USING SENSORS (IoT) TO MONITOR AND IMPROVE THE EFFICIENCY OF LIVING GREEN INFRASTRUCTURE IN URBAN DEVELOPMENT
(LITERATURE REVIEW)

by

Zarin Afroze
Honors Bachelor of Science, University of Toronto, 2018

A Master's Research Project

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Engineering

in the program of

Civil Engineering

Toronto, Ontario, Canada, 2019

Author's Declaration

I hereby declare that I am the sole author of this MRP. This is a true copy of the MRP, including any required final revisions.

I authorize Ryerson University to lend this MRP to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this MRP by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my MRP may be made electronically available to the public.

Using Sensors (IoT) To Monitor and Improve the Efficiency of Living Green Infrastructure in Urban Development (LITERATURE REVIEW)
Zarin Afroze
Master of Engineering, 2019
Civil Engineering, Ryerson University

Abstract

The use of information and communication technology for environmental purposes in urban development can help establish a smart city. Creating a network of sensors that monitor the various parameters of living structure would allow industry professionals to better manage, plan and design storm water mitigation practices. By using IoT, the data from the sensors is stored in the cloud where it can be retrieved and analyzed as needed. There are currently monitoring systems that focus on one particular aspect of the urban environment such as storm water, air pollution or green roofs but this literature review focuses on how these individual approaches can be combined into one to monitor various aspects of living infrastructure including hydrological, atmospheric, soil based and ecological. Based on the literature available, several limitations are identified that need to be addressed before such a monitoring system is possible and can be incorporated into mainstream practice.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Climate change and storm water management have been ongoing issues that cities must take into consideration as they continue to develop. For this reason, incorporating living infrastructure into urban development has become an increasingly popular option for cities around the world given its multitude of environmental, economic and social benefits (ACTGovernment, 2018). Living infrastructure integrates both natural and engineered elements into the design and operation of cities thus providing a range of environmental, social and economic services (ACTGovernment, 2018). It is considered a holistic approach to planning, design, construction, maintenance and renewal of urban environments (ACTGovernment, 2018). There are four basic components of living infrastructure: plants and vegetation, open spaces (parks, pathways), lakes and ponds (for storm water treatment) and soils and surfaces (ACTGovernment, 2018). Examples of living infrastructure include bioswales, infiltration trenches, wetlands, green roofs, urban farms, rain gardens and more. Living infrastructure provides a sustainable approach to addressing urban environmental concerns and is relatively easy to implement by retrofitting existing infrastructure or incorporating into future projects (ACTGovernment, 2018).

In the pursuit of becoming a sustainable city, living infrastructure can address multiple concerns simultaneously and are therefore considered an economically feasible solution to various issues (ACTGovernment, 2018). The following considers the mitigating and adapting benefits of living infrastructure from various perspectives. *Water Quality and Quantity*: Storm water runoff in urban areas delivers pathogens, nutrients, sediments and heavy metals into water systems (EPA, 2018). During events of high rainfall, increased storm water flows can result in untreated sewage entering surrounding bodies of water (EPA, 2018). Living infrastructure can treat storm water as well as retain rainfall (slowing storm water discharge could prevent flooding) and reduce rainfall discharges, therefore lowering pollutant loads (EPA, 2018). *Air Quality*: The urban heat island effect is when an urban area is significantly warmer than its surrounding area as a result of intensified human activities (EPA, 2018). Smog is formed when nitrogen oxide and volatile organic compounds interact with heat and sunlight and can cause intense summers and respiratory issues (EPA, 2018). Living infrastructure with vegetation can reduce temperatures and remove air pollutants by absorbing and filtering particulate matter (EPA, 2018). *Climate Resiliency*: By moderating micro climates and combating unusually warm temperatures, living infrastructure can create resilience against climate change (EPA, 2018). *Habitat and Wildlife*: Typical urban environments are comprised of impermeable surfaces and concrete pavements that are not ideal for wildlife. Increased vegetation provides habitats for birds, mammals, amphibians and other organisms in the urban setting (EPA, 2018). Parks and urban forests also help facilitate wildlife movement and populations between habitats (EPA, 2018). *Communities*: An integral part of cities is the community that makes city living possible (Ecology Center, 2016). Living infrastructure helps support urban communities by providing city aesthetics and recreation spaces as well as encouraging community involvement and establishing food security through urban farms (Ecology Center, 2016).

Living infrastructure can also help achieve circular urban planning and therefore a circular economy. While the focus on sustainability has increased in the last few decades, it is vaguely defined and therefore difficult to work towards. However, the idea of a circular economy puts sustainability into context by addressing both the economy and environment into a single approach. The purpose of a circular economy is to first and foremost minimize waste and make the most of resources before they are discarded (Campbell-Dollaghan, 2019). Urbanized cities produce large amounts of waste and have high resource and energy consumption relative to the space that is occupied (Campbell-Dollaghan, 2019). To address and combat these concerns for future generations, the ideas behind a circular economy can be implemented using living infrastructure. Green roofs for example can assist with mitigating waste by increasing the longevity of roof surface materials as the vegetation can protect against weathering and harsh sunlight (Campbell-Dollaghan, 2019). Another core concept of a circular economy is to reduce and reuse. Through the use of green roofs and constructed treatment ponds for handling storm water the rain water can be naturally treated and reused for irrigation and flushing toilets which require less energy than traditional treatment methods (Campbell-Dollaghan, 2019). As mentioned previously living infrastructure can reduce runoff and by doing so, reduces runoff entering wastewater treatment plants so that floods and overflows can be reduced.

Although living infrastructure can provide numerous benefits for urbanized cities there are still improvements that need to be made to ensure that moving forward, projects and operations are efficiently executed. Since living infrastructure is a fairly new concept that is being integrated into urban development, the industry lacks long term operating experience and has limited collaboration of the multiple disciplines that should be working together. Professionals such engineers, researchers, policy makers and scientists from disciplines including but not limited to physics, biology, chemistry, geography and politics bring unique backgrounds and experiences to the table with expertise on how to improve varying aspects of living infrastructure. Additionally, there is a lack of guidance for green infrastructure and urban rooftop professionals and farmers on how to properly manage and operate living infrastructure for long term and worthwhile functionality. To address these concerns, smart technology should be utilized, more specifically sensors, monitoring networks, internet of things (IoT) and information and communication technology to allow greater insight into the performance of living infrastructure to assist with managing current infrastructure and plan for the future (Jayaraman et al, 2016). This data can then be shared with professionals from multiple disciplines as well as the public to see how external (i.e. weather and irrigation) and internal factors (i.e. soil moisture and temperature) are influencing the behavior of living infrastructure from various perspectives. The objective of this paper is to develop a comprehensive review of the relevant industries and applications of sensors that can potentially be used to improve the efficiency of living infrastructure in cities.

Chapter 2: Current and Past Applications of IoT and Smart Technology and Management for Environmental Purposes – Case Studies

The emergence of information and communication technology to improve city living can be seen worldwide however much of the research in this field is still new and under works before it can be considered into mainstream practice. The case studies presented look at how sensors, monitoring networks, internet of things (IoT) are being used to better understand living infrastructure and farming with the intention of becoming more efficient, less wasteful and creating an optimized system. Each case study is from a different part of the world, each with different reasons for implementing the use of communication technology and lessons to learn from. The following are key phrases that are recurring themes throughout the case studies.

"Smart" city/technology/management: the use of data technology to create efficient and interactive systems, improve sustainability and development, enhance quality of living through the use of sensors, cameras, wireless devices.

Monitoring System/Network: hardware, software used for data collection, analysis, distribution from sensors and/or devices.

IoT (Internet of Things): "*the interconnection via the Internet of computing devices embedded in everyday objects, enabling them to send and receive data without human interaction*" (IOT, n.d.). IoT often uses the cloud for data storage and retrieval.

IoT Platform: "*a multi-layer technology that enables straightforward provisioning, management, and automation of connected devices within the Internet of Things universe*" (Kaa Platform, n.d.)**.**

1. Internet of Things Platform for Smart Farming in Melbourne, Australia

Jayaraman et al states that farm productivity can be increased by understanding crop performance and the environmental conditions that affect crop yield. However data collection on crop performance is currently slow or done manually resulting in low quality data (Jayaraman et al, 2016). For this reason, Internet of Things (IoT) technologies presents opportunities to collate vast amounts of environmental and crop performance data using wireless networks, network connected weather stations, cameras and smart phones (Jayaraman et al, 2016). Data can be collected using sensors and recorded using mobile devices so Jayaraman et al created SmartFarmNet, an IoT based platform that can automate the collection of environmental, soil, fertilization and irrigation data while correlating the data, filtering out invalid information with regards to assessing crop performance and forecasting conditions for future recommendations. SmartFarmNet can be integrated with any IoT device to store their data in the cloud for performance analysis and recommendations (Jayaraman et al, 2016). Benefits of SmartFarmNet include the following:

- Allows a bring-your-own IoT sensor principle, i.e., permits effortless integration and use of virtually any IoT device, including commercially available sensors, cameras, weather stations, etc. This reduces sensor installation and maintenance costs, while providing for easy upgrade to newer and more advanced sensors.
- Supports scalable data analytics that can continuously process large crop performance data.
- Offers do-it-yourself tools that allow plant biologists and farmers/growers to analyze and visualize plant performance data. (Jayaraman et al, 2016)

SmartFarmNet was developed by professionals from multiple disciplines including crop biologists, computer scientists, growers and farmers (Jayaraman et al, 2016). Phenonet is a phenotyping field lab using IoT technologies such as sensor networks, IP camera and mobile smartphones (Jayaraman et al, 2016). IoT allows for real time crop data that can be immediately assessed to predict crop performance for any given environment (Jayaraman et al, 2016). Using IoT, Phenonet is helping achieve the following:

- identify the influence of different conditions on a variety of crops in real-world outdoor farm environments
- understand water resource consumption in order to manage it effectively
- study the impact of various fertilizers
- get real-time data to forecast crop performance
- share data and results (Jayaraman et al, 2016)

Jayaraman et al uses soil moisture sensors and canopy temperature sensors to track crop root extraction of water from the soil during the grown season, this information is used to asses root activity and crop growth. An example of sensor placement for this Phenonet study can be seen in Figure 1 where a parcel of land is divided into plots.

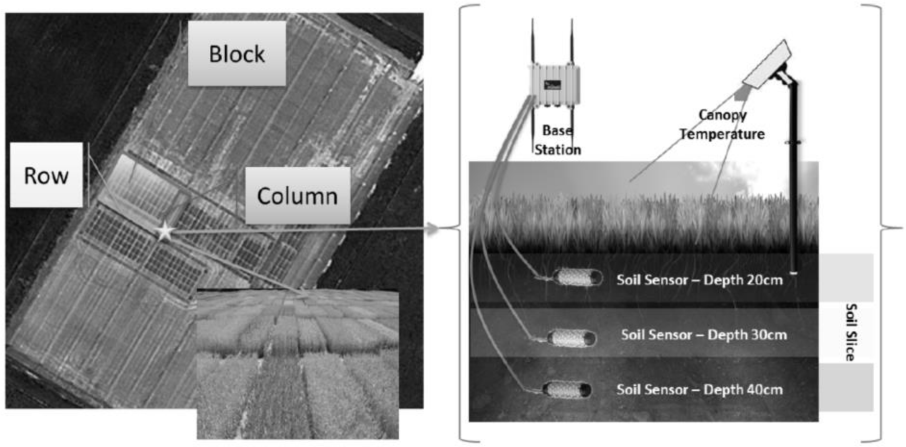


Figure 1: Setup of Phenonet study (Jayaraman et al, 2016)

The challenge with collecting such large quantities of data is that the performance of the systems is compromised by time series data (Jayaraman et al, 2016). There are currently middleware platforms that filter and aggregate data to make the systems more efficient (Jayaraman et al, 2016). Examples include: UBIDOTS, Xively, Thing Speak, Open.Sen.se, and SensorCloud, Amazon IoT and IBM IoT platforms (Jayaraman et al, 2016). However SmartFarmNet differs from these platforms by being able to manage large volumes of data that supports rapid responses and real time user interaction (refer to Table 1).

Table 1: Comparison of SmartFarmNet with other IoT Platforms (Jayaraman et al, 2016)

Platform	Sensor Discovery	Bring-Your-Own IoT Device	Scalable Data Analysis	Sharing Sensor, Data, and Analysis Results (Virtual Lab)
UBIDOTS	Not Supported	Yes, but requires considerable efforts to develop new interfaces	No	No. Only provides API for raw data access
Xively	Partial support with no specific approach for metadata description/management	Yes, but requires considerable efforts to develop new interfaces	No	No. Only provides API for raw data access
SensorCloud	Not Supported	Supports only vendor-specific sensors (some support for CSV file data)	Partial	Partial
IBM Bluemix	Not Supported	Yes, but requires considerable efforts to develop new interfaces	Partial with additional development required	Partial by using existing bluemix infrastructure as a service platform
Amazon IoT	Not Supported	Yes, but requires considerable efforts to develop new interfaces	Partial, with additional development required	Partial by using existing EC2 infrastructure as a service platform
IoTCloud	Not Supported	Yes, but requires considerable efforts to develop new interfaces	No	No
Apache Storm	Not Supported	Yes, but requires considerable efforts to develop new interfaces	No	No
SmartFarmNet	Supported via Semantic Web Technologies	Yes with in-built support for 30+ commercial and experimental sensors	Yes, real-time data analytics functions are built in	Yes, easy to use e-commerce-like use interaction model

SmartFarmNet's data model is comprised of 4 levels: users, experiments, nodes and streams as displayed in Figure 2 (Jayaraman et al, 2016). "Users" represents the entity using the SmartFarmNet system (i.e. project, research group) and "Experiments" are the crop studies (each experiment has one "user") (Jayaraman et al, 2016). Each experiment is comprised of multiple nodes (nodes can belong to multiple experiments) and each node is a group of data streams (sensor data) from IoT devices and virtual sensors (Jayaraman et al, 2016). To further understand how SmartFarmNet works, Figure 3 illustrates the architecture of the SmartFarmNet platform which includes three main components: SmartFarmNet Gateway, cloud store and sensor explorer. The gateway is where the initial data streams from the sensors are collected, filtered and processed from any IoT device (Jayaraman et al, 2016). Next is the cloud store, where the data from the SmartFarmNet gateway is stored and managed (Jayaraman et al, 2016). Lastly is the sensor explorer which allows previously collected data to be re used and re purposed (Jayaraman et al, 2016).

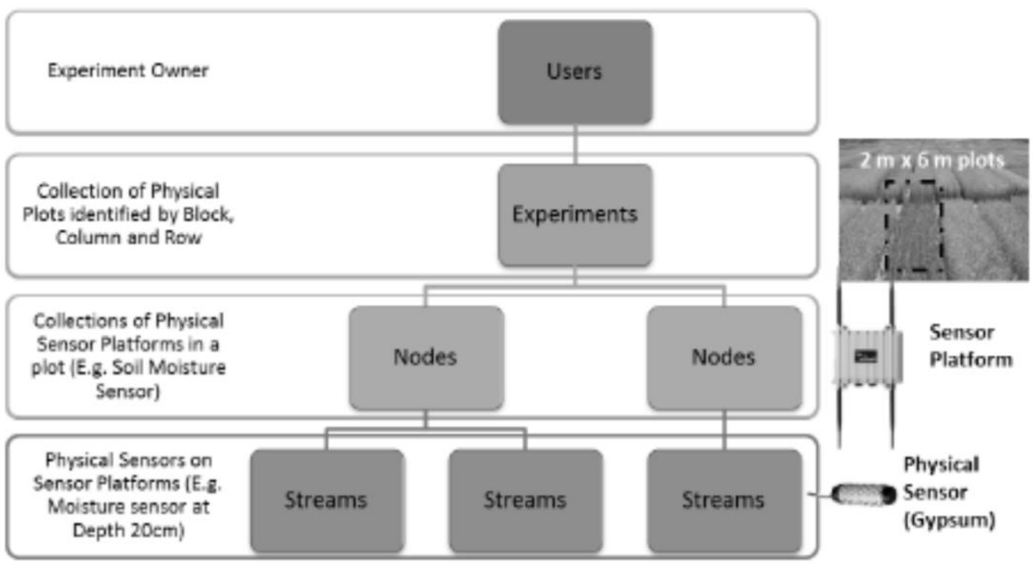


Figure 2: SmartFarmNet Data Model (Jayaraman et al, 2016)

Jayaraman et al shows that SmartFarmNet is a scalable and elastic platform that can handle high velocity data streams in real time with real time responses. For the purposes of living infrastructure, a platform such as SmartFarmNet can assist with urban farms. A commendable example of a roof top urban farm is the Ryerson Urban Farm located on the roof of the George Vari Engineering and Computing Centre building on the Ryerson University campus. This rooftop urban farm produces roughly 10 000 pounds of produce annually that is distributed among the local community (Ryerson, n.d.). An urban farm such as this could benefit from SmartFarmNet which would allow the employees and volunteers working on the urban farm to know precisely when to water the crops and with the right amount of water. SmartFarmNet is versatile with the devices it is compatible with, making it easier to use for people who may not be well versed in information and communication technology. Based on historic weather patterns in an area and the data from soil sensors, SmartFarmNet can customize irrigation patterns for an urban farm.

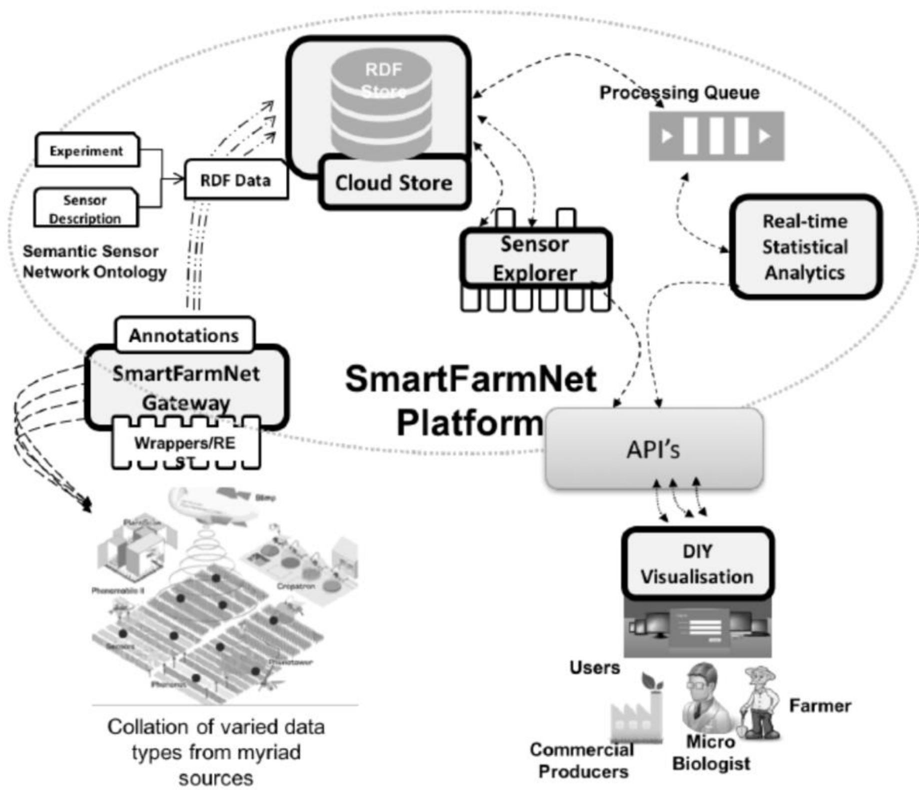


Figure 3: SmartFarmNet architecture (DIY – do it yourself, RDF – resource description framework, API – application programming interface) (Jayaraman et al, 2016)

2. Green Roof Environmental Monitoring and Meteorological Network in New York City, New York

Gaffin et al describes green roofs as versatile environmental mitigation technology that covers flat urban roofs with vegetation. Green roof popularity is credited to its ability to address multiple concerns such as heat and runoff simultaneously however; there is limited data on the performance of green roofs in an urban environment (Gaffin et al, 2009). Collecting this data will be useful for policy makers as the cost and benefits of mitigation technologies is considered further therefore the purpose of this study was to identify the performance of green roofs in New York City (Gaffin et al, 2009). Gaffin et al deployed research stations on various green roofs in the area and monitored various aspects using a selection of sensors to study energy balance. The green roofs are engineered systems that consist of the following layers (bottom to top)***:***

- a waterproof and root-proof membrane
- a drainage layer for excess water
- a filter fabric
- growth medium - which is not soil but engineered lightweight granular medium typically consisting of expanded shales and clay minerals
- plants, available in a growing variety, but typically sedum (Gaffin et al, 2009)

Monitoring equipment chosen for the green roofs, control roofs and weather station were based on their ability to collect sufficient data on determine surface energy balance and surface water balance (Gaffin et al, 2009). Parameters that were considered include longwave fluxes, shortwave fluxes, latent heat, convective heat and heat conduction of the green roofs (Gaffin et al, 2009). Although appropriate sensors exist for most of these parameters, it is not the same case for mass transport latent heat and sensible fluxes which will be more challenging to quantify (Gaffin et al, 2009). Shortwave radiation have a bandwidth of 300-2800 nanometers and were monitored using a sensor with the same measurement band, the Kipp and Zonen CMP3 pyranometer (Gaffin et al, 2009). Two of these sensors were placed on the green roofs to monitor downward and upward fluxes of shortwave radiation in order to check the albedo (Gaffin et al, 2009).

The company Kipp and Zonen also produce all in one units that measure shortwave and longwave fluxes (Gaffin et al, 2009). These sensors have back to back pyranometers for shortwave radiation and pyrgeometers for longwave radiation, together the unit produces net readings on radiation flux at the surface of a green roof and is typically mounted 1.5 above the surface (Gaffin et al, 2009). For surface temperatures, surface infrared temperature sensors and humidity sensors were installed to obtain radiometric temperatures and vapor density calculations (Gaffin et al, 2009). To determine the heat flow, heat flow sensors were used but an alternative method was employed as well by measuring the vertical temperature profile (Gaffin et al, 2009). Developing a network of green roof research stations will allow researchers to study differences in systems but the data collected is yet to be definitively analyzed (Gaffin et al, 2009). The preliminary findings include: higher albedo for sedum green roofs, reduction in temperatures for buildings with green roofs with implications for reduced energy building cooling and heating requirements and ability to study micro climate variations in the metropolitan area (Gaffin et al, 2009). The most popular choice of living infrastructure in an urban environment with minimal additional space are green roofs (Gaffin et al, 2009). This study is precisely the type of monitoring system that could be employed by Ryerson Urban farm and others alike within a city. By collecting data from various green roofs that vary in media material, vegetation, location and additional characteristics, professionals can determine what works and how well to address issues such as warmer microclimates within cities.

3. Array of Things in Chicago, Illinois

Sensors play a crucial role in understanding how the modern urban environment functions and can assist with managing and planning green infrastructure. In 2015, Chicago launched the "Array of Things" (AoT) urban sensor initiative that collects data on a combination of factors (environment, infrastructure and activity) that impact a cities climate, air quality and noise. AoT provides real-time location based data on the urban environment and infrastructure that is accessible by researchers and the public (AoT, 2019). AoT is based on Waggle Technology, an open platform for computing and intelligent wireless sensors; the Waggle software and hardware supports environmental and atmospheric science (AoT, 2019). Additionally, AoT data is published at Plenario, a web based portal that supports open data search, exploration and downloading of datasets (AoT, 2019). The purpose of AoT is to help "*engineers, scientists, policymakers and residents work together to make Chicago and other cities healthier, more livable and more efficient*" (AoT, 2019).

There are currently 200 nodes installed throughout Chicago primarily at intersections, 20 feet above the street (AoT, 2019). Each node is comprised of approximately 18 sensors which cover environmental sensors, air quality sensors and light and infrared sensors (refer to Table 2) (AoT, 2019). The environmental sensors collect data on air temperature, humidity, barometric pressure, vibration and sound intensity (AoT, 2019). The air quality sensors collect data on nitrogen dioxide, ozone, carbon monoxide, hydrogen sulfide and sulfer dioxide and the light and infrared sensors collect data on light intensity and frequency of pedestrian activity (AoT, 2019). Aside from the current measured parameters, research is underway to develop sensors to monitor flooding and standing water (AoT, 2019). The data collected can be grouped together in various ways to provide information on how to improve urban functionality and data on air quality, sound and vibration can be used to suggest the healthiest walking times and routes in the city as well as suggesting ways to reduce congestion related pollution (AoT, 2019). Additionally, data on urban flooding can provide insight into how services and infrastructure can be improved to prevent property damage (AoT, 2019).

A smart city requires the deployment of sensors and cameras that detect both environmental and human behavior to improve urban functionality, the matter of security and privacy is often called into question. AoT has a set of privacy policies to ensure that that the personal privacy of the public is protected (https://arrayofthings.github.io/final-policies.html), the main purpose of such a technology is to monitor and analyze the environment and its surroundings rather than individuals, privacy protection is built into the design of the sensors (AoT, 2019). Data is also not stored for later use; it is analyzed within each node in real time (AoT, 2019). It is important that the public is involved and heard in projects work towards a smart city; with feedback and insight from pedestrians and locals the technology can be improved accordingly to meet their needs and expectations from the city they reside in.

Table 2: Sensors used for Array of Things (AoT, 2019)

Measurement	**Purpose/Application**	**Sensor(s) Used**
Carbon Monoxide	Air Quality/Health	SPEC Sensors 3SP-CO-1000
Hydrogen Sulphide	Air Quality/Health	SPEC Sensors IAQ-100
Nitrogen Dioxide	Air Quality/Health	SPEC Sensors 3SP-NO2-20
Ozone	Air Quality/Health	SPEC Sensors 3SP-O3-20
Sulfur Dioxide	Air Quality/Health	SPEC Sensors 3SP-H2S-50
Air Particles	Air Quality/Health (PM 2.5 to ~40)	Alphasense OPC-N2 (included in ~20% of 2018 nodes); Plantower PMS7003 (all 2019 nodes)
Barometric Pressure	Weather Conditions	Bosch BMP180
Humidity	Weather Conditions	Honeywell HIH4030, Honeywell HIH6130, Measurement Specialties HTU21D, Sensirion SHT25
Temperature	Weather Conditions	Honeywell HIH6130, Measurement Specialties HTU21D, STMicroelectronics LPS25H, U.S. Sensor PR103J2, Sensirion SHT25, Bosch Sensortec BMP180, Measurement Specialties TSYS01, Texas Instruments TMP112 & TMP421
Physical Shock/Vibration	Detect heavy vehicles, shock to street pole (e.g. accident)	Freescale Semiconductor MMA8452Q
Acceleration and Orientaion		Bosch BMI160
Magnetic Field	Detect heavy vehicle flow	Honeywell HMC5883L
Infrared Light	Cloud cover, sunlight intensity	AMS-TAOS USA TSL206RD

Light	Cloud cover, sunlight intensity	LAPIS Semiconductor ML8511, Melexis MLX75305
Ultraviolet Intensity	Cloud cover, sunlight intensity	Silicon Labs Si1145
Visible Light	Cloud cover, sunlight intensity	AMS-TAOS USA TSL250RD, Avago Technologies APDS-9006-020
RMS Sound Level	Sound intensity (loudness)	Knowles SPV1840LR5H-B
Camera	Street conditions, traffic flow, events	ELP-USB500W02M-L 170, ELP-USB500W02M-L 140

Chicago has been a leader in this industry with its various initiatives for monitoring environmental conditions with innovative use of technology. While green infrastructure has been incorporated into many cities across North America, their effectiveness has yet to be analyzed in depth. Aside from AoT, the SGIM project by City Digital has installed sensors underneath Chicago streets to collect stormwater runoff data . These sensors record precipitation amounts, humidity levels, soil moisture measurements, air pressure levels, and chemical absorption rates (Crncevic et al, 2018). The ultimate goal is to build a platform of sensors and advanced computing technology to serve as a tool for water infrastructure management and planning; the first sensors were installed in bioswales and then sewer systems (Crncevic et al, 2018). Partners on the SGIM project include Opti (storm water technology firm) and Microsoft (assisting with cloud capabilities). Although they are not primarily meant for living infrastructure purposes, both Array of Things and SGIM have provided a depth of knowledge about types of sensors and insight into how smart technology can be used for aspects of living infrastructure with respect to monitoring temperature, runoff, soil moisture etc.

4. Smart Water Management Platform: IoT-Based Precision Agriculture in Brazil, Italy and Spain

Smart management of freshwater for precision irrigation in agriculture can increase crop yield while decreasing costs and maintaining environmental sustainability (Kamienski et al, 2019). The Smart Water Management Platform (SWAMP) is an IoT based smart water management platform that aims to reduce the loss of productivity caused by water stress (Kamienski et al, 2019). Over irrigation and under irrigation both lead to negative outcomes such as water wastage or poor crop yield and can be prevented if farmers are aware when crops need to be irrigated (Kamienski et al, 2019). The SWAMP platform can be customized to adapt to different conditions around the world, for example variances in climate, soil and crops. It uses FIWARE (*"A market-ready open source software, combining components that enable the connection to IoT* *with Context Information Management and Big Data services in the Cloud*" (Kamienski et al, 2019)) as one of its main components.

The emergence of IoT technology can be attributed to the inexpensive devices, low-power wireless technology, cloud data storage and high performance computing to make data analysis more efficient (Kamienski et al, 2019). However, IoT still requires work to perform seamlessly in practice and SWAMP is a step in the right direction as it is replicable and scalable, both of which are concerns with IoT applications (Kamienski et al, 2019). Kamienski et al recognizes that there are still challenges to overcome, primarily the automatization of smart applications for irrigation for agriculture, advanced software platforms and the integration of advanced sensors. Additionally, depending on the architectural structure of IoT platforms, the system scalability and real time decision making can be affected.

SWAMP considers three phases of water management for agriculture: water reserve, water distribution (longer time scale, not real time) and water consumption (with real time responses) (Kamienski et al, 2019). The SWAMP architecture consists of five layers, *Layer 1*: Device & Communication is the collection of sensors and technologies used to gather data on soil moisture, plants, weather; both commercial and homemade sensors probes are used along with drones (Kamienski et al, 2019). *Layer 2*: Data Acquisition, Security & Management is the collection of software used for data acquisition as well as security and device management (Kamienski et al, 2019). *Layer 3*: Data Management contains software to store, process and distribute data. Historical data is also stored here to assist with weather forecast (Kamienski et al, 2019). *Layer 4*: Water Irrigation & Distribution Models contains models for estimating plant water needs and uses soil sensors to determine soil moisture in order to optimize techniques for water distribution (Kamienski et al, 2019). Layer 5: Water Application Services is the interface/platform available to farmers to access the collected data (Kamienski et al, 2019).

SWAMP pilot projects were deployed in several locations in Brazil, Italy and Spain, each with varying needs. Each scenario had personalized components for SWAMP and FIWARE and results showed that additional research is required to provide higher scalability while using less computational resources (Kamienski et al, 2019). Additional research is required before SWAMP is commercially available. As mentioned earlier, a circular economy can be achieved through reduction and reuse of resources and a crucial resource that is wasted within cities is water. Living infrastructure, such as urban farms, are mainly for food supply or stormwater management practices but due to vegetation, irrigation systems be taken into consideration as well. The goal with watering living infrastructure should be to reuse rainwater that has been collected by rain barrels or contained through porous green roof media. Although SWAMP is still under works, there is potential to automate the reuse of stormwater for irrigation purposes to reduce water wastage while maintaining crop yield.

5. Green infrastructure planning for climate smart and green cities in Belgrade, Serbia

The idea behind a smart sustainable city is to use information and communication technology (ICT) to improve urban operations and services. A smart city can only be achieved when all aspects of a working city such as the economy, citizens, administration and the living environment are smart as well. Crncevic et al discusses smart data management of green infrastructure planning using GIS for a climate smart and green city. The current status of green infrastructure planning in Serbia as well as various international cases was reviews where a common limitation was that the planning of green infrastructure was not integrated into the urban planning process with no guidance on how to optimize cost and operations (Crncevic et al, 2018). Additionally, there is a lack of legislative support and information based guidance for industry professionals to follow and abide by (Crncevic et al, 2018). To address these concerns, information and communication technology through the use of GIS would be helpful in converting a city into a smart green city by mapping and analyzing the percentage of land occupied by green infrastructure and identifying local valuable areas to prioritize for protection (Crncevic et al, 2018).

An example of using GIS to create a green infrastructure system is the Belgrade project in Serbia, initiated in December 2002 called the Green Regulation of Belgrade (Crncevic et al, 2018). The project consisted of four phases: analyzing current situation of green infrastructure, mapping and evaluating Belgrade's biotope and planning for general regulation of green infrastructure in Belgrade (Crncevic et al, 2018). The project was completed in 2008 and provided detailed software and telecommunication specifications for the green infrastructure in Belgrade (Crncevic et al, 2018). This included green areas such as parks, squares, street corridors, urban and suburban forests, residential green areas and did not include nurseries and wetlands (Crncevic et al, 2018). Overlapping green area maps, temperature maps and maps of catchment areas enabled professionals to understand the proper distribution of green areas in order to regulate temperatures at a micro location level as well as how to better manage surface waters (Crncevic et al, 2018).

The benefit of using GIS is that it connects environmental and statistical data allowing for more efficient and economical maintenance, planning and implementing of green areas and infrastructure whether individual or as a system (Crncevic et al, 2018). The GIS GA process is as follows: analyze existing data, review cartographic material, elaborate method to survey and digitize data, develop catalogue of units, digitize maintenance units, control mapping quality and data entry and enter data into GIS (Crncevic et al, 2018). Creating a database on GIS to monitor green infrastructure and green areas allows industry professionals to determine the conditions of the area, manage maintenance cost, better communicate with administration and public enterprises with transparent, information based system. Moving forward, adequate support is needed within GIS such as data, maps and tools or a new tool is required for water management and water infrastructure planning within urban areas in order to support local authorities and have a framework for smart planning and management of green infrastructure.

Crncevic et al also mentions additional initiatives in this field including the Focus Group on Smart Sustainable Cities and the City Digitals Smart Green Infrastructure Project (SGIM). The Focus Group On Smart Sustainable Cities is a platform for exchanging information on information and communications based technology for smart cities from the perspective of various stakeholders (research, municipalities, government organizations etc). It has also published various papers on the standardization and integrated management for smart cities. The purpose of SGIM was to create a tool for water management and water infrastructure planning in Chicago by monitoring the quantity and flow of water in order to reduce and/or prevent urban flooding (Crncevic et al, 2018). This was achieved by combining sensors and cloud computing on five sites to collect data on storm water runoff, humidity level, soil moisture, air pressure, chemical absorption rates (Crncevic et al, 2018). Data collected from these sensors were relayed via cellular network into analytics platform where performance of green infrastructure is monitored in real time (Crncevic et al, 2018). Results will show which green elements work best and where; this data will be beneficial for future implementation and planning of green infrastructure in urbanized environments (Crncevic et al, 2018).

Although this case study does not particularly consider living infrastructure in general or the application of IoT, it demonstrates the need for closer monitoring of living/green infrastructure and the lack of guidance and integrated management that currently exists within the field- which appears to be a global issue. If a monitoring system can be created using sensors within a city such as Toronto, then the following step would be to incorporate this data into a program such as GIS for proper visual comparison of living infrastructure throughout the city and the associated parameters such as temperature, humidity, runoff etc. Smart technology and management is a combination of various practices that includes the use of both IoT and mapping programs such as GIS. By creating a database within GIS of living infrastructure that can be accessed around the world, it would be more feasible to set an example of successful management practices.

Chapter 3: Types of Sensors for Living Infrastructure

This section is dedicated to the types of sensors that could potentially be used to monitor living infrastructure. There is a wealth of information available of on each of the sensors mentioned below, particularly on the mechanics and science behind of their function. However, for the purpose of this paper, each type of sensor is presented with its purpose, common configurations, two scholarly articles about how the specific type of sensor has been incorporated into IoT and/or smart city management and what can be taken away from these examples.

1. Water Based

Living infrastructure plays an integral role in the management of water in an urban environment. It is a two way relationship; living infrastructure can treat and retain water but also needs water to function properly whether it relies on irrigation or rainfall for replenishment. Sensors that gather data on the characteristics of water on and around living infrastructure will allow for greater insight into the effectiveness of living infrastructure is in terms of water management.

1.1 Water Quality

Water quality sensors can be used for many reasons in a city including identifying compliance with regulatory requirements, identifying non-regulatory water quality for critical users (e.g. industries), verifying water quality modeling, planning hydrant flushing and implementing a contamination warning system (Water Quality Sensors, 2012). The chemical, physical and biological conditions of water dictate its quality and it is crucial that quality of water is maintained to prevent contamination of water resources (Water Quality Sensors, 2012). Water quality can be determined using parameters such as residual chlorine, total organic carbon, turbidity, conductivity, pH, salinity, oxygen reduction potential and more (Water Quality Sensors, 2012). There are sensors for each of these parameters; the type of sensors chosen for a study depends on the intention of its use. For the purposes of monitoring water quality in living infrastructure, residual chlorine sensors may not be as insightful to their performance compared to salinity, ph and turbidity sensors.

Living infrastructure such as bioswales, constructed wetlands and green roofs are comprised of several layers that can facilitate water treatment. Monitoring water quality of precipitation as a control variable and comparing it to the quality of water that has drained from living infrastructure will illustrate the effectiveness, if any, of living infrastructure on treating water. Depending on the material of the membrane, there is potential to improve the effectiveness of water treatment of living infrastructure. Although not all living infrastructure are built with the same considerations, with storm water management in mind, living infrastructure should contain drainage layers to allow for the treated water to be reused or redistributed in order to maximize its use.

1.1.1 Stormwater Quality

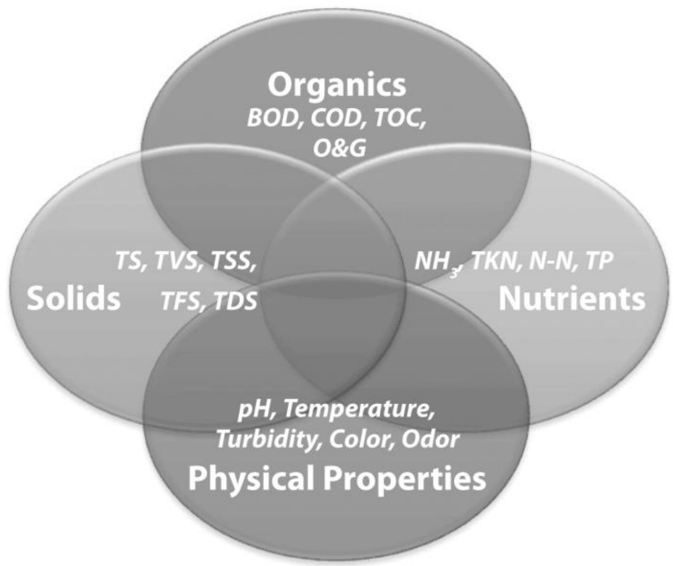


Figure 4: Water Quality Factors (UGA, n.d.)

One of the main purposes of living infrastructure is to address the stormwater issues in urban development, primarily stormwater/runoff quality. Although the indicators of water quality mentioned above can apply to stormwater quality as well, there are additional indicators that are more relevant to urban runoff such as nutrients, BOD, COD and TSS (refer to Figure 4). Water quality problems associated with stormwater arise from uncontrolled pollution from various sources and types of water quality issues include public health risks, eutrophication, dissolved oxygen depletion and others (i.e. sedimentation, chemical materials) (Kumar et al, 2018). Indicators, such as nutrients and BOD, for runoff quality can quantify the nature and extent of pollution present in order to determine the appropriate response (Kumar et al, 2018). Water quality sensors are seldom created for single parameter measurements, most sensors will account for water temperature, nutrients, BOD/COD and TSS all in one as these parameters provide greater insight into stormwater quality when considered simultaneously (Kumar et al, 2018).

Nutrients, most commonly nitrogen and phosphorous, support plant and algal growth and are naturally found in the ecosystem. However, elevated levels of nutrients in water can have detrimental effects on water quality and stream ecosystems. Excess amounts of nutrient in stormwater can result from fertilizers or waste that is washed away by runoff, ultimately entering water systems and bodies of water (Alliance for the Bay, n.d.). High levels of nutrient in water bodies can cause eutrophication which expedites algal growth, causing aglal blooms. Algal blooms can outcompete other plant species be a nuisance for the surrounding environment once the algae decomposes; causing foul odour and toxic waters for wildlife and humans (Alliance for the Bay, n.d.). Using nutrient sensors to determine nutrient levels in and around living infrastructure can illustrate which areas have higher nutrient content in runoff and whether or not living infrastructure is aiding in efforts to reduce nutrients. During rainfall events in the summer, nutrient levels in runoff are expected to increase; since living infrastructure is comprised of vegetation, it is important to consider using native plants that require minimal artificial fertilizer.

Another concern is oxygen demanding material found in stormwater which are organic and inorganic substances that reduce dissolved oxygen in water (Li, 2017). These materials consume and deplete the dissolved oxygen available in water which can be a threat to aquatic life (Li, 2017). Biochemical and chemical oxygen demand measures the amount of oxygen required to breakdown substances; these parameters are used to measure the organic matter in wastewater, treated effluent and stormwater runoff. Increased levels of BOD and COD is caused by greater organic matter in water by means of plants, manure, sewage, food waste as well as substances such as ammonia which is inorganic but creates oxygen demand (Stormwater Rx, 2019). Similar to high nutrient levels, COD/BOD can facilitate toxic algal blooms and by decreasing dissolved oxygen, can cause hypoxic conditions which can reduce cell function and disrupts fluid balance in aquatic species (Stormwater Rx, 2019). Additionally, hypoxic waters can release pollutants stored in sediment. To reduce COD/BOD, passive media filtration can be implemented via living infrastructure (Stormwater Rx, 2019). By strategically placing living infrastructure such as constructed wetlands near bodies of water, runoff can be filtered through media that reduce the organic matter before it enters the water system (Stormwater Rx, 2019). Using sensors to determine BOD and COD further enables professionals to monitor the organic content in stormwater, ensuring that any issues are dealt with in a timely and appropriate manner before conditions worsen (Stormwater Rx, 2019).

Turbidity and total suspended solids (TSS) are often used interchangeably to describe water clarity however TSS refers to the particles that are larger than 2 microns found in water whereas turbidity refers to the overall visual appearance of water (Minnesota Pollution Control Agency, 2018). TSS includes both living and non living (organic and inorganic) solids such as sediment, silt, sand, plankton and algae (Minnesota Pollution Control Agency, 2018). The decompositions matter in water causes small particles to break away and become suspended in water where increased TSS can compromise water clarity and reduce light penetration in water bodies (Minnesota Pollution Control Agency, 2018). In an urban environment, solids in stormwater can originate from erosion of surfaces, dust, litter, exhaust emissions, road salt, soil material and additional particles that remain on impervious surfaces (Minnesota Pollution Control Agency, 2018). In highly urbanized and densely populated areas, TSS has become a major problem for stormwater management. To control or reduce TSS loading, the sources should be identified with appropriate practices to address them. General TSS management practices include:

- pollution prevention and source control
- pre-treatment for structural best management practices
- infiltration
- settling
- filtration (Minnesota Pollution Control Agency, 2018)

where living infrastructure can assist with infiltration, settling and filtration of runoff prior to discharge into water systems or bodies. Infiltration can be accomplished through bioretention, rain gardens, bioswales with a bioinfiltration base and trees. For settling practices, constructed wetlands and ponds allow retention of stormwater long enough for suspended solids to settle beforehand, removal rates range from 60-90% (Minnesota Pollution Control Agency, 2018). For filtration of TSS, green roofs, swales and vegetated strips can act as pretreatment for stormwater by removing 77-90% of TSS (Minnesota Pollution Control Agency, 2018). By employing sensors to monitor TSS, the effectiveness of living infrastructure can be determined: when the total sum of suspended solids during infiltration, settling and filtration is recorded, the data will demonstrate the amount of TSS that has been bypassed by living infrastructure from entering water systems and bodies (Minnesota Pollution Control Agency, 2018).

<u>Literature Review</u>:

Spandana et al address the traditionally complex and time consuming methodology for wireless network systems and proposes a system that is easy to understand and implement which collects data on water temperature, CO_2, pH and water levels with sensors that are connected to a WIFI module. The data is collected on a web server which can be accessed from anywhere in the world and by using a Wi Fi module, interfacing is done on a single chip therefore making the system feasible (Spandana et al, 2018). The system accomplishes low cost and time conserving environmental management of water quality (Spandana et al, 2018). This study was conducted with easily accessible sensors and equipment, unlike other approaches, it is ready to use once all materials have been gathered (Spandana et al, 2018). However this approach does not take into consideration many of the stormwater parameters that would be useful for living infrastructure and is more of a general approach to monitoring water quality. The relevance of this article is in the simplicity of its system, four sensors and a wifi module. There is potential to take what has been done in this article and add additional sensors to broaden the collected data while maintaining a relatively straight forward system.

Wang et al states that China's urban landscape waters are currently monitored manually which is labor intensive, time consuming and can have ineffective outcomes. These operational conditions cannot effectively predict quality variations and trigger points for eutrophication therefore environmental monitoring and surveillance via IoT is being developed (Wang et al, 2013). Wang et al presents an online water quality management system (OWQMS) which was developed to monitor and manage landscape water from reclaimed wastewater and freshwater (refer to Figure 5). OWQMS is composed of: a multiparameter water quality analyzer that was set at middle reaches of the scenic river and was operated by solar power, an information transmission system and a computer system unit (Wang et al, 2013). A master computer is used to analyze water quality characteristics (i.e. organic nitrogen and phosphorous) and controlled the pump supplying fresh water from the Xinglin Bay (Wang et al, 2013). When the amount of reclaimed wastewater cannot maintain the minimum water level required for a river, OWQMS sends an order to the lift pump to draw water from the bay and into the wetland (Wang et al, 2013). OWQMS proved to be an effective management tool for water quality by maintaining standards of quality and demand (Wang et al, 2013).

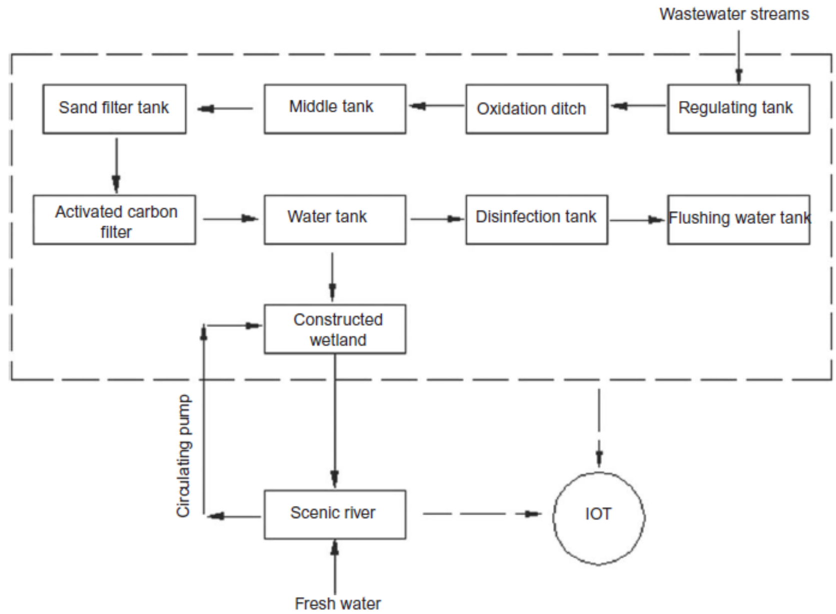


Figure 5: OWQMS Structure (Wang et al, 2013)

Wang et al provides a potential approach to monitoring water quality, especially nutrients, using IoT. Although OWQMS is designed around a river, it also takes into consideration constructed wetlands and the system can be manipulated to appropriately address stormwater quality issues. Instead of placing the water quality analyzer in water bodies, it can be placed around living infrastructure, in areas with high runoff, or downstream areas to determine stormwater quality during precipitation events. The remaining components of the system, such as an information transmission system and a computer system unit, would remain unchanged and can store and assess stormwater quality data.

1.2 Water level (Runoff/Stormwater/Cumulative Precipitation)

Monitoring water level and flow using sensors can provide data on storm water behaviour. These measurements can be used to determine the amount of water in a closed container (i.e. water barrel) or the flow of water in open areas (i.e. rooftops, pavements) (SST, 2019). Sensor types that are able to detect this data are pressure, ultrasonic, open channel and radar level sensors. Ultrasonic sensors are ideal for applications such as water, wastewater, bulk solids and viscous fluids (SST, 2019). Pressure level sensors can also measure water level by sensing the force applied to an area by fluid pressure. Radar level sensors are ideal for long range and difficult environmental conditions with dust, vapours and steam (SST, 2019). The choice of sensor depends on the intent of the use, as different sensors will have varying submersible levels, pressure tolerances, configurations, temperature range and either be analog or digital (SST, 2019).

Monitoring water level is relevant for living infrastructure for more than stormwater purposes. If rain barrels or precipitation that has drained from living infrastructure is used to irrigate the vegetation, these sensors can keep track of the amount of water used and at what temperature (SST, 2019). In terms of storm water, the sensors can measure the level of rainwater that has accumulated on a rooftop or open area and determine the amount of water that living infrastructure is retaining and therefore the amount of runoff that is reduced as a result. There are many water level sensors that can be purchased as a singular sensor and need to be connected to a transmitter to show the measurement. In order to be smart technology, the transmitters must be capable of storing the data on cloud so that it can be accessed through a network. Not all water level sensors that are commercially available explicitly state the IoT capabilities, this must be determined on a case by case basis.

Literature Review:

Moreno et al looks at how river water levels can be monitored to avoid flooding with the help of IoT technology called RiverCore (refer to Figure 6). Although using IoT technology to provide real time data can be efficient, it is crucial that the technology is able to withstand the large amounts of incoming data to avoid delays for real time scenarios (refer to Table 3) (Moreno et al, 2019). When measuring water levels for rivers, variables that are considered are flow, volume, speed and relative humidity. These variables can be measured but the issue is with retrieving real time data, creating uncertainty and the inability to use that data to create future forecasting models (Moreno et al, 2019). Some sensors that have been used in other studies have proved to be high maintenance and prone to damage. The Rivercore module integrates different sensors to sense river width, flow speed, water height using ultrasonic sensors (Moreno et al, 2019). This information is sent through cellular communications module to monitor over a web interface. The Rivercore node is made up of five individual devices: 32-bit microcontroller unit, a 3G cellular modem electronic board, a regulated power supply, a solar charge controller and a 12 V 80 Ah battery (Moreno et al, 2019). Rivercore is a first prototype of the fixed node and contains the proper materials and components to be deployed in a remote location and can work continuously during the rainy season even without direct sunlight (Moreno et al, 2019). Moreno et al concludes that a system such as RiverCore might reduce the impact of floods by providing information for city planning and giving citizens to get away from flood zones.

Table 3: Types of IoT technology (Moreno et al, 2019)

Name		Frequency	Range	Data Rate	Best Use
Cellular	3G/4G/LTE	900 MHz–2.6 GHz	Depends on area coverage	1 Mbps	For data intensive interactive user services like videoconferencing or telemedicine.
Low-Power Wide-Area Network (LPWAN)	SigFox	Regional sub-GHz bands	3 to 50 km	100 bps up, 600 bps down	For applications that need to send small or infrequent data bursts such as alarm systems or simple metering.
	LoRaWAN		2 to 15 km	0.3 kbps–50 kbps	For long-range and low-power connectivity applications.
	OnRamp/Ingenu	2.4 GHz	500 km	20 Kbps	Offers long-range connectivity for smart grid, intelligent lighting and advanced metering infrastructure, among others.
	Weightless P	Regional sub-GHz bands	Up to 10 km	200 bps to 100 kbps	Ideal for private networks where both uplink data and downlink control are important.

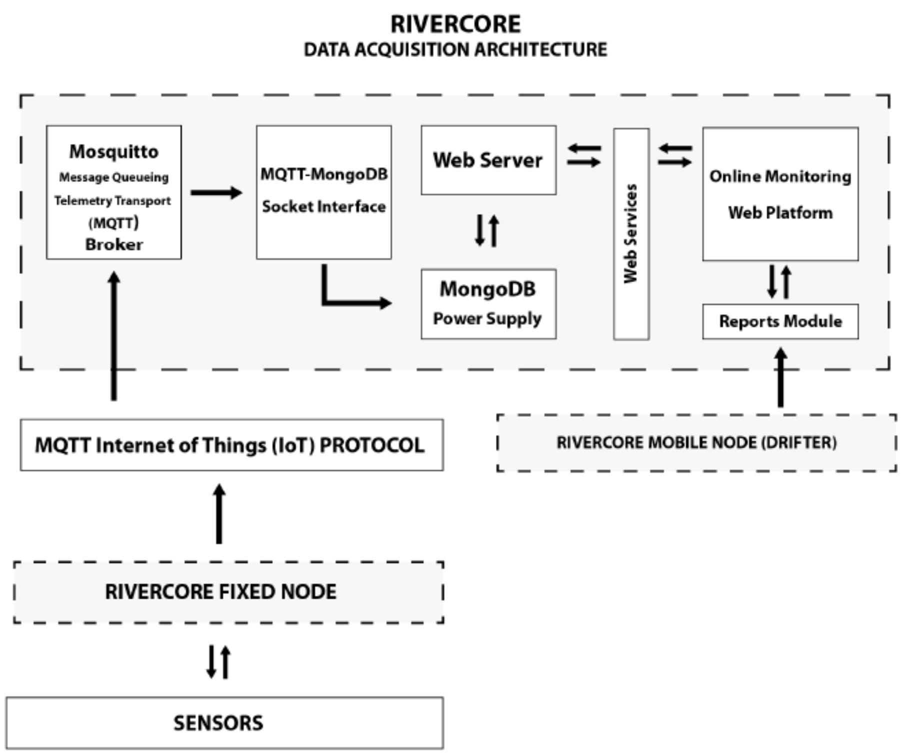


Figure 6: Rivercore Architecture (Moreno et al, 2019)

Both the Rivercore node and the Array of Things node (see case study 3) compile multiple sensors into a single node to allow easy compilation of data that is accessible at once. Rather than deploying many sensors at various locations with individual systems, building a singular node with sensors that cover various water based parameters is a more feasible approach, when compilation of sensors is possible. The goal of using sensors to monitor living infrastructure is to ultimately collect, store and retrieve data as necessary, this cannot be achieved if the technology used cannot withstand large amounts of incoming information.

Rivercore is a successful example of how to approach collection of data while using the data to forecast future conditions to help with city planning. This is important for urban development where floods have increased in recent years, by assessing how quickly water levels are increasing (whether in rain barrels or on impervious surfaces) cities can better prepare for such conditions.

In another study, Malche & Maheshwary take a general approach to how water level monitoring in villages can be done using IoT technologies with a proposed prototype (see Table 4 for system components). The idea is to work towards a smart village to promote digital inclusion with access to IoT services (Malche & Maheshwary, 2017). The proposed system has three layers: physical, service and presentation. The Physical layer will consist of sensor nodes and communication technologies where data is collected and related to the service layer (Malche & Maheshwary, 2017). The service layer is there the applications and business logic is implemented and where data is stored to be analyzed (Malche & Maheshwary, 2017). The presentation layer is where users can access data and interact with the system (Malche & Maheshwary, 2017). Once data is picked up by sensors it is uploaded to carriots which is a cloud application platform for IoT and can receive data from WSN in real time (Malche & Maheshwary, 2017). Data can be visualized by users through Freeboard which is a dashboard that works as a visualization tool by receiving data from carriots (Malche & Maheshwary, 2017). Although still under works, data from water level monitoring in remote locations can be useful for better management of water resources (Malche & Maheshwary, 2017). Malche & Maheshwary provide a general approach to using IoT to monitor water levels in water tanks, with greater emphasis on how to monitor than what is being monitored. The concept can be applied to living infrastructure that uses rain barrels for irrigation. During periods of low rainfall, monitoring water level in these barrels is crucial for the vegetation that relies on an adequately filled rain barrel, if water level falls below a given amount then this can be addressed, ensuring vegetation remains sufficiently watered.

Table 4: Prototype components (Malche & Maheshwary, 2017)

Hardware specification	Software & Services Specification
• Arduino Uno R3 • Arduino Ethernet shield • Liquid Level sensor • Male-Female jumper wires • Water source	• Arduino Software • An account on Carriots.com • An account on Freeboard.io

1.3 Water Flow Rate

Flow rate sensors (or flow meters) measure the volumetric flow rate of a fluid passing through a pipe. There are five main types of flow meters: differential pressure, positive displacement, velocity, mass and open channel flow meters (Don Johns, 2016). The differences between the flow meters include materials, construction and the fluid they are ideal for measuring (Don Johns, 2016). All five of these meters are suitable to monitor the flow rate of water but some are more ideal than others. For example, mass flow meters are more ideal for wastewater treatment plants whereas open channel flow meters are ideal for bodies of water and irrigation channels (Don Johns, 2016). Flow meters should be chosen based on the intent of use as not purchased before understanding the environment it will be used in (Omega Engineering, 2019). Considerations when selecting a flow sensor include: temperature, pressure, viscosity, conductivity, corrosiveness and cleanliness of the fluid (Omega Engineering, 2019). A common configuration of flow rate sensors consists of a small turbine, magnet and sensor circuit. When the water passes through the turbine wheel, it rotates and the magnet located at the top picks up the current and sends a pulse to the sensor circuit at a specific time which determines the flow rate (MachineDesign, 2013).

Literature Review:

Karray et al tackles the issue of power consumption and computational performance for pipeline monitoring where current wireless networks are not suitable or adequate for pipeline monitoring as power is not always available. They created a prototype IoT-based wireless sensor network for water pipeline monitoring called WiRoTip (refer to Figure 7) which has a leak detection algorithm (Karray et al, 2018). The purpose of this prototype is to achieve energy preservation and enhance sensing capabilities of output signal of sensors (Karray et al, 2018). WiRoTip consists of three layers (refer to Figure 8), the first layer is where data is collected and processed, the second layer stores the data and in the case of a leak the information is forwarded to the cloud (Karray et al, 2018). The third layer is where users can interact with the sensor information where data is compiled into information, statistics and graphs on leaks, with up to date insight on pipeline state (Karray et al, 2018). As a prototype, there is little indication whether or not it was successful; additional research is currently being conducted to ensure ultra low power consumption (Karray et al, 2018). The relevance of this article for monitoring living infrastructure is mainly related to irrigation pipes for structures such urban farms. If a pipe is experiencing a leak, this will have impacts on the flow of water causing water waste and insufficient irrigation. By having a system that can properly identify leaks and update on the state of a pipeline, damages can be avoided. However this study assumes accessibility to pipelines in order to equip them with sensors, this may not be feasible as some areas may be older with hidden or inaccessible pipelines. One possible approach to address this issue would be to attach sensors to new pipelines that are built but additional information and research is required for this to be a feasible option.

Figure 7: WiRoTip prototype (Karray et al, 2018)

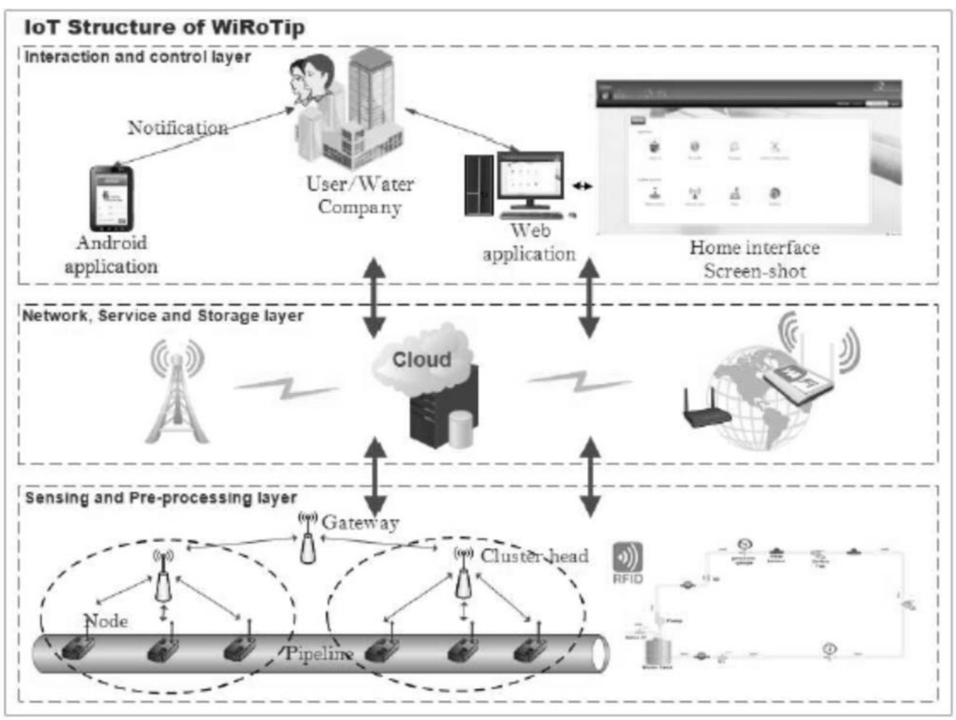


Figure 8: WiRoTip Structure (Karray et al, 2018)

A study by Mullapudi et al describes an approach to managing stormwater discharge across a watershed using IoT and sensors. By releasing water from retention basins, they achieve the desirable flow regime downstream which currently is not possible with existing infrastructure (Mullapudi et al, 2018). Current designs for monitoring downstream changes in water bodies are static and do not account for future changes in weather, population growth and regulatory requirements (Mullapudi et al, 2018). By controlling stormwater basins, water quality can be improved by removing contaminants from stormwater (Mullapudi et al, 2018). Additionally, regulating discharges from constructed wetlands can help rehabilitate aquatic habitats (Mullapudi et al, 2018). The smart stormwater system used valves and sensors to manage discharge and was able to maintain downstream flow at a constant rate and prevent sediment transport (Mullapudi et al, 2018). To replicate the smart stormwater system, the components of the system are available at http://open-storm.org/. Although not directly related to living infrastructure, this smart stormwater system has great potential for urbanized environments where downstream flow is a concern during extreme weather and demonstrates the need for flow sensors in such cases. Incorporating flow sensors into smart water management systems is necessary to monitor flow patterns and behaviours of runoff, providing insight into the implications it may have on downstream waterbodies.

2. Atmospheric Based

Living green infrastructure can reduce air temperature, combat the urban heat island effect and reduce water thermal pollution by cooling and filtering the surrounded air. Currently there is little information on the effects of living green infrastructure on differential pressure, but the positive implications for air pollution, humidity and temperature are well documented. By combining the sensors for the following parameters and comparing it to a test value from areas within the same vicinity without living green infrastructure can demonstrate the effectiveness of living infrastructure on atmospheric conditions.

2.1 Air Quality

The quality of air within highly urbanized areas is subject to continuous pollution from industrial, commercial and vehicular sources. Common air pollutants of interest that are detrimental to human health and/or the environment are ozone, carbon monoxide, carbon dioxide, sulphur dioxide, nitrogen dioxide, volatile organic compounds and particulate matter (Raj & Kumar, 2017). Traditionally, air quality is monitored using expensive instruments at a fixed location, with multiple spread across a city. However this arrangement fails to accurately provide spatio-temporal distribution of pollutants and identify pollution hotspots (Raj & Kumar, 2017). Recent advancement in wireless communication networks and IoT have allowed for high resolution air pollution data with low cost sensor note for real time monitoring (Raj & Kumar, 2017). Air pollutants are categorized into primary and secondary pollutants where primary pollutants are smaller than 10 microns and secondary pollutants are smaller than 2.5 microns. There are two main types of sensors used for air quality monitoring, particulate matter sensors and gas sensors. Particulate matter sensors can be filter-based-gravimetric method, β-attenuation method, optical method and others but the optical method is low cost with low power requirements thus being the method of choice (Raj & Kumar, 2017). For gas sensors, the two available types are metal oxide semi conductor sensors and electrochemical sensors, both of which are relatively low in cost (Raj & Kumar, 2017).

Literature Review:

Alvear et al reviews the current technologies that allow for crowdsensing of air quality in densely populated areas. Crowdsensing uses the communication technology that is widely available (i.e smart phones) for monitoring purposes; this allows users to monitor air quality while compiling the data in the cloud. Controlling air pollution levels has been an ongoing issue as it is difficult to do and static monitoring stations are not suitable for existing densely populated areas that are limited in space (Alvear et al, 2018). This prevents data collection from the areas that are in most need of air quality monitoring and instead yields data from sparsely populated areas which do not effectively represent the overall issue (Alvear et al, 2018). The idea behind crowdsensing is to collect data on air quality while users go about their daily activities (i.e. using their smart devices) which would require cheap and small sensors that can easily be transported (Alvear et al, 2018). Alvear et al found the following about the relevant technology:

- Raspberry Pi is best for quick prototyping
- Arduino Nano platform is best in terms of price, weight and power consumption
- Intel Edison is best for higher processing capacity prototyping
- Arduino is best for restricted environments (Alvear et al, 2018)

Moving forward, the intent is to incorporate sensors into vehicles such as cars, buses and bikes. The advantage of using mobile devices for monitoring is that it allows for dynamic data collection. By using GPS coupled with sensor data, the exact location and associated air quality conditions can be assessed. It would be an interesting approach to overlap the sensor data on GIS maps where air quality near and around living infrastructure can be compared to areas with no significant green infrastructure, demonstrating whether or not living infrastructure has a significant impact on improving air quality.

Similarly, in 2017 Gupta & Kumar developed a portable, low cost and efficient pollution monitoring device that can be used on rooftops to determine ambient air quality with IoT capabilities. Energy consumption of the device is low as it functions on sleep mode and can be solar powered (Gupta & Kumar, 2017). Similar to Alvear et al, this article makes the point of current air pollution monitoring to be expensive and incorrectly placed (Gupta & Kumar, 2017). The device, called My Enviro, was created to monitor air quality, analyze different gases in air and to display data on computers (refer to Figure 9) (Gupta & Kumar, 2017). Advantages of the device include automated system which does not need to be physically operated, low maintenance and flexible as sensors can be added or changed (Gupta & Kumar, 2017). The device currently does not perform to mitigate or control the source of pollution therefore moving forward this is an improvement that will be taken into consideration (Gupta & Kumar, 2017). Although Gupta & Kumar attempt to address the issue of static devices, this device remains static unless it is physically transported elsewhere to monitor air quality. This is a limitation of the device with regards to determining air quality for an area rather than a sparsely populated or remote location. Compared to Alvear et al's crowdsensing approach, the My Enviro device may fall short of the type of advancement in technology needed to keep up with the urban population.

Figure 9: Structure of My Enviro (Gupta & Kumar, 2017)

2.2 Differential Pressure

Pressure sensors are devices meant for measuring the pressure of gases or liquids (the force per unit of surface area) (HBM, 2018). The sensor generates an electrical signal based on the pressure imposed by a fluid or gas and converts the information into an output signal (HBM, 2018). Types of pressure sensors differ in characteristics such as measure range, temperature range and range of operation (HBM, 2018). The pressure sensors ideal for atmospheric purposes include gauge, sealed and differential pressure sensors. Differential pressure sensors measure the difference between two pressures and can be used to measure pressure drops in fluid levels and flow rates (HBM, 2018). A gauge pressure sensor is technically also a differential pressure sensor but one side of the sensor is open to the ambient atmosphere, it measures the relative atmospheric pressure (HBM, 2018). As for a sealed pressure sensor, it is similar to a gauge pressure sensor but the measure is relative to a known/fixed pressure and not the ambient atmosphere. Pressure sensors can also differ in the technology and materials used to pick up signals, these include strain gauge based pressure sensors, capacitive pressure sensors, resonant pressure sensors and piezo resistive pressure sensors (HBM, 2018). There is little to no literature on the effects of living infrastructure on differential pressure or on any IoT based systems for monitoring differential pressure. Therefore it is worth studying and looking into further by employing differential pressure sensors around living infrastructure, particularly at higher elevations.

2.3 Relative Humidity and Atmospheric Temperature

These parameters are often considered together as temperature has implications for humidity. Majority of monitoring systems meant for this purpose will function for both relative humidity and temperature simultaneously. Literature will reference articles that consider both parameters into one device and/or system.

2.3.1 Relative Humidity

Humidity sensors measure the moisture and temperature in the air (ElectronicsFU, 2018). More specifically relative humidity is the amount of moisture in the air compared to what it should be at that given temperature (ElectronicsFU, 2018). Humidity sensors detect changes in the air that alter electrical currents or temperature (ElectronicsFU, 2018). There are three basic types of humidity sensors: capacitive, resistive and thermal. Capacitive humidity sensors use a metal oxide strip and two electrodes, the metal oxide's electrical capacity changes with relative humidity (ElectronicsFU, 2018). They can be used in a range of temperatures without compensating on accuracy. Resistive humidity sensors use salt ions to measure electrical impedance, changes in humidity causes the resistive of the electrodes to change as well (ElectronicsFU, 2018). Thermal humidity sensors contain two sensors in two different mediums that conduct electricity based on humidity; one of the sensors measures ambient air and the difference between the measurements from the two sensors will give humidity (ElectronicsFU, 2018).

2.3.2 Air Temperature

Air temperature sensors are temperature sensors that are ideal for atmospheric conditions. There are four basic types of temperature sensor technologies: negative temperature coefficient (NTC) thermistor, resistance temperature detector (RTD), thermocouple and semiconductor based (Ametherm, 2019). NTC thermistor (thermally sensitive resistor) has a high accuracy and is ideal for large variations in temperature, it exhibits changes in resistance based on temperature with (i.e. lower resistance for higher temperature, higher resistance for lower temperatures) (Ametherm, 2019). Resistance temperature detectors correlate resistance of the detector with temperature where accuracy of the measurement depends on the element used for the RTD (Ametherm, 2019). The most accurate ones use platinum while the low cost RTD's use nickel or copper. Thermocouple temperature sensors are made up of two wires with different metals that are connected at two points where change in voltage between the points is proportional to changes in temperature (Ametherm, 2019). These sensors have low accuracy but has a larger temperature range than NTC thermistors (-200C to 1750C) (Ametherm, 2019). Semiconductor sensors consist of two diodes with temperature sensitive voltage, this can be used to monitor differences in temperature. However these sensors are known to be the least accurate with slow response times and limited temperature range (-70C to 150C) (Ametherm, 2019). As mentioned earlier, living infrastructure can reduce high temperatures caused by heat island effect and monitoring temperature around living infrastructure can demonstrate the extent of temperature reduction.

<u>Literature Review:</u>

In 2016, J. Liu created an intelligent environment monitor control system for a grape greenhouse that considers environmental factors such as air temperature, air humidity, illumination, CO_2 concentration and soil moisture (refer to Figure 10). The purpose was to create a system that can fuse data from multiple sensors in the gateway of the network layer to make it more interactive (Liu, 2016). Compared to previous studies, this monitoring system presented three advantages: it can record and treat data without protocol limits, works well for great data collection in a short period of time and analysis of data is managed automatically (Liu, 2016). Results showed that this design allowed data from various sensors to be transmitted, stored and analyzed on a universal level (Liu, 2016). In the future, more sensors can be incorporated to provide greater insight into greenhouse conditions (Liu, 2016). Liu considers both air temperature and humidity but within a closed environment, although it demonstrates a successful system, whether or not it will be suitable outdoors during harsh weather conditions is questionable. The relevance of this study lies in the fusion and analysis of data from multiple sensors before it reaches the cloud, this allows data to be considered together rather than individually to see how the parameters effect one another.

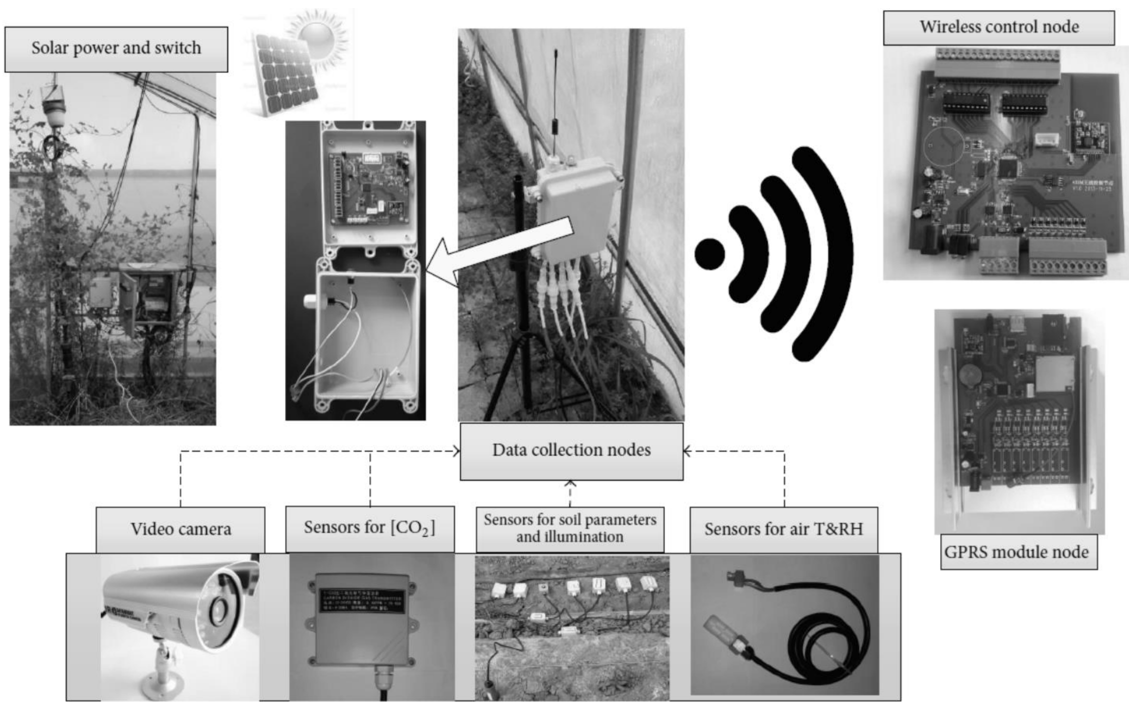


Figure 10: Sensor system layout (Liu, 2016)

An article by Zafar et al looks at an environmental monitoring system that uses sensors for temperature and humidity to monitor a given area. The system allows data to trigger actions to control heating and/or cooling devices based on the sensor data (Zafar et al, 2018). The system uses Wi Fi where the collected data is stored in the cloud and can be access via Android applications (Zafar et al, 2018). A single sensor that senses both temperature and humidity was used, a DHT11 composite sensor chip, which is low cost, small in size with a fast response time; Table 5 outlines the additional components of the system (Zafar et al, 2018). Results of test runs showed that data was accurate and as expected (Zafar et al, 2018). This paper is interesting for its use of a single sensor that senses two crucial parameters for atmospheric monitoring. This is the route that should be taken when creating such systems as it can reduce cost, weight, technical requirements and power consumption when a single sensor is employed for multiple measurements.

Table 5: System components (Zafar et al, 2018)

System Component	Details
Sensor	DHT11
Connectivity	Wi-Fi ESP8266
Microcontroller	Arduino UNO
Cloud	ThingSpeak
User Interface	Android Application

3. Soil Based (Soil Quality)

A wealth of literature is available on soil quality monitoring, primarily originating from countries that specialize in agriculture. Soil quality encompasses the ability of soil to sustain plant and animal productivity and maintain or enhance water (Soil Quality, n.d). Soil quality indicators can be categorized as physical, chemical or biological; for monitoring purposes the common parameters that are considered together are soil temperature (physical), ph (chemical) and moisture (physical) (USDA, n.d). Healthy soil should provide qualities such as filtering pollutants, nutrient cycling and water regulation. For the purposes of living infrastructure, soil is the primary growth medium for vegetation that can reduce runoff by providing permeable surface area in the city (USDA, n.d). Although soil has inherent qualities, management of the soil can alter its quality for example adding excessive amounts of fertilizer can cause unhealthy levels of nutrients (USDA, n.d). This is particularly important for urban farms and rooftop gardens that grow crops and plants for aesthetic, in these cases soil not only functions to retain stormwater but as a growing medium that needs to be able to support long term plant growth (Soil Science Society of America, n.d). Monitoring soil quality can provide insight into how urban stormwater can affect soil quality and the ability of different types of soil to filter pollutants (Soil Science Society of America, n.d).

3.1 Soil Temperature

Soil temperature has implications for both pH, soil moisture and other soil characteristics. It is crucial to have a suitable temperature as it can affect germination and growth which can be difficult to achieve when multiple plants and/or crops have different ideal temperature requirements (Swagata, 2016). For this reasons it is suggested that similar crops are grown together to ensure they all receive the desirable temperature. Additionally, areas with colder climates and harsh winters should use soils that drain well, these soils warm up earlier during the spring (Swagata, 2016). Seeds will not germinate in very low soil temperatures and could potentially be injured if the soil is too hot. Factors that can affect soil temperature include: nature of soil (inorganic or organic), soil moisture content, soil texture, land slope, vegetation and depth (Swagata, 2016). Soil temperature sensors differ from in air temperature sensor in that in needs to be able to withstand conditions of being submerged in soil and contact with moisture for long periods of time (National Instruments, 2019). The sensor types however are the same as mentioned in 2.3 but given that depth is a consideration for soil monitoring, sensors for soil temperature come in the form of probes and/or are comprised of longer cables to accommodate depth.

3.2 Soil Acidity

Soil acidity (pH) can impact vegetation growth and is therefore an important aspect to monitor (Heath, 2018). Average soil pH ranges from 4-8 and depending on the type of vegetation that is used, a different pH level will be ideal for optimal growth. For most plants however, 6.2 to 7.2 is a standard pH level (City of Vancouver, n.d.). One of the main soil nutrients is phosphorus which also depends on soil pH, soil conditions that are too acidic or too basic can decrease phosphorous availability (City of Vancouver, n.d.). All pH sensors rely on voltage tests to determine hydrogen ion levels, the more hydrogen ions the more conductive the soil will be (WD Tools, n.d.). When the soil comes in contact with the two electrodes in the sensor probe, the voltage difference between the two electrodes is translated to a pH measurement (WD Tools, n.d.). When selecting the type of soil pH sensor (mainly the build and materials used), it is important to look at how sensitive the sensor is to temperature changes as this may cause inaccuracies in the reading (Heath, 2018).

3.3 Soil Moisture

Soil moisture sensors measure the water content of soil (refer to Figure 11) and are used in fields such as agriculture, land irrigation and gardening (Garg et al, 2016). By monitoring soil moisture, irrigation and plant growth are optimized and water use costs are reduced (Garg et al, 2016). The main group of soil moisture sensors are water potential sensors (Garg et al, 2016). Water potential sensors provide insight into water availability for plants and monitoring with these sensors will indicate when soil had become too hard for plants to access water (Garg et al, 2016). There are two types of water potential sensors: tensiometer sensors and granular matrix sensors (i.e. gypsum block) (Prince, 2018). Tensiometers measure suction pressure at its porous tip where water is drawn in depending on water availability (Prince, 2018). Measurements can be logged using a pressure transducer (Prince, 2018). Granular matrix sensors use currents that pass through a porous media (i.e. gypsum) where the electrical resistance is dependent on the amount of water drawn in and out of the media. Table 6 compares these sensors as three individual types. Monitoring soil moisture can have a multitude of purposes optimize water usage for vegetation. By understanding when soil moisture is low or high, irrigation times can be optimized.

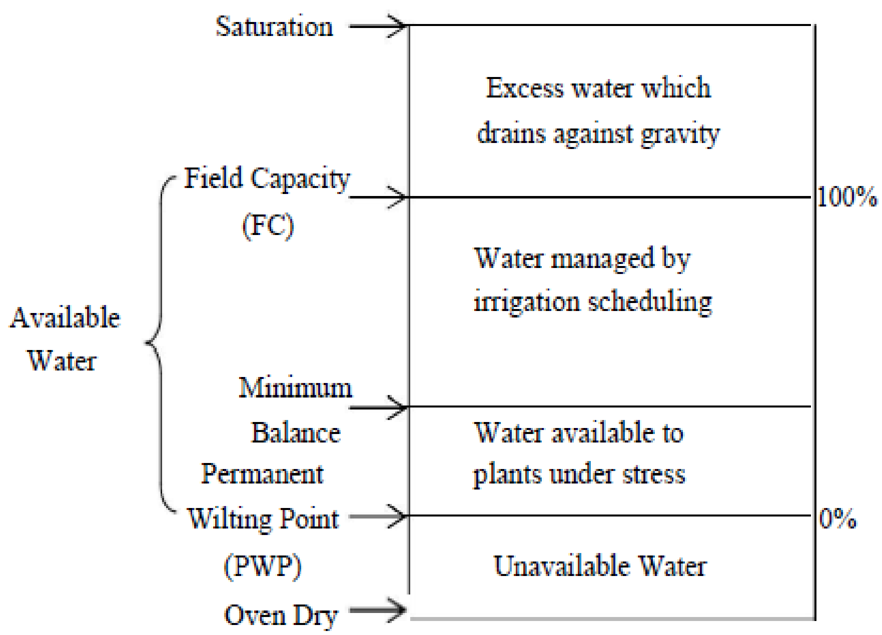


Figure 11: Water levels in soil (Garg et al, 2016)

Table 6: Ideal soil moisture sensor for soil types (Prince, 2018)

Soil and crop type	Tensiometer	Granular matrix	Gypsum block
Soil type			
Coarse sand	Yes	No	No
Sandy loam, loam, loamy clay	Yes	Yes	Yes
Heavy clay	Yes	Yes	Yes
Crop type			
Vegetables and strawberries	Yes	No	No
Perennial fruit and table grapes	Yes	Yes	No
Pastures	Yes	Yes	yes
Wine grapes	No	No	Yes
Maintenance required	Moderate	Low or none	Low or none

Literature Review:

In a 2014 article, Sakthipriya proposes wireless sensor technology to determine leaf wetness, soil moisture, phH, atmospheric pressure and temperature. The technology can trigger water sprinklers during water scarcity and turn off when crops have been watered adequately, thus demonstrating ing precision agriculture. The data is also collected on a mobile device via GSM (global system mobile) technology. In terms of hardware, the monitoring system includes: sensors (including a resistance soil moisture sensor), actuators, connectors, interface boards, input and display panels, routers, computers, generators and transformers. Farmers can reliably collect data on a micro scale as well as have access to historical data, this study was conducted in agro-ecology fields with success.

Additionally, in 2016 Sumarudin et al built a monitoring system for continuous monitoring of soil moisture, humidity, pH and temperature that can help farmers make decisions about soil treatment. The device is able to store data that can then be displayed on a website as a line chart with information from the last 24 hours. Results of the study showed that the device was successful in terms of accuracy of sensor readings and that the process of monitoring temperature and ambient temperature was more efficient than traditional approaches.

In 2017, Na et al created an IoT based system for remote monitoring of soil quality characteristics such as pH, temperature and moisture with real time data to help farmers increase drop yield. Although there have been previous research on using sensors to measure the mechanical, chemical and electrical properties of soil, they were expensive, imprecise and not a real time system. The device created by Na et al is reliable, cost effective, power efficient, provides real time data and uses Bluetooth communication that can be accessed by smartphone. The sensor unit uses three different sensors for pH (electrode sensor), moisture (resistance sensor) and temperature (DS18B20 sensor). The device was tested on garden pots and fields with satisfactory results. This study identified that efficient sensors remain expensive and inexpensive sensors do not have the digital capabilities to support IoT functions.

These three studies were specifically chosen due to the similar approaches and purposes for the creation of the soil quality monitoring prototype which could be compared and contrasted. Each one created original monitoring systems for soil quality that have IoT capabilities, with minor variations. Given the numerous studies available on this topic for the purposes of agriculture with details on the types of sensors, protocols, power consumption and platforms used, creating one from scratch for living green infrastructure can be attempted. The main concern with monitoring systems for soil quality presented by these articles is of the price of sensors and power consumption, both of which need to be reduced for the system to be feasible and to be accepted into mainstream practice. A common issue within the articles is claiming that it can help farmers and those who are responsible for crop production. It is easy to claim the potential of a system as it is a vague statement, sometimes with little merit. Right now these systems can be difficult to understand and utilize by public users, with multiple components that need to be understand for proper use and troubleshooting when necessary. Manuals do not exist to walk users through how to use the system, although apps for data display may be user friendly it is the monitoring system itself that needs to be installed properly before it can gather the desired data. Many times, the target users of some of these monitoring systems are not well versed in communication technology, as these articles refer to farmers in remote areas who can potentially benefit from real time soil quality data. Additionally, although some of the studies were conducted in field, it is difficult to tell whether it is versatile with regards to location and therefore is currently not representative of worldwide applications and therefore the potential to help farmers in general is not within reach.

Currently these prototypes are in the very early stages, it is evident that mainstream application of agricultural monitoring of soil quality is in demand but not quite where it needs to be. To bring the focus back to living infrastructure, the best approach would be to build a monitoring system from scratch, based on the components outlined in these articles, but with considerations for urban farms and the impact of harsh Canadian winters on outdoor monitoring systems to ensure the monitoring system yields the desired data. After water analysis, soil quality is most relevant for living infrastructure monitoring. It would be ideal to combine the two systems as they go hand in hand, particularly in terms of irrigation. Automated irrigation systems that are triggered when soil moisture sensors indicate low moisture not only address low water content in soil but also conservation of water as irrigation only lasts until the soil moisture sensor indicates sufficient moisture has been restored. By combining water and soil sensors into a single monitoring system, there is an opportunity to understand how one affects the other, to what extent and how this relationship can be manipulated to improve the efficiency of living infrastructure.

4. Solar Based

One of the benefits of living green infrastructure is its heat-mitigating abilities from sources such as solar radiation. Living infrastructure, mainly green roofs and urban rooftop farms, have a cooling affect on buildings because the heat is deflected and/or absorbed thus not transferred to the building. However vegetation also requires solar radiation for energy, which is where photosynthetic flux density is relevant. Monitoring the solar radiation that living infrastructure receives can provide data on the amount of radiation that is deflected by living infrastructure and the photosynthetic flux density can provide insight into what portion of the incoming radiation is usable for vegetation growth.

4.1 Solar Radiation

Solar radiation serves as the source of energy for plants and is therefore a crucial element that needs to be monitored to track how much solar radiation an area is receiving (Hinckley, 2017). Solar radiation sensors are also known as pyranometers (for shortwave radiation) and pyrgeometer (for long wave radiation).For the purposes of this paper, only pyranomters will be discussed (Hinckley, 2017). A pyranometer measures the total radiation; it converts solar radiation into an electrical signal that can be measured. There are two types of pyranometers, thermopile and silicon photocell (Hinckley, 2017). Thermopile pyranometers: “use thermoelectric junctions to provide signals indicating the temperature difference between a black absorbing surface and a reference” (Hinckley, 2017). Thermopile pyranometers are considered the most accurate yet expensive solar radiation sensor (Hinckley, 2017). Silicon photocell phyranometers produce output currents that pass through a resistor and converted into a voltage signal (Hinckley, 2017). They only measure a portion of the shortwave spectrum and are not as accurate but also less expensive (Hinckley, 2017).

Literature Review:

Hidalgo et al developed a low cost pyranometer with low cost components and a PT202C phototransistor; the device is more sensitive which allows for better sensor response. When test results were compared to a commercially available pyranometer, a 0.9909 correlation was found between the results (Hidalgo et al, 2013). Solar irradiance can be measured using pyranometers, pyrheliometers and albedometers which produce highly accurate results and are therefore expensive which may not be feasible for institutional (i.e. schools and universities) research (Hidalgo et al, 2013). The proposed sensor is able to measure global and diffuse irradiance and is resistant to extreme heat conditions (Hidalgo et al, 2013). However, a limitation of the low cost pyranometer is that it receives less irradiance than its commercial counterpart, the CMP11. Overall, the proposed device is reasonably accurate (Hidalgo et al, 2013).

Solar irradiance differs from solar radiation in that solar radiation is the electromagenetic radiation emitted by the sun whereas solar irradiance is the exposure of an object to solar radiation. The sensors used to measure both are the same (i.e. pyranometers). Much of the literature available on solar radiation and IoT deals with how solar power and energy can be used to support IoT technology rather than using IoT to monitor solar radiation for environmental purposes. The article by Hidalgo et al is relevant because it exhibits how pyranometers can be made cost effectively. If a monitoring system was to be created that encompassed sensors from various fields, to ensure that it is feasible the sensors used must be cost effective otherwise it may not be practical. Although further research is required to ensure accuracy of this device, data can be adjusted with the standard deviation. This article did not consider IoT based monitoring with the sensor, moving forward the intent would be to incorporate solar irradiance sensors into a monitoring system that has IoT capabilities. Monitoring living infrastructure can benefit from solar irradiance sensors in that different areas receiving different amounts of sunlight can be compared to understand to what extent the solar irradiance is affecting the living infrastructure productivity.

4.2 Photosynthetic photon flux density (PPFD)

Photosynthetic flux density measures the photosynthetically active radiation (PAR) hitting a surface per unit area per unit time; it is measured in units of micromoles per square meter per second (µmol/m2/s) (StellarNet, 2017). Photosynthetically active radiation is the portion of solar radiation (400 to 700 nanometers) that can be used for photosynthesis (Fluence, 2019). PPFD is considered a spot measurement of a specific location and does not consider a large area (Fluence, 2019). For this reason, PPFD measurements should be taken at multiple heights and at multiple locations within a given area. When purchasing a PPFD sensor, the manufacture must define the following (Fluence, 2019): measurement distance from light source (vertical and horizontal), number of measurements included in the average, and the min/max ratio) (Fluence, 2019). PPFD sensors can be used in a variety of environments including greenhouses with lamps, plant canopies and growth chambers all of which rely on different sources of light for photosynthesis (natural, artificial or mixed) (Fluence, 2019).

Literature Review:

Yadav et al designed and optimized a PAR sensor (wireless, customizable) which preformed successfully during a field test. Plants only use a portion of the visible spectrum of the sunlight, 400-700nm, which is known as photosynthetically active radiation (PAR) (Yadav et al, 2018). The amount of PAR used is different for every plant and monitoring PAR is important to understand plant productivity under test environments (Yadav et al, 2018). The novel PAR sensor had a -/+ 4% error which is an improvement from a commercially available PAR sensor, the Licor Quantum sensor which has an output error of -/+5% (Yadav et al, 2018). Since the system is wireless, it has a lower power consumption as well as compact and mobile (Yadav et al, 2018). Yadav et al outlines how to build the novel PAR sensors which can be customized to add GPS or GSM to know the exact location of a measurement. Since the device is replicable, cost efficient and wireless, there is potential to incorporate it into a larger monitoring system to monitor the productivity of living infrastructure vegetation to determine if the PAR received by different sites vary and what are the associated impacts on productivity. Since monitoring PAR can be complex and very specific, it has yet to be introduced to IoT and a monitoring system, although sensors for it do exist, there is a lack of research on how to upload the data to the cloud.

5. Ecology Based

A side effect of urbanization is the destruction of inner city habitats and the negative impacts on the ecology. However living infrastructure can work towards restoring some of this damage, primarily to the bee population, rodents and birds (insects and smaller organisms are also included but are not as straight forward to detect). Living infrastructure sites have the capacity to be great bee keeping locations if the proper vegetation is planted. Monitoring bee traffic as well as the presence of rodents and birds at living infrastructure sites can demonstrate the effectiveness to sustain and/or improve bee populations and how frequently the site is visited by animals.

5.1 Bee Keeping

Bee populations have been under crisis on a global level experiencing severe decline due to industrial factors, agricultural factors (i.e. intensification, insecticides, monocultures and industrial-style practices), pathogens and climate change (Greenpeace, 2014). One of the major reasons under industrial factors is the destruction of habitats and therefore a lack of biodiversity which reduces bee survival rates (Greenpeace, 2014). For these reasons, bee keeping has become ever more important to help restore the bee population. Monitoring bee activity ensures that the correct actions are taken to sustain healthy bee colonies (Greenpeace, 2014). Monitoring manually is the traditional method how it is time consuming and can interfere with bee activity causing disturbances and damages (BeeTime, 2018). Bee activity can be measured by external parameters such as temperature, humidity, rainfall and hive weight (Melixa, 2018). An example of why monitoring is necessary can be seen during high number of flights during sunny days but a decrease in hive weight, which would indicate that foraging has not been effective (Melixa, 2018). Modern technology has allowed for data from weight, temperature and humidity sensors to be compiled in the cloud database where it can be available anywhere allowing for improved management and decision making (Bayer, 2018).

Literature Review:

Gil-Lebrero et al created a honey bee colony remote monitoring system called WBee which is low cast, scalable, and deployable. It is important to obtain information on the environmental conditions that impact beehives but this is difficult to do when manual monitoring can be intrusive (Gil-Lebrero et al, 2017). A wireless system such as WBee does not disrupt the bees' working conditions therefore yielding reliable data (Gil-Lebrero et al, 2017). WBee can monitor multiple spots of a hive instead of just one with real time data collection that is accessible on the cloud (refer to Figure 12). WSN (wireless networks) allows for minimal invasion, small size nodes and sensors, deployment in remote areas and real time monitoring with low energy consumption (Gil-Lebrero et al, 2017). The WSN system is a three level system: wireless nodes, local data server and a cloud data server (Gil-Lebrero et al, 2017). The humidity and temperature sensors used for this system are three SHT15 sensors by Sensirion for their low power consumption, reliability and stability (Gil-Lebrero et al, 2017). It has a -/+2% error for humidity and a -/+3 degree Celsius error for temperature

(Gil-Lebrero et al, 2017). WBee was reliable, accurate without compromising the beehive conditions and bee behavior (Gil-Lebrero et al, 2017). This is relevant for studying living infrastructure because sites such as green roofs and urban farms are prime locations for beekeeping, by working to restore vegetation and habitats for bee populations these monitoring systems can keep track of success or lack thereof. Since the components of the WBee system are commercially available, it becomes more feasible to recreate as needed locally. Much of the literature on bee monitoring is similar to this article but are limited in either the number of spots or the types of parameters being monitored. This paper covers and compares their system with other bee monitoring systems to show the low power consumption.

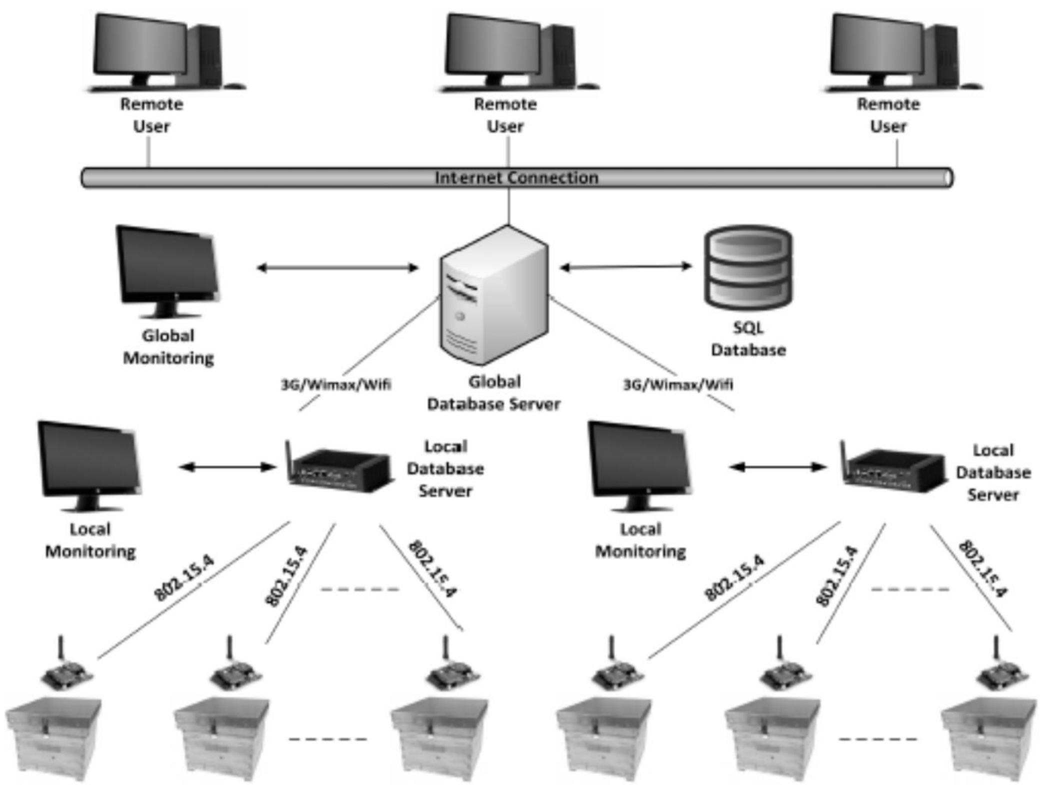


Figure 12: WBee system architecture (Gil-Lebrero et al, 2017)

5.2 Detection of birds/rodents (motion sensors)

The impacts of industrialization and urbanization can be extended beyond bees to birds, squirrels, chipmunks and other rodents that rely on local flora for sustenance. Wildlife in the city is subject to local species extinction as biodiversity is threatened by urbanization. Living infrastructure can help restore some of what was lost by using constructed wetlands, parks, green roofs, bioswales and urban farms as an opportunity to replant trees and vegetation, creating food sources and habitats. It is difficult to measure how effectively living green infrastructure can provide for birds and rodents which is why a monitoring system that detects animals on and around living infrastructure can offer insight into this matter. The most feasible way to go about this is through motion detection using motion sensors. This avoids the use of cameras which is often considered an invasive way to monitor as these would be placed around a city. Motion sensors detect motion with little to no indication on the subject other than size. Most motion sensors are used for meant for indoor home alarm systems where a sensor will send a signal to an automated alarm but the basic components can be manipulated to be used elsewhere. Types of motion sensors include: passive infrared, ultrasonic, microwave and tomography (ElProCus, 2016). Passive infrared (PIR) sensors have a pyroelectric film that responds to infrared radiation emitted by warm blooded animals and tend to be on the cheaper side (ElProCus, 2016). Ultrasonic sensors generate sound wave pulses and react to the reflection of these waves off a moving object however some animals may pick up on these waves which can disturb monitoring their natural behavior (ElProCus, 2016). Microwave sensors use microwave pulses to calculate the reflection off objects, moving or otherwise; they are also sensitive and therefore consumed a lot of power (ElProCus, 2016). Tomographic sensors emit radio waves that, if disturbed, are picked up by the sensor. However they are expensive and are mostly employed for commercial level security purposes (ElProCus, 2016).

Literature Review:

Guo et al states that monitoring animal behavior in response to environmental changes is crucial to the understanding of animal ecology and using an IoT sensor network to accomplish this can provide accurate, real time and comprehensive data for wildlife conservation. Current monitoring systems using radiowaves to record data can give out within 1-3 years with little opportunity for data access and recovery after the fact (Guo et al, 2015). Additionally, monitoring without human contact is necessary and can be done with infrared cameras (Guo et al, 2015). Radiofrequency identification (RFID) can also be used to track and mark animals through wireless communication technology but using RFID can be time consuming and labor intensive as it requires direct monitoring by a person (Guo et al, 2015). To address these monitoring concerns, magnetic induction wireless positioning with automatic sensor array equipment has been a desirable alternative (Guo et al, 2015). This article mainly considers reviews how IoT can be used to monitor animal ecology but does not provide real life examples of how it can be done (Guo et al, 2015). Advantages of using IoT for monitoring animals includes: acquiring continuous data, remote monitoring without human disturbance and monitoring without being on location (Guo et al, 2015). Some recommendations made by the article in the case that IoT is to be used for animal monitoring are: sensor type should be chosen carefully depending on the animal being studied, careful considerations should be made for energy output, data storage and battery model to ensure long term use and a plan should be in place for data transfer and storage as large amount of data will be acquired (Guo et al, 2015). It is difficult to create a replicable monitoring system if different sensors are ideal for different animals but this article also reinforces the importance of understanding how animals are affected by their surroundings, in the case of living infrastructure and the potential to benefit local fauna it would be worthwhile to develop an IoT monitoring system to track animal traffic and behavior on and around living infrastructure. Little research currently exists on the impact of living infrastructure on animals beyond stating that it can provide habitats but to what extent is living infrastructure benefitting animals is still questionable and should be researched further.

Chapter 4: Discussion

1. Sensors and IoT

Common themes throughout the literature discussed in this paper include the following.

- the need for low cost and low power consumption sensors;
- ability of a monitoring system to store large amounts of data that can be accessed;
- the scalability and replicability of a monitoring system;
- importance of real time data collection

All four factors are important to having a system that can be adopted into mainstream practice. The literature focused on very specific uses of sensors and it is evident that most monitoring systems discussed are intended for a single general purpose (i.e. agriculture, stormwater data, ecology). Even when two articles look at the same parameters, the intention behind the study may vary therefore so do the types of sensors that are used. Unless the same parameters need to be studied in the specific configuration mentioned in the articles, adjustments would need to be made for a monitoring system to suit a similar yet different study. For instance, monitoring the effectiveness of living infrastructure in an urbanized city could very well use many of the sensors included in the Array of Things node. However not all the parameters accounted for in "Array of Things" are relevant to monitoring living infrastructure, such as sound intensity. In this case the basic idea of the node can be used as a starting point, but the sensors used can be swapped for one that is more relevant to living infrastructure.

It is not enough that a sensor is designed for a certain parameter, choosing the ideal sensor has many considerations including cost, calibration, accuracy, power consumption, battery life, working conditions and materials. Depending on the use of the sensor as well as the make and model, differences in these features can influence measurements. Appendix A is a compiled list of commercially available sensors that can potentially be used for monitoring living infrastructure; most are manufactured by independent companies that specialize in sensors. The data sheet covers sensors for water, atmospheric, soil, solar and ecology based parameters with details on the manufacturer, model, accuracy, output signal (or power consumption) and protocol (or communication). Although some sensors available online have thorough descriptions available to the public, others do not. This is important because the sensors that are well established tend to be more costly at prices up to $200CAD for a single sensor, which is not feasible for creating a monitoring system that requires multiple sensors. As discussed previously, there are sensors that have dual purposes and can account for more than one parameter simultaneously (i.e. temperature and humidity, pH and moisture, COD and BOD). For the purpose of a monitoring system that requires many sensors, this is a very practical and affordable option. However, whether or not accuracy is compromised with such sensors should be taken into consideration.

The other components of IoT that succeed sensors are connectivity (cellular, WiFi, Bluetooth, LPWAN, WSN), data processing and user interface; these components are individually well established given advancements in computers, software and mobile devices (McClelland, n.d.). However there are issues associated with IoT that still need to be addressed (refer to Figure 13). For connectivity, depending on the selected method, there are variations between power consumption, range and bandwidth (McClelland, n.d.). Connectivity is how data from sensors are able to reach user interface technology, if this crucial component does not function properly then a significant disconnect will exist between data collection and data accessibility. Once connectivity is successful and data has reached the cloud, in terms of data collection, the issue arises with processing large amounts data which can be difficult to accomplish when data must be stored, continually processed in real time and be accessible on demand (McClelland, n.d.). Delayed response and measurements in the case of floods and incoming extreme events would not be acceptable so it is important to ensure that an IoT based monitoring system can keep up with real time data processing. The user interface completes an IoT system, allowing the processed data to be available to the user in a format that is easy to understand and use for a given purpose. The user should be able to interact with the data (i.e. make decisions about sensors based on the data received) and since this is the last step of an IoT system, there are minimal issues associated with it.

Figure 13: Technological challenges of IoT (Banafa, 2017)

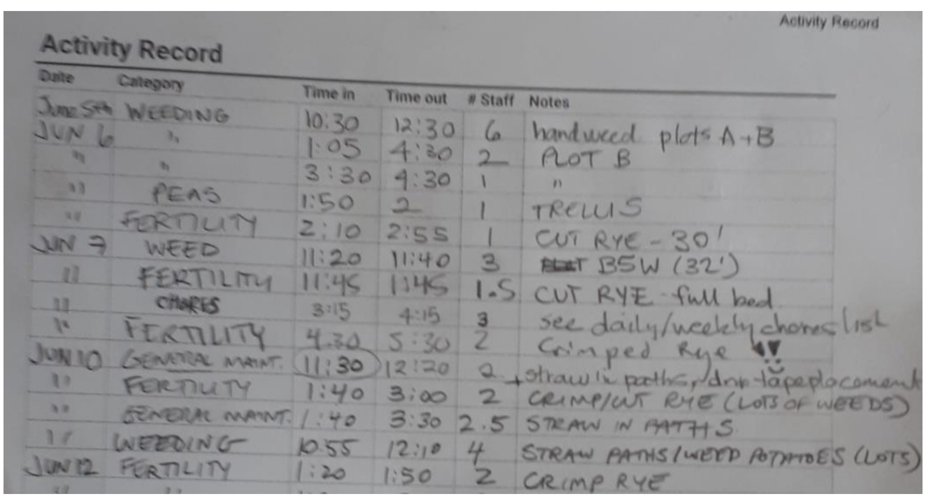
IoT systems are not free of external challenges, there are concerns for security, privacy and cloud attacks. The concept of collected data and information being available in the cloud makes it vulnerable to hacking and cyber theft (Albert, 2018). With the appropriate skills, it can be possible to steal and claim data without consequences. IoT devices are subject to exploitation, with advancements in technology comes stronger malware and ransomware which renders any collected or stored data useless if it is inaccessible (Albert, 2018). It is possible to render sensors/devices useless if they are controlled by user interface actions, for these reasons the use of cameras should be limited or avoided (Albert, 2018). Array of Things properly addresses the issue of cybersecurity when using IoT by disposing of camera based data however it may be possible to intercept this process, further enforcing the need for proper privacy regulatory structure. Although companies agree that an IoT "security code of practice" should be implemented to protect data, it is not something that currently exists (Albert, 2018). However as the use of IoT monitoring systems becomes common practice, laws and regulations will have to be incorporated to ensure a safe and reliable system.

2. Living infrastructure and urban agriculture

The most promising type of living infrastructure is an urban farm, particularly urban rooftop farms (refer to Figure 14). Not only are they capable of delivering the benefits of traditional green infrastructure but can also be used to grow crops to sustain local populations. Rooftop gardens and/or farms can capture rainwater minimizing the impact on roads and absorb carbon emitted by traffic and surrounding infrastructure (Kumar et al, 2019). Additionally, a rooftop garden/farm can reduce energy consumption of a building needed for heating and cooling as it provides insulation by decreasing transport heat (Kumar et al, 2019) However, there are concerns about whether or not the urban environment is suitable for agriculture due to the soil and water contamination caused by adjacent land use (Hallett et al, 2016). Additionally, soil, water and air pollution has negative implications for crops, worker safety and consumer safety (Hallett et al, 2016). Sources of contamination in an urban environment are primarily from vehicular exhaust, stormwater runoff and improperly treated wastewater which can contaminate urban farms with lead, solvents and solvents (Hallett et al, 2016). As mentioned previously, a benefit of living infrastructure is the ability to be sustained by using reclaimed or recycled water to irrigate vegetation and crops however this water may be contaminated, making its use questionable for urban farms. Contaminated water can impact soil quality and result in nutrient loading of stormwater runoff (Hallett et al, 2016). For this reason, it is important to be able to monitor the different factors that can affect the quality of urban farm crop production. With a monitoring system which contains sensors for water quality and soil quality, urban farm staff can make decisions based on what is in the best interest of the crops. If, in the future, IoT irrigation systems using reclaimed water are common practice, a monitoring system can notify staff if the quality is up to standards.

Figure 14: Ryerson University Urban Rooftop (Ryerson, n.d.)

There is also potential to monitor activities of staff by automating some manual tasks through activity monitoring and tracking tool usage and farm tending activities. For example, staff and volunteers at the Ryerson Urban Farm manually keep track of the type of activity that is conducted and at what time and date (refer to Figure 15). By allocating certain tools (or a combination of tools) to certain tasks, with tools that have sensors that can document use, time and date using IoT then the tracking process can be made digital where staff can easily refer to past activities.



Activity Record

Activity Record

Date	Category	Time in	Time out	# Staff	Notes
June 5th	WEEDING	10:30	12:30	6	handweed plots A+B
JUN 6	"	1:05	4:30	2	PLOT B
"	"	3:30	4:30	1	"
"	PEAS	1:50	2	1	TRELLIS
"	FERTILITY	2:10	2:55	1	CUT RYE - 30'
JUN 7	WEED	11:20	11:40	3	BSW (32')
"	FERTILITY	11:45	1:45	1.5	CUT RYE - full bed
"	CHORES	3:15	4:15	3	see daily/weekly chores list
"	FERTILITY	4:30	5:30	2	Crimped Rye
JUN 10	GENERAL MAINT.	11:30	12:20	2	straw in paths, drip tape placement
"	FERTILITY	1:40	3:00	2	CRIMP/CUT RYE (LOTS OF WEEDS)
"	GENERAL MAINT.	1:40	3:30	2.5	STRAW IN PATHS
"	WEEDING	10:55	12:10	4	STRAW PATHS/WEED POTATOES (LOTS)
JUN 12	FERTILITY	1:20	1:50	2	CRIMP RYE

Figure 15: Activity record of Ryerson Urban Farm Staff

However according to an article that looked at the opportunities for interactive systems to support urban food production, using information and communication technology for such purposes was not popular amongst urban farm staff (Odom, 2010). Workers were heavily resistant to technological augmentation, such as sensing technology, for their agricultural practices because it would interfere with direct interaction with the urban farm (Odom, 2010). Additionally, such technology was speculated to be too heavily relied on and would take away from the instructional interactions of senior community members with new members; overall the benefits of the use of new technology to augment agricultural practice appeared to be questionable to staff members (Odom, 2010). However, there may be a shift in perspective as younger generations, who are heavily reliant on and well versed with mobile devices and technology, begin to look after urban farms. While some tasks may be automated, the goal is not to replace the community aspect of urban farms but to enhance its efficiency.

Figure 16: Staff and volunteers working on the Ryerson Urban Rooftop Farm (Greenroofs, 2015)

Chapter 5: Conclusion

The purpose of this paper was to review the literature available on how sensors and IoT can be used to monitor environmental factors that are relevant to living infrastructure. Case studies were discussed to demonstrate what is currently being done around the world in terms of monitoring the environment using smart technology, followed by the types of sensors that can potentially be used to monitor living infrastructure. The categories of sensors mentioned were water, air, soil, solar and ecology based sensors which were accompanied by brief descriptions of the types of sensors available for measuring each a given parameter. The literature that was covered offered several ways to recreate and build a customizable monitoring system that uses low cost and minimal power consuming sensors combined with data processing software that can withstand large amounts of incoming data. For the purpose of monitoring living infrastructure, the lessons learned from these articles as well as taking the recommendations into consideration should allow researchers and institutions create a monitoring system with nodes for each category of sensors (i.e. a node for soil with sensors that would cover soil temperature, humidity and pH all in one) which can be connected to either the same data processing software or different data processing software, in the case that data from multiple nodes overwhelms the software. Once all the data is processed it can be compiled into a single user interface that includes data from the five categories of sensors mentioned previously, accessible at one place. This will allow industry professionals to have access to the various parameters that are relevant to monitoring living infrastructure. For example, civil engineers who are concerned with stormwater data will also have access to soil data and will have the opportunity to draw conclusions by comparing how the data changes for one set of data is influenced by another set of data.

Establishing such a system is important because of what living infrastructure can mean for an urban development. Urbanization will continue and so will the associated negative effects of stormwater management challenges, urban heat island effect and microclimate change. Living infrastructure has many potential benefits but it is necessary to monitor how efficient they are and what are the best management and planning practices to optimize their function. Once the performance of a type of living infrastructure is quantified and understood by professionals from various backgrounds, experts can come together to make the best possible decisions to ensure that the living infrastructure projects are utilized in a way that maximizes its use while keeping costs low. By creating living infrastructure that is efficient and performs as needed, cities will be one step closer to achieving a circular economy. Living infrastructure is designed to reduce and reuse waste, water and materials. Living infrastructure shows promise and potential for addressing various problems, creating a proper monitoring system will help this field move forward.

Appendix A: List of Potential Sensors to Monitor Efficiency of Living Infrastructure

Measure	Parameter	Manufacturer	Model	Accuracy	Output Signal	Protocol	Availability
Water Quality	Water Conductivity/Salinity /Resistivity	GF Signet	GF Signet 2819-2823 Conductivity/Resistivity Electrodes	±2% of reading	4-20 mA	n/a	https://www.instrumart.com/products/20763/gf-signet-2819-2823-conductivityresistivity-electrodes#!description
	Water pH	Sensorex	S272 pH Sensor with Digital Communication	n/a	4-20 mA	n/a	https://sensorex.com/product/improved-s272cd-online-process-ph-sensor/
	Water Turbidity	OBS	OBS-3+ Turbidity Sensor	±2% & ±4% of reading for mud and sand	0-5V for -5 output option and 4-20mA for -20 output option	n/a	https://www.campbellsci.com/obs-3plus
	Nutrient (covers BOD, COD, TSS, pH as well)	Libelium	Smart Water sensor board v3 Waspmote v15	multiple sensors, varies (2-5%)	3.3V-5V, ranges from 160uA to 3.5mA	n/a	http://www.libelium.com/smart-water-sensors-to-monitor-water-quality-in-rivers-lakes-and-the-sea/
	BOD	VELP Scientifica	BOD EVO Sensor	n/a	115 V or 230 V / 50-60 Hz	n/a	https://www.velp.com/en/products/lines/2/family/31/bod_analysis/22/bod_evo_sensor_bod_analysis
	COD (covers BOD, TSS as well)	YSI	701/705 IQ SensorNet CarboVis	±3%	n/a (8W power consumption)	n/a	https://www.ysi.com/carbovis
	TSS (turbidity as well)	ABB	Aztec ATS430	turbidity: ±2 %, for TSS depends on sample	n/a	n/a	https://new.abb.com/products/measurement-products/analytical/continuous-water-analysis/turbidity-measurement/aztec-ats430-turbidity-and-total-suspended-solids-sensor
Water Level	Water level	Nile	WaterLOG Nile Series (502/504/517)	±2 mm (0.08 in) over range of 1.06 to 20 m (3.5 to 66 ft)	13.5 mA	SDI-12, RS-232	https://www.ysi.com/Nile
	Pressure level sensor	Solinst	Solinst Levelogger Edge Model 3001	±0.05%	n/a	Optical Infrared Interface. Conversion to RS-232, USB, SDI-12. Serial at 19,200 bps, 38,400 bps with USB	https://www.rshydro.co.uk/groundwater-monitoring-sampling-equipment/water-level-monitoring/water-level-data-loggers/levelogger-edge-data-loggers/solinst-levelogger-edge/
	Ultrasonic level sensor	Gems Sensors & Controls	UCL-510 Ultrasonic Continuous Level Sensor	n/a	4-20mA	n/a	https://www.gemssensors.com/home/level/continuous-transmitters/ultrasonic/ucl-510
Water Flow	water flow sensor	SeeedStudio	G1&2" Water Flow Sensor YF-21	n/a	15mA	n/a	https://www.seeedstudio.com/G1-2-Water-Flow-Sensor-p-635.html
	flowmeter	n/a	DN20 G3/4 Copper Water Flow Sensor Pulse Output 1.75Mpa 2~45L/min Flowmeter SEN-HZ43WB	±10%	15mA	n/a	https://www.banggood.com/DN20-G34-Copper-Water-Flow-Sensor-Pulse-Output-1_75Mpa-245Lmin-Flowmeter-p-1266296.html?rmmds=buy&cur_warehouse=CN

	water flow meter	Hadronix	1/4 Quick-Connect Food-Grade Water Flow Meter Hall Sensor HDRX-YF-S402B	n/a	n/a	n/a	https://www.amazon.com/Hadronix-Quick-Connect-Food-Grade-Water-HDRX-YF-S402B/dp/B07JWD4C46?_encoding=UTF8&psc=1
Air Quality	noise level and air quality (CO, NO, NO2, SO2)	Libelium	Waspnote Plug & Sense	±0.1-1 ppm	n/a	RS-485	http://www.libelium.com/libelium-releases-new-iot-smart-cities-platform-enhancing-accuracy-in-noise-level-and-air-quality-pollution-sensors/
	particulate matter (PM), nitrogen dioxide (NO_2) and ozone (O_3)	Aeroqual	AQS 1 Urban Air Quality Monitor	particulate matter: <±(5 µg/m3 + 15% of reading OR <±(2 µg/m3 + 5% of reading	4 x 4-20mA	n/a	https://www.aeroqual.com/product/aqs-urban-air-quality-monitor
	NO, NO2, NOx, O3, CO, SO2, H2S, PM1, PM2.5, PM10, relative humidity, pod temperature, atmospheric pressure and noise	AQMesh	AQMesh Gas algorithm v5.0, PM algorithm V3.0 (and V3.0h)	±2-5	n/a	n/a	https://www.aqmesh.com/product/
Differential Pressure	differential pressure transmitter	prosense	DPTA Series Differential Air Pressure Transmitters	±1%	4-20mA	n/a	https://www.automationdirect.com/adc/overview/catalog/process_control_-a-_measurement/pressure_sensors/differential_pressure_transmitters
	air velocity and differential pressure	Omni Instruments	Multi-Point Air Velocity Probes & PA267 Differential Pressure Sensor	±1%	4-20mA	n/a	https://www.omniinstruments.co.uk/pressure-sensors/low-range-differential-air-pressure-sensors/multi-point-air-velocity-probes-pa267-differential-pressure-sensor.html
	amplified pressure sensor	NCD	AMS 5812 Amplified pressure sensor with analog and digital output	±0.5-1.5%	5mA (current consumption)	standard I2C communication protocol	https://store.ncd.io/product/iot-long-range-wireless-pressure-sensor-bidirectional-differential/
Relative Humidity	humidity sensor	Phase IV	Humidity Sensor, High Accuracy External Sensor, Compact – Wireless Sensor Network (WSN)	±1.8%	n/a	n/a	https://www.phaseivengr.com/product/humidity-sensor-high-accuracy-compact-wireless-sensor-network-wsn/
	temperature humidity sensor	NCD	IoT Long Range Wireless Temperature Humidity Sensor	±1.7%	n/a (battery, 2 AA)	n/a	https://store.ncd.io/product/industrial-long-range-wireless-temperature-humidity-sensor/
	wireless humidity sensor	webility	wireless humidity sensor	±3%	n/a (battery, 2 AA)	n/a	https://webility.ca/iot/product/humidity/7-wireless-humidity-sensor
	wireless temperature sensor	webility	wireless temperature sensor	±1%	n/a (battery, 2 AA)	n/a	https://webility.ca/iot/product/temperature/1-wireless-temperature-sensor

Air Temperature	wireless temperature sensor	Phase IV	Wireless Temperature Sensor, Industrial, One K-Type Thermocouple, -300F to 3000F, Large Battery, Flange Mount – Leap Sensors	±0.15%	n/a (3.6V battery)	Standard and established 6LoPan and Thread	https://www.phaseivengr.com/product/wireless-temperature-sensor-industrial-two-k-type-thermocouple-300f-to-3000f-large-battery-leap-sensors/
	temperature sensor	Efento	LTE-M and NB-IoT Temperature sensor with external probe	±0.5°C	n/a (battery 2 x 3.6 V, AA)	Communication: Bluetooth Low Energy (BLE)	https://getefento.com/product/lte-m-and-nb-iot-temperature-sensor-with-external-probe/
Soil Temperature	soil temperature	Hukseflux Thermal Sensors	ST01 soil temperature sensor	±0.25°C	n/a (cable required)	n/a	https://www.hukseflux.com/products/heat-flux-sensors/soil-temperature-sensors/st01-soil-temperature-sensor
	soil temperature	Vegetronix	Soil Temperature Sensor Probe THERM200	±0.5%	3V (power consumption, <3mA)	n/a	https://www.vegetronix.com/Products/THERM200/
	soil temperature	RKA	Rk520-02 Iot Network Combined Soil Temperature Humidity Ec Sensor for Agriculture	±0.3%	0-2V	RS485	https://www.made-in-china.com/showroom/rika2016/product-detailMsamnWdzXBkL/China-Rk520-02-Iot-Network-Combined-Soil-Temperature-Humidity-Ec-Sensor-for-Agriculture.html
Soil Acidity	pH sensor	Hanna Instruments	HALO® Wireless Soil pH Meter - HI12922	±0.005 pH	n/a (battery: CR2032 3V lithium ion)	n/a (Bluetooth Smart (Bluetooth 4.0), 10 m (33') range)	https://hannainst.com.au/halo-ph-electrode-for-direct-soil-measurement-hi12922.html
	pH measurement	National Instruments	Sensorex S8000 pH Electrode with NI Wireless Sensor Networks (WSN)	n/a	4-20mA	n/a	http://www.ni.com/product-documentation/9955/en/
	pH sensor	Pasco	Wireless pH Sensor - PS-3204	+/- 0.1 pH (when calibrated) +/- 0.5 pH (without calibration)	n/a (battery, coin cell)	n/a (Bluetooth® Smart (Bluetooth 4.0))	https://www.pasco.com/prodCatalog/PS/PS-3204_wireless-ph-sensor/index.cfm
Soil Moisture	water-presence/soil moisture/water level sensor	Wireless Sensor Tags	Wireless Water/Moisture Sensor Version 2.0	n/a	n/a	n/a	https://store.wirelesstag.net/products/wireless-water-moisture-sensor-2-0
	soil moisture	Spio	Wireless Soil Moisture Sensor SP-110	n/a	n/a	n/a (Cellular - 3G/4G)	https://spiio.com/soil-moisture-sensor/
	soil moisture	Spruce	Gen3 Spruce Soil Moisture Sensor	n/a	n/a (battery - CR123)	n/a (Wireless 802.15.4 2.4ghz)	https://spruceirrigation.com/order/
Solar Radiation	uv and solar radiation	Davis Instruments	Wireless Vantage Pro2™ Plus including UV & Solar Radiation Sensors	±5%	8mW	n/a	https://www.davisinstruments.com/product/wireless-vantage-pro2-plus-including-uv-solar-radiation-sensors/
	pile pyranometer sun	Barani Design	MeteoSolar SR05	< ±1.8 %	power consumption: 800µA at 1Hz output	rS-485 with Modbus rTU & ASCI	https://www.baranidesign.com/meteosolar-sr05
	solar radiation	Smarty Planet	SPR200-04 solar radiation sensor	<±3%	4-20mA	RS485	https://www.smartyplanet.com/en/products-smartyplanet/sensor-de-radiacion-solar/

Photosynthetic flux density	Photosynthetically Active Radiation	Li Cor	LI-190R Quantum Sensor	± 5%	n/a	n/a	https://www.licor.com/env/products/light/quantum.html
	photosynthetically active radiation	Apogee Instruments	full-spectrum 500 series quantum sensor	± 5 nm	n/a	n/a	https://www.apogeeinstruments.com/quantum/
	quantum light	Solar Light	Analog Quantum Light (PAR) Sensor PMA1132-S-420-2400	±5%	4-20mA	n/a	https://solarlight.com/product/par-quantum-light-sensor-pma-1132/
Bee Keeping	beehive condition	ApisProtect	ApisProtect	n/a	n/a	n/a	https://www.apisprotect.com/technology
	Detect swarming, missing queen, healthy, sick, or collapsed hives in real-time. Monitor temperature, humidity, barometric pressure, and local weather conditions.	OS Bee Hives	BuzzBox	n/a	n/a (lithium ion battery)	n/a	https://docs.osbeehives.com/
	in-hive temperature and humidity and records the buzzing frequencies of the bees	Bee Smart Technologies	Beebot	n/a	n/a (recharging battery)	n/a	https://pollenity.com/product/beebot/
Detection of birds/rodents	motion sensor	NetOP Technology	NETOP Motion sensor	n/a	n/a (AA Battery 3.6 V Li-SOCl2-Saft LS 14500)	Internet Protocol Feature: Support IPv4/TCP/UDP, Full duplex communication	https://www.iot-shops.com/product/motion-sensors-nb/

References:

ACTGovernment. (2018). *Canberra's Living Infrastructure - Information Paper*. (February). Retrieved from www.environment.act.gov.au

Albert, C. (2018, June 11). Problems With the Internet of Things You Need to Know! - DZone IoT. Retrieved from https://dzone.com/articles/problems-with-internet-of-things-you-need-to-know

Alliance for the Bay. Reduce Your Stormwater. Retrieved from http://www.stormwater.allianceforthebay.org/glossary-of-terms/nutrients

Ametherm. (2019, June 21). 4 Most Common Types of Temperature Sensor. Retrieved from https://www.ametherm.com/blog/thermistors/temperature-sensor-types

AoT. (2019). Array of Things. Retrieved from https://arrayofthings.github.io/index.html

Banafa, A. (2017, March 14). Three Major Challenges Facing IoT. Retrieved from https://iot.ieee.org/newsletter/march-2017/three-major-challenges-facing-iot.html

Bayer. (2018). Using Sensor Technologies to Inspect Hives: Bee Health. Retrieved from https://beehealth.bayer.us/what-is-bayer-doing/bayer-research/using-sensor-technologies-to-inspect-hives

BeeTime. (2018, December 19). Bee Hive Smart Sensor Technology for Optimal Development of the Bees. Retrieved from https://beetime.eu/bee-hive-smart-sensor-technology-for-optimal-developmentt-of-the-bees/

Campbell-Dollaghan, K. (2019, June 30). You've heard of the circular economy. Now meet the circular city. Retrieved from https://www.fastcompany.com/90368933/how-circular-cities-could-make-life-healthier-safer-and-less-expensive-for-all-of-us

City of Vancouver. Soil Temperature, Moisture and pH. Retrieved from https://www.cityofvancouver.us/sites/default/files/fileattachments/public_works/page/18517/soil_temperature_moisture_and_ph.pdf

Crncevic, T., Tubic, L., & Bakic, O. (2018). Green infrastructure planning for climate smart and "green" cities. *Spatium*, *434*(38), 35–41. https://doi.org/10.2298/spat1738035c

Don Johns. (2016, September 23). 5 Types of Flow Meters. Retrieved from http://www.donjohns.com/blog/5-types-of-flow-meters/

Ecology Center. (2016, March 1). 10 Ways Urban Farms Benefit The Community. Retrieved from https://www.theecologycenter.org/10-ways-urban-farms-benefit-the-community/

ElectronicsFU. (2018, December 14). Humidity Sensor: Basics, Usage, Parameters and Applications. Retrieved from https://electronicsforu.com/resources/electronics-components/humidity-sensor-basic-usage-parameter

ElProCus. (2016, September 27). Different Types of Motion Sensors And How They Work. Retrieved from https://www.elprocus.com/working-of-different-types-of-motion-sensors/

ElProCus. (2018, September 12). Passive Infrared Sensor (PIR) working with Applications. Retrieved from https://www.elprocus.com/passive-infrared-pir-sensor-with-applications/

EPA. (2018, December 5). Benefits of Green Infrastructure. Retrieved from https://www.epa.gov/green-infrastructure/benefits-green-infrastructure

Fluence. (2019). Horticulture lighting metrics PPFD, PPF, PAR. Retrieved from https://fluence.science/science/par-ppf-ppfd-dl

Gaffin, S., Khanbilvardi, R., & Rosenzweig, C. (2009). Development of a Green Roof Environmental Monitoring and Meteorological Network in New York City. *Sensors*, *9*(4), 2647–2660. https://doi.org/10.3390/s90402647

Garg, A., Munoth, P., & Goyal, R. (2016). APPLICATION OF SOIL MOISTURE SENSORS IN AGRICULTURE: A REVIEW Calibration of VH400 Soil Moisture Sensors View project APPLICATION OF SOIL MOISTURE SENSORS IN AGRICULTURE: A REVIEW. *Water Resources and Coastal Engineering*, (December), 1662–1672. Retrieved from https://www.researchgate.net/publication/311607215

Gil-Lebrero, S., Quiles-Latorre, F. J., Ortiz-López, M., Sánchez-Ruiz, V., Gámiz-López, V., & Luna-Rodríguez, J. J. (2017). Honey bee colonies remote monitoring system. *Sensors (Switzerland)*, *17*(1). https://doi.org/10.3390/s17010055

Greenpeace. (2014). Causes. Retrieved from http://sos-bees.org/causes/

Greenroofs Projects. (2015). Ryerson Urban Farm (formerly Rye's Homegrown). Retrieved from https://www.greenroofs.com/projects/ryerson-urban-farm-formerly-ryes-homegrown/

Guo, S., Qiang, M., Luan, X., Xu, P., He, G., Yin, X., … Li, B. (2015). The application of the Internet of Things to animal ecology. *Integrative Zoology*, *10*(6), 572–578. https://doi.org/10.1111/1749-4877.12162

Hallett, S., Hoagland, L., & Toner, E. (2016). Urban agriculture: Environmental, economic, and social perspectives. In *Horticultural Reviews* (Vol. 44). https://doi.org/10.1002/9781119281269.ch2

Heath, D. (2018, November 8). 7 Best Soil pH Tester Reviews: Grow Strong and Healthy Plants in Perfect Soil Conditions. Retrieved from https://morningchores.com/best-soil-ph-tester/

HBM. (2018, December 7). What is a Pressure Sensor? Retrieved from https://www.hbm.com/en/7646/what-is-a-pressure-sensor/

Hidalgo, F. G., Martinez, R. F., & Vidal, E. F. (2013). Design of a Low-Cost Sensor for Solar Irradiance. *Oceanoptics.Com*, 1–8.

Hinckley, A. (2017, June 14). Pyranometers: What You Need to Know. Retrieved from https://www.campbellsci.com/blog/pyranometers-need-to-know

How to Electronics. (2018, June 5). Retrieved from https://www.youtube.com/watch?v=y841yf-WjqE

IOT. IOT. Retrieved from https://iotintl.com/iot/

Jayaraman, P. P., Yavari, A., Georgakopoulos, D., Morshed, A., & Zaslavsky, A. (2016). Internet of things platform for smart farming: Experiences and lessons learnt. *Sensors (Switzerland)*, *16*(11), 1–17. https://doi.org/10.3390/s16111884

Kaa Platform. What is the Internet of Things Platform - All About IoT Technology and Applications. Retrieved from https://www.kaaproject.org/what-is-iot-platform

Karray, F., Triki, M., Jmal, M. W., Abid, M., & Obeid, A. M. (2018). WiRoTip: An IoT-based wireless sensor network forwater pipeline monitoring. *International Journal of Electrical and Computer Engineering*, *8*(5), 3250–3258. https://doi.org/10.11591/ijece.v8i5.pp3250-3258

Kamienski, C., Soininen, J. P., Taumberger, M., Dantas, R., Toscano, A., Cinotti, T. S., … Neto, A. T. (2019). Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors (Switzerland)*, *19*(2). https://doi.org/10.3390/s19020276

Kumar Jha, M., Kumari Sah, R., Rashmitha, M. S., Sinha, R., Sujatha, B., & Suma, K. V. (2018). Smart Water Monitoring System for Real-Time Water Quality and Usage Monitoring. *Proceedings of the International Conference on Inventive Research in Computing Applications, ICIRCA 2018*, (Icirca), 617–621. https://doi.org/10.1109/ICIRCA.2018.8597179

Kumar, J.R., Natasha, B., Suraj, K., Kumar, S.A., & Manahar, K. (2019). *Malaysian Journal of Sustainable Agriculture (MJSA) ROOFTOP FARMING : AN ALTERNATIVE TO CONVENTIONAL FARMING FOR*. *3*(3), 12–16.

Li, J. (2017). *CV8202: Surface Water Pollution,* week 1, lecture 1 notes [Pdf document]. Retrieved from RAMSS

Liu, J. (2016). Design and implementation of an intelligent environmental-control system: Perception, network, and application with fused data collected from multiple sensors in a greenhouse at Jiangsu, China. *International Journal of Distributed Sensor Networks*, *12*(7). https://doi.org/10.1177/155014775056460

Malche, T. & Maheshwary, P. (2017). *Proceedings of International Conference on Communication and Networks*. *508*(February 2019). https://doi.org/10.1007/978-981-10-2750-5

Machine Design. (2013, March 31). Flow Sensors. Retrieved from https://www.machinedesign.com/basics-design/flow-sensors

McClelland, C. (n.d.). IoT Explained - How Does an IoT System Actually Work? Retrieved from https://www.leverege.com/blogpost/iot-explained-how-does-an-iot-system-actually-work

Melixa. Melixa System. Retrieved from http://melixa.eu/en/products/melixa-system/
Melixa. (2018). Why monitoring the bees is important. Retrieved from http://melixa.eu/en/monitoring-the-bees/

Minnesota Pollution Control Agency. (2018, November 15). Total Suspended Solids (TSS) in stormwater. Retrieved from https://stormwater.pca.state.mn.us/index.php/Total_Suspended_Solids_(TSS)_in_stormwater

Moreno, C., Aquino, R., Ibarreche, J., Pérez, I., Castellanos, E., Álvarez, E., … Clark, B. (2019). Rivercore: IoT device for river water level monitoring over cellular communications. *Sensors (Switzerland)*, *19*(1). https://doi.org/10.3390/s19010127

Mullapudi, A., Bartos, M., Wong, B., & Kerkez, B. (2018). Shaping streamflow using a real-time stormwater control network. *Sensors (Switzerland)*, *18*(7), 1–11. https://doi.org/10.3390/s18072259

Na, A., Isaac, W., Varshney, S., & Khan, E. (2017). An IoT based system for remote monitoring of soil characteristics. *2016 International Conference on Information Technology, InCITe 2016 - The Next Generation IT Summit on the Theme - Internet of Things: Connect Your Worlds*, (October), 316–320. https://doi.org/10.1109/INCITE.2016.7857638

National Instruments. (2019, March 14). Overview of Temperature Sensors. Retrieved from https://www.ni.com/en-ca/innovations/white-papers/06/overview-of-temperature-sensors.html

Odom, W. (2010). "Mate, we don't need a chip to tell us the soil's dry": Opportunities for designing interactive systems to support urban food production. *DIS 2010 - Proceedings of the 8th ACM Conference on Designing Interactive Systems*, (July), 232–235. https://doi.org/10.1145/1858171.1858211

Omega Engineering. (2019, May 10). Flow meters. Retrieved from https://www.omega.ca/en/resources/flow-meters#articleBody

Prince, R. (2018, September 5). Soil moisture monitoring: a selection guide. Retrieved from https://www.agric.wa.gov.au/horticulture/soil-moisture-monitoring-selection-guide

Rai, A. C., & Kumar, P. (2017). Summary of air quality sensors and recommendations for application. *Ref. Ares*, (689954), 65. Retrieved from https://www.iscapeproject.eu/wp-content/uploads/2017/09/iSCAPE_D1.5_Summary-of-air-quality-sensors-and-recommendations-for-application.pdf

Ryerson University. (n.d.). Ryerson Urban Farm. Retrieved from https://www.ryerson.ca/foodsecurity/activities/activity_ryerson_urban_farm/

Sakthipriya, N. (2014). An effective method for crop monitoring using wireless sensor network. *Middle - East Journal of Scientific Research*, *20*(9), 1127–1132. https://doi.org/10.5829/idosi.mejsr.2014.20.09.114152

Soil Quality. Soil Quality Indicators: Measures of Soil Functional State. Retrieved from http://soilquality.org/indicators.html

Soil Science Society of America. Green Roofs. Retrieved from https://www.soils.org/discover-soils/soils-in-the-city/green-roofs

Spandana, K., & R. Seshagiri Rao, V. (2018). Internet of Things (Iot) Based Smart Water Quality Monitoring System. *International Journal of Engineering & Technology*, *7*(3.6), 259. https://doi.org/10.14419/ijet.v7i3.6.14985

SST. (2019, February 19). 7 Main Types of Level Sensing Methods – How do they differ? Retrieved from https://www.sstsensing.com/7-main-types-of-level-sensors/

StellarNet. (2017, November 10). What is Photosynthetic Photon Flux Density? Retrieved from https://www.stellarnet.us/photosynthetic-photon-flux-density/

Stormwater Rx. (2019, July 24). Chemical Oxygen Demand (COD) Stormwater Treatment. Retrieved from https://stormwaterx.com/resources/industrialpollutants/chemical-oxygen-demand-cod/

Sumarudin, A., Ghozali, A. L., Hasyim, A., & Effendi, A. (2016). Implementation monitoring temperature, humidity and mositure soil based on wireless sensor network for e-agriculture technology. *IOP Conference Series: Materials Science and Engineering*, *128*(1). https://doi.org/10.1088/1757-899X/128/1/012044

Swagata. (2016, August 17). Soil Temperature: Importance, Factors and Its Control. Retrieved from http://www.soilmanagementindia.com/soil-temperature/soil-temperature-importance-factors-and-its-control/3512

UGA. (n.d.). Understanding Labratory Wastewater Tests. Retrieved from https://extension.uga.edu/content/extension/publications/detail.html?number=C992

USDA. Natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/co/home/?cid=nrcs144p2_063020

Wang, S., Zhang, Z., Ye, Z., Wang, X., Lin, X., & Chen, S. (2013). Application of Environmental Internet of Things on water quality management of urban scenic river. *International Journal of Sustainable Development and World Ecology*, *20*(3), 216–222. https://doi.org/10.1080/13504509.2013.785040

WD Tools. How does a soil pH meter work? Retrieved from https://www.wonkeedonkeetools.co.uk/soil-ph-meters/how-does-a-soil-ph-meter-work/

Yadav, D. M., & Thomas, B. T. (2018). Design of Photosynthetically Active Radiation Sensor. *Examines in Physical Medicine & Rehabilitation*, *1*(5), 1–7. https://doi.org/10.31031/EPMR.2018.01.000521

Zafar, S., Miraj, G., Baloch, R., … D. M.-, Applied, T. &, & 2018, undefined. (2018). An IoT Based Real-Time Environmental Monitoring System Using Arduino and Cloud Service. *Etasr.Com*, *8*(4), 3238–3242. Retrieved from http://www.etasr.com/index.php/ETASR/article/view/2144