution Research** 19: 1271-1279.

MacAvoy S.E., E. Ewers, K. Bushaw-Newton. 2009. Nutrients, oxygen dynamics, stable isotopes and fatty acid concentrations of a freshwater tidal system, Washington, D.C. **Journal of Environmental Monitoring** 11:1622-1629.

Presentations

12/14/16 American Geophysical Union Annual Meeting, San Francisco, CA. Session Co-Chair and Co-Convener. B31C-0486: Influence of Land Use, Discharge and Impervious Surfaces on the Geochemistry of the Anacostia River DC, USA. **Stephen E. MacAvoy*** and Nicholas De Filippis

12/17/2015 American Geophysical Union Annual Meeting, San Francisco, CA. Session Co-Chair and Co-Convener. Session **B41B:** Biogeochemistry of Rivers and Soils in the Urban Ecosystem and Their Climate Impacts Posters. "Geochemical Characteristics of an Urban River: Influences of an Urban Landscape" SE **MacAvoy*** and E Petersen.

12/11/13 American Geophysical Union, Annual Meeting, San Francisco CA. H31H-1282 "Geochemical characteristics of an urban river: Geochemical contamination and urban stream syndrome" Nicholas P. Connor, Stephanie L. Sarraino, Deborah E. Frantz, Karen Bushaw-Newton, Stephen E. **MacAvoy***

12/5/11 American Geophysical Union, Annual Meeting. San Francisco CA. " Biogeochemical characteristics of a polluted urban stream (Anacostia River, Washington DC, USA): inorganic minerals, nutrients and allochthonous vs. autochthonous production"
S.L. Sarraino, D.E. Frantz, K Bushaw-Newton and S.E. **MacAvoy***

12/16/10 American Geophysical Union, Annual Meeting. San Francisco CA. "Seasonal nutrient dynamics in the Anacostia River (D.C., USA): geochemistry and hydrocarbon biomarkers"
S.L. Sarraino, D.E. Frantz and S.E. **MacAvoy***

9/27/16 University of Virginia, Department of Environmental Science
"Concrete, Catfish and Contaminants: "Urban Stream Syndrome" in the Anacostia River, Washington DC"

6. Student Support

2 Undergraduate students trained (2017/2018)
4 Graduate students trained (2 in Biology, 2 in Environmental Science) (2017/2018)

Total number of students benefiting: 6

7. Conclusion

Progress is being made on the chemical analysis (organic and inorganic). Work needs to progress on analysis including incorporation of the GIS component of the project.

8. Acknowledgement. We thank WRRI for providing the funding for this research.

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Velinsky, D.J., Wade, T.L., Schlekat, C.E., McGee, B.L., & Presley, B.J., 1994. Tidal river sediments in the Washington, D.C. area. I. Distribution and sources of trace metals. Estuaries, 17, 305-320.
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Walsh C.J., Roy A.H., Cottingham P.D., Groffman P.M., Morgan R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. J. N. Am. Benthol. Soc., 24(3), 706-723.
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Assessing the effectiveness of urban gardens in reducing stormwater pollution

Basic Information

Title:	Assessing the effectiveness of urban gardens in reducing stormwater pollution
Project Number:	2017DC191B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Water Quality
Focus Categories:	Agriculture, Hydrology, Nutrients
Descriptors:	None
Principal Investigators:	Karen Knee

Publications

1. Spiller, Anna. 2017. Monitoring the Quantity and Quality of Runoff from Urban Farming. "Master's thesis," Agricultural Sciences and Resource Management in the Tropics and Subtropics, University of Bonn, Germany, pp 118.
2. Spiller, Anna, Harrison Hyde, Keeli Howard and Karen Knee. 2018 Assessing the effectiveness of urban gardens as green infrastructure in the Washington, DC area. In Abstract of the National Capital Region Water Symposium, Washington, DC, April, 2018.

Cover Page

Assessing the effectiveness of urban gardens in reducing stormwater pollution

Progress Report

Dr. Karen L. Knee, Principal Investigator

Department of Environmental Science, American University

April, 2018

1. **Executive Summary:** The goal of this project is to better understand how urban gardens in Washington, DC, prevent runoff and reduce stormwater pollution. Urban gardens are increasing in popularity and are present in all of DC's eight wards, often in public green spaces such as city parks, schoolyards and the U.S. Arboretum. Although many of the benefits and ecosystem services provided by urban gardens are well-documented, their ability to reduce runoff and stormwater pollution, especially in comparison to other types of vegetated urban land cover, has not been quantified. This project is addressing that data gap by collecting field data from 9 planted beds in urban gardens, as well as 3 grassy plots and 3 green roof plots for comparison. A rainfall simulator is being used to simulate a heavy but realistic level of rainfall, and runoff collectors installed at each site collect runoff from the plot during simulated and real rainfall events. Sampling with the rainfall simulator will be conducted monthly to observe how runoff quantity and quality varies over the course of the growing season and during fallow periods. Real rainfall events will be sampled as much as possible and compared to simulated rainfall events to assess how realistic the simulations are. During each sampling event, the quantity of real or simulated rain falling on the plot, the quantity of runoff generated, and *in situ* water quality parameters of the runoff (temperature, conductivity, and pH) will be measured and samples will be collected for later analysis of nutrient and dissolved metal concentrations at American University. An EasyChem plus discrete analyzer will be used to measure nutrient (nitrate+nitrite, phosphate, and ammonium) concentrations and an ICP-OES will be used to measure dissolved metal concentrations. This project builds upon research conducted by graduate student Anna Spiller, which resulted in the development of effective designs for the rainfall simulator and runoff collector as well as preliminary data suggesting that urban garden plots differ substantially from adjacent grassy plots in terms of the runoff they generate. Currently, one graduate student (Keeli Howard) and three undergraduates (Abigail Dias, Harrison Hyde and Gwynn Pollard) are involved in the project. This project will quantify the hydrological ecosystem services provided by urban gardens and to compare them directly to other types of green space or green infrastructure commonly found in the urban environment. The data generated will help agencies such as DC Water, District Department of the Environment and the Department of Parks and Recreation make informed decisions about how urban gardens can be part of the District's overall stormwater management plan, thus promoting better stormwater management and leading to improved water quality in local rivers and streams. The results will also be broadly applicable to other cities with similar climate and rainfall where urban gardens are present.

2. **Introduction:** Stormwater pollution is a widespread problem in urban areas, including Washington, DC, where approximately 65% of the total area is covered by impervious surfaces (DOH 2013). Impervious surfaces, which include rooftops, roads, parking lots, and unpaved surfaces that are highly compacted, have two main deleterious effects on urban hydrology and water quality. First, they decrease infiltration of water into the ground and increase runoff velocity, leading to flooding and erosion. Second, they accumulate contaminants such as heavy metals, pathogens, nutrients, sediments, and salts, which are transported into waterways during storms (NRDC 1999). Vegetation and green infrastructure in urban areas can help reduce and manage stormwater runoff (USEPA 2011, Pataki et al. 2011, Cameron et al. 2012). Urban gardens are an increasingly popular type of green space in and around Washington, DC; the Department of Parks and Recreation (DPR)'s Urban Garden Programs currently supports over 30 community gardens in all eight wards (http://dpr.dc.gov/page/dpr-community-gardens). The problem that this study will address is that we currently do not understand how urban gardens compare to other types of vegetation/green infrastructure in terms of reducing runoff quantity and stormwater pollution.

3. **Methodologies:** ***Field sampling procedures*** I plan to include ~15 study plots (9 planted beds in urban gardens, 3 grassy plots and 3 green roof plots) in the study. The specific sites will be chosen after a survey of urban gardens in DC conducted during the first month of the funding period (see **13**), but I anticipate including plots within the two gardens from Anna Spiller's study that were located within the District (K Street and Washington Youth Garden), UDC's Firebird Research Farm and/or Muirkirk Farm, and green roofs on the AU and UDC campuses. Infiltration rate, slope, and basic soil characteristics will be determined for each site before beginning sample collection.

   A runoff collector (Fig. 2) will be installed at each study plot for the duration of the funding period. The runoff collector, which was designed and field-tested by Anna Spiller during her master's research, consists of four gutters forming a 0.75 m x 0.75 m square. The gutters are placed into the ground so that any runoff from the plot flows into them by gravity, and a pipe leading to a collection bucket is connected to the lowest corner of the square. The bucket is sealed at the top so that no real or simulated rain can fall directly into it. The gutters are covered at the top so that rain cannot fall directly into them and can only enter horizontally, as runoff. Once per month from April through December

Figure 1: Runoff collector installed in a garden plot before crops are planted. Photo courtesy of Anna Spiller.

2017, the rainfall simulator will be used to simulate half an hour of heavy rainfall (500 mL/minute for 30 minutes) on each plot. The rainfall simulator consists of a Fuljet 3/8HH 17WSQ spray nozzle (Kibet et al. 2014) suspended 2 m above the ground and connected to the water supply at each garden, with a flow regulator to ensure a consistent flow rate among sites (Fig. 3).

During each sampling event, the total amount of simulated rainfall applied and the volume of runoff collected in the bucket will be recorded. Runoff samples for nutrient (nitrate+nitriate, phosphate, ammonium) will be collected from the bucket, filtered (0.2 □m pore size) in the field into 30-mL amber HDPE bottles and frozen until analysis. Samples for dissolved metal analysis will be filtered (0.2 □m pore size) in the field into 15-mL centrifuge tubes, acidified to pH 2 with trace metal grade nitric acid, and stored in the refrigerator until analysis. Temperature, conductivity, and pH of the runoff will also be measured with a YSI Pro Plus multi-parameter instrument.

Figure 2: Rainfall simulator placed over a grassy plot. Photo courtesy of A. Spiller.

Whenever possible, sites will be sampled immediately within 24 hours of heavy rainfall events that occur during the study period. Simple rain gages will be installed at each site, and high-frequency rainfall data will also be obtained from a weather station on the American University campus. Nutrient and dissolved metal samples will be collected and preserved as described above and YSI data (with the exception of temperature, which would not be relevant if the water has been sitting in the bucket for up to 24 hours) will be recorded.

Laboratory procedures: Nutrient (nitrate+nitrite, phosphate, and ammonium) concentrations will be analyzed using an EasyChem Plus (Westco Scientific) discrete analyzer. The EasyChem uses automated colorimetric chemistry to determine the concentration of various analytes. Dissolved metal concentrations (K, Zn, Cd, Cu, Cr, As, Pb, Co, Fe, Mn, Mo, Ni, and Al) will be analyzed on an ICP-OES. A new calibration curve, blanks, standard reference materials, and duplicate samples will be included in each EasyChem and ICP-OES sample run for quality control.

4. **Results and Discussion:** Due to delays in receiving the funding and challenges involved with building additional equipment for the project, we are still working on installing the equipment at all the gardens. I am hoping to get that done and start collecting data by late May or early June, and then collect data throughout the rest of the growing season (October or November).

5. **Project outcomes, presentations, publications or thesis (book chapter journals or conference proceedings)**

Spiller, Anna. 2017. Monitoring the Quantity and Quality of Runoff from Urban Farming. Master's thesis, Agricultural Sciences and Resource Management in the Tropics and Subtropics, University of Bonn, Germany.

Spiller, Anna, Harrison Hyde, Keeli Howard and Karen Knee. 2018 Assessing the effectiveness of urban gardens as green infrastructure in the Washington, DC area. Oral presentation at National Capital Region Water Symposium, Washington, DC, April, 2018.

6. Student supports

One master's student (Keeli Howard) and one undergraduate (Harrison Hyde) have been supported by this grant so far. Another undergraduate (Gwynn Pollard) has been working on the project for independent study credit, and a fourth student (Abigail Dias) is going to be supported by the grant over the summer.

7. Extramural funding received or pending

So far, there is no extramural funding received or pending related to this project.

8. Conclusion

This project is still in progress. I anticipate having it fully completed by December 2018 and the results will be made available at that point.

9. Acknowledgement

Thank you to WRRI for funding this project. Anna Spiller conducted much of the preliminary work upon which this project is based. Tolessa Deksissa and members of his laboratory group generously collaborated with Anna, providing supplies, laboratory facilities and analytical services. Jonathan Newport helped cut PVC pipes to make runoff collectors. Stephanie DeStefano and other members of the grounds team at American University helped us find appropriate sites to install runoff collectors at AU and provided tools and guidance. Also thank you to Benny, Rondell and the other garden managers who have worked with us to make this research possible.

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Quantifying the Recharge and Evapotranspiration Rates of the Chesapeake Bay Watershed using Land Surface State Observations

Basic Information

Title:	Quantifying the Recharge and Evapotranspiration Rates of the Chesapeake Bay Watershed using Land Surface State Observations
Project Number:	2017DC192B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Climate and Hydrologic Processes
Focus Categories:	Groundwater, Hydrology, Methods
Descriptors:	None
Principal Investigators:	Leila Farhadi

Publications

1. Farhadi, Leila. 2017. Estimation of Land Surface Fluxes through Assimilation of Surface Temperature and Moisture States into Models of Terrestrial Water and Energy Balance via the VDA Approach, Poster presentation, American Geophysical Union AGU (12/15/2017)
2. Farhadi, Leila. 2017. Estimation of Key Parameters of the Coupled Energy - Water Model by Assimilating Land Surface Temperature and Soil Moisture, Poster presentation, GWU R&D showcase (2/21/2018).
3. Farhadi, Leila. 2017.Monitoring Water and Energy Cycle from Space, In Abstract of American Water Resource Association, National Capital region AWRA-NRC (4/6/2018)

Quantifying the Recharge and Evapotranspiration Rates of the Chesapeake Bay Watershed using Land Surface State Observations

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April, 2018

1. Executive Summary

Recharge to the aquifers and evapotranspiration from the landscape are two critical fluxes in water cycle that are most sensitive to human alteration of landscape. As a result these fluxes have already changed dramatically in the historical era and by orders of magnitude. Fields of diffusive recharge flux and evapotranspiration play a pivotal role in (1) the global water, energy and biogeochemical cycles, (2) the sustainability of aquifers; (3) crop productivity; (4) ecosystem health and (5) climate. Evapotranspiration and recharge can amplify changes in precipitation and radiative forcing resulting from climate change. Small changes in the magnitude, seasonality and intermittency of precipitation and radiation can be magnified in the recharge and evapotranspiration signals. As a result, the future of these two critical fluxes under a changing atmospheric composition may be even more uncertain. Despite the importance of these fluxes and their historical change, there are no direct measurements – in situ or by remote sensing - that can allow any mapping or any global or regional estimation.

The objective of this study is to develop and integrate state-of- the-art computational and data assimilation techniques that enable the quantification and mapping of the evapotranspiration and recharge flux using spaceborne and airborne remote sensing measurements of land surface state variables. The ultimate goal is to quantify these fluxes over the Chesapeake bay watershed at spatial scales of several hundred meters to several kilometers (order 0.1–10 km) and temporal scales of 1–3 days, relevant to the current and foreseeable range of applications in water resources and operational weather and climate predictions. In this study, the feasibility of the developed approach is tested at point scale using synthetic data set (hereafter true data) generated by the simultaneous heat and water (SHAW) model. In a synthetic study the true system is exactly known which is ideally suited for algorithm performance tests and is considered as a first step toward a field site application with remotely sensed data. Results of this study demonstrate the feasibility of the developed approach for large scale application.

2. Introduction

Evapotranspiration and recharge are fluxes at the land-atmosphere interface. Evaporative flux links the surface and atmospheric systems and the recharge flux links the surface and subsurface systems. These are two critical fluxes in the water cycle that play a pivotal role in (1) global water, energy and biogeochemical cycles (Entekhabi and Moghaddam 2007); (2) crop productivity (Irmak et al. 2003); (3) sustainability of aquifers (Dillon 2005); (4) ecosystem health (Irmak et al. 2003); and (5) climate (Earman and Dettinger 2011). These water fluxes are intimately related to the distribution and functioning of vegetation cover and type (Stephenson 1990) and therefore are sensitive to human alteration of the landscape (DeFries and Eshleman 2004). As a result, these fluxes have already changed dramatically over time and by orders of magnitude. In addition, evapotranspiration and recharge flux amplify changes in precipitation and radiative forcing that result from climate change. Small changes in the magnitude, seasonality and intermittency of precipitation and radiation can be magnified in the recharge and evapotranspiration signals (Earman and Dettinger 2011). Therefore, the future of these two critical fluxes may be even more uncertain under a changing atmospheric composition. Knowledge of changes in the magnitude and regional patterns of these fluxes in the future is critical to understanding the impacts of climate change.

Despite the importance of these fluxes and their historical change, there are no direct measurements – in situ or by remote sensing – that can allow any mapping or any global or regional estimation of the rate of evapotranspiration and recharge. Long-term and spatially explicit (mapped) monitoring of evapotranspiration and recharge flux have been elusive goals and a grand challenge for hydrologists (NRC 2012). Understanding recharge to aquifers, evapotranspiration and their linkages has been recognized as a grand challenge for Earth system science in the coming decade (NRC 2012).

Evaporation and recharge are closely coupled and they depend significantly on the soil state of the land surface water budget. The soil moisture profile in the top few centimeters to meters of soil plays a key role in determining the rate of evapotranspiration and the rate of recharge (Entekhabi and Moghaddam 2007; Jackson 2002). The spatial variation of evapotranspiration and recharge flux is related to soil type, topography, vegetation and climate. Their dynamics are affected by variation in plant growth, weather and seasonal climate. To adequately characterize them, mapping at spatial scales of order 0.1-10km and at fine temporal scales (< week) is needed at minimum. Characterization at these scales is needed for the current and foreseeable range of applications in water resources (monitoring surface water bodies, aquifer recharge and discharge), in regional biogeochemical budgets, in operational numerical weather prediction (model initializations), in flood forecasting, and in drought hazards mitigation (Entekhabi and Moghaddam 2007).

Direct measurement of recharge can be made by using lysimeters, seepage meters and chemical tracers. However, point measurements of these fluxes are not characteristic of large-scale conditions. Moreover, installing networks of these instruments for mapping is not practical. The chemical tracer method can yield recharge estimates for effective large areas. The limitation of this method is that this direct measurement technique is labor-intensive and can only be performed experimentally. The approach cannot be scaled to provide large-scale mapping and global estimates (Gee and Hillel 1988; Entekhabi and Moghaddam 2007).

Indirect methods for the estimation of recharge mainly rely on linking recharge to other measurements (e.g., precipitation, stream discharge, etc.) through the use of models. In these methods, recharge has been estimated indirectly as the residual of the surface or subsurface water balance (Gee and Hillel 1988; Goodrich et al. 2004; Scott et al. 2000). Estimates of recharge using residual techniques cannot separate model structural and parameters errors, observation errors and any other closure errors from the identified flux values (Zhang and Schilling 2006). In addition, a major limitation of the current suite of indirect approaches is their lack of capability to develop spatial mapping.

More recently several techniques have been developed for estimating parameters of recharge flux (i.e., effective soil hydraulic parameters) at the scale of remote sensing footprints (Mohanty 2013; Ines and Mohanty 2008, 2009; Santanello et al. 2007). The basic premise of these techniques is that surface soil moisture temporal dynamics hold the memory of hydrologic fluxes and can be used to provide an effective representation of soil hydraulic properties of the entire domain (Ines and Mohanty 2008, 2009). ***Key limitations*** of these techniques are (1) these methods fail to take into account the inherent coupling/link between evapotranspiration and recharge flux in the estimation of the parameters of recharge flux; and (2) these methodologies suffer from non-uniqueness of the estimated variable/parameters, which affects confidence in the accuracy of the estimated fluxes.

Similarly, *in-situ measurements of evapotranspiration flux* are both difficult and costly. Point measurements from sparse flux tower networks such as Fluxnet and a few limited area and short duration field campaigns are available, such as The First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) (Sellers et al. 1992), Boreal Ecosystem-Atmosphere study (BOREAS) (Sellers et al. 1995) and Fluxnet network (Baldocchi et al. 2001). These measurements can be used to provide insight on local-scale evapotranspiration processes. Point measurements obtained from these field sites need to be scaled up to obtain regional values (mapping) (Li and Lyons 1999). However, such approaches are hampered by the presence of strong spatial heterogeneity in factors such as surface moisture, vegetation cover and terrain. Moreover, the eddy correlation systems on towers can rarely be extended to large areas (French et al. 2005).

Indirect methods for estimation of evapotranspiration mainly depend on the linkage of evapotranspiration flux to land surface state variables of temperature (LST) and/or vegetation index (VI). The majority of these approaches fall within one of three main categories. The first category consists of empirical methods, which use the apparent correlation between evapotranspiration, temperature and/or vegetation index (VI) (e.g., Nemani and Running 2002; Gillies and Carlson 1995; Moran et al. 1993). The major drawback of these models is that they mainly depend on the relationship between VI and LST, and thus are site-specific. The second category is diagnostic methods, which estimate the components of surface energy balance, including evapotranspiration, through land surface temperature state, LST (e.g., Jiang and Islam 2001; Su 2002). The major shortcoming of diagnostic approaches is that the ground heat flux is taken to be a fraction of net radiation and therefore it is locked in phase with the net radiation. In reality, net radiation and ground heat flux are out of phase and by definition this assumption introduces significant errors into the estimation of the evapotranspiration flux.

More recently a third category of methods has been proposed for indirect estimation of evapotranspiration flux at the scale of remote sensing footprints that is based on the assimilation of a sequence of LST observations into dynamic models of energy balance via Variational Data Assimilation approach (VDA) (Castelli et al. 1999; Boni et al. 2001; Caparrini et al. 2004a, b; Bateni and Entekhabi 2012; Bateni et al. 2013a, b; Xu et al. 2014, 2015). These studies aim to estimate two key parameters: a bulk heat transfer coefficient under a neutral condition (C_{HN}) that governs the sum of fluxes, and an evaporative fraction (EF) that represents the partitioning between sensible (H) and latent heat (LE) flux. VDA is a calibration-free method and does not require fluxes measurement for parameters estimation. This makes it suitable for large scale applications. In the hydrological application, VDA assimilates the land surface states that can be easily measured in large scale (by remote sensing) within physically-based land surface models. The optimal values of key parameters of model obtained by minimization of a cost function which aggregate the squared errors between the state predictions with respect to the available observation and parameters estimation with respect to prior values (Bateni, Entekhabi, & Jeng, 2013b; Caparrini, Castelli, & Entekhabi, 2004b; Sini, Boni, Caparrini, & Entekhabi, 2008).

Bateni (Bateni & Liang, 2012) applied the VDA approach to assimilate land surface temperature (LST) data into the dual-source surface energy balance model with the aim of estimating the key parameters of model (hereafter, called VD_{AT}). However, in this study the interaction between the water and energy transfer in the soil–plant–atmosphere continuum is not considered which may be the main reason for the poor performance of VD_{AT} in the energy-limited regime. In addition, the effectiveness of VD_{AT} is undermined by the fact that the VDA method does not explicitly compute the error covariance matrix and consequently does not provide estimates of the predictive uncertainty of estimated parameters and fluxes. Furthermore, the inherent shortcoming of the VDA method (i.e., tendency to be ill-posed) does not grantee the unique optimal solution. In other words, simultaneous optimization of unknown parameters may result in a continuum of possibilities for different parameters that produce essentially identical measurement-model misfit errors (Crow & Kustas, 2005). The other issue that is not taken into consideration in any of previous hydrological VDA problems is identifying and tackling saddle points. In a high-dimensional non-linear minimization problem, a saddle point may be surrounded by plateaus of small curvature and gives a illusive impression of the reaching the local minimum.

In this study, we apply the VDA method to assimilate LST and soil moisture (SM) data into the parsimonious coupled water and dual-source energy balance model (hereafter, called $VDA_{T,S}$). The water and energy movement within the column of soil are modeled by the heat and moisture diffusion equations which are introduced to $VDA_{T,S}$ as the physical constraints. The key unknown parameters of model that regulate the partitioning of available energy between soil and canopy sensible and latent fluxes are neutral bulk heat transfer coefficient (C_{HN}), and soil and canopy evaporative fraction (EF_s and EF_c, respectively).

Considering the interaction between water and energy transfer in the soil–plant–atmosphere continuum through coupling the water and energy budgets improves the poor performance of VDA_T in the energy-limited regime. Soil moisture controls not only the partitioning of available energy into sensible and latent heat fluxes through its influence on evapotranspiration but also the partitioning of evapotranspiration into soil evaporation and canopy transpiration (Crow et al., 2015; Entekhabi & Moghaddam, 2007; Lu, Steele-Dunne, Farhadi, & van de Giesen, 2017). Therefore, assimilating SM information in addition to LST improves the performance of VDA_T.

We also develope an integrated framework (IF) to resolve some of issues associated with previous application of the VDA method such as tendency to be ill-posed, existence of saddle points, and inability to perform uncertainty analysis explicitly. In this framework, first the optimum values of the unknown parameters are obtained via the VDA method (i.e. minimization problem). Then, the Hessian matrix in vicinity of optimum point is computed via the Lagrangian method (Burger, Brizaut, & Pogu, 1992; Le Dimet, Navon, & Daescu, 2002). Analysis of second-order information (i.e. Hessian matrix) provids a tool to tackle a comment issue in a high-dimensional non-linear optimization problem (Pascanu, Dauphin, Ganguli, & Bengio, 2014). It has been shown that the invert of Hessian matrix provides a good approximation to the error covariance matrix of parameters even in the nonlinear case (e.g. Shutyaev et al. 2008; Gejadze et al. 2011; Farhadi et al. 2016). Preforming the uncertainty analysis and defining the correlation between estimated parameters through the information provided by the error covariance matrix guide towards the formulation of a well-posed estimation problem.

In summary, we enhance the performance of VDA_T by 1- coupling water and energy budgets through the flux of evapotranspiration, 2- assimilating simultaneous LST and soil moisture (SM) data, 3- adding Richards equation as a new physical constraint of system, and 4- identifying and tackling the saddle point by computing the Hessian matrix of cost function at the vicinity of obtained critical point, and 5- performing the uncertainty analysis to compute the uncertainty associated with the VDA estimates and guide a well-posed estimation problem.

3. Methodologies

3.1. Model Description

3.1.1. Soil Moisture Submodel

The water movement in the unsaturated column of soil obeys the Richards equation (Richards, 1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right) - \frac{\partial K}{\partial z} \tag{1}$$

where θ is volumetric water content (also called soil moisture, SM), h is the pressure head, K is the unsaturated hydraulic conductivity and z denotes the vertical dimension and is positive downward. Considering the important role of vegetation in the hydrological cycles, the modified form of the Richards equation is introduced as:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}(K\frac{\partial h}{\partial z}-K)-S(z,t) \tag{2}$$

where S is the water sink by the plant-root system and is related to the transpiration from canopy (T) via

$$T(t)=\int_{0}^{RZD} S(z,\mathrm{t})\,\mathrm{dz} \tag{3}$$

where RZD is root zone depth. S depends on many factors such as root-density distribution, soil moisture, and atmospheric demand (Lai & Katul, 2000). In climate and hydrologic models, it is difficult to explicitly describe all these influencing factors. In this work, the root distribution function (f_{root}) in Community Land Model is used (Oleson et al., 2010) to define S as:

$$S(z,\mathrm{t})=\frac{f_{root}(z)(\theta(z)-\theta_r)}{\sum_{z=0}^{RZD} f_{root}(z)(\theta(z)-\theta_r)} \tag{4}$$

where θ_r is residual soil moisture. At the surface, the net flux (q) results from precipitation/irrigation (P), evaporation (E), and runoff (R_{off}) as:

$$q_{z=0}=P-E-R_{off} \tag{5}$$

In this study, runoff is neglected assuming that the precipitation rate is less than saturated hydraulic conductivity (e.g. in our case study) or a layer of water is formed on top of the soil surface during heavy rains which prevents initiation of runoff. At the bottom of soil column, the gravitational drainage which is used in many land models is assumed.

The hydraulic properties of unsaturated soil are parameterized using the Clapp and Hornberger model which are widely used in land models for weather and climate studies (Clapp & Hornberger, 1978):

$$h=h_{sat}(\frac{\theta}{\theta_{sat}})^{-B} \tag{6}$$

$$K=K_{sat}(\frac{\theta}{\theta_{sat}})^{2B+3} \tag{7}$$

In (6) and (7), θ_{sat}, K_{sat}, and h_{sat} are the saturated soil moisture, hydraulic conductivity, and soil matric potential, respectively, and are the functions of the soil texture. B is a soil parameter which describes the shape of the water release characteristic. Bruke et al. (1997) has found that soil models are least sensitive to Ksat and most sensitive to B. Therefore, in this work we approximate the value of θsat, Ksat, and hsat based on the soil texture from the look-up table (Clapp & Hornberger, 1978) and use the Expectation-Maximization algorithm (Moon, 1996) to obtained effective pore size index, beff, which represents the pore size index of column of soil.

3.1.2. Soil Temperature Submodel

In the dual sourced model (i.e. method of choice in this research) the contributions of soil and canopy to the land surface temperature is separated (Caparrini et al., 2004b; Kustas, Humes, Norman, & Moran, 1996). The distribution of temperature in the column of soil (subscript "s" represents soil) is governed by the one-dimensional heat diffusion equation:

$$c\frac{\partial T_s}{\partial t} = p\frac{\partial^2 T_s}{\partial z^2} \tag{8}$$

where c is the soil volumetric heat capacity and p is the soil thermal conductivity (Campbell, 1985). It is assumed that the diurnal variation of heat wave is negligible beyond depths 0.5m (Hirota et al. 2002), therefore the Neumann boundary condition is considered for bottom boundary condition.

The surface boundary condition, T_s (z = 0, t), is obtained by the surface forcing equation,

$$p\frac{\partial T_s}{\partial z} = -G \tag{9}$$

where G is the ground heat flux evaluated at the surface through the soil energy balance equation as:

$$G = Rn_s - LE_s - H_s \tag{10}$$

where H_s, LE_s, and Rn_s are respectively the soil sensible, latent, and net radiation fluxes. Rn_s can be formulized as a balance among the incoming and outgoing shortwave and long wave radiation fluxes as:

$$R_{ns} = (1-f_c)[(1-\alpha_s)R_s^{\downarrow} + R_l^{\downarrow} - \varepsilon_s \sigma T_s^4] \tag{11}$$

In (11), α_s and ε_s denote the soil albedo and emissivity, respectively, and σ is the Stefan Boltzmann constant. $R_s^{\downarrow}$ is the incoming solar radiation and $R_l^{\downarrow} = \varepsilon_a \sigma T_a^4$ is the downwelling longwave radiation where ε_a is the atmospheric emissivity. f_c is the vegetation cover fraction and can be obtained as a function of leaf area index (LAI) as (Anderson, Norman, Diak, Kustas, & Mecikalski, 1997; Caparrini et al., 2004b):

$$f_c = 1 - \exp(-0.5LAI) \tag{12}$$

Soil sensible heat flux can be represented in terms of the gradient of temperature between soil (T_s) and air within the canopy volume (T_w) as:

$$H_s = (1 - f_c)\rho c_p U_w C_{HS}(T_s - T_w) \tag{13}$$

where c_p is the specific heat of air, ρ is the air density, and U_w is the wind speed within the canopy. In this equation, C_{HS} represents coefficient of heat transfer from soil to air within the canopy. The soil conductance ($U_w C_{HS}$) can be estimated as a function of the decay starting reference value ($C_H U$) at the height where wind speed measurements are made as follows (Bateni & Liang, 2012; Caparrini et al., 2004b):

$$U_w C_{HS} = UC_H \exp(-\frac{a_h LAI}{2}) \tag{14}$$

where a_h is an empirical extinction parameter which is a function of vegetation type and U is the wind speed above the canopy. On the basis of literature reports for various vegetation types, $a_h = 0.4$ is adopted for the study site. The bulk heat transfer coefficient (C_H) depends on the surface roughness for heat and momentum exchange and atmospheric stability condition. Therefore, C_H can be split into two parts: the heat transfer coefficient under neutral atmospheric condition (C_{HN}) and the atmospheric stability correction function. The stability correction function, f(Ri), is a function of stability indicator (i.e. Richardson number (Ri)). In this study, in lieu of empirical and site-specific stability correction functions (e.g., Garratt and Francey 1978; Castelli et al. 1999), the stability correction function proposed by Caparrini et al. (Caparrini, Castelli, & Entekhabi, 2004a) and produced successful results in various studies (Bateni, Entekhabi, & Jeng, 2013a; Caparrini et al., 2004a; Crow & Kustas, 2005; Farhadi, Entekhabi, Salvucci, & Sun, 2014; Sini et al., 2008) is applied.

Soil latent heat flux can be written as $LE_s = \frac{EF_s}{1 - EF_s} H_s$ using the definition of soil evaporative fraction (EF_s):

$$EF_s = \frac{LE_s}{H_s + LE_s} \tag{15}$$

There is empirical evidence that EF_s is constant during the days that evaporation is strong (Crago & Brutsaert, 1996). Soil latent heat flux is related to the amount of water transfer trough soil evaporation via:

$$LE_s = \frac{E}{\rho_w L} \tag{16}$$

where ρ_w and L are the water density and latent heat of vaporization, respectively. This relationship provides a tool to couple soil moisture and temperature submodels (see (5) and (10)).

3.1.3. Canopy Submodel

In the dual source model, canopy heat capacity is assumed zero. Therefore, the canopy energy balance is described as (subscript "c" represents canopy):

$$Rn_c - LE_c - H_c = 0 \tag{17}$$

where H_c, LE_c, and Rn_c are respectively the canopy sensible, latent, and net radiation fluxes. Canopy net radiation is formulized as:

$$R_{nc} = (1 - f_c)[(1 - \alpha_c)R_s^{\downarrow} + R_l^{\downarrow} - \varepsilon_c \sigma T_c^4] \tag{18}$$

In (18), α_c and ε_c denote the canopy albedo and emissivity, respectively and T_c is canopy temperature. The canopy sensible and latent heat fluxes are defined as:

$$H_c = f_c \rho c_p U_w C_{Hc} (T_c - T_w) \tag{19}$$

$$LE_c = \frac{EF_c}{1 - EF_c} H_c \tag{20}$$

Like the soil conductance, the canopy conductance ($U_w C_{Hc}$) can be obtained as a function of $C_H U$ as follows:

$$U_w C_{Hc} = UC_H \exp(-\frac{a_h LAI}{2}) \tag{21}$$

Canopy evaporative fraction (EF_c) scales partitioning between the canopy sensible and latent heat fluxes.

LE_c is related to the amount of water transfer trough transpiration (water uptake by plant root) via:

$$LE_c = \frac{T}{\rho_w L} \tag{22}$$

This relationship provides a tool to couple canopy and soil moisture submodels (see (3) and (17)).

3.2. Variational Data Assimilation

In the hydrological application, the variational data assimilation method (VDA) improves the performance of physical land surface models (which are generally defined as (23)**Error! Reference source not found.**) by assimilating the vector of state observations, $\mathbf{X_{obs}}$.

$$\begin{aligned} \frac{d\boldsymbol{X}}{dt} &= F(\boldsymbol{X},\boldsymbol{Y}) + \boldsymbol{w}(\mathrm{t}), \quad t \in [t_0\ t_1] \\ \boldsymbol{X}(t_0) &= \boldsymbol{X_0} \end{aligned} \tag{23}$$

where $\mathbf{X}$ is the vector of land surface states, $\mathbf{Y}$ is the vector of unknown parameters, and $\mathbf{w}$ is the set of model structural errors. In a VDA parameter estimation problem, the optimum value of parameters are obtained by minimization of the cost function, *J*, which aggregates errors on state estimation with respect to observations and parameters estimation with respect to „„prior"" values, $\boldsymbol{Y'}$, within the assimilation window (t_0, t_1):

$$J = \int_{t_0}^{t_1} (\boldsymbol{X}-\boldsymbol{X_{obs}})^T \boldsymbol{C}_X^{-1} (\boldsymbol{X}-\boldsymbol{X_{obs}})\mathrm{dt} + (\boldsymbol{Y}-\boldsymbol{Y'})^T \boldsymbol{C}_Y^{-1} (\boldsymbol{Y}-\boldsymbol{Y'}) + \int_{t_0}^{t_1} \boldsymbol{\lambda}^T [\frac{d\boldsymbol{X}}{dt} - F(\boldsymbol{X},\boldsymbol{Y})]dt + \int_{t_0}^{t_1}\int_{t_0}^{t_1} \boldsymbol{w}(t')^T \boldsymbol{C}_{\boldsymbol{w}}^{-1}(t',t'')\boldsymbol{w}(\mathrm{t''})\mathrm{dt'dt''} \tag{24}$$

The physical constraint is adjoined through the vector of Lagrange multipliers $\boldsymbol{\lambda}$. The last term of (24) accounts for the model error (also called model uncertainty). For simplicity in this study w is assumed unbiased (nonzero mean) with error covariance $\boldsymbol{C_w}$. $\boldsymbol{C_X}$ and $\boldsymbol{C_Y}$ correspond to the error covariance of observations and parameters prior to data assimilation (Reichle, McLaughlin, & Entekhabi, 2001). The minimum value of *J* which leads to optimum values of parameters is obtained by setting its first variation equal to zero (δJ=0). Setting δJ to zero leads to the set of the so-called Euler-Lagrange equations including adjoint models (25), a set of equations for updating the prior value of parameters (26) as well as model error estimation equation (27).

$$\frac{d\boldsymbol{\lambda}}{dt} = -\boldsymbol{\lambda}^T \frac{\partial F}{\partial \boldsymbol{X}} + (\boldsymbol{X} - \boldsymbol{X}_{\boldsymbol{obs}})^T \boldsymbol{C}_{\boldsymbol{X}}^{\boldsymbol{-1}}$$
$$\boldsymbol{\lambda}(t_1) = 0 \tag{25}$$

$$\boldsymbol{Y} = \boldsymbol{Y'} + \boldsymbol{C}_{\boldsymbol{Y}} \int_{t_0}^{t_1} \boldsymbol{\lambda}^T \frac{\partial F}{\partial \boldsymbol{Y}} \tag{26}$$

$$\boldsymbol{w} = \int_{t_0}^{t_1} \boldsymbol{C}_w(t, t')\boldsymbol{\lambda}^T(\mathrm{t'})\,\mathrm{dt'} \tag{27}$$

The optimal values of the unknown parameters are found via an iterative process, which is initiated by solving the forward model (24) to estimate **X** during the assimilation window [t_0 t_1]. It continues by solving the adjoint model (25) to obtain **λ**. Once the state variables and the Lagrange multipliers are calculated, the algorithm updates **Y** and **w** via (26) and (27). The iterative process is terminated when the gradient of cost function vanishes (i.e. the unknown parameters converge to their optimal values).

In this study, the vector of states is defined as $\boldsymbol{X}$=[*LST SM*] where LST and SM data are assimilated in hourly and daily intervals, respectively. The vector of parameters is defined as $\boldsymbol{Y}$=[*R EFs EFc b*], where $R=\ln(C_{HN})$. R varies in monthly basis while EFc and EFs very in daily basis (Bateni & Liang, 2012; Caparrini et al., 2004b) and b is the pore size index of the soil. Bruke et al. (1997) has found that soil models are least sensitive to the saturated hydraulic conductivity K_{sat} and most sensitive to the pore size index b. The optimization is constrained by heat and moisture diffusion equations.

3.3. Uncertainty Analysis

The VDA method itself does not provide estimates of the predictive uncertainty of estimated parameters (Liu & Gupta, 2007; Reichle et al., 2001). In this research a Hessian-based approach is proposed for uncertainty quantification. The Hessian of cost function (*J*) is a measure of uncertainty in the estimation of model parameters associated with the best fit values of the data, at the point of optimum.

The two well-known methods for calculation of the Hessian matrix of cost function are the Lagrangian technique and the direct differentiation method (Alekseev & Navon, 2002; Burger et al., 1992; Le Dimet et al., 2002; Papadimitriou & Giannakoglou, 2008). Studies show that the Lagrangian technique requires less computational time and provides higher accuracy in calculating the Hessian matrix compared to the direct differentiation method (Burger et al., 1992; Symes, 1991; Wang, Navon, Zou, & Le Dimet, 1995).

To construct the Hessian matrix using the Lagrangian method, N_Y new cost functions (*i.e.*, L_y, $y \in \boldsymbol{Y}$) are introduced, where N_Y is the number of unknown parameters. The new cost functions consist of the gradient of J (*i.e.* $\partial J/\partial y$) and two new adjoint variables $\boldsymbol{q_y}$ and $\boldsymbol{p_y}$, defined as:

$$L_y = \frac{\partial J}{\partial y} + \int_{t_0}^{t_1} \boldsymbol{q}_y^T \left[\frac{d\boldsymbol{X}}{dt} - F(\boldsymbol{X},\boldsymbol{Y}) \right] dt + \int_{t_0}^{t_1} \boldsymbol{p}_{\boldsymbol{y}}^T \left[\frac{d\boldsymbol{\lambda}}{dt} + \boldsymbol{\lambda}^T \frac{\partial F}{\partial \boldsymbol{X}} - (\boldsymbol{X} - \boldsymbol{X}_{\boldsymbol{obs}})^T \boldsymbol{C}_{\boldsymbol{X}}^{-1} \right] dt \quad (28)$$

Setting the first variation of the new cost functions with respect to $\boldsymbol{X}$ and $\boldsymbol{\lambda}$ equal to zero, a new set of Euler-Lagrange equations is derived which enable estimation of $\boldsymbol{q_u}$ and $\boldsymbol{p_u}$. After estimation of $\boldsymbol{q_u}$ and $\boldsymbol{p_u}$, the next step is the construction and inversion of the Hessian matrix, $\boldsymbol{H}$, to obtain the covariance matrix of parameters, $\boldsymbol{\Sigma}$.

$$\boldsymbol{\Sigma} = \boldsymbol{H}^{-1} = \left[h_{ij} \right]^{-1}, i = 1,\ldots,N_Y, j = 1,\ldots,N_Y \quad (29)$$

where the components of the Hessian matrix are computed by:

$$h_{ij} = \frac{\partial L_{y_i}}{\partial y_j} \quad (30)$$

4. Results and Discussion

Including Figures and Tables the performance of the proposed assimilation algorithm is investigated using an experiment based on a synthetic data set (hereafter true data) generated by the simultaneous heat and water (SHAW) model. In a synthetic study the true system is exactly known which is ideally suited for algorithm performance tests and is considered as a first step toward a field application with remotely sensed data.

The driving forces and meteorological data for SHAW including precipitation, air temperature, wind speed, solar radiation are taken from the FIFE experiment near Manhattan, Kansas (Sellers et al., 1992). In Fig. 1 precipitation time series as well as its cumulative values are shown. The soil type falls in the texture classes of silty clay loam at the upper layer (0-0.15 m) and silty clay at the deeper layer (0.15-1 m). The hydraulic parameters are obtained using the look-up table proposed by Clapp and Hornberger (Clapp & Hornberger, 1978). The vegetation cover predominately is classified as grassland (Betts & Ball, 1998).

Our experiment extends for 90 days from May 28, 1987 to Aug 25, 1987, which are covered by three assimilation intervals (i.e. three 30-day periods). The flow domain of the soil profiles is one meter with a spatial discretization of 1 cm. Model errors are represented as unknown fluxes in the surface water and energy budgets (i.e. (5),(10), and (19)).

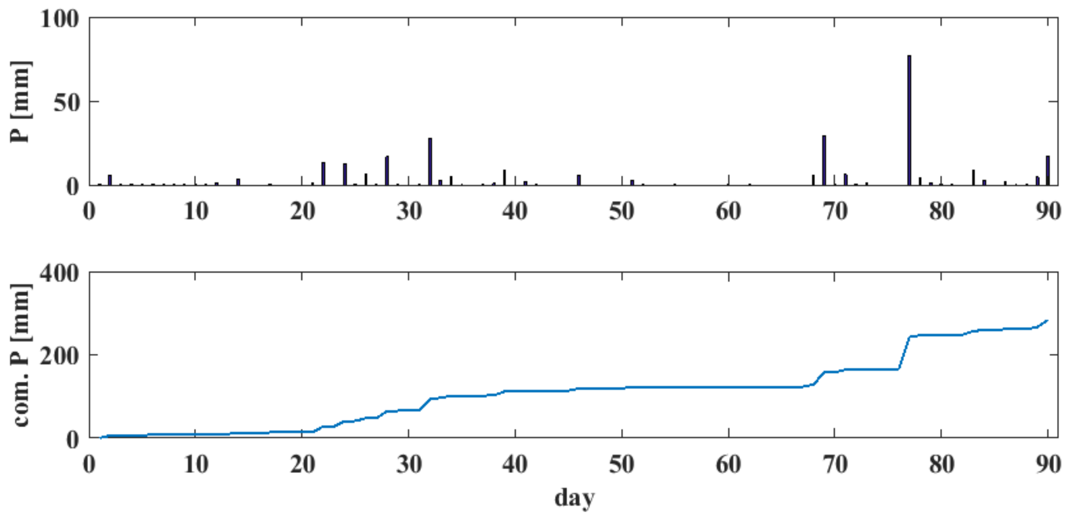

Fig. 1- The daily and cumulative precipitation time series.

4.1. Estimation of Land Surface Fluxes

4.1.1. Heat flux Estimation

The performance of proposed algorithm, $VDA_{T,S}$, in the estimation of land surface sensible (H) and latent (LE) heat fluxes is illustrated in Fig. 2 and Fig. 3, respectively. The time series of daytime-averaged values of total, soil, and canopy sensible and latent heat fluxes estimates are shown in first, second and third panels, respectively. For the sake of comparison, the true value of heat fluxes and so-called open-loop estimates (hereafter OL) are shown, as well. Please note by open-loop, we mean estimation of fluxes using the numerical models described in Section 2 based on the prior values of parameters (also called best initial guess) before assimilation of SM and LST data.

Assimilating land surface states (LST and SM) reduces the error between the OL estimates and true value of land surface fluxes. The good agreement between the true and $VDA_{T,S}$ estimates, in terms of magnitude and daily dynamic, highlights the effect of data assimilation on the land surface fluxes retrieval.

Root mean square error (RMSE) and bias of $VDA_{T,S}$ flux estimates are compared with those of VDA_T in Table 1. Recall that in VDA_T, only LST is assimilated and the only physical constraint of cost function is heat diffusion equation while in $VDA_{T,S}$, SM and LST are simultaneously assimilated and the cost function is constrained with both heat and moisture diffusion equations. Comparison between $VDA_{T,S}$ and VDA_T indicates that assimilating SM improves the performance of the VDA method in accurate estimation of total sensible and latent heat fluxes. In addition, assimilating SM data (with valuable embedded information) and constraining the estimation process with the moisture diffusion equation enables $VDA_{T,S}$ to more accurately partition the total latent heat fluxes into the soil and canopy latent heat fluxes which consequently leads to the more accurate partitioning of evapotranspiration into the flux of evaporation (from soil) and transpiration (canopy).

Table 1- Comparison between RMSE and bias (presented in parentheses) of heat fluxes

	Sensible heat flux (H)			Latent heat flux (LE)		
	Total	Soil	Canopy	Total	Soil	Canopy
OL	74 (-12)	45 (-12)	44 (-1)	112 (-20)	73 (18)	64 (-38)
VDA_T	69 (-53)	18 (-10)	61 (-44)	66 (48)	36 (18)	54 (30)
$VDA_{T,S}$	39 (-12)	22 (4)	38 (-16)	43 (6)	35 (6)	39 (0)

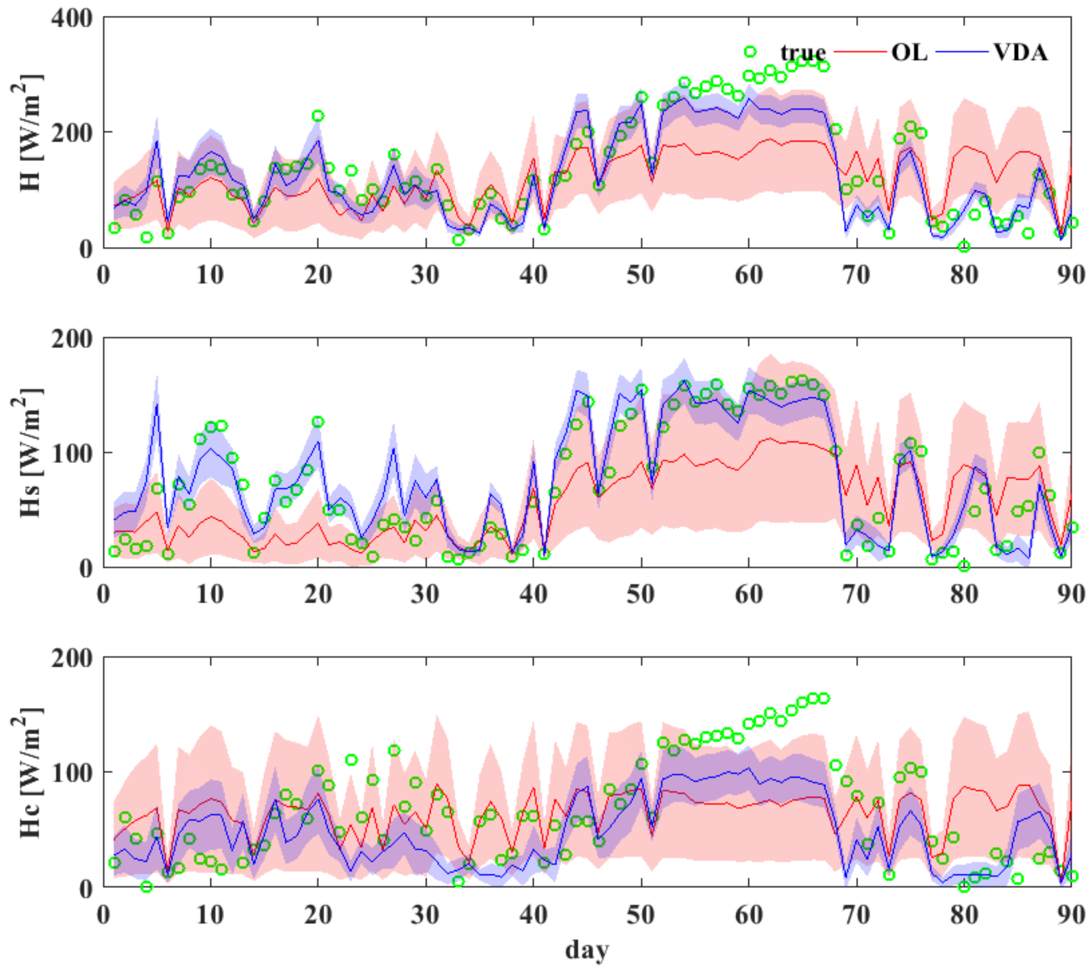

Fig. 2- Day-time average of prior and posterior $VDA_{T,S}$ estimates of total, soil, and canopy sensible fluxes versus true value. The red and blue shade error band shows the prior and posterior uncertainty of fluxes, respectively.

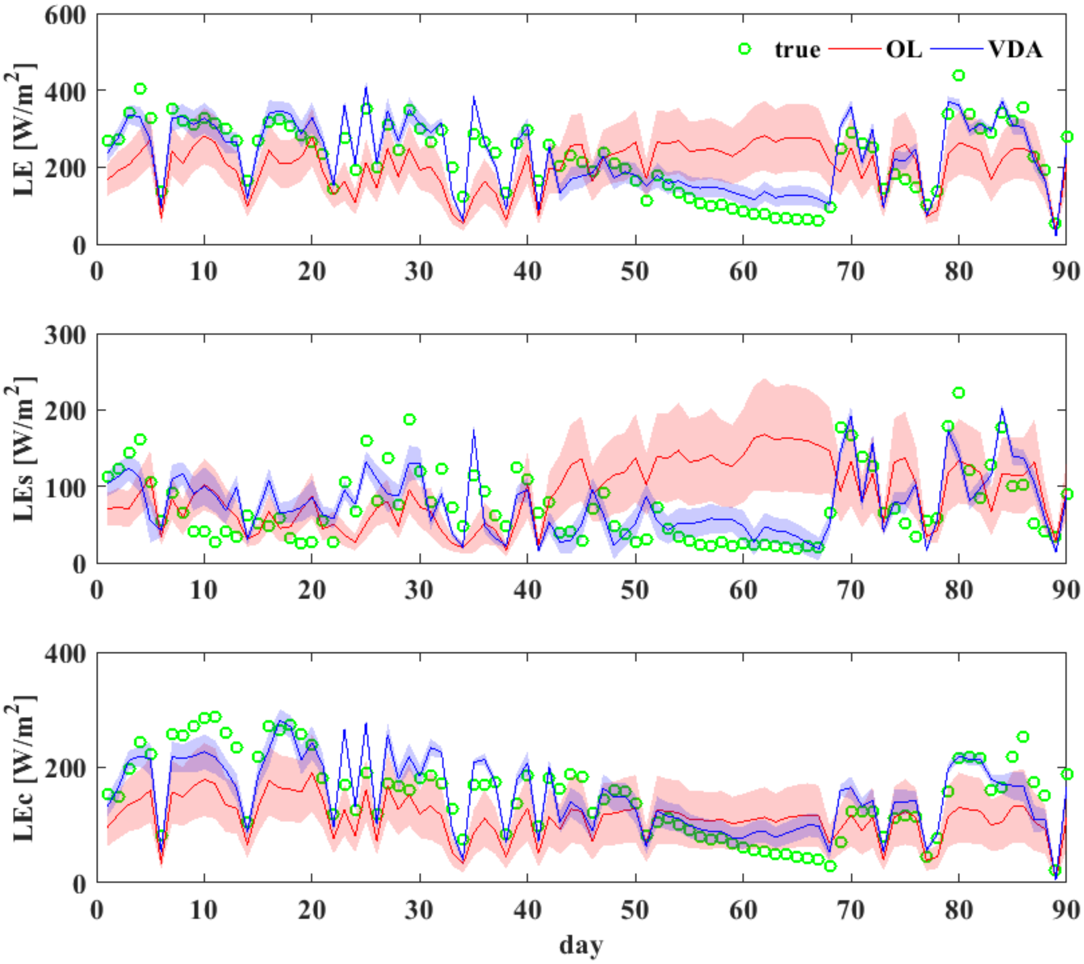

Fig. 3- Day-time average of prior and posterior $VDA_{T,S}$ estimates of total, soil, and canopy latent fluxes versus true value. The red and blue shade error band shows the prior and posterior uncertainty of fluxes, respectively.

Like any optimization problem, the performance of the VDA method in obtaining optimal value of parameters depends on the initial values of unknown parameters. In hydrological VDA, the initial values of unknown parameters are define based on the prior knowledge of system such as vegetation/soil characteristics and weather condition.

In Fig. 4, RMSE of sensible (H) and latent (LE) fluxes estimates via VDA_T and $VDA_{T,S}$ are shown versus various initial values of unknown parameters. As it is obvious, one of the important effect of assimilating SM data (in addition to LST data) is reducing the sensitivity of the VDA method to the initial value of unknown parameters. RMSE of VDA_T estimates varies considerably as the initial values changes (from 45 to 95 W/m^2 for H and from 44 to 87 W/m^2 for LE) while RMSE of $VDA_{T,S}$ estimates are almost constant versus initial value of R and changes little with variation of EF_s and EF_c initial values (from 34 to 51 W/m^2 for H and from 48 to 52 W/m^2 for LE). This reveals that $VDA_{T,S}$ is able to obtain the optimal values of parameters though the initial knowledge of land surface characteristics is poor and initial values are not chosen close to the true values. Indeed, constraining the cost function with moisture diffusion equation in addition to heat diffusion equation improves the performance of the VDA method in optimization of parameters and consequently estimation of land surface fluxes (note that due to space limitation only results for the second assimilation period are shown in this manuscript).

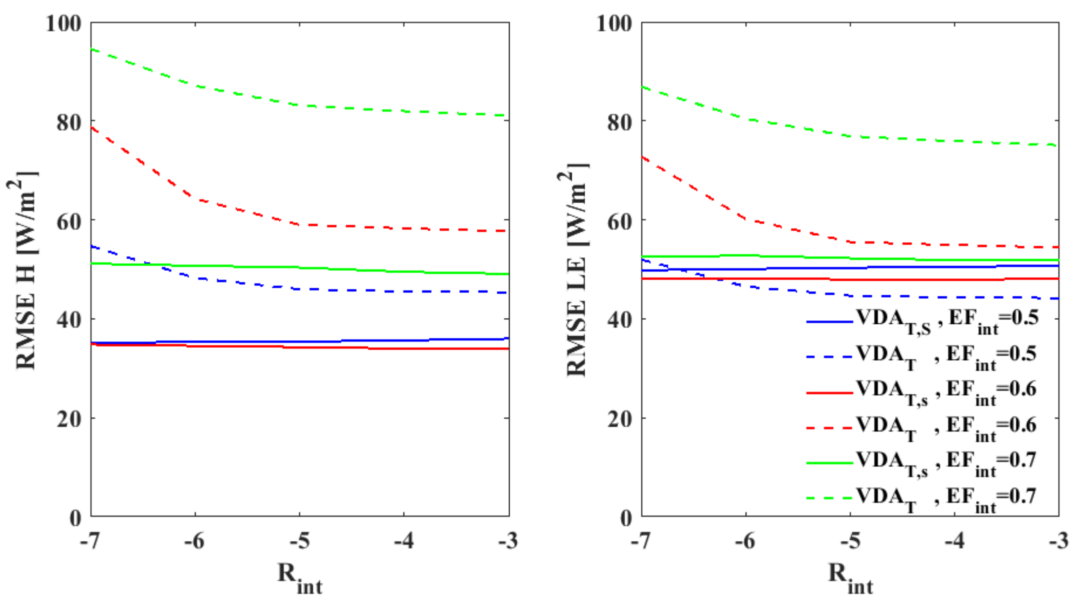

Fig. 4- Sensitivity of $VDA_{T,S}$ and VDA_T to initial value of parameters (results for day 31-60)

4.1.2. Water Fluxes Estimation

To solve the Richards" equation, the soil hydraulic properties should be defined ((2),(6), and (7)). Bruke et al. (1997) has found that soil models are least sensitive to K_{sat} and most sensitive to b. Therefore, in this work we approximate the value of θ_{sat}, K_{sat}, and h_{sat} based on the soil texture on the surface (e.g. obtained from FAO-UNESCO 1984 soil maps) from the look-up table (Clapp and Hornberger 1978) and use the Expectation-Maximization algorithm (Moon 1996) to obtain the effective pore size index, b_{eff}, which represents the pore size index of column of soil. By a synthetic experiment, we show the effect of replacing two layers of soil with one uniform soil layer (see Fig. 5 for experiment setup) which has the same θ_{sat}, K_{sat}, and h_{sat} as first layer and the b value is equal to b_{eff}. In order to find the b_{eff}, we run $VDA_{T,S}$ with varies range of b (e.g. from 4 to 8) and obtain the cost function value at the optimum point. The value of b_{eff} is correspond with the b value which produce the minimum cost value (see Fig. 6, b_{eff}=6.5).

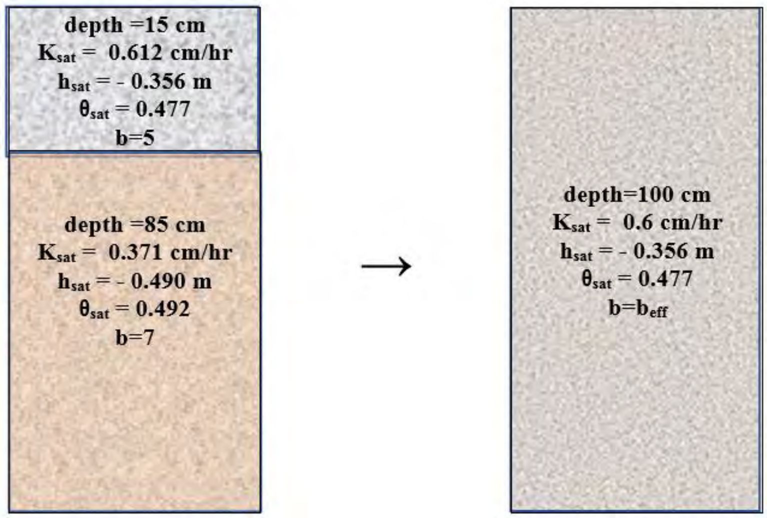

Fig. 5- Simulating two layers of soil with various soil hydraulic properties with one effective soil layer

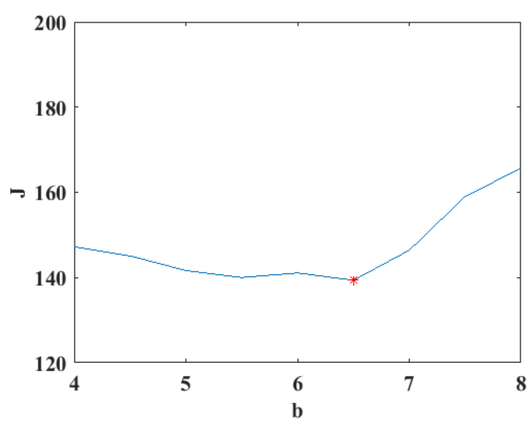

Fig. 6- Obtaing effective pore size index, b_{eff}

Using the soil hydraulic properties and estimated b_{eff}, the daily recharge (normlized by K_{sat}) is estimated via $VDA_{T,S}$ and compared with true values at different depths in Fig 7. The results of estimated daily evapotranspiration (ET) and corresponding true values are are shown in figure 8. The RMSE and bias of ET is 0.9 and -0.13 mm, respectively.

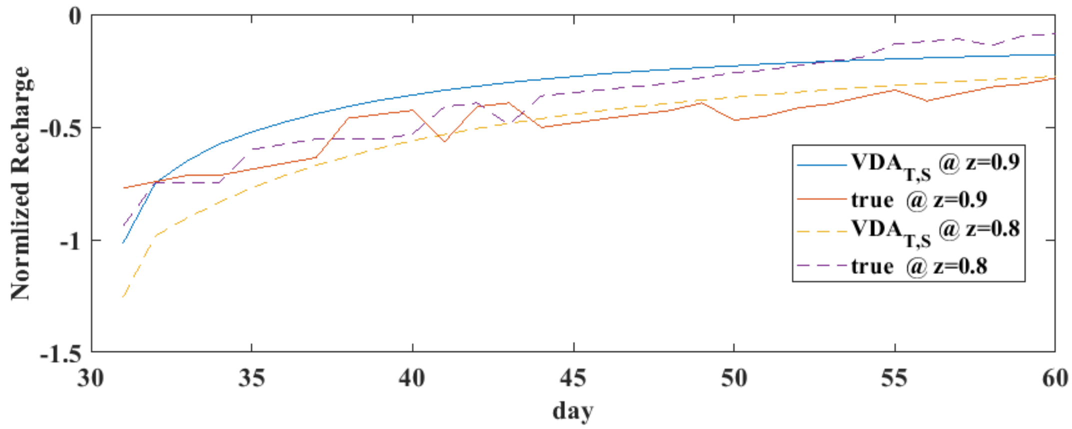

Fig. 7- Time series of estimated and true normlized daily recharge at various depth

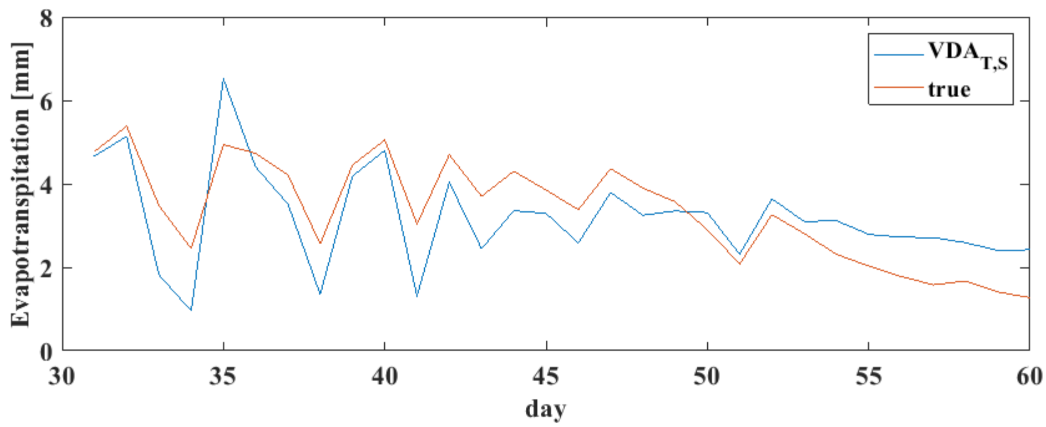

Fig. 8- Time series of estimated and true daily evapotranspiration

4.2. Integrated Framework

In a high-dimensional non-linear minimization problem, such as hydrological VDA problems (e.g. Caparrini et al. 2004a; Bateni and Liang 2012; Abdolghafoorian et al. 2016), one of the profound difficulty is the existance of saddle points. Such saddle points are surrounded by plateaus of small curvature and give the deceptive impression of the reaching the local minimum (Pascanu et al., 2014).

Motivated by this issue, we propose an integrated framework (IF) for obtaining the optimum values of the unknown parameters. In this framework, frist the critical point (where the gradient of cost function vanishes) is obtained via the VDA method, then the Hessian matrix in vicinity of critical point is computed via the Lagrangian method described in Section 2. If all eigenvalues of the Hessian matrix are non-zero and positive, then the critical point is a local minimum. If the eigenvalues are non-zero and they are both positive and negative eigenvalues, then the critical point is a saddle point.

In this section, we demonstrate the application of proposed framwork by a set of experiment. In section 4-1, we illustrated the sensitivity of VDA_T to the initial value of parameters. It was shown that if our initial knowledge of land surface characteristics is poor, we might choose the initial values of parameters in such a way that the RMSE of retrival heat fluxes are not acceptable, indicating the the optimal values of parameters (i.e. minumum point of cost function) are not reached. Note that in a real problem the true value of heat fluxes are not knonw and there is no way to identify this issue. The proposed integrated framwork is a great tool to tackle the issue.

The VDA method starts from the initial values of parameters and finally retrieves optimum values. This proccess is done iteratively until the convergence is reached. Fig. shows the value of cost function and RMSE of LST as a function of the iteration number in the process of finding the critical point. The cost function decreases as the number of iterations increases, but at a certain iteration number this misfit reduces only slightly meaning that the optimal value obtained. Finding the critical point of cost function is first step of IF (note that in the perivios studies, analysis of J and RMSE of LST as a function of the iteration number was the only available tool for identifying the minimum/optimal point).

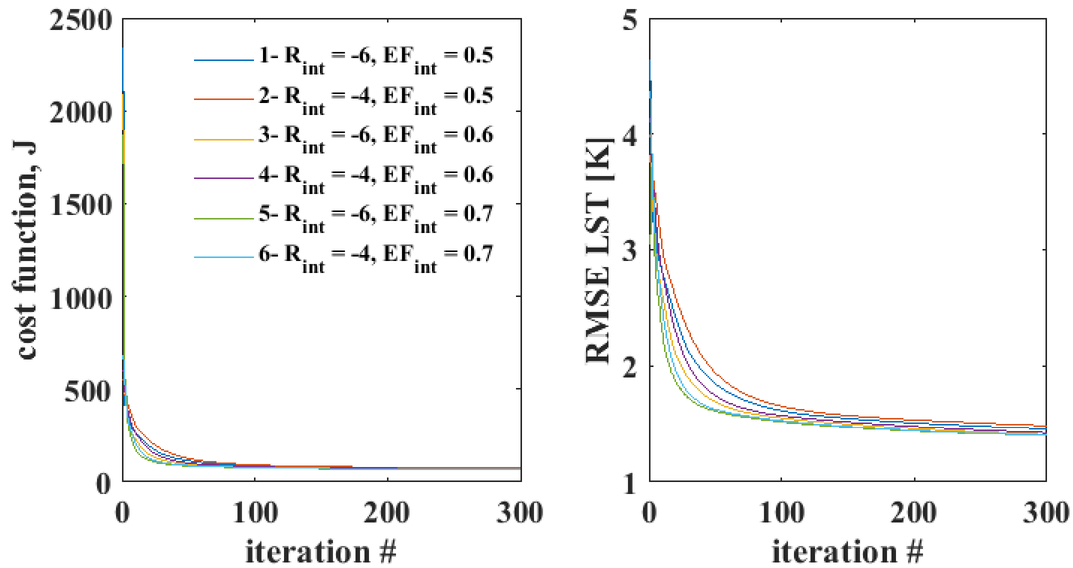

Fig. 9- Cost function and RMSE of LST as a function of the iteration number (result for day 31-60)

In the next step, the Hessian matrix of cost function and its eignvalues are computed using the Lagrangian methodology. Table 2 shows the analysis of the Hessian matrix for the six combinations defined in 9. Although the cost function and the RMSE of LST for six combinations shows the similar results, analysis of the Hessian matrix at the critical points reveals that in combination 3, 5, and 6 the VDA method reaches a saddle point (not a minimum). To demonstrate the effeciency of IF, the RMSE of heat fluxes are shown in Table 2, as well. As it is shown, the saddle points are correspond with high RMSE of heat fluxes while the minimum points correspond with low RMSE. It should be emphsized that if the initial guess of parameters is not based on the precise knowledge of land surface charactrestic and atmospheric condition (e.g. in a large scale application), without analysis of Hessian matrix there is no way to be assured that the VDA estimates are robust. To our knowledge, this is the first attempt to distinguish between saddle and minimum point of the cost function in the hydrological application of VDA and enhances the efficiency of VDA in large scale applications.

Table 2- Illustration of the integrated framework application (result of day 31-60)

Combination (see Fig.)	1	2	3	4	5	6
Eignvalues	+	+	+ / -	+	+ / -	+ / -
Critical point	minimum	minimum	saddle	minimum	saddle	saddle
RMSE H [W/m^2]	35	27	62	53	87	82
RMSE LE [W/m^2]	39	35	59	51	80	76

4.3. Uncertainty Analysis

In this section, the result of uncertainty analysis using the hessian-based methodology described in section 2 are presented. Fig. compares the prior and posterior uncertainty of parameters obtained via $VDA_{T,S}$. Assimilating LST and SM data which charactrize the state of the land surface reduces the prior uncetrainty of parameters. To demonstrate the effect of simultanouse assimilation of SM and LST (rather than only LST), the postrior uncertainty of the VDA_T estimates is presented in 10, as well. SM data can contribute valuable information when used in the hydrological VDA system and improve the uncertainty of estimates.

One of the important information obtained by performaing the uncertainty analysis and computing the error-covarice matrix is the correlation between parameters. In an ideally well-posed optimization problem, the soluson is unique. High correlation between retrieved parameters means that the VDA method is unable to separate the parameters from each other and obtain the unique optimal solution. In Table 3, the avarage correlation between the parameters obtained by $VDA_{T,S}$ and VDA_T are presented. Comparison betweeen $VDA_{T,S}$ and VDA_T indicates that by constraing the optimization problem with the new physical model (i.e., moisture diffusion equation) and coupling the water and energy budges, the correlation between the parameters is reduced and the VDA method is oriented toward well-posedness. In additon, reducing the correlation between canopy and soil evaporative fraction (EFs and EFc) effects the robustness of method in partitioning the total sensible and latent heat fluxes between soil and canopy components (as shown inTable 3).

Table 3- Uncertainty of parameters and correlation between them (the values show 90-day average)

	Uncertainty			Correlation		
	R	EFs	EFc	R,EFs	R,EFc	EFs,EFc
VDA_T	0.15	0.15	0.14	-0.16	-0.23	-0.51
$VDA_{T,S}$	0.10	0.10	0.11	-0.10	-0.22	-0.21

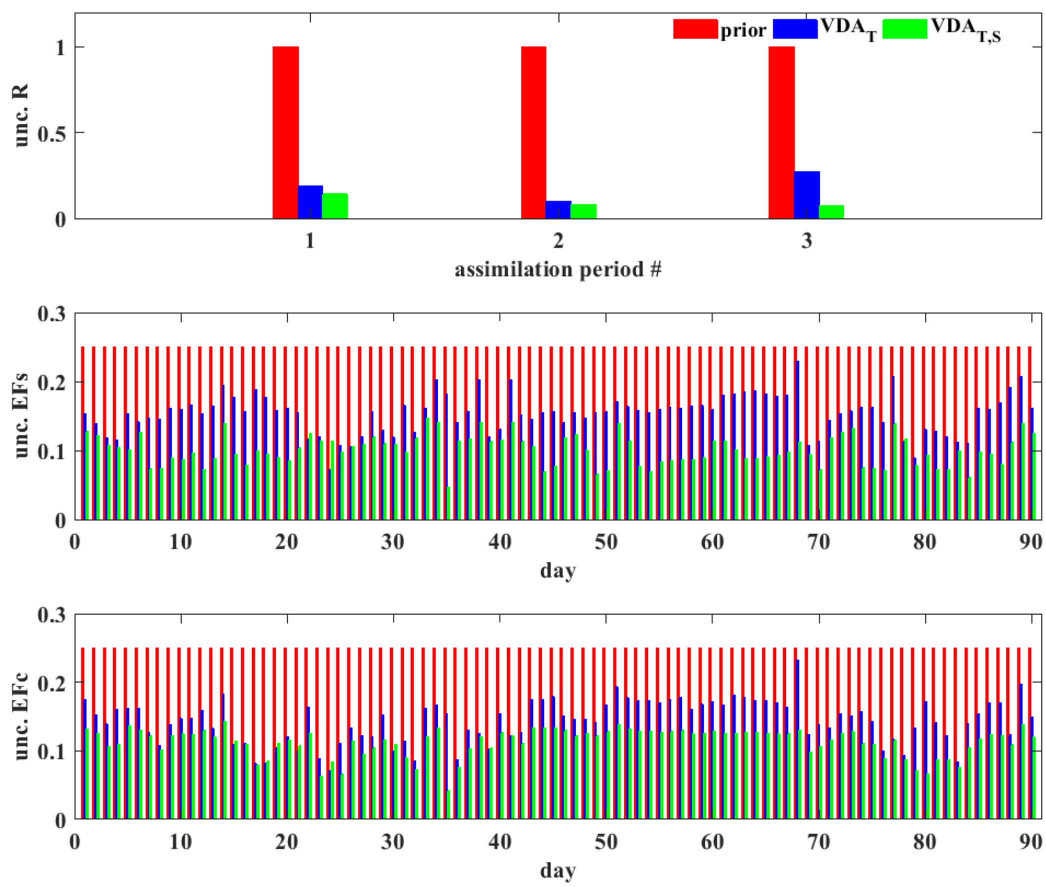

Fig. 10- Prior and posterior uncertainty of parameters

The uncertainty of heat fluxes is quantified through the Monte Carlo algorithm. Fig. 2 shows the prior (blue error band) and posterior (red error band) uncertainties associated with the sensible and latent heat fluxes. The prior uncertainty of fluxes reduces by assimilating land surface states. Comparison between the uncertainties of fluxes obtained by $VDA_{T,S}$ and VDA_T reveals that assimilatig both LST and SM (rather than only LST) reduces the uncertainty of sensible (latent) fluxes from 25 (129) to 22 (72) W/m^2.

The previous studies have shown that the performance of the VDA method for obtaining land surface fluxes by assimilating LST is not satisfactory during 1- the energy-limited regime (i.e. when soil is relatively wet), 2- in days when the average T_s-T_a is small and 3- where land surface is densely vegetated. (e.g. Crow and Kustas 2005; Bateni et al. 2013b; Abdolghafoorian and Farhadi 2016). In this study, we investigate the effect of adding SM as a new assimilated data and coupling water and energy balance budges on the uncertainty and accuracy (i.e. absolute error between the true value and estimation) of the VDA land surface estimates in these condition. Fig. 11 illustrates the uncertainty (blue asterisk) and accuracy (red circle) of fluxes obtained by $VDA_{T,S}$ and VDA_T on days with 1- small T_s-T_a (i.e. T_s-T_a < 3 K), 2- relatively high SM (i.e. SM > 50%) and high LAI (i.e. LAI>2). Generally speaking, simultaneous assimilation of SM and LST enhances the performance of the VDA method by reducing the uncertainty and increasing the accuracy of sensible and latent heat fluxes in the aformentoned conditions.

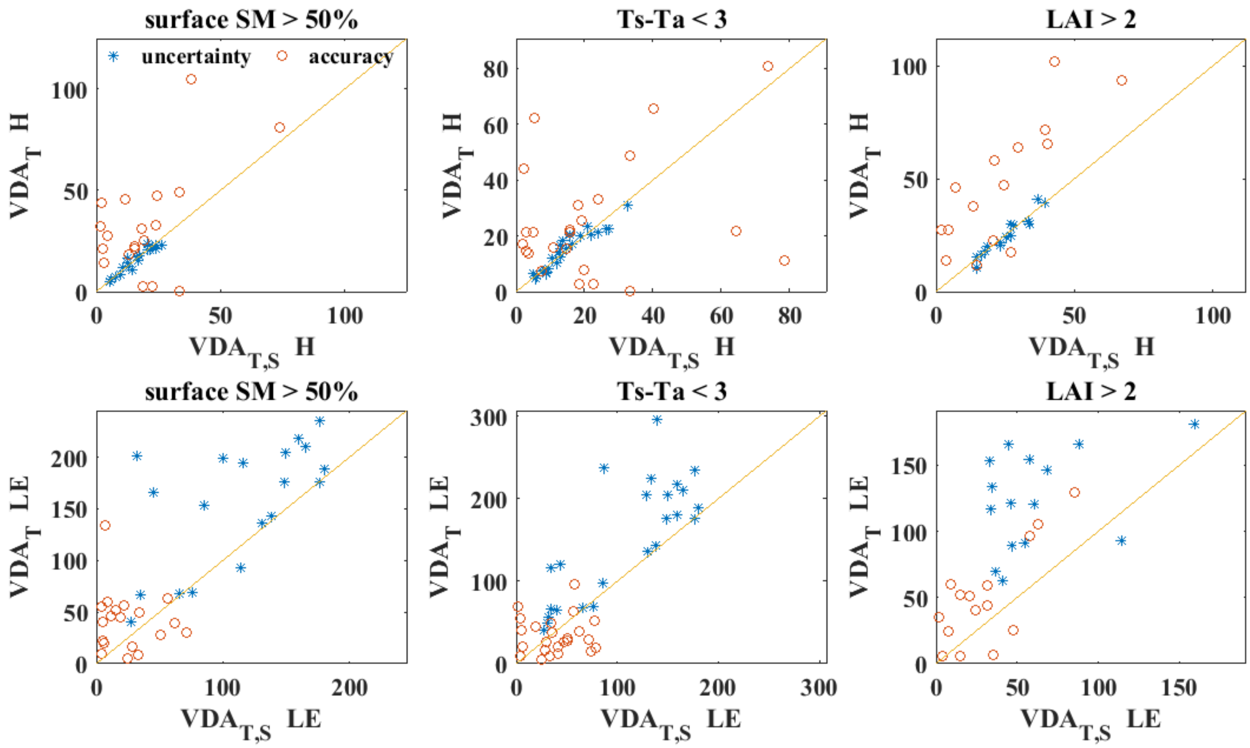

Fig. 11- Uncertainty and accuracy of sensible, H (first row) and latent, LE (second row) fluxes obtained by $VDA_{T,S}$ and VDA_T on days with: 1- SM > 50%, 2- T_s-T_a < 3, and 3- LAI > 2.

4.4. Feasibility of assimilating space-borne data

The ultimate goal of this study is to employ the proposed $VDA_{T,S}$ integrated framework to estimate land surface fluxes in large scale application by assimilating space-born LST and SM data. As a step toward this goal, we examine the effect of assimilating SM and LST data with low temporal resolution (corresponds with various satellite overpass intervals or/and cloudy sky conditions at the time of satellite overpass) on the performance of $VDA_{T,S}$.

The effect of LST and SM frequency on the accuracy of heat fluxes estimates are shown on the left and right panels of Fig 12, respectively. The results of left panel obtained by assimilating SM data with 3-day interval and various LST frequency (Note that in order to simulate the random occurrence of cloudy sky, the time of LST assimilation is randomly chosen in the assimilation window). The results of right panel obtained by assimilating hourly LST data and various SM frequency. Assimilating SM data with 3-day interval corresponds to overpass of Soil Moisture Active Passive (SMAP) and Soil Moisture Ocean Salinity (SMOS) remote sensing missions and daily SM data to future L-band missions or to a combination of different sensors

Based on the results in Fig. 12, the RMSE of fluxes are more sensitive to the availability of LST data than SM data. It also can be concluded that $VDA_{T,S}$ is not able to estimates LE accurately when the availability of LST data is limited to 3 or 4. In general, it can be concluded that although higher frequency of LST and SM improves the performance of $VDA_{T,S}$, acceptable RMSEs of fluxes obtained by assimilation of data with low temporal resolution indicates the feasibility of extending proposed approach to use space-borne land surface state data set.

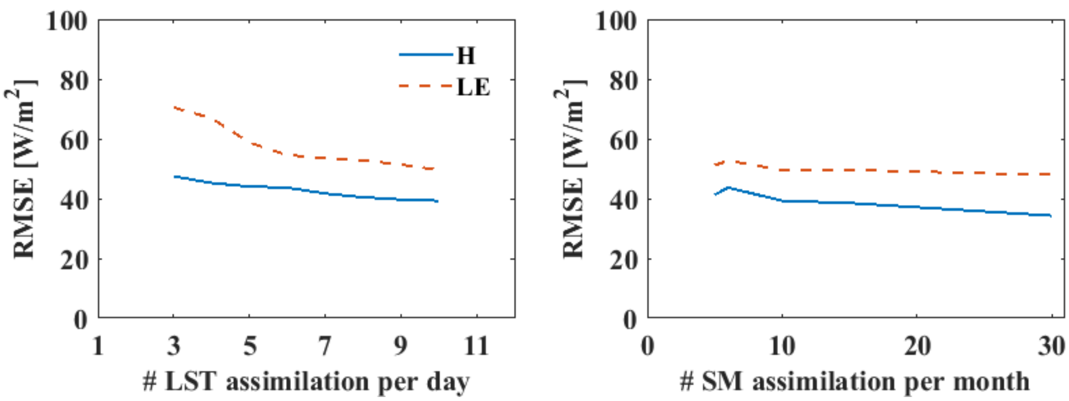

Fig. 12- Effect of assimilating low temporal resolution SM and LST data on the performance of $VDA_{T,S}$ (results for day 31-60)

The penetration depth is the other issue with space-borne data that should be taken into consideration. The penetration depth of signals for SM measurements depends on soil moisture content and soil type (Entekhabi & Moghaddam, 2007). On average, L-band radiometers (e.g. SMAP and SMOS) measure soil moisture in the top 5 cm of soil, not in the root zone (Shellito et al., 2016). On the other hand, the important role of initial soil moisture profile for assimilation of surface soil moisture measurements has been discussed in previous studies (e.g. Das and Mohanty 2006; Walker et al. 2001).

Table 4 shows the result of our investigation into the effect of poor initialization (caused by lack of information about the true soil moisture profile) on the performance of $VDA_{T,S}$. The initial soil moisture profile is assumed uniform equal to the soil moisture in the top 5 cm of soil ($SM_{0\sim5}$) with minimum value of 0.15. Given this assumption, the estimates of land surface fluxes is not sensitive to the initial soil moisture profile if the initial soil moisture. Indeed, assimilation of LST and SM data at the surface corrects the incorrect initialization of soil moisture profile. The results are compatible with the findings of other studies e.g. Walker et al. (Walker, Willgoose, & Kalma, 2002). It should be mentioned that our investigation showed that (results not presented in this manuscript) if $SM_{0\sim5}$ on the initial day is smaller than 0.15 and the field of study is not a arid region (i.e. deep layer of soil are not very dry), assuming the uniform profile of soil mositure equal to $SM_{0\sim5}$ leads to the inaccurate land surface fluxes estimation.

Table 4- Effect of poor initialization on the performance of $VDA_{T,S}$

Initial profile of SM	RMSE H	RMSE LE	RMSE SM @ z=0	RMSE SM @ z=0~100cm
Known	39	43	0.04	0.06
Unknown (Assumed uniform equal to $SM_{0\sim5}$)	35	44	0.04	0.03

5. Project outcomes, presentations, publications or thesis (book chapter journals or conference proceedings)

- American Geophysical Union AGU (12/15/2017): Estimation of Land Surface Fluxes through Assimilation of Surface Temperature and Moisture States into Models of Terrestrial Water and Energy Balance via the VDA Approach, Poster presentation

- GWU R&D showcase (2/21/2018): Estimation of Key Parameters of the Coupled Energy - Water Model by Assimilating Land Surface Temperature and Soil Moisture, Poster presentation

- American Water Resource Association, National Capital region AWRA-NRC (4/6/2018): Monitoring Water and Energy Cycle from Space, presentation

6. Student supports

1 PhD student supported for a period of 4 months from this grant.

7. Extramural funding received or pending

I received NASA Young Investigator Award in Earth Sciences in March 2018.

Funding I received from GWU and WRRI for this project helped me produce some of the preliminary results that I demonstrated in my proposal to NASA.

8. Conclusion

The PI‟s goal in this project was to advance the understanding and modeling of large-scale evapotranspiration and recharge flux. In order to achieve this objective, the PI has developed and integrated state-of-the-art computational and data driven techniques to yield first order accurate estimates of key state and parameters (e.g., estimation control variables) of evapotranspiration and recharge flux from implicit information contained in the Land Surface state observations of Temperature (LST) and Soil Moisture (SM). The developed approach is based on the variational data assimilation (VDA) scheme that assimilates state observations of LST and SM into a coupled system of surface energy balance and surface water balance. The cost function consists of the LST and SM misfit terms and deviations of parameter estimates from prior values. Parsimonious heat and moisture diffusion equation are adjoined to the cost function as strong constraints. Efficient solution procedures (Euler-Lagrange) are available for such systems. The Hessian of the cost function, which yields a measure of uncertainty in the estimation, is derived and used in this study to guide the formulation of a well-posed estimation problem. The accuracy of this method is tested at point scale using synthetic measurements of turbulent heat fluxes and soil moisture profiles. The promising results obtained in this project demonstrate the feasibility of the approach for large scale estimation of evapotranspiration and recharge over Chesapeake bay watershed.

9. Acknowledgement

I recognize funding agency (WRRI) and the George Washington University (GWU) for the financial support of this project.

I would like to thank Dr Tolessa Dekissa (head of water resources research Institute), Dr Majid Manzari (Chair of Civil and Environmental Engineering at GWU) and my PhD student Abedeh Abdolghafoorian for their contribution to the success of this project.

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Examining genetic microbial diversity to monitor pathogens and toxins and in the Anacostia River, DC

Basic Information

Title:	Examining genetic microbial diversity to monitor pathogens and toxins and in the Anacostia River, DC
Project Number:	2017DC193B
Start Date:	3/1/2017
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	DC
Research Category:	Water Quality
Focus Categories:	Ecology, Water Quality, Education
Descriptors:	None
Principal Investigators:	Caroline Solomon, Derek Braun, Gaurav Arora

Publications

1. Solomon, C.M., Arora G., Vazquez G. (2018). Assessing the effectiveness of the Anacostia River tunnel in reduction of eutrophication, Poster Presentation, North American Congress for Conservation Biology. Toronto, CA.
2. Humlicek, G., Arora, G., & Solomon, C.M. 2017. Analysis of Bacterial and Algal Diversity in the Anacostia River, Poster Presentation, Maryland Water Monitoring Council Annual Conference. Linthicum,Maryland.
3. Humlicek, G., Arora, G., & Solomon, C.M. 2017. Analysis of Bacterial and Algal Diversity in the Anacostia River, Poster Presentation, AASD-STEM/SEAPD STEM INCLUDES Meeting, Auburn University, Auburn, AL.
4. Kyre, C. J., Lauevicius, A., Humlicek, G., Vazquez, G. Arora, G., & Solomon, C.M. 2017. Examining the effect of nutrients on algal communities in the Anacostia River. Poster Presentation, AASD-STEM/SEAPD STEM INCLUDES Meeting. Auburn University, Auburn, AL
5. Humlicek, G., Arora, G., & Solomon, C.M. 2017. Analysis of Bacterial and Algal Diversity in the Anacostia River, Poster Presentation, UMBC Undergraduate Research Symposium, Baltimore, MD.

Examing genetic microbial diversity to monitor pathogens and toxins in the Anacostia River, DC

Progress Report

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April 20, 2018

1. Executive Summary

The Anacostia River in Washington, D.C. is classified as an impaired river due to many anthropogenic influences based on several indicators. In this study, we offered to look at three main indicators (**fecal bacteria**, **chlorophyll *a***, and **toxins)** used in the Anacostia River report card using genetic tools to provide a closer resolution about the exposure and health risks associated with full- and limited-contact recreational activities.

We monitored the genetic diversity of phytoplankton, bacteria and viruses, especially those that would be considered **"contaminants of concern"** either because they are pathogenic or produce toxins that could cause health risks over a nutrient gradient in the Anacostia River. Samples were collected at three sites during spring, summer, and fall (two times each season) in 2017 to assess relationships between genetic diversity and environmental conditions (temperature, dissolved oxygen, nutrients (N and P) to better understand the persistence and growth conditions of microbes in the Anacostia River to prevent potential hazardous conditions. This project directly contributes to monitoring the influence of the pre- and post-construction of green and gray infrastructure to the changing nutrient dynamics for local phytoplankton, bacterial and viral communities and how it impacts local residents who use the Anacostia River for recreation.

2. Introduction

The Anacostia River, which flows through the District of Columbia, is a "major area of concern" and is one of the nineteen designated urban water locations by the U.S. EPA (2016; Murray et al. 2015). It is one of the most urbanized watersheds in the country and formal restoration efforts began in 1987 with the signing of the Anacostia Watershed Agreement and the formation of the Anacostia Watershed Restoration Committee (AWRC; AWRP 2016). By 2006, it was becoming evident that established targets would not be met by 2010. In response to this concern, the Anacostia Watershed Restoration Partnership (AWRP) was established (AWRP, 2016) to monitor and coordinate efforts to restore the river. The recent Anacostia River report card distributed by the Anacostia Watershed Society graded the ecosystem health of the river as an F, which shows that yet much has to be done to restore the river (AWS, 2016).

Report cards are developed to inform citizens in a transparent and timely manner about issues so that they can respond with corrective action (Spitzer, 2015). Stakeholders decide which indicators are included in the report card in order to better understand the issue. The 2016 Anacostia Report Card includes indicators that are important to the Anacostia watershed including **fecal bacteria**, **chlorophyll *a***, and **toxins** (AWS, 2016).

The first indicator, **fecal coliform bacteria**, is included because of the antiquated sewage system in the District of Columbia that includes 17 combined sewage outfalls (CSO) that are situated along the Anacostia (Natural Resources Defense Council, 2012; DC Water and Sewer Authority, 2012). Each year during rain events greater than half an inch to an inch, approximately two to three billion gallons total of untreated sewage are mixed with storm water and released into the river carrying with it fecal coliform bacteria, nutrients, trash and sediments (DC Water and Sewer Authority, 2012). Fecal coliform bacteria are measured as MPN/mL of *Escherichia coli* (*E. coli*), and are consistently observed after near CSOs after storm events (DC DOEE, 2014). Recently, there were revisions to the allowable TMDL loads to take in account of daily surges

(DC DOEE, 2014). However, other bacteria that are also considered fecal bacteria are not included in this measurement, despite some earlier studies looking at the effect of temperature on growth and activity of *Aeromonas* spp that showed higher numbers during the summer months in the Anacostia River (Cavari et al. 1981).

Another possible pathogen (or contaminant) from the sewage outfalls are viruses that have not yet been examined in the Anacostia River. There are more than 100 different type of viruses found in human waste and can be potentially transmitted by water (Berg 1983) and their survival periods surpass those of fecal coliform bacteria in similar environments (Melnick & Gerba 1989). This suggests that fecal coliform bacteria indicators are limited as predictors of viral pathogens (Jiang et al. 2001, Miagostovich et al. 2008)

Chlorophyll *a*, as an indicator of phytoplankton (microalgae) biomass, is useful in understanding water clarity and dissolved oxygen levels. High chlorophyll *a* levels are an indicator of eutrophication that leads to lower water clarity and depletion of dissolved oxygen due to decomposition of phytoplankton that is not consumed by grazers (Kemp et al. 2005). High chlorophyll *a* levels are fueled by nitrogen (N) and/or phosphorus (P) enrichment due to different anthropogenic sources, but information about the phytoplankton community composition at different sites along the River are scarce (Guerrero 1991, Krogmann et al. 1986). Recent observations using FlowCam and pigment analysis using HPLC have detected trends in major phytoplankton groups (Solomon et al., *in progress*; Jackson, 2016) but not on a species level.

Toxins are defined in the report card as industrial chemicals such as PCBs and PAHs, not other types of toxins. Many links have been made between these chemicals, that are typically found in sediments, and red lesions, skin and liver tumors observed on brown bullhead catfish (Pickney et al. 2001; Pickney et al. 2004).

However, toxins can be produced by harmful algal and bacterial species. For instance, the toxin, microcystin, from the freshwater cyanobacteria *Microcystis aeruginosa* (which has appeared in the Potomac River in the past; Krogmann et al. 1986), are N-containing molecules and are synthesized by biochemical pathways that involve polyketide and nonribosomal peptide synthases (Dittman and Borner 2005) thus would be expected to increase with N enrichment. There are many other algal toxins that include saxitoxin and domoic acid that are also N-containing molecules that come from an array of dinoflagellates and diatoms (van Dolah, 2000). The bloom of the dinoflagellate, *Gymnodinium,* that occurred in the Anacostia during summer 2011 (Metropolitan Washington Council of Governments, 2011) could have released substantial amounts of saxitoxins.

We look more closely at the three indicators (**fecal bacteria, chlorophyll *a*, and toxins**) with a much closer resolution with genetic tools and their relationship to nutrient dynamics of the River to better ***prevent contamination of water supplies*** and ***toxin monitoring*** with the ultimate goal to restore the River.

Statement of results or benefits

Many residents of District of Columbia use the Anacostia River for recreational purposes (e.g. kayaking, canoeing, boating, rowing, paddling and sport fishing) despite D.C. law prohibiting swimming in this waterway. Many of these residents are unaware of studies related to exposure and health risks of limited and full-contact recreation. However, those studies (with the exception of two) are not local to the Anacostia River and are case studies from other areas affected by fecal contamination (*Addressing the Risk*, 2012; Murray et al. 2015). **This study uses bioinformatics to have a better resolution of "possible contaminants of concern" such as toxic and harmful algae, pathogenic bacteria and viruses and how their abundance is influenced by nutrient loading.** We hope data from this study will help us better understand what the exposure and health risks are for the Anacostia River and how it is influenced by changing nutrient dynamics.

There is currently a two-prong approach to building sustainable infrastructure in Washington DC to create a cleaner city and improve the water quality of the Anacostia River: (1) building tunnels to retain excess sewage and storm water (e.g., gray infrastructure) and (2) encouraging the construction of rain gardens and green roofs, planting of trees, and use of rain barrels (e.g., green infrastructure; Sustainability DC, 2013). The data from this project is instrumental in helping determine the baseline conditions (pathogenic and/or toxic microbes related to the nutrient dynamics) both before and during these gray and green infrastructure are in place.

3. Methodologies

Water samples were collected two times a season (spring, summer and fall) from 3 designated sites on the Anacostia River in partnership with the Anacostia Riverkeeper (AK) from March to November (**Fig. 1**).

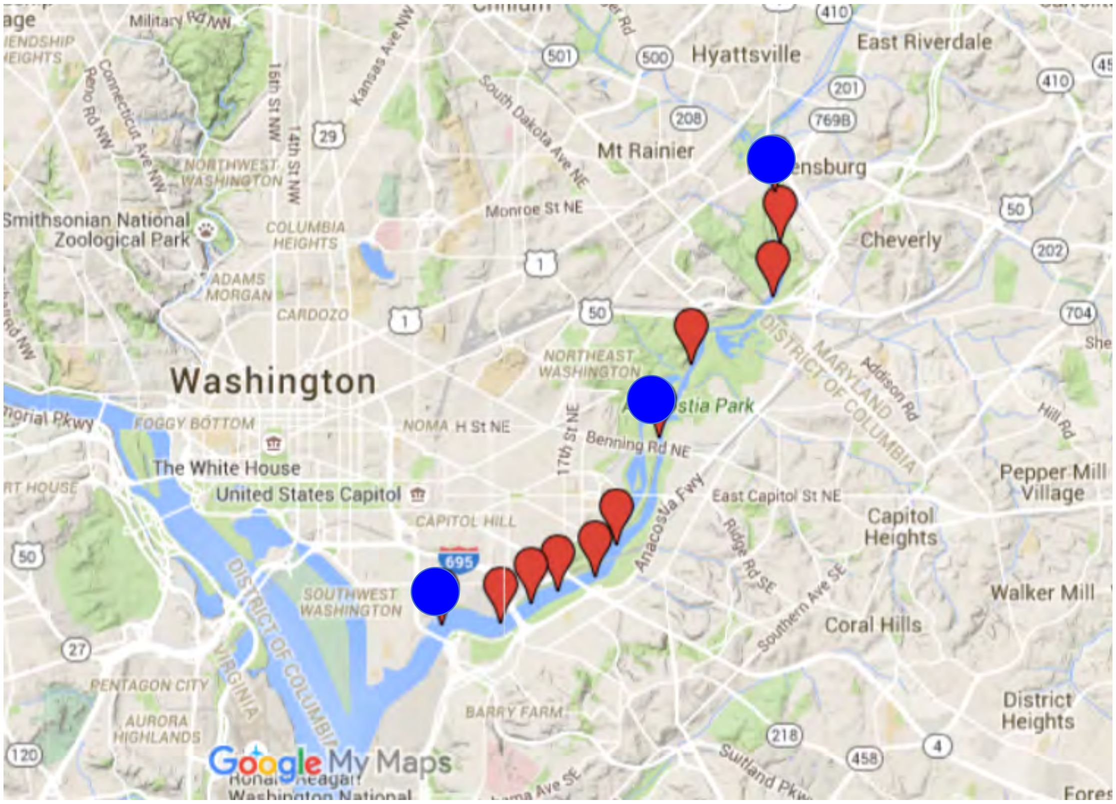

Figure 1: The eleven sampling sites on the Anacostia River for nutrient analysis (as shown by the red arrows). The three sampling sites (Site 1, 5, and 9) for microbial biodiversity are shown by the blue dots.

(1) Nutrients: NO_3^- were analyzed according to the vanadium (III) reduction method (Miranda et al. 2001, Doane and Horwath. 2003), NH_4^+ by the method of Parsons et al. (1984), urea by the method developed by Revilla et al. (2005), and total phosphorus (TP) by APHA (1998) using an automatic Shimadzu UV-1800 spectrophotometer.

(2) Chlorophyll and associated pigments: Chlorophyll were measured using a modified protocol of Parsons et al. (1984) on a Turner 10-AU flourometer while pigment samples will be sent to the analytical services at University of Maryland's Horn Point Laboratories as they have expertise and capability to analyze such samples on their Hewlett Packard high-performance liquid chromatograph (HPLC Model 110 system; van Heukelem et al. 1994, van Heukelem and Thomas, 2001).

(3) Eukaryotic and prokaryotic biodiversity: Samples were sent to Juniata College for extraction and sequencing. Sequencing of the 16S and 18S biomarkers was done on an Illumina MiSeq platform. The sequenced data were checked for quality control using FASTQC and FASTX programs. Macqiime (Caporaso et. al. 2010) was used to create the Operational Taxonomic Unit (OTUs) table and calculate the alpha and beta diversity. Principal component analyses plots will be created using Macqiime.

(4) Viral analyses: The composition of viral communities were determined via viral metagenomics, following a shotgun sequencing approach by Dr. Ian Hewson's research group at Cornell University. Viruses were collected in the 0.2 - 0.02 μm size fraction. Viral nucleic acids (RNA and DNA) were extracted from 0.02 μm filters, amplified using a linker-amplified shotgun library (DNA) or whole transcriptome (RNA) approach, then sequenced using Illumina MiSeq. Sequence data was then assembled and viruses identified by comparison against databases of known eukaryotic viruses. Genome completion on these viruses were performed if they are small (i.e. circular rep-encoding single stranded DNA viruses, parvoviruses, picornaviruses) and used quantitative PCR to determine their abundance during the season.

(4) Phytoplankton and bacterial composition: Samples for phytoplankton and bacteria enumeration were collected and preserved with 4% glutaraldehyde or Lugol's solution, stored at 4°C until stained with DAPI (4'-6-Diamidino-2-phenylindole) and were counted on an epiflourescent microscope. The phytoplankton and microbial community size structure were determined by flow cytometry at University of Maryland's Horn Point Laboratory by undergraduate students.

4. Results and Discussion

Data in this progress report include both spring and summer 2017, while the fall samples have yet to be either processed or analyzed with some exceptions (temperature and dissolved oxygen concentrations).

Compared to previous years sampled (2013-2016), the spring was relatively dry (water temperatures ranging from 9.9 to 17°C) but late spring and and mid-summer were relatively wet (water temperatures ranging from 17 to 29.4°C) based on the amount of discharge from the North Branch of the Anacostia River (Figure 2) and this had an influence on the amount of nutrients in the river. Fall water temperatures ranged from 14.3 (late fall) to 25.9°C (mid-fall).

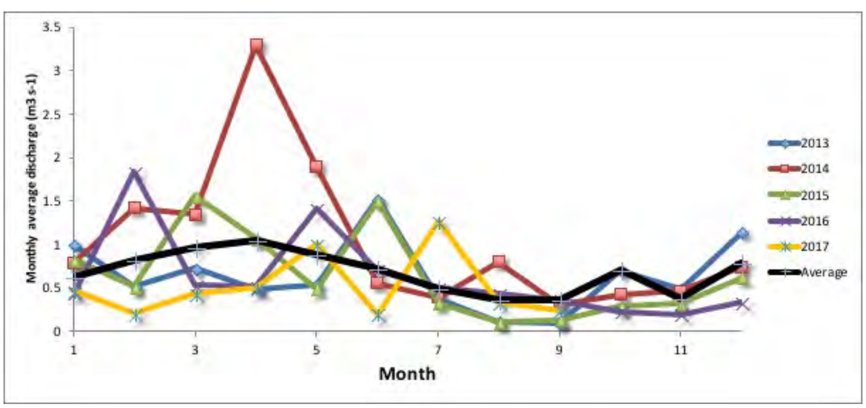

Figure 2: Monthly flow data from the North Branch of the Anacostia River. Data shown include the years in which samples were collected for the study herein (2013-2017, individual symbols) and the 7-year average (2011-2017, black line). Data for 2017 is from January to August. Data were downloaded from the USGS Site 01650500 near Colesville and were multiplied by 0.02832 to convert $ft^3\ s^{-1}$ to $m^3\ s^{-1}$.

Nutrients: Trends in nutrients are not yet know for the later part of 2017, but NO_3^- concentrations were high during the early part of the year (> 40 µmol N L^{-1}), especially in the upper portion of the River. This is consistent with past years regardless it was a wet or dry year (Solomon et al. *in progress*; Figure 3). In the mid and lower river, NH_4^+ and urea concentrations increased by summer which again is consistent with trends in past years (Figure 3). NH_4^+: NO_3^- ratios were higher at Site 5 than the other sites during both spring and summer (Table 1). During the summer, there was more NH_4^+ relative to NO_3^- available to the microbial community at Site 5.

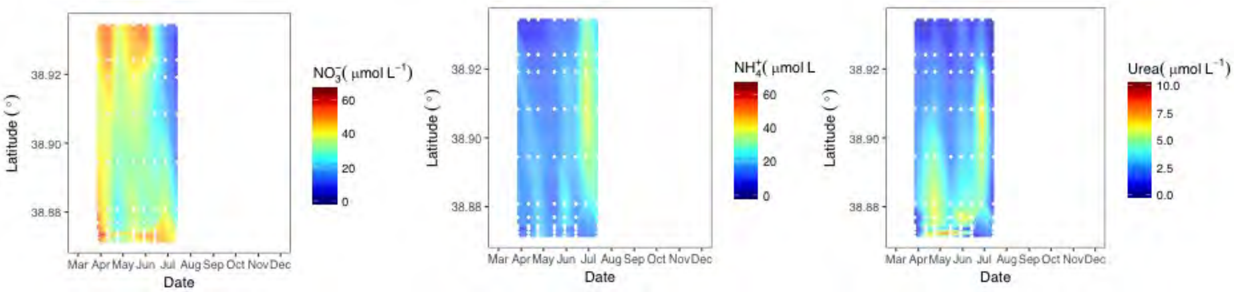

Figure 3: Nitrogen (NO_3^-, NH_4^+ and urea) concentrations along latitudal transects on the Anacostia River for the first part of 2017.

Average dissolved TP concentrations per season remained low (Table 2) and are consistent with what was observed in 2013 and 2016 when discharge levels were similar. Dissolved oxygen concentrations in March and April were a bit lower than past years (Solomon et al. *in progress;* Figure 4), but this may be due to lower discharge compared to previous years.

Site	Spring	Summer
Site 1	0.14	0.92
Site 5	0.60	1.04
Site 9	0.32	0.21

Table 1: Average NH_4^+: NO_3^- at all sites (Site 1, 5, 9) dring spring (March -April) and summer (May-August) seasons on the Anacostia River.

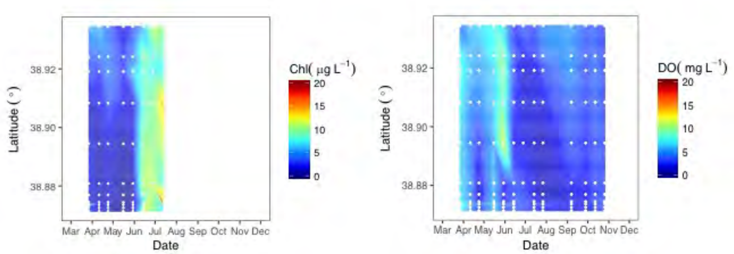

Figure 4: Chlorophyll *a* and dissolved oxygen concentrations along latitudal transects on the Anacostia River.

Season	Average total dissolved P (TDP) concentrations (µM-P)
Spring (March-April)	1.37
Summer (May-August)	1.59
Fall (September-November)	Still being analyzed

Table 2: Average total dissolved phosphorus (TDP) concentrations during three separate seasons on the Anacostia River.

Phytoplankton communities (from chlorophyll and pigment analysis and bioinformatics analyses):

Chlorophyll *a* concentrations increased during the summer. All sites (1, 5, 9) saw a decrease in diatoms (fucoxanthin: chl *a*) from spring to summer (Figure 5). Cyanobacteria (zeaxanthin: chl *a*) peaked during the summer and were highest at Site 9 and included primarily *Synechococcus*. Chlorophytes (chlorophyll b: chl *a*) and cryptophytes (alloxanthin: chl *a*) increased from spring to summer at Sites 1 and 9, and decreased at Site 5. While patterns of diatoms and cyanobacteria were consistent with past years at all sites (Solomon et al. *in progress*), trends in chlorophytes and cryptophytes were slightly different at Sites 5 and 9 than in past years.

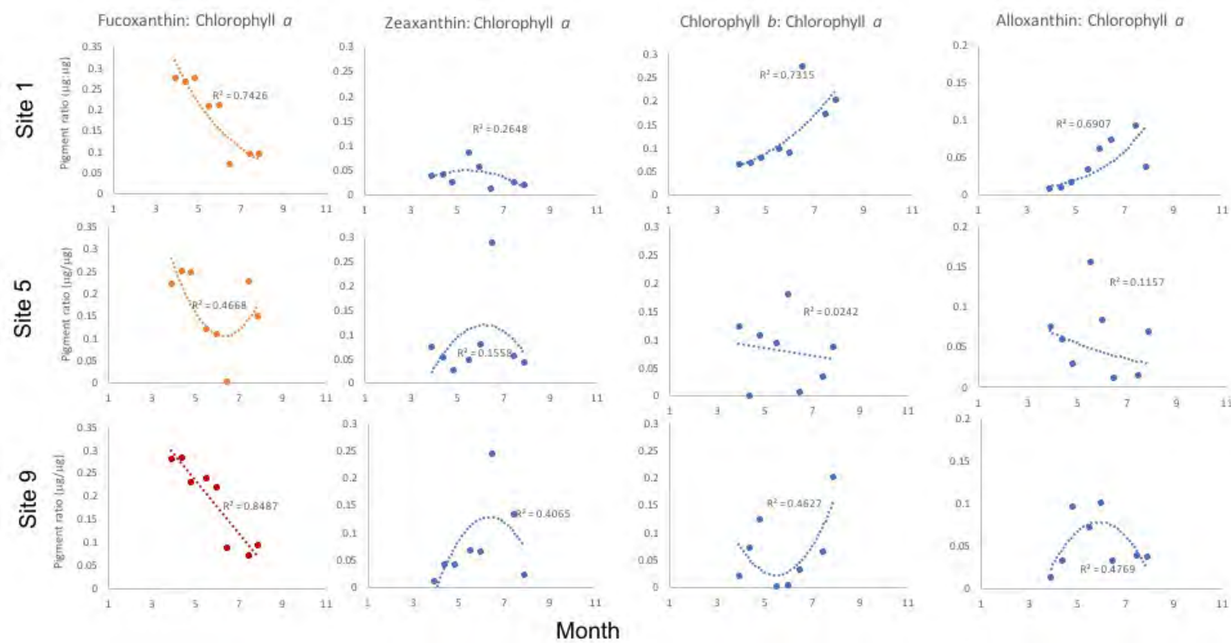

Figure 5: Phytoplankton pigment ratio data (HPLC) for first part of 2017. Coefficients of determination are given.

Bioinformatics (16S & 18S) analysis: The microbial community (both prokaryotes (16S) and eukaryotes (18S) have been analyzed for the spring and summer seasons, while the fall samples still need to be analyzed.

The bacterial community was different at each site (Figure 6). Site 1, near Bladensburg Water Park, consisted mostly of *Bacteriodetes* and *Proteobacteria* while Site 5 consisted of *Verrucomicrobia* and *Proteobacteria*, but by summer had *Cyanobacteria*. Site 9 bacterial community consisted of mostly *Proteobacteria* and *Cyanobacteria*. It will require more analysis to see if some opportunistic pathogens such as *Nocardia*, *Bacteriodes Burkholderia* and *Enterobacteriales* (the former two fall under Proteobacteria) are present in the samples. The environment during summer months (June-August) are ideal for proliferation of these bacteria as temperatures range on average from 26-27°C, but can reach 30°C (Solomon et al. *in progress*). In the lower part of the river where NH_4 concentrations are the highest, it is not surprising that there are more cyanobacteria as they are more tolerant of high NH_4^+ concentrations (e.g. Collos & Harrison 2014).

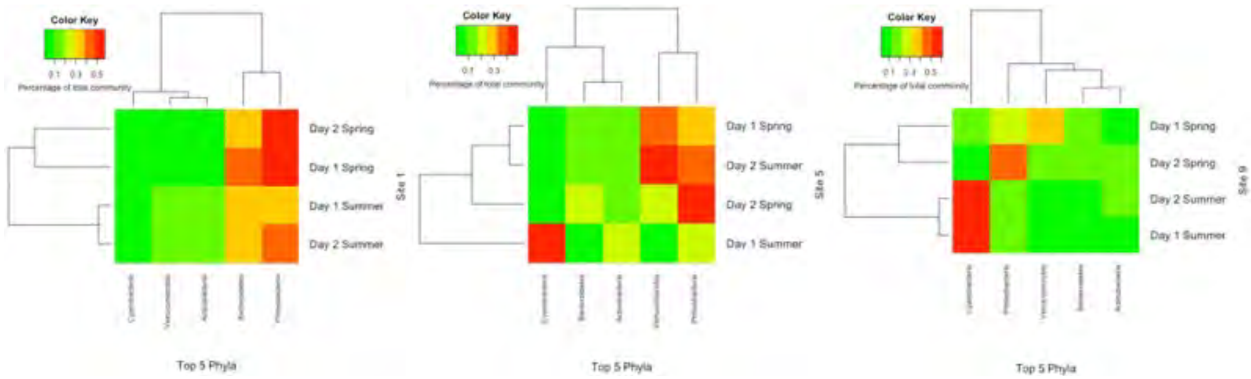

Figure 6: The alpha (top; within samples) and beta (side; between samples) 16S diversity of each site (1, 5 and 9) during the spring and summer seasons.

There was more similiaries between the bacterial community within seasons at Site 1 and 9 (e.g. beta diversity) but the same was not true for Site 5. There was a lot of similiaries within samples among bacterial groups (e.g alpha diversity).

In addition to looking at the bacterial diversity within samples and among seasons, we plan to also look at bacterial species richness to compare to previous studies that have looked at the composition and enumeration of bacteria over a limited time period and mostly in sediments. Concentrations of bacteria in the sediments decrease downstream (MacAvoy et al. 2009, Bushaw-Newton et al. 2011) while concentrations of bacteria in the water column follow a different trend by increasing downstream (MacAvoy et al. 2009). Bacterial species richness in the sediments (measured in OTUs) also increases downstream.

While 18S samples have been sequenced, the comparisons between sites and seasons still needs to be completed. The literature currently does not provide much guidance which photosynthetic and mixotrophic phytoplankton to report for riverine ecosystems such as the Anacostia (e.g. Keeling et al. 2014, Tragin et al. 2017).

Relationship between microbial community and nutrients: Solomon et al. (*in progress*) has observed that there is a positive relationship beween diatoms (fucoxanthin: chl a) and NO_3^- concentrations, and the opposite is true for cyanobacteria (zeaxanthin: chl a; Figure 7). The increase in NH_4^+: NO_3^- in 2017 from Site 1 to Site 9 (with a peak at Site 5) is consistent with trends in past years and the phytoplankton community response to the changing nutrient dynamics from the upper to the lower portion of the Anacostia. The upper River near Bladensburg, MD is characterized by high NO_3^-: NH_4^+ that decreases downstream to the lower River near Navy Yards. This suggests that NH_4^+ is the more dominant N form for phytoplankton (and bacteria) in the lower portion of the Anacostia. More diatoms were found in the upper part of the River where there was more NO_3^- while chlorophytes and cyanobacteria were more prevalent in the lower part of the River where there was more NH_4^+ relative to NO_3^-. These results are consistent with general observations where different compositions of phytoplankton species develop under NH_4^+ vs. NO_3^- enrichments (at comparable N-equivalent concentrations). For instance, Domingues et al. (2011) showed that enrichment by NH_4^+ in a freshwater tidal estuary favored chlorophytes and cyanobacteria, whereas diatoms were favored under NO_3^- enrichment.

Viruses: Samples are still being analyzed by Dr. Ian Hewson, Cornell University.

Phytoplankton and bacterial composition: Preserved samples will be analyzed this summer by summer undergraduate interns at University of Maryland's Horn Point Laboratory.

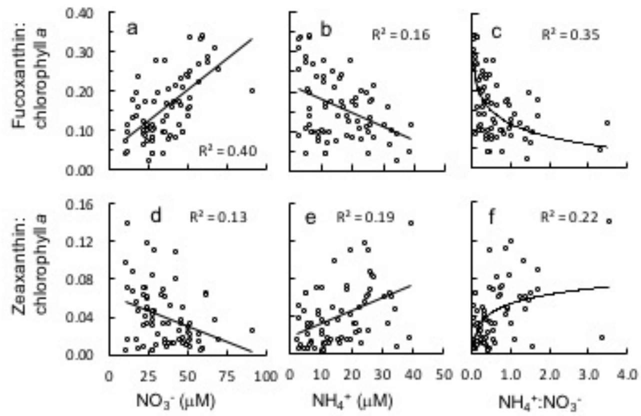

Figure 7: Relationships between the ratios of fucoxanthin:chlorophyll *a* (panels a-c, indicative of diatoms) and zeaxanthin:chlorphyll *a* (panels d-f, indicative of cyanobacteria) and the concentrations of NO_3^- (panels a,d), NH_4^+ (panels b,e) and the ratio of $NH_4^+:NO_3^-$ (panels c,f). Data are from years 2015-2016 and are inclusive of all flow conditions. Coefficients of determination are shown are are significant at p<0.05. From Solomon et al. *in progress*.

5. **Project outcomes, presentations, publications (book chapter journals or conference proceedings)**

All of the following are poster presentations at various meetings & conferences:

Solomon, C.M., Arora G., Vazquez G. (2018). Assessing the effectiveness of the Anacostia River tunnel in reduction of eutrophication. North American Congress for Conservation Biology. Toronto, CA.

Humlicek, G., Arora, G., & Solomon, C.M. (2017). Analysis of Bacterial and Algal Diversity in the Anacostia River. Maryland Water Monitoring Council Annual Conference. Linthicum, Maryland.

Humlicek, G., Arora, G., & Solomon, C.M. (2017). Analysis of Bacterial and Algal Diversity in the Anacostia River. AASD-STEM/SEAPD STEM INCLUDES Meeting. Auburn University, Auburn, AL.

Kyre, C. J., Lauevicius, A., Humlicek, G., Vazquez, G. Arora, G., & Solomon, C.M. (2017). Examining the effect of nutrients on algal communities in the Anacostia River. AASD-STEM/SEAPD STEM INCLUDES Meeting. Auburn University, Auburn, AL

Humlicek, G., Arora, G., & Solomon, C.M. (2017). Analysis of Bacterial and Algal Diversity in the Anacostia River. UMBC Undergraduate Research Symposium. Baltimore, MD.

Kyre, C. J., Lauevicius, A., Humlicek, G., Vazquez, G. Arora, G., & Solomon, C.M. (2017). UMBC Undergraduate Research Symposium. Baltimore, MD.

Humlicek, G., Arora, G., & Solomon, C.M. (2017). Analysis of Bacterial and Algal Diversity in the Anacostia River. End of summer internship presentations, Gallaudet University.

Kyre, C. J., Lauevicius, A., Humlicek, G., Vazquez, G. Arora, G., & Solomon, C.M. (2017). End of summer internship presentations, Gallaudet University.

6. Student supports

Five undergraduate students worked on the project in the past year. Three students worked on the project during summer 2017 (Camac Kyre, Gabrielle Humlicek, Anthony Laucevicius, and two of them continued into the 2017-2018 academic year (GH & AL). Two new students joined during the academic year (Heath Hampton and Brian Podlisny).

7. Extramural funding

The data from several DCWRRI grants listed below helped obtain a two year grant with Maryland Sea Grant (*Assessing the effectiveness of the Anacostia River tunnel in reduction of eutrophication*; $64,335; February 2018-February 2020):

DC Water Resources Research Institute. *Examining genetic microbial diversity to monitor pathogens and toxins in the Anacostia River, DC*. March 2017-March 2018.

DC Water Resources Research Institute. *Influence of consistently high levels of ammonium on food web dynamics in the Anacostia River*. March 2016-March 2017.

DC Water Resources Research Institute. *Continuous Monitoring of Urea Concentrations and Harmful Algal Productivity and Physiology in the Anacostia River* March 2013-March 2014.

8. Conclusion

The goal of this study was to use bioinformatics to have a better resolution of “possible contaminants of concern” such as toxic and harmful algae, pathogenic bacteria and viruses and how their abundance is influenced by nutrient loading**.** We now have a picture of the general trends of patterns of algae and bacteria in relation to nutrient loading, but we need to delve deeper into our bioinformatic data to look for microbes that could be of concern and whether their abundance could be lessened in 2018 due to the first phase of the Anacostia River Tunnel system going on-line. It went on-line on March 20, 2018 and prevented approximately 170 million of gallons from entering the River when heavy rains battered DC in early April 2018 (DC Water, 2018). Despite diverting a large volume of discharge from the River, we were able to detect high levels *E. coli* abundance after the storm that was shared with the public via the Swim Guide website & app via our new grant. It is important to continue to monitor the Anacostia River to see if nutrient dynamics and microbial community change and over what time scale to better understand the River’s restoration and recovery.

9. Acknowledgement

We would like to acknowledge the support of DCWRRI for supporting this and past studies on the Anacostia River. We would like to thank the following people who were involved and contributed to the success of this project: Gina Lam and Christopher McLimans from Juanita College who did the 16S and 18S extraction and sequencing, Dr. Derek Braun who helped with detecting potential pathogenic bacteria, and all the students who have worked on this project.

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Information Transfer Program Introduction

In addition to research and training, the Institute also engages its stakeholders in information transfer or in disseminating research findings. Even if there was no funded information transfer project during this reporting period, the Institute continued conducting successful information transfer projects through the regional annual water symposium. In collaboration with the American Water Resources Association in the National Capitol Regional Section (AWRA-NCR), the Institute organized the 5th Annual Water Symposium on April 6, 2016, at the University of DC. The theme of the Symposium is “Resilient Solutions for Water Management in Urban Environments: Advances in Research, Technology, Financing and Policy.” The agenda included a keynote address from the nationally recognized, if not world know experts in water science and technology as well as invited panelists who discussed the symposium theme, and breakout sessions featuring submitted oral and poster presentations in response to call for abstracts. This one-day symposium sought to bring together experts from governmental agencies, academia, the private sector, and non-profits to present and discuss rethinking the value of water: innovations in research, technology, policy, and management.

Furthermore, in close collaboration with other academic and land-grant centers in CAUSES at UDC such as the Center for Sustainable Development, the Institute continued in supporting the training workshops in green infrastructure maintenance. Funded by the DC Water (DCWASA), UDC provided a certificate training program in green infrastructure maintenance technician. In 2017, 60 participants received certificates. The WRRI organize a 3-day of training workshop in December 2017 to train 25 international Water Professionals in Flash flood management. The Institute will continue working closely with both local and international collaborators to build on its current success of information transfer activities.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	19	0	0	0	19
Masters	8	0	0	0	8
Ph.D.	1	0	0	0	1
Post-Doc.	0	0	0	0	0
Total	28	0	0	0	28

Notable Awards and Achievements

DC Water/Environmental Quality Testing Laboratory is now nationally accredited with NELAC standard with the following areas: 1. Microbial test (E. Coli and Total Coliforms) in potable and non-potable waters 2. Trace metals, minerals and mercury in potable and non-potable waters 3. Trace metals, minerals, and mercury in soil, biosolids or solid samples.