Dredged Material for Green Infrastructure

Final Report

Submitted by
Shruti Bhairappanavar, M.S.
Erin Laffay, MLA
Nina Nina Anani-Manyo
Rui Liu, Ph.D., P.E.
Reid Coffman, Ph.D.

Kent State University
College of Architecture and Environmental Design
132 S. Lincoln St. CAE210
Kent, OH 44236
Telephone: (330) 672-0611 Fax: (330) 672-2916
E-mail: rliu5@kent.edu

Submitted to
Ohio Lake Erie Commission
347 North Dunbridge Road,
Bowling Green, Ohio 43402

December 2018

A part of the report has been peer-reviewed and published:

Bhairappanavar, S., Liu, R., and Coffman, R. (2018). Beneficial Uses of Dredged Material in Green Infrastructure and Living Architecture to Improve Resilience of Lake Erie. *Infrastructure*, 3(4), 42 https://doi.org/10.3390/infrastructures3040042

ACKNOWLEDGEMENTS

The Kent State University would like to acknowledge the financial support provided by the Ohio Lake Erie Commission – Lake Erie Protection Fund. The investigators would also like to thank Sandra Kosek-Sills who coordinated this study. A special thanks goes out to David Emerman, and Kurt Princic from Ohio Environmental Protection Agency, Joe Cappel from Toledo - Lucas County Port Authority, James White from Cleveland- Cuyahoga County Port Authority, and Jason Ziss from Kurtz Brothers, Inc. who advised the research team, helped acquire the dredged material samples from Ports of Toledo and Cleveland, and reviewed the interim and final reports.

Supervised by the Professor Christopher Groening from the Department of Marketing and Entrepreneur at the Kent State University, marketing studies to promote the beneficial use of dredged material in the green infrastructure were completed by 4 groups, a total of 14 senior students majored in Marketing. Their names are listed below:

Matt Bianoco; Megan Henrich; Sydney Shepherd; Kelly Robson; Jessica Nesbitt; Brenna Berry; Lauren Transue; Whitney Foster; Joe Defallo; Brenna Kennelly; Jordan Savren-Streem; Kendra Molyet; Tina Xu; Kelsey Volker

Assisted by the LauchNET directed by Professor Julie Messing, the research team worked with the marketing students to develop business model to promote using the dredged material in green infrastructure construction.

The authors would also like to thank many undergraduate and graduate students from the College of Architecture and Environmental Design at the Kent State University who contributed to this research study.

ABSTRACT

This project focuses on the performance evaluation of using the dredged material in various green infrastructure (GI) applications, sustainability issues, and development of a business model in promoting the use of the product made from the dredged material. The study advanced investigations of the performance of raw dredged material and the LWA made from dredged material as a green roof growth substrate. Potential applications of both materials have been proposed in various types of GI e.g. porous pavement, bioretention swales, bioretention cells or rain gardens, etc. The growth media made from dredged material were successfully developed in the lab, with excellent water retention capabilities to manage the storm water. Native, exotic, and rare plants including Sedum Album, Sedum Kamchaticum, and Solidago Ptarmicoides have been investigated for their potential applications in the newly developed growing media made from the dredged material samples taken from Maumee River (Toledo) and Cyhahoga River (Cleveland). The commercialized Rooflite® sample had the highest average growth. But all three species have comparable performances in the three growth media tested in the field in this study. Business models were discussed to determine market relevance of the technology through partnerships with industry and manufacturing. Green roofing was projected to account for 8% of all roofing installed in 2017, and there is a natural trend towards sustainable architecture overall. Startup Canvas was included in this report to develop a business model and commercialize the product.

Table of Contents

1. INTRODUCTION 8
1.1 Background 8
1.2 Study Objectives 11
1.3 Scope of Study 11
2. Beneficial Uses of Dredged Material in Built Environment 13
2.1 Green Infrastructure and Living Architecture 13
2.2 Quality of Dredged Material and Testing Methods 17
2.3 Suitability of Dredged Material in GI Construction 18
3. Growth Media Developed using Dredged Material and Experimental Design for Vegetation Study 23
3.1 LWA Manufacturing 23
3.1.1 LWA Production 23
3.2 Green Roof Material using Cleveland Samples (Phase I) 24
3.2.1 Plant Growth Media Development (Phase I) 24
3.2.2 Water Retention Capacity, unit weight and Leachate Quality 24
3.2.3 Vegetation Growth and Establishment on the Growth Media Made by Dredge Material 25
3.3 Green Roof Material using 100% Dredged Material (Phase II) 27
3.3.1 Plant Growth Media Development (Phase II) 27
3.3.2 Vegetation Study 28
3.3.3 Harvest 31
3.4 Summary 32
4. Experimental Results and Discussions 33
4.1 Experimental results of Phase I 33
4.1.1 Water Retention Capacity, unit weight and Leachate Quality 33
4.1.2 Vegetation Growth and Establishment on the Growth Media Made by Dredge Material 35
4.1.3 Phase I discussions 36
4.2 Experimental Results of Phase II 37
4.2.1 Growth of Plants 37
4.2.2 Solidago Ptarmicoides Germination Study 40

4.2.3 Biomass 40
4.3 Summary 42
5. Market Research 44
5.1 Findings from Market Research 44
5.2 Business Model Canvas 45
6. Conclusions 47
7. References 49
Appendix A 53

LIST OF FIGURES

Figure 1 Map of Lake Erie: physical features and areas with immediate action required. (Reference: NOAA- National Center for Environmental Information, US Army Corps of Engineers, Environmental Canada) 8
Figure 2 Challenges of Dredged Material Management 10
Figure 3 Beneficial Uses of dredged material 13
Figure 4 Benefits of GI 16
Figure 5 Bioretention system hydraulic process and pollutants removal mechanism (Ref: North shore city council (NSCC) and Auckland council report 2013). 19
Figure 6 The role of the green roof growth media or substrate 21
Figure 7 Material used in the green roof growth media 22
Figure 8 Aggregates Manufacturing 23
Figure 9 A testing device for demonstrating the water retention capacity of samples. The 3 tubes in the left image consist of Type 1 substrate, the tubes in the middle image consist of Type 2 substrate and the image on the right demonstrates the addition of distilled water into the substrates using a glass beaker. 25
Figure 10 Vegetated (*Viola pedatifida*, Prairie Violet) green roof media. Growth media with the dredged material (left) and Rooflite® growth media (right). 26
Figure 11 L1-3100C Area Meter (left), used to measure the leaf coverage area (right). 27
Figure 12 Sieve Analysis Comparison 28
Figure 13 Testing Cells for Vegetation Study 29
Figure 14 Experimental Design for Vegetation Study 29
Figure 15 Before planting. Left to right: Cuyahoga, Maumee, Rooflite® 30
Figure 16 After planting. Left to Right: Cuyahoga, Maumee, Rooflite® 30
Figure 17 Harvested Plants from Rooflite® 31
Figure 18 Harvested Plants from Maumee (Toledo Sample) 31
Figure 19 Harvested Plants from Cuyahoga (Cleveland Sample) 32
Figure 20 Relationship between water retention capacity and wet unit weight of substrates 34
Figure 21 NDVI comparison graph, Violets in Dredge vs. Violets in Rooflite® 35
Figure 22 Average Growth of Plants (Inches) 37
Figure 23 Plants Growth in Cleveland Sample (Inches) 38
Figure 24 Plants Growth in Toledo Sample (Inches) 39
Figure 25 Plants Growth in Rooflite® Sample (Inches) 39
Figure 26 Germination Study 40
Figure 27 Biomass in Grams from Cleveland Sample 41
Figure 28 Biomass in Grams from Toledo Sample 41
Figure 29 Biomass in Grams from Rooflite® sample 42
Figure 30 Total Biomasses from Different Growth Media 42

LIST OF TABLES

Table 1: Benefits of green infrastructure 15
Table 2: Lab Testing of Dredged Material for Quality Control in GI construction 17
Table 3: Metals in the dredged material from the Cleveland CDF (Adapted from [5] 18
Table 4: Bioretention practice guidelines 20
Table 5 Sieve Analyses 28
Table 6 Water retention capacity and wet unit weight of substrate 33
Table 7 Leachate quality assessment of all three substrates (Rooflite®, Type 1 and Type 2) 34
Table 8 Plant Coverage Area value 36
Table 9 Startup Canvas 45
Table 10 Business Model Canvas 46

1. INTRODUCTION

1.1 Background

Lake Erie is the most productive lake among the five Great Lakes. It promotes tourism, recreational opportunities, and serves as a source of drinking water for millions of people living along its shoreline. The Lake is divided into three basins: the Western basin, the Central basin, and the Eastern basin (Figure 1). It is 388 km (241 miles) long and about 92 km (57 miles) wide, where the Eastern basin has a maximum depth of 64 m (210 feet). It has 502 km (312 miles) of shoreline in the State of Ohio where there are eight major federal navigation harbors built along the coast. These harbors serve the purposes of either commercial (i.e. to transport mineral sources like salt and limestone within the basin), or recreational, or both [1].

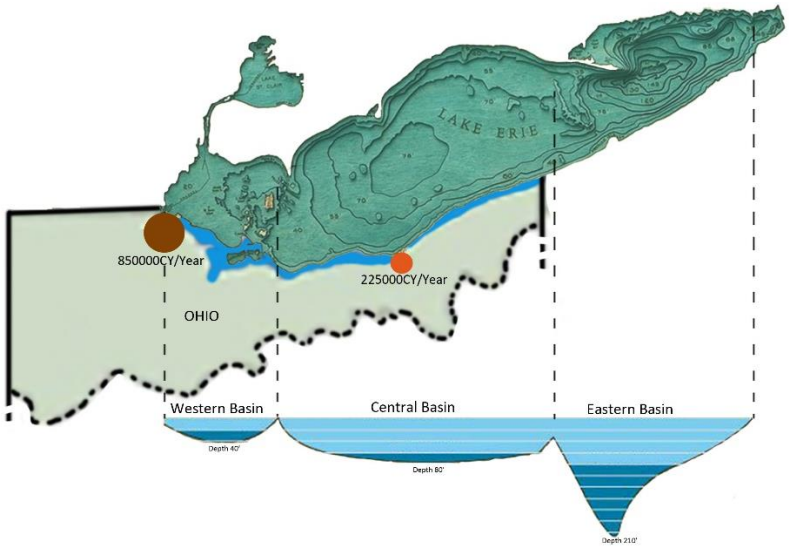


Figure 1 Map of Lake Erie: physical features and areas with immediate action required. (Reference: NOAA- National Center for Environmental Information, US Army Corps of Engineers, Environmental Canada)

Algal blooms plague Lake Eire and coastal areas across the Northern Ohio. Excess nutrients, particularly phosphorus, is primarily responsible for the impairment, which has a potential to impact public health, local tourism and increase the cost of treating public drinking water. Meanwhile, to maintain economic viability and sustainable development of harbors and ports built along the coast of Lake Erie, 1.15 cubic meters (1.5 million cubic yards, CY) of dredged material need to be removed annually. Landfill of these dredged material is costly and occupies valuable land space, while open water placement (occurring in most harbors) has the potential to

deteriorate water quality through siltation, increased turbidity and mobilization of potential contaminants, therefore increasing the risk of algal bloom. Challenges of dredged material management are illustrated in Figure 2. However, the traditional method of open water placement of dredged material in Lake Erie will be banned in the State of Ohio after July 1, 2020. In Cleveland, dredged material is disposed of in a 42.1-hectare (104-acre) Confined Disposal Facility (CDF) maintained by the Cleveland-Cuyahoga County Port Authority. Nevertheless, additional capacity of the facility is needed to accommodate the 172,000 m3 (225,000 CY) of sediment that needs to be disposed of in this facility annually to keep the site operational and maintain its economic viability for the Port of Cleveland. Therefore, raising a major challenge of how to treat the huge amount of material removed from the ports in Ohio. Moreover, the disposal of dredged material in a CDF is costly and has a major impact on the surrounding and the water table below. An alternative to disposal is to reuse the dredged material in the built environment like construction and landscaping material [2][3][4].

The dredged material mostly consists of a mixture of gravel, sand, silt, and clay, which can be used for habitat restoration and development, beach nourishment, park and recreation. It has the potential for use in engineering construction, after dewatering and sieving, as backfill material for highway construction and structures located in low lying areas, as a cover or liner material for sanitary landfills, as a soil-blending material. One of the beneficial uses of the dredged material identified by U.S. Army Corps of Engineers [3] is to produce lightweight aggregate (LWA). LWA, which are formed by sintering the dredged material with or without mineral admixtures (e.g. calcium and magnesium carbonates and/or silicates), can be used in subsequent constructions [4][5].

Many cities in the Lake Erie region are transitioning away from industry and manufacturing economies in hopes of reclaiming urban cores lost in the later twentieth century as a part of global trade and suburbanization. This has resulted in new core architecture growth and dispersed remnant vacant post-industry lands. In some cases, the combination of concentrating development in an urban core while planning for distributed urban green infrastructure could be mutually beneficially. For example, Cleveland has a several neighborhood hubs focusing on high-rise and low-rise development, while possessing an estimated 5,666 hectares (14,000 acres) of brownfields [6].

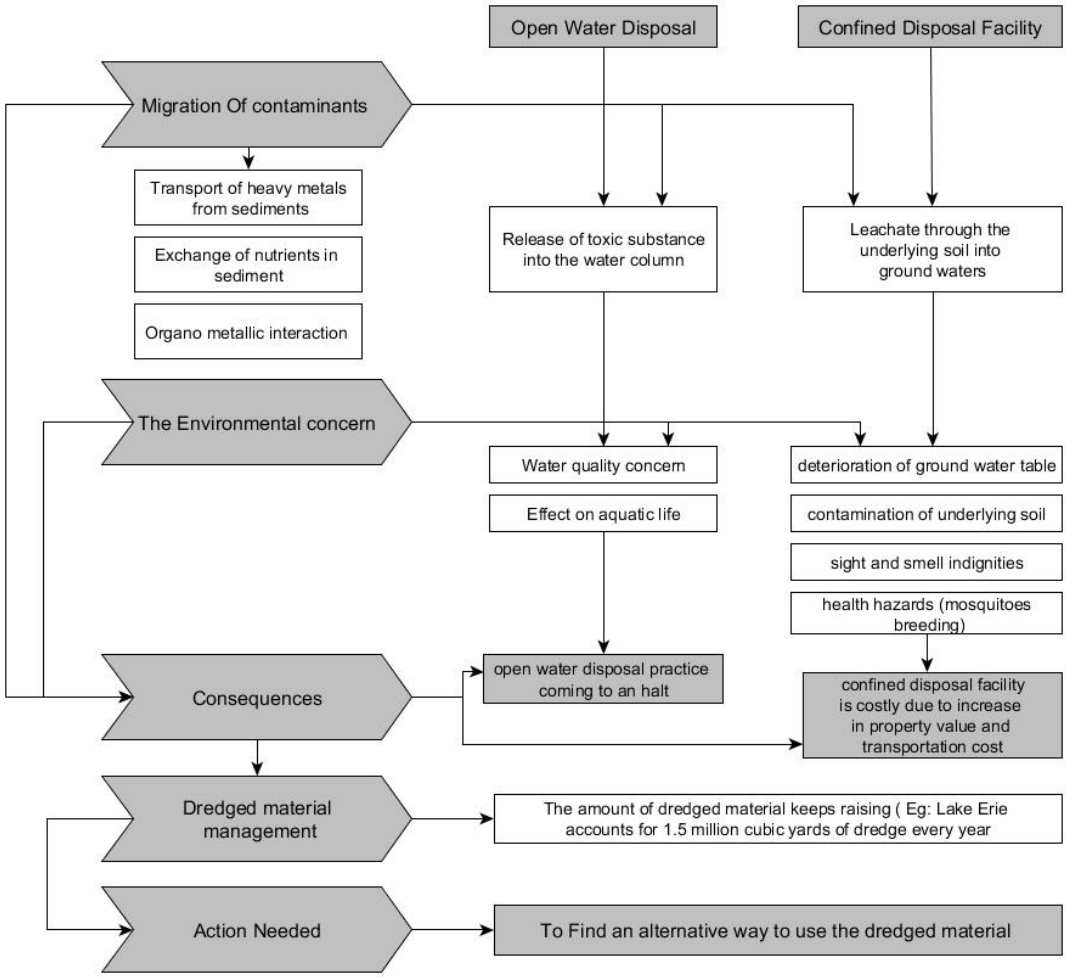


Figure 2 Challenges of Dredged Material Management

Complicating the brownfield's conditions, many vacant properties possess over 90% impervious surface to abate potential pollutions at these post-industry lands. However, this practice conflicts with "infiltration" the principle required by contemporary stormwater strategies. In addition, these un-remediated brownfields devalue and destabilize neighborhoods around these area, and the impervious surface increases flooding concerns in combined sewer overflow areas where many brownfields are located. Green infrastructure (GI), e.g. rain gardens, bioretention ponds et al., emphasizes infiltration and hydrological retention, and could potentially provide a flexible and affordable solution to remediate urban brownfield in Cleveland and many other cities. Living architecture, e.g. vegetated roofs and walls, can provide rainfall capture and recycle for environmental co-benefits on building structure and infiltration limited locations. Therefore, utilizing the dredge material in GI and living e architecture would help improve the resilience of

the Lake Erie in one hand and mitigating the issue of infiltration on the other, a seemingly inevitably solution.

1.2 Study Objectives

To beneficially use the dredged material in GI construction, several challenges must be addressed: (1) determine the contamination of the dredged material and its suitability to be used in the built environment; (2) evaluate the performance of the dredged material as a GI construction material; (3) investigate the cost and sustainability issues; and (4) evaluate regulatory issues and public acceptance. The toxicity risk of using the dredge LWA was proved to be low in the recent completed project "Dredged Material for Stormwater Management" by Liu and Coffman [5]. The proposed project focuses on the performance evaluation of using the dredged material in various GI applications, sustainability issues, and development of a business model in promoting the use of the product made from the dredged material. The dredged material may supply nutrients to plant growth in GI, and raw mineral materials to produce LWA which has high hydrological retention capacity for GI construction. This study discusses the strategy on how the dredged material could be used in the construction of GI to address multiple challenges facing 11 million people residing the coast of Lake Erie. The paper also discusses the initial performance criteria that can be achieved and acknowledge the sustainability achieved using the dredged material.

1.3 Scope of Study

Technical guides and material specifications on the GI construction were reviewed extensively in Chapter 2. The LWA sintered from the dredged material possesses promising traits of hydrological and structural capacities which demand further investigation into various forms of bioretention mixes used in green infrastructure. Following the literature review, promising applications of using the dredged material in GI construction were proposed in Chapter 2. Plant growth media were developed for green roof construction in Chapter 3. Mixtures using raw dredged material and the dredged material LWA taken from the CDFs in Cleveland and Toledo were designed and tested in the laboratory and in the field according to corresponding standards. The research results were summarized in Chapter 4. In addition, Chapter 4 examines plant species suitability in the laboratory and in the field trials for the new developed growing media made from the dredged material. Native, exotic and rare plants were investigated for potential

application within in the Lake Erie basin green infrastructure. Marketing study and business models in manufacturing the product were discussed in Chapter 5 to determine the investment opportunities and constrains for a Lake Erie or Great Lakes market product. Conclusions are summarized in Chapter 6.

2. Beneficial Uses of Dredged Material in Built Environment

2.1 Green Infrastructure and Living Architecture

An engineering manual developed by the U.S. Army Corps of Engineers (1987) mentions ten beneficial uses of dredged material, which can be summed up into three broad categories, “Environmental enhancement”, “Agricultural & product use”, and “Engineering applications” (Figure 3). The re-use of dredged material has a robust history, including nearly 2,000 man-made islands and 1,100 habitat development projects [7]. This shows that dredged material is already used for the various purposes in the built environment and that it's economic viable and feasible.

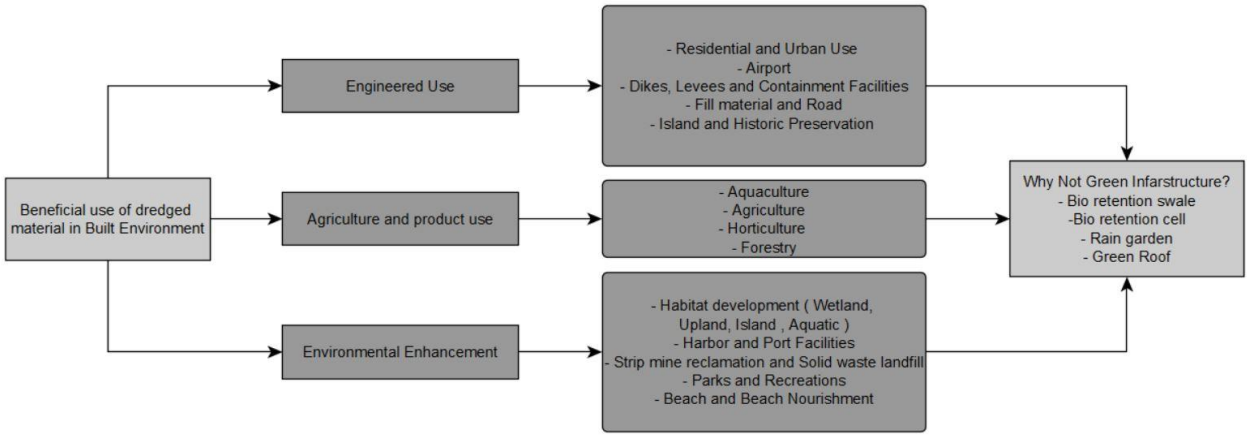


Figure 3 Beneficial Uses of dredged material

The City of Cleveland being the manufacturing and industrial center for Cuyahoga County hosted many industries back in the days, which resulted in dense residential neighborhoods. After 1980’s the City of Cleveland observed the period of high unemployment due to the shutdown of industries. Most of these industrial sites which were heavily polluted turned out to be brownfield with almost 90% of impervious surfaces. These impervious surfaces adversely affected the ecosystem of the city due to the reduction in the volume of soil infiltration, resulting in the increase of the rate and volume of stormwater runoff in the nearby water bodies, alongside contributing to be the source of pollutants. This effect of the increased impervious surface has transformed the physical, chemical, and biological properties of the stream ecosystems, which has motivated public agencies to develop management strategies to alleviate the impact of built infrastructure at the state, and local level.

GI, also defined as best management practices and low impact development, includes forested watersheds, bioretention, rain gardens, rain barrels, swales, permeable pavement, constructed wetlands etc [8]. GI improves degrading green spaces available in urban and suburban areas, with major functions of reducing volume of storm-water runoff and peak flow and providing a broad range of ecosystem services e.g. reduction of concentrations of nutrients and metal in nearby water bodies, mitigation of urban heat island effect, carbon sequestration, improvement of aesthetics and community livability etc [9].

Living architecture, (LA) in the form of vegetated roofs and walls, provides an array of ecological services in hydrology, air temperature, biological diversity, and human wellness and is separating itself as a field of study focusing on structural and mechanical building adaptions using soils and vegetation [9] [10] [11]. Conceived mainly as rainfall interceptors to reduce storm-water runoff, roofs are now being designed as novel ecosystems possessing suites of ecosystem service ranging from providing habitat for rare wildlife species [12] [13] to nature access for human restoration and wellness [14]. The major benefits provided by GI and LA are summarized in Table 1.

Currently, GIs such as green roofs and bioretention systems, taking advantages of plants and engineered soils, mainly function as stormwater management tools, reducing runoff quantity and improve the water quality. The plants use the physical, chemical, and biological processes to filter and clean the stormwater. And the engineered soil retains the runoff. A significant amount of runoff is lost in the processes of evaporation and evapotranspiration, while a small amount is uptaken by the plants. The remaining water is allowed to percolate either in the underlying soil or the drain, therefore reducing the peak flow and treating the pollutants as the water passes through the different layers of the GI. The benefits of various types of GI are illustrated in Figure 4.

As discussed above, excess nutrients, particularly phosphorus, are primarily responsible for the impairments of Lake Erie, which was caused by non-point pollutions with nutrients flushed into the lake by the stormwater runoff. The impervious surfaces of post-industry lands in cities like Cleveland accelerated the impairment due to the stormwater runoff. GI could be one of the potential solutions addressing the problems in the long term. Considering the large quantities of dredged material generated each year from harbors along the lake, it is projected to construct GIs

using dredged material to address multiple challenges facing the local communities along the coast of Lake Erie. Before projecting the use of dredged material in the built environment it is vital to consider the following factors: (1) contamination level of the dredged material; (2) suitability of these materials in green infrastructure construction; (3) performances of the green infrastructure; and (4) sustainability.

Table 1: Benefits of green infrastructure

	Benefits	**Action**	**Reference**
1	Urban temperature regulation	Ecological infrastructure buffers the effect of urban heat islands	[15]
		Vegetation reduces temperature by providing shade and by evapotranspiration	[16][17]
		Water from the plants absorbs heat as it evaporates, cooling the air	[18]
		Trees decrease the heat load by reflecting the solar radiation	[19]
2	Noise reduction	The urban soil and plants attenuate noise pollution through absorption, deviation, reflection, and refraction of sound wave	[20][21][22]
		Different plant species mitigate noise differently	[23] [24]
		Vegetation factors like density, width, height and length of the tree belts as well as leaf size and branching characteristics help reduce noise	[22]
3	Air purification	Vegetation in urban system can improve air quality by removing pollutants from the atmosphere, including ozone, Sulphur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 10µm	[25] [26] [27]
4	Moderation of climate extremes	Green infrastructures formed by mangroves, deltas and coral reefs act as natural barriers that buffer cities from extreme climate events and hazards	[28][29][30][31]
5	Runoff mitigation	Vegetation reduces surface runoff by intercepting	[32]
		Green patch reduces the pressure on the urban drainage system by percolating water	[16] [33]
		Green roofs, bio-swales and rain gardens help mitigate water runoff	[34] [35] [8] [32]

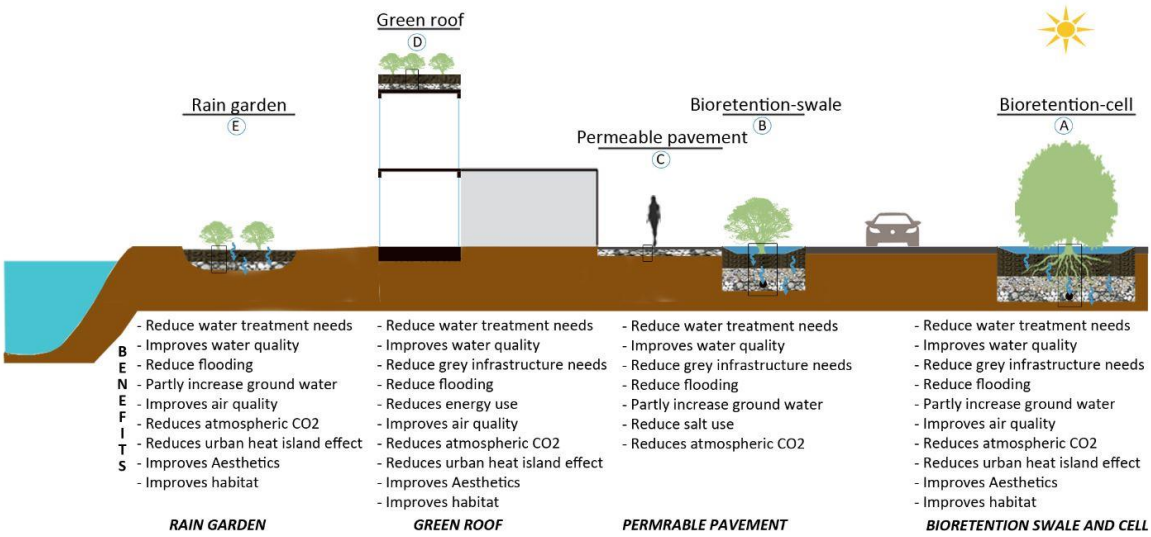


Figure 4 Benefits of GI

During the study, it was observed that there were two types of dredged material products. that could be used in the GI construction, Raw dredged material and sintered products. The raw dredged material is the sediment in its original unaltered form, and the sintered material is the manufacturing and processing of the sediment into an industrial "baked" commercial product. The application of raw dredge is most common and occurs within the categories of beneficial use discussed above: habitat; beach nourishment; parks and recreation; agriculture forestry, horticulture and aquaculture; strip-mine reclamation/solid waste management and construction/industrial development. The beneficial use of raw dredge material stems from the growing demand for construction materials and dwindling inland sources. LWA has been successfully made from sintering dredged material taken from Harbor of Cleveland [5], which could potentially create an ecologically beneficial product, as well as an economical alternative compared to the presently produced LWA. Bremmer and Ries (2007) stated "…lightweight concrete [aggregate] is an effective material in enhancing sustainability as compared to other construction materials". In addition, LWAs can provide important environmental components for sustainability when it is used for improving water quality as well as when it is used as the growing medium for green roof use to combat the urban heat island effect." Currently, LWAs are usually made of shale, clay, or slate. Depending on the application both are often mixed with organics or addition soil properties to meet the intended use.

2.2 Quality of Dredged Material and Testing Methods

In response to concerns regarding contamination of the dredged material. Many researchers have suggested the quality assessment and contamination mitigation methods [36][37][38], where the contaminated sediment is treated with a chemical, biological, and physical processes. Although most of the dredged material in the USA according to the USACE has been proved to have low harmful contaminates, but in rare cases, these mitigation methods help remove contaminants hence lowering the associated risk.

To improve the performances of dredged material and the LWA sintered from dredged material in the GI construction, the following tests listed in Table 2 are recommended to classify and characterize the dredged material.

Table 2: Lab Testing of Dredged Material for Quality Control in GI construction

Test	Description
ASTM D421	Standard practice for dry preparation of soil samples for particle size analysis and determination of soil constants
ASTM D422	Standard test method for particle size analysis of soils
ASTM D4318	Standard test methods for liquid limit, plastic limit & plastic index of soils
ASTM F1815	Standard test methods for saturated hydraulic conductivity, water retention, porosity & bulk density
ASTM D29	Unit weight voids in aggregate
ASTM D2922	Standard test method for density of soil and soil aggregate in place by nuclear methods
ASTM D4972	Determination of soil pH

In addition, the suitability of recycling the dredged material from Harbor of Cleveland in the built environment was evaluated by [5], which was funded by Ohio Lake Erie Commission, and supervised by Ohio Environmental Protection Agency (EPA). Ohio EPA is monitoring the contaminant levels throughout the CDF in the Harbors of Cleveland. Open water placement is currently employed by other federal harbors in the State of Ohio until July 1, 2020. The contents of heavy metals from the three sampling depths at one location in the Cleveland CDF are listed and compared with the Risk Screen Levels (RSL) specified by U.S. EPA for industrial and residential uses in Table 3 [5]. The contents of the majority metals are lower than the RSL specified for residential uses except for Arsenic, Iron, and Manganese. The levels of Arsenic

from the three samples are higher than the industrial RSL. The RSLs for metals specified by USEPA are more stringent than soil direct contact standards for industrial and residential uses specified in Ohio EPA's Voluntary Action Programs (VAP). For example, the upper limits for Arsenic listed in 2014 Ohio VAP are 77 mg/kg for the industrial direct contact, and 12 mg/kg for the residential direct contact respectively. The tested Arsenic levels are below the Ohio VAP value for industrial use. In addition, the research group completed the leaching test using Toxicity Characteristic Leaching Procedure to examine leaching potentials of heavy metals from the sintered lightweight aggregate made from dredged material taken from the CDF in Cleveland. All heavy metals were not detected from the leachate. Hence the toxicity risk of the aggregates sintered from the dredged material has been proved to be low.

Table 3: Metals in the dredged material from the Cleveland CDF (Adapted from [5]

Heavy Metals	Soil RSL Industrial	Residential	0-0.91m (0-3')	0.91-1.82m (3'-6')	1.82-2.74m (6-9')
	TR=1X10-6, THQ=0.1 (mg/kg)		(mg/kg)	(mg/kg)	(mg/kg)
Aluminum	110,000	7,700	3,700	2,700	6,700
Arsenic	3	0.67	7.4	6.4	11
Barium	22,000	1,500	24	21	53
Cadmium	98	7	0.85	0.31	1
Calcium	NS	NS	5,300	7,100	11,000
Chromium	NS	NS	11	22	18
Copper	4,700	310	42	49	36
Iron	82,000	5,500	15,000	16,000	22,000
Lead	800	400	14	15	31
Magnesium	NS	NS	2,000	2,400	4,200
Manganese	2,600	180	210	380	460
Selenium	580	39	0.59	<0.31	0.54
Silver	580	39	<0.056	<0.058	0.078
Zinc	35,000	2,300	100	87	170
Mercury	4	0.94	0.026	0.021	0.093
Chromium(VI)	6.3	0.3	<0.31	0.41	<0.37

Note: NS = Not Specified

2.3 Suitability of Dredged Material in GI Construction

2.3.1 Bio-retention system

A bio-retention system, such as a bio-retention cell, bio-retention swale, and rain garden (Figure 5), is a flat-bottomed basin that vary in depth, which help adapt different variety of plants to

prevent storm-water runoff from collecting it and allowing it to percolate slowly. Bio-retention systems are designed to treat the runoff water from various pollutants that are associated with the urban storm-water. The storm-water is treated as it passes through the various layers of bio-retention such as vegetation, a mulch layer, engineered soil media, a gravel layer and subsequently underdrain or underlying soil.

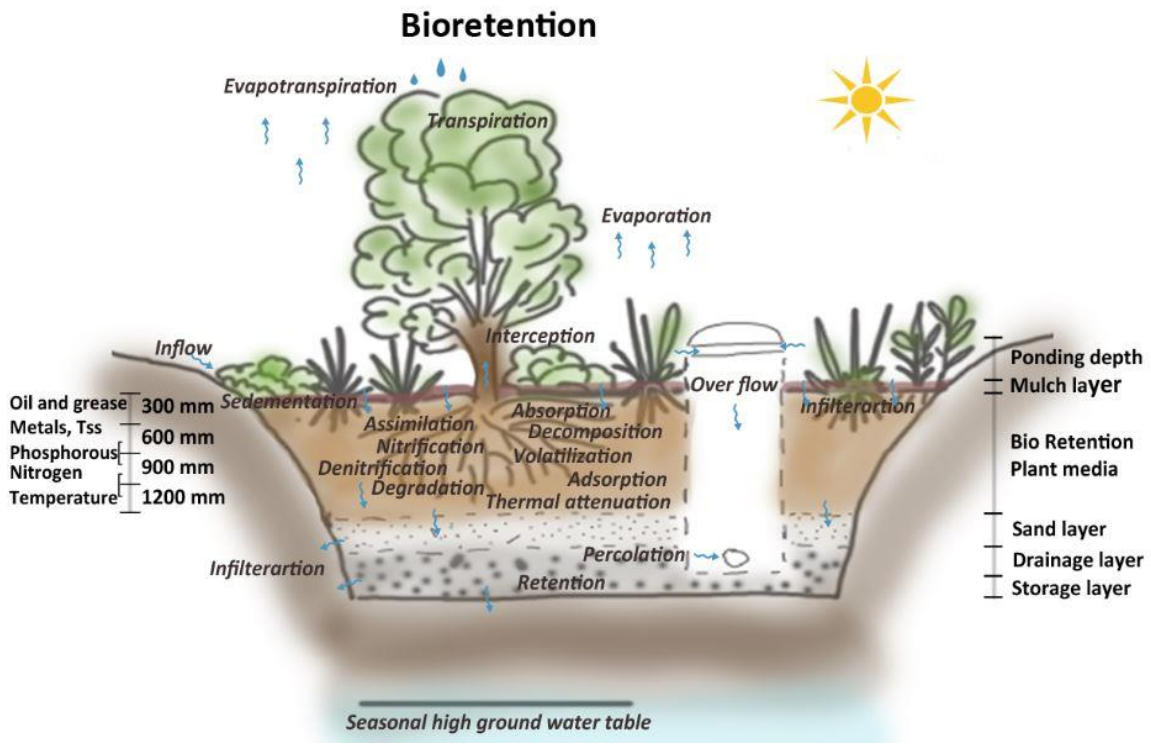


Figure 5 Bioretention system hydraulic process and pollutants removal mechanism (Ref: North shore city council (NSCC) and Auckland council report 2013).

The composition of the filter media is fundamental for the success for the bioretention system. The system uses the engineered filter media, microorganism, and the plants to manage runoff and treat the pollutants from the storm water. The contaminants are removed by sedimentation, assimilation, adsorption, absorption, ion exchange, volatilization, decomposition, denitrification, nitrification, and thermal attenuation. Most of the bio-retention systems rely on the characteristics of the filter media because it acts as an adequate infiltration and permeability medium for the storm-water. It also holds all the necessary nutrients for the plants to grow and microorganism to flourish, to remove all the pollutants from the storm water. The soil media retains the significant amount of water, therefore delays the peak flow. Hence the bio-retention filter media plays a critical role to ensure the performance of the system.

Most of the bio-retention practice guidelines see Table 4, specify the use of different mixtures basically to archive desired hydraulic conductivity. The traditional mixture design for the bio-retention engineered soil specified by most of the guidelines demonstrates that, the filter media is a homogeneous mix of sand, clay, silt and organic matter, where the sand accounts for 50% to 60% on an average, compost for 20% to 30%, and clay & silt for 10%. Whereas the soil pH is between 5.5 and 7.5, and soil depth ranging from 305 mm (12”) to 1,219 mm (48”), depending on which bio-retention system is being designed and which pollutant being targeted for mitigation.

Table 4: Bioretention practice guidelines

Guideline	Media composition	Organic matter	pH	Soil depth	Permeability	Mulch layer	Drainage layer	reference
BMP (Best management Practice) 2014	60% sand;30% triple-shredded hardwood mulch 10% aged, STA certified compost (not specified "by volume" or "by weight")	2%	6-7.0	18” - 24”	5-7”/hr	2”-3”	Rice gravel ¼” Min. 3” cover on underdrain; min. 2’ sump below invert of underdrain	[39]
Prince George’s county (Maryland)	50-60% sand, 20-30% top soil, 20-30% leaf compost (by volume)	<10 %	5.5-6.5	30”-48”	0.52-2.41”/hr or greater	3”-4” Raw Hardwood	Gravel stone size may not be greater than ½” to 1.5” diameter. (Blue stone, double washed, #57 stone) Depth- 12”	[40]
Washington state university	60-65% sand,35-40% compost (by volume)	8%-10%	5.5-7	18”	12”/hr			[41]
Santa Clara valley	60-70% sand 30-40% compost (by volume)				5”/hr	1”-2”		[42]
Lake county	50% sand, 30% topsoil,20% compost (not specified "by volume" or "by weight")	1.5 – 10%	5.5-7	12”		3” Shredded hardwood	3” of gravel(no.57) over 3” of pea gravel(no.805 78) under	[43]

County Denver	80-90% sand, 3-14% silt, 3-14% clay (by weight)	<1.5%	6.8-7.5	18”-38”		Shredded		[44]

Therefore, as discussed above dredged material (both sintered and raw dredged material) can be used to develop the composition of the engineered media with a mixture of lightweight aggregate that can replace the gravel. Sand, silt and clay can be replaced by the actual sand, silt and clay sieved out from the raw dredged material, and a commercial organic matter can be mixed into the engineered media for the plants’ development.

2.3.2 Vegetative Roofs

Vegetative roofing addresses environmental problems associated with urbanization [19]. For centuries, vegetative roofs were embraced for providing thermal benefits. Over the last two decades, green roofs have been adopted by many countries in different climate zones because of their storm-water management capacities [19]. The growth substrate plays multiple important roles in the green roof construction, see Figure 6. One can divide the role of growth media into four broad functions. First and foremost, the growth media plays a vital role towards the building, by reducing it thermal mass, protecting its roof membrane, and by insulation. Second, the growth media is widely known for its water management mechanism where the rain water is retained hence causing delay in the peak flow. Third, growth media is a source of moisture, nutrients and physical support to the plants. And finally, the growth media plays a major role towards water quality.

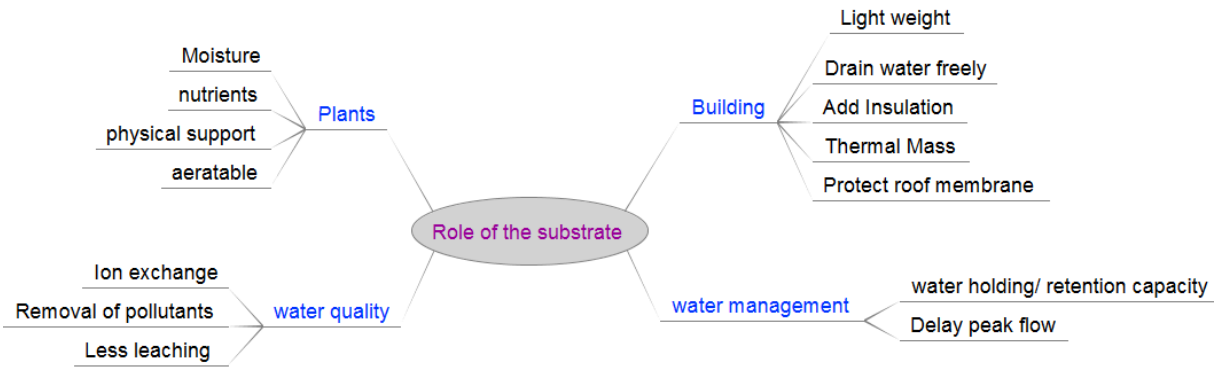


Figure 6 The role of the green roof growth media or substrate

As shown in Figure 7, a standard vegetated roof growth media consists of three main components, i.e. aggregate (a porous LWA material), sand, and organic matter [45]. The composition of the growth media depends on the availability of material and the cost. Different from the natural soils, the growth media designed for the green roof are heterogeneous and consist of organic and inorganic materials with different particle size distributions. [45] [46]

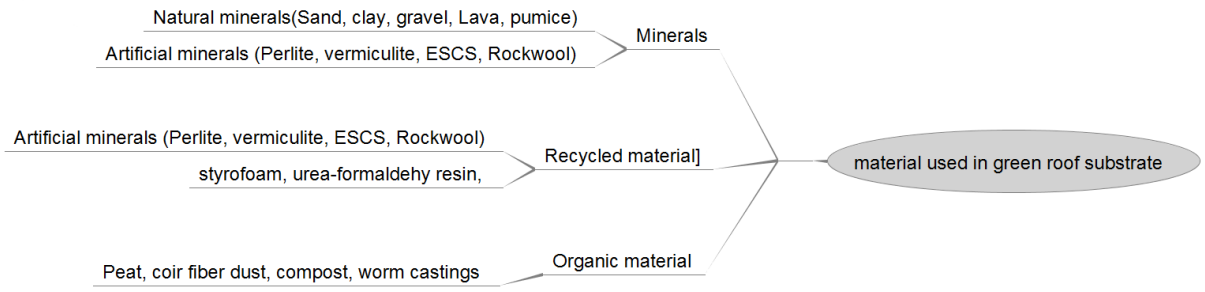


Figure 7 Material used in the green roof growth media

Hence, the growth media shows potential to be designed using dredged material. Where the sand, silt and clay sieved from the raw dredged material can replace the natural minerals, and the sintered LWA made by dredged material, can replace the shale, clay, or slate for green roof substrate construction.

3. Growth Media Developed using Dredged Material and Experimental Design for Vegetation Study

Dredged materials were sampled from CDF 12 managed by Cleveland – Cuyahoga County Port Authority and a CDF at the new Center of Innovation of Toledo managed by Toledo-Lucas County Port Authority for LWA manufacturing to develop plants growth media and vegetation study.

3.1 LWA Manufacturing

3.1.1 LWA Production

The dredged material samples were dried in the air and pulverized. The LWA is produced by mixing the dredged material with certain amounts of water, and firing in a furnace at a temperature of 1100℃. The water content was adjusted to achieve a desired plasticity with a cohesive status. The raw dredge mixtures were used to make small pellets with 1/2 in. diameter or less (Figure 3-4b) in the lab. The fresh pellets were dried in the air for minimum 24 hours before firing. The dried balls were packed in a furnace (Sentro Tech ST 1150-458 high temperature box furnace) with a chamber sizing 4"×5"×8" and fired according to a schedule determined in a previous study [5].

Figure 8 Aggregates Manufacturing

3.2 Green Roof Material using Cleveland Samples (Phase I)

3.2.1 Plant Growth Media Development (Phase I)

Two types of green roof growth media, Type 1 and Type 2, were developed in Phase I using the raw dredged material and LWA made from dredged material taken from the Harbor of Cleveland. The newly developed growth media was then compared with a commercialized product Rooflite® to evaluate the hydraulic performance of the newly developed growth media and its practical feasibility to be used as a locally available alternative growth media.

The commercial growth media Rooflite® was subjected to sieve analysis (ASTM D422) to understand the particle size distribution (PSD). The same particle distribution pattern as the Rooflite® was used to develop two new types of growth media made from the dredged material. The first type (Type 1) of growth media was prepared by replacing the aggregates in the Rooflite® with the LWA made by the dredged material (by volume). Here, all Rooflite® materials that were retained on the sieve #4 (4.76 mm) were replaced with the LWA made from the dredged material (by volume). The second type (Type 2) of growth media was developed using 100% dredged material, considering the same PSD as the Rooflite®. Here, the raw dredged material (sand, silt and clay) was used in place of all the particles that passed #40 (0.42 mm) sieve in exactly the same quantity as the Rooflite® PSD. The large diameter samples (LWA used in Rooflite®) that retained on the #4 (4.76 mm) and #10 (2.00 mm) sieve were substituted by the LWA made by the dredged material by volume. The two developed growth substrates made from the dredged material were tested in the material lab at Kent State University for their unit weights, water retention capacities, and leachate quality.

3.2.2 Water Retention Capacity, unit weight and Leachate Quality

A testing device (see Figure 9) was built to measure the water absorption capacities of the three types of growth media (Rooflite®, type 1 and type 2). The device was constructed using three polyvinyl chloride (PVC) pipes with a length of 305 mm (12”) and a diameter of 100 mm (4”), which was attached to a 25 mm (1”) thick wood board. A mesh was laid at the bottom of each PVC pipe attached by a cap with several holes to drain the water. The dry samples were then weighted and filled in all three pipes, one type at a time, up to 254 mm (10”) to get three readings/iterations.

Distilled water was further added to the tubes filled with growth media, one at a time using a glass beaker. Before adding the distilled water, it was tested for pH, total alkalinity, total chlorine, total hardness, nitrate nitrogen, and nitrite nitrogen. Here, the water was added until it passed through the media depth and a few drops were collected in a container below. A timer was set to note down the percolation time (time taken by the water to travel the substrate depth). After 15 min of waiting time (i.e., to allow the water to get absorbed by the growth substrate and excess water to drain), the wet weight of the samples present in each pipe was noted down separately with the help of a weighing scale. The samples were then placed in the oven for 24 h at 230 °F (110 °C) for water to evaporate. After 24 h, the dried samples were weighed, and the reading was noted down. With the dry and wet weights, the water retention capacity and the unit weight (kg/m3) were determined. A similar procedure was carried out for all three growth media (Rooflite®, type 1 and type 2).

Further, the excess drained water collected in the container below was used to evaluate the leachate quality of the newly developed growth media. The growth substrate, made of the dredged material, was tested for pH, total alkalinity, total chlorine, total hardness, nitrate nitrogen, and nitrite nitrogen using test strips, and was compared with the distilled water.

Figure 9 A testing device for demonstrating the water retention capacity of samples. The 3 tubes in the left image consist of Type 1 substrate, the tubes in the middle image consist of Type 2 substrate and the image on the right demonstrates the addition of distilled water into the substrates using a glass beaker.

3.2.3 Vegetation Growth and Establishment on the Growth Media Made by Dredge Material

In a subsequent phase, a field examination was conducted at Cleveland Industrial Innovation Center, Cleveland, Ohio, to explore vegetation growth and establishment. Eight individual plants (Viola pedatifida, a rare Ohio native plant) per substrate mix were planted in 10-gallon

polyethylene mixing tubs configured with sub-drainage and filtration fabric and containing partially replaced dredged material substrate (Type 1) in one tray and Rooflite® substrate in the other. The plants were planted in eight inches deep growth media (i.e., one iteration pre substrate mix) and were irrigated manually every week for the entire summer (Figure 10). In that summer, plant growth was recorded by hand-held NDVI (Normalized Difference Vegetative Index, GreenSeeker® Crop Sensing System, Trimble® , HQ 935 Stewart drive Sunnyvale, California 94085) to allow incremental non-destructive sampling. NDVI provides a comprehensive measure of plant health, growth, and vitality, allowing a numerical comparision of the plant establishment in the two different growth media. At the end of the growing season, each plant's above ground biomass (stems and leaves) was harvested and evaluated for the Leaf Area Index, where the leaf area was calculated to determine the coverage area/canopy development of the plant in each substrate using the L1-3100C Area Meter (Li-Cor) at 1 mm2 resolution. See Figure 11.

Figure 10 Vegetated (*Viola pedatifida*, Prairie Violet) green roof media. Growth media with the dredged material (left) and Rooflite® growth media (right).

Figure 11 L1-3100C Area Meter (left), used to measure the leaf coverage area (right).

The experimental results are summarized in Chapter 4.

3.3 Green Roof Material using 100% Dredged Material (Phase II)

3.3.1 Plant Growth Media Development (Phase II)

Once enough LWA was sintered for both the Toledo and Cleveland samples, the development of the green roof growth medium with 100% dredged material could be started. The goal was to compare the performances of the green roof material developed using dredged material with the commercial green roof soil medium, Rooflite®. To understand the properties and gradation of the different particle sizes in the Rooflite®, a sieve analysis was completed. Five 1000 g samples of Rooflite® were taken and put through the mechanical sieve in the Materials Lab and an average was taken to get the percent of each gradation.

Rooflite® had a 0.18% by weight amount of woodchips retained on the No. 5 sieve. However, no woodchips were added to the Cleveland or Toledo samples.

The next step was to develop the green roof medium using the Cuyahoga LWA and Maumee LWA. The sintered LWA was crushed to meet the size and amounts needed for each Sieve size to total 10kg. Once completed, three separate samples were taken and ran through the mechanical sifter for analysis. Since Rooflite® has some organic matter in it, another 10kg of the LWA was crushed into specific gradation, with 10% compost added. The same was completed for the Toledo sample. Sieve analysis results for all samples are summarized in Table 5 and the data are compared in Figure 12. The green roof growth media developed from the 100% dredged material had a similar PSD to the Rooflite®.

Table 5 Sieve Analyses

Sieve Analysis Comparison					
Seive #	Rooflite %	Cuyahoga LWA with 10% Compost %	Cuyahoga LWA with no compost %	Maumee LWA with 10% Compost %	Maumee LWA with no compost %
0.5	0.18	0	0	0	0
0.37	0.46	1.20	0.60	1.35	0.93
4	31.9	24.77	31.10	30.3	37.77
8	20.42	19.53	22.27	22.05	21.9
16	22.32	19.87	18.23	21.95	19.1
50	22.7	30.27	18.70	18.45	14.5
100	1.84	3.70	4.53	4.3	3.13
200	0.04	0.30	1.87	1.1	1.23
container	0	0.03	3.37	0.2	1.23

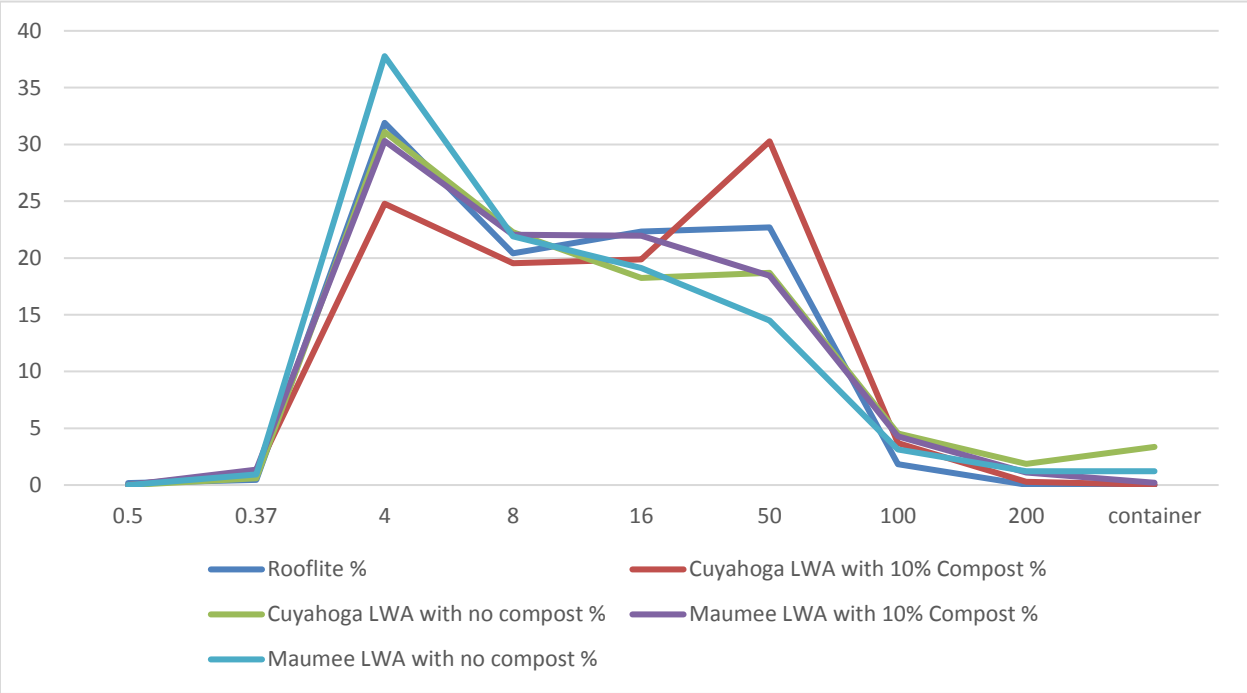


Figure 12 Sieve Analysis Comparison

3.3.2 Vegetation Study

Next was to prepare for the field study. Plant growth of three species, Solidago ptarmicoides, Sedum album, and Sedum kamtchaticum would be compared in the three growing mediums:

Rooflite®, Cuyahoga based medium with 10% compost, and the Maumee based medium with 10% compost. Each growing medium would be put into a 36 cell flat, with each cell holding 134g of medium.

Figure 13 Testing Cells for Vegetation Study

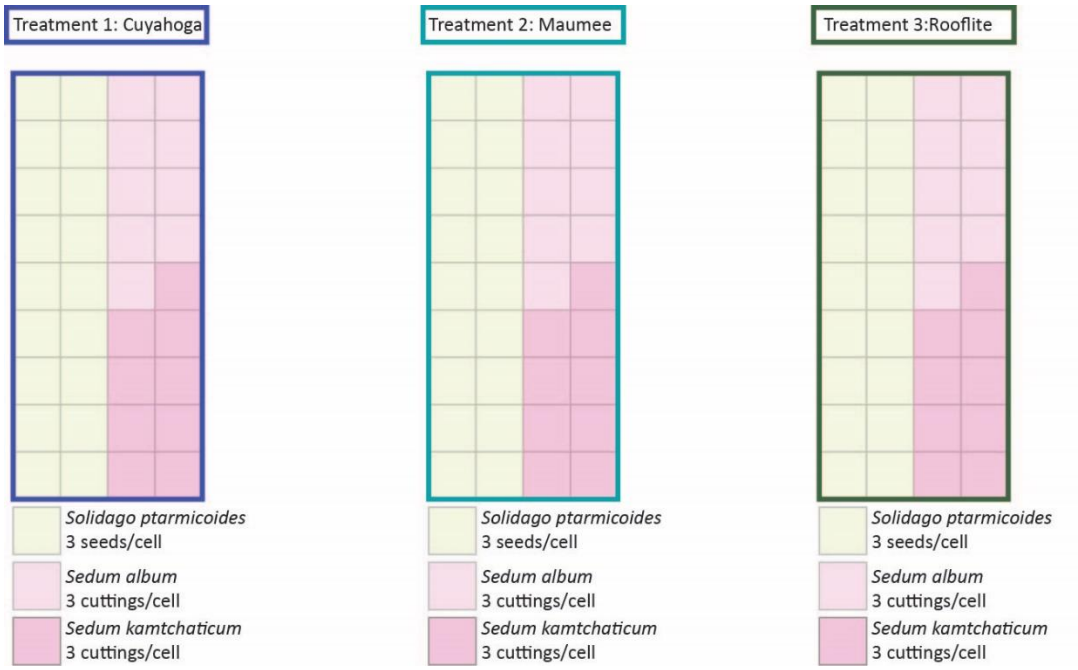


Figure 14 Experimental Design for Vegetation Study

Once the flats were filled with the growing medium, they were taken to the site where they would be seeded. Over the next three days, the soil was saturated with rainwater from storms, making conditions suitable for seeding and planting. The three flats were seeded and planted.

Attention was taken to make sure the cuttings of the Sedums were the same size/weight. Then, they were watered from rainwater collected in a rain barrel on site.

Figure 15 Before planting. Left to right: Cuyahoga, Maumee, Rooflite®

Figure 16 After planting. Left to Right: Cuyahoga, Maumee, Rooflite®

3.3.3 Harvest

Plants were harvested 10 weeks after planting. Within each treatment, three plants of each species were randomly chosen and harvested. Therefore, there were 3 Sedum album, 3 Sedum kamchaticum, and 3 Solidago for each of the treatments. The Rooflite® treatment is the only exception since there was only one Solidago ptarmicoides seedling. It was surprising how much root growth there was considering they were planted as cuttings with no roots, and because the shoot growth was minimal.

Sedum album Sedum kamchaticum Solidago ptarmicoides

Figure 17 Harvested Plants from Rooflite®

Sedum album Sedum kamchaticum Solidago ptarmicoides

Figure 18 Harvested Plants from Maumee (Toledo Sample)

Sedum album Sedum kamchaticum Solidago ptarmicoides

Figure 19 Harvested Plants from Cuyahoga (Cleveland Sample)

After the harvest, plants were taken to the lab where they were weighed for their fresh/wet weight and then were dried in the oven for 1 day. Immediately after taken out of the oven they were weighed again for their dry weight/biomass. Following is the data analysis of the study. The data are reported in Chapter 4.

3.4 Summary

The experimental plan and methods were discussed in Chapter 3 to assess the potential of using the dredged material to develop plants growth media, and to evaluate the lab and field performances of the green roof material incorporated with LWA made from the dredged material. The findings of the experiments are discussed in Chapter 4.

4. Experimental Results and Discussions

4.1 Experimental results of Phase I

4.1.1 Water Retention Capacity, unit weight and Leachate Quality

The water retention capacity and wet unit weight of substrate testing results are summarized in Table 6. Here, it was observed that by partially replacing the aggregates of Rooflite® growth media with the LWA made from the dredged material (i.e., Type 1 substrate), the unit weight was reduced by 13.83% and water retention capacity was observed to be increased by 51.02% (Figure 20). Whereas, the 100% dredged material (Type 2 substrate) was observed to have the highest water retention capacity, 71.9% and 13.6% higher than the Rooflite® substrate and partly replaced substrate (Type 1), respectively. However, it was observed to have a higher unit weight than the Rooflite® substrate and partly replaced substrate (Type 1). See Figure 20.

Table 6 Water retention capacity and wet unit weight of substrate

Specimens	Dry Material wt. (kg)	Water Adsorbed (ml)	Wet wt. of Sample (kg)	Water Retention (%)	Wet Unit Weight (kg/m3)
		Rooflite® substrate			
Column1	1.3	276.69	1.58	21.18	786.5
Column2	1.33	181.46	1.51	13.65	751.2
Column3	1.38	204.11	1.58	14.7	789.55
Average	1.33	220.75	1.56	16.51	775.77
Standard Deviation	0.04	49.75	0.04	4.08	21.32
		Partly Replaced (Type 1) substrate			
Column1	1.03	270	1.3	25.04	650
Column2	1.08	280	1.36	25.52	676.7
Column3	1.09	270	1.36	24.38	679
Average	1.07	273.33	1.34	24.98	668.45
Standard Deviation	0.03	5.77	0.03	0.57	16.12
		100% dredged material (Type 2) substrate			
Column1	2.22	598.74	2.82	26.9	1403.2
Column2	2.13	557.91	2.69	26.17	1337.8
Column3	1.31	421.84	1.74	32.06	1425.6
Average	2.13	526.16	2.42	28.38	1389.2
Standard Deviation	0.50	92.62	0.59	3.21	45.62

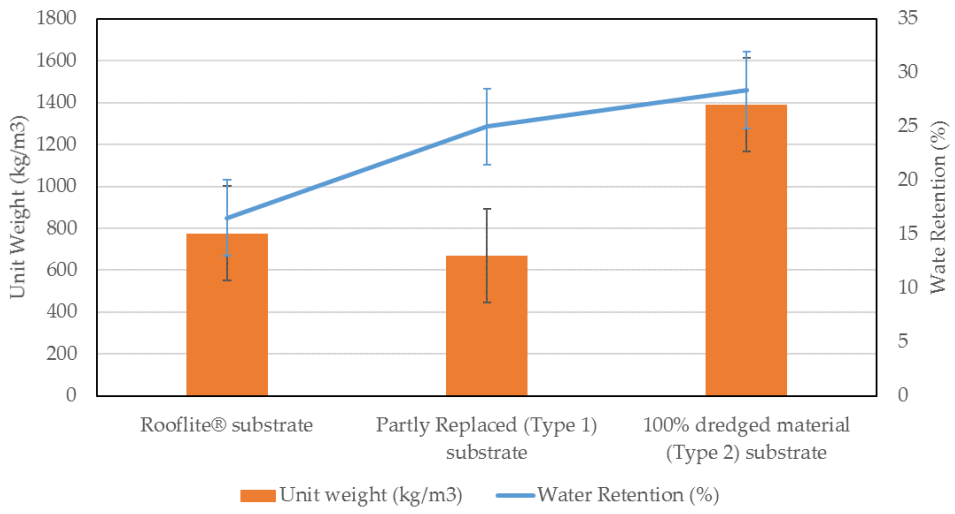


Figure 20 Relationship between water retention capacity and wet unit weight of substrates

The leachate test results demonstrated the water quality of Type 1 and Type 2 substrate in Table 3. When compared with distilled water, it was observed that the water after passing through the newly developed substrates had total alkalinity reduction from 500 mg/L to 240 mg/L. There was no trace of chlorine, even though the distilled water had 0.2 mg/L. The total hardness of leachate water was observed to be increased from 50 mg/L to 425 mg/L. Additionally, there was a trace of nitrate nitrogen (50 mg/L) and nitrite nitrogen—0.3 mg/L. However, the two indices were comparable to the drained water from Rooflite® (pH-8.5, total alkalinity 180 mg/L, total chlorine 0 mg/L, total hardness 425 mg/L, nitrate nitrogen 50 mg/L, and nitrite nitrogen 0.3 mg/L).

Table 7 Leachate quality assessment of all three substrates (Rooflite®, Type 1 and Type 2)

Quality	Distilled Water	Rooflite®	Type 1 Substrate	Type 2 Substrate
pH	8.5	8.5	8.5	8.5
Total Alkalinity (mg/L)	500	180	240	240
Total Chlorine (mg/L)	0.2	0	0	0
Total Hardness (mg/L)	50	425	425	425
Nitrate Nitrogen (mg/L)	0	50	50	50
Nitrite Nitrogen (mg/L)	0	0.3	0.3	0.3

4.1.2 Vegetation Growth and Establishment on the Growth Media Made by Dredge Material

A 12-month study confirmed that a rare Ohio native plant, (Viola pedatifida, Prairie Violet) grew and overwintered in the growth media consisting of the LWA made from dredged material and composted organic materials (Figure 10).

Each individual plant survived the initial 12-month study in both treatments, indicating the viability of the experimental media to provide overwintering of vegetation (n = 8). It was observed that the rare native Prairie Violet which is known to live for a short-term and difficult to establish in disturbed sites, flourished in both the green roof substrates. The NDVI (Figure 21) showed the plants in the dredged material-based media to possess slightly lower but comparable growth to the market standard product Rooflite®. In addition, the data in Table 8 indicates the differences of biomass harvested at the end of growing season are not statistically significant between the dredged material-based media and Rooflite®.

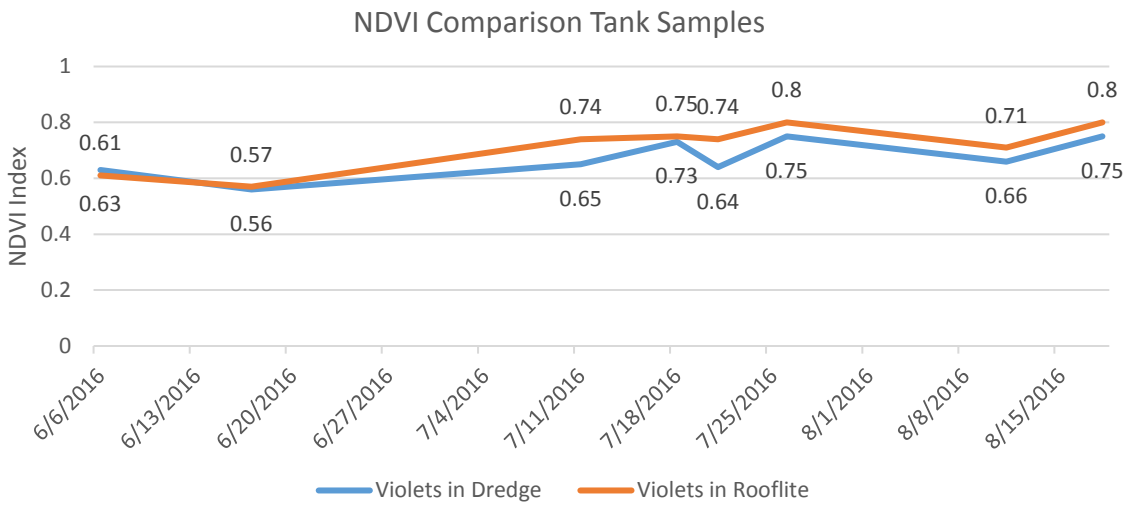


Figure 21 NDVI comparison graph, Violets in Dredge vs. Violets in Rooflite®.

Table 8 Plant Coverage Area value

Sample No.	Plant Cover Area (cm2) Dredged Material	Plant Cover Area (cm2) Rooflite® Material
1	253.8	348.232
2	168.613	322.59
3	415.631	255.38
4	215.126	334.13
5	302.2	514.31
6	450.426	558.38
7	511.941	407.85
8	244.844	239.5
Total (sq.cm)	2562.581	2980.372
Average (cm2)	320.323	372.547
Standard Deviation (cm2)	123.786	114.561
Probability (t-test)	0.198 > 0.05 (Statistically insignificant)	

4.1.3 Phase I discussions

The primary aim of conducting the water retention capacity, unit weight and leachate quality tests on the newly developed growth media was to evaluate its hydraulic properties (water retention capacity). As indicated in the Figure 20, the reduction in the weight of type 1 substrate would have been caused due to the low specific gravity of dredge material (SG 1.46–1.74), whereas the increase in water absorption was due to high porosity of LWA made from the dredged material whose water absorption rate ranged between 10.96% and 23.40%. Further, the higher unit weight of type 2 substrate could have been because, in the Type 1 substrate, only the material retained on the sieve #4 was replaced by the dredged material LWA; whereas, in the case of the Type 2, the whole substrate was developed using the dredged material whose physical properties (bulk density was observed to be 0.498 kg/m3) differ from the Rooflite® material (whose bulk density was observed to be 0.304 kg/m3). Hence the mass/ material weight increased. Due to heterogeneous nature of the substrate and the differing physical property (density) of each particle (LWA, sand, silt and clay), there is a need to develop a lightweight growth media composition with a high water retention capacity that would help retain a high volume of storm water. Type 2 would require a higher loading capacity for the roof structure if applied on the rooftop, therefore, only Type 1 was compared with Rooflite® in the plant established test.

The alkalinity reduction in leachate test of type 1 and type 2 substrate could have been due to the porous microstructure of the lightweight aggregates increasing the contact area to remove some chemicals, or the complex reactions between the chemicals and minerals present in the substrate.

The obtained results on the rare plant *Viola pedatifida* growth and establishment on the growth substrate made by dredged material were encouraging. The dredged material-based media had no effect on plant biomass growth. The performances of dredge-based material were competitive with that of the Rooflite® growth media. A two-sample unequal variance t-test with two-tailed distribution was performed to compare the differences of the plants harvested from the Type 1 growth media developed using dredged material and Rooflite®. The results showed the plant coverage area comparison for the substrates were statistically insignificant (Table 8).

4.2 Experimental Results of Phase II

4.2.1 Growth of Plants

Figure 22 compares the average growth of plants in the growth media developed using different materials. The Rooflite® sample had the highest average growth. The Maumee (Toledo) and Cuyahoga (Cleveland) samples average growth were very similar. The ranges of growth for both the Maumee and Cleveland samples reached the average inches grown in the Rooflite® sample.

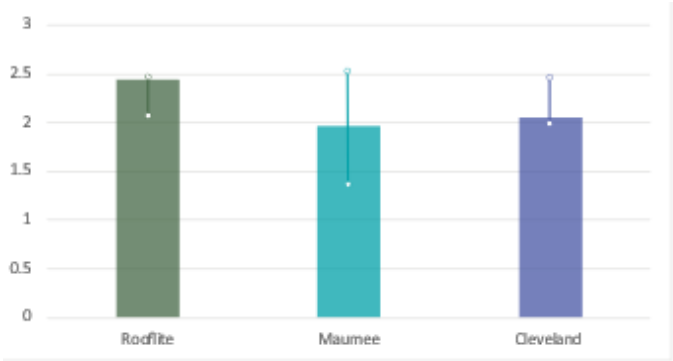


Figure 22 Average Growth of Plants (Inches)

(1) Cuyahoga (Cleveland) Sample

Sedum Kamtchaticum had the highest average growth in the Cleveland sample, next being *Solidago Ptarmicoides* and then *Sedum Album*. The low end of the range was similar to all of the species and *Sedum Kamtchaticum* had the largest range. See Figure 23.

The *Sedum Album* and *Sedum Kamtchaticum* cuttings had very similar growth patterns. They lost leaves, were not vibrant in color and seemed to be deteriorating over time. At harvest time, it was surprising to see the great amount of root mass grown over the seven-week study. The majority of growth took place in the roots. The Cleveland sample had the most successful germination of

Solidago Ptarmicoides at the beginning of the study, but after the fifth week, seedlings began to dry out and die even when being watered daily.

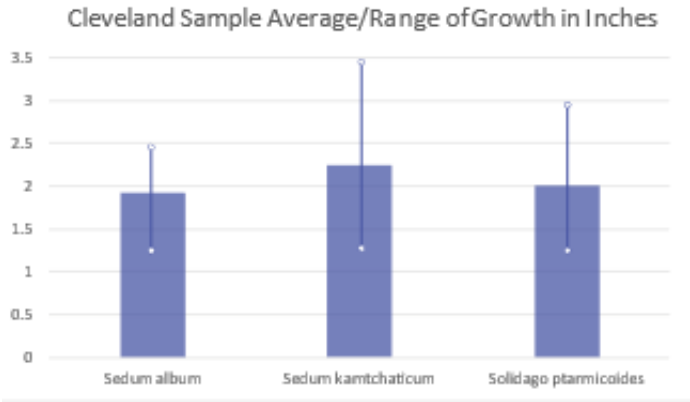


Figure 23 Plants Growth in Cleveland Sample (Inches)

(2) Maumee (Toledo) Sample

As shown in Figure 24, *Sedum Katchaticum* had the most average growth in the Maumee sample as well as the largest range. The *Sedum Album* had the second most growth with a smaller range. The *Solidago Ptarmicoides* had the lowest average growth.

The patterns of the *Sedum Album* and *Sedum Kamtchaticum* cuttings had very similar growth patterns to the Cleveland sample. They also lost leaves, were not vibrant in color and seemed to be deteriorating over time. The *Sedum Album* started off especially weak. At harvest time, it was surprising to see the great amount of root mass grown over the seven-week study. The Maumee sample had the second most *Solidago Ptarmicoides* germinate, but most of them also died halfway through the study.

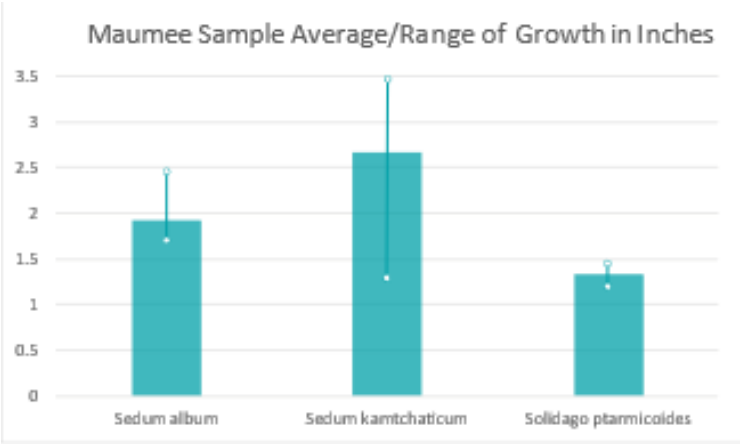


Figure 24 Plants Growth in Toledo Sample (Inches)

(3) Rooflite® sample

It can be seen from Figure 25 that all species grown in the Rooflite® sample had greater growth than the Cleveland and Maumee samples. Here *Sedum Kamtchaticum* had the most average growth and largest range. The *Sedum Album* had a smaller range of growth. The Rooflite® sample had the least amount of *Solidago Ptarmicoides* germinate over the seven weeks with only 1 living at harvest date.

Over the seven-week study, the Rooflite® substrate sample had the most significant growth with the *Sedm Album* and *Sedum Kamtchaticum* cuttings. The *Sedum Album* had significantly more leaves, put off new shoots, and was a vibrant green color. The *Sedum Kamtchaticum* was also much greener than the *Sedum Kamtchaticum* of the Cleveland.

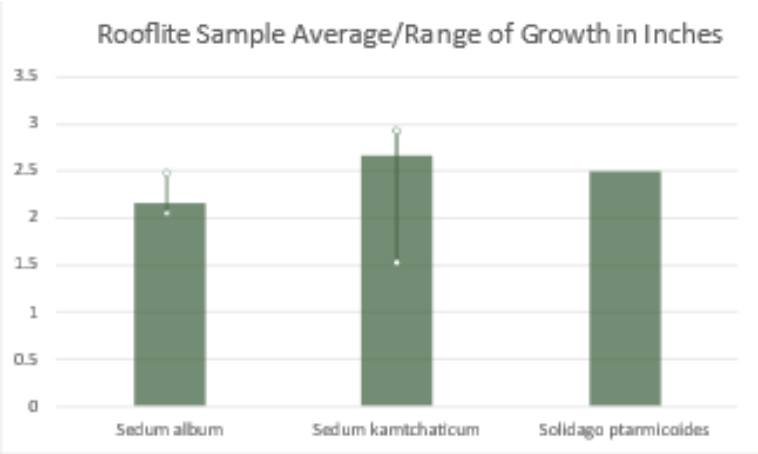


Figure 25 Plants Growth in Rooflite® Sample (Inches)

4.2.2 Solidago Ptarmicoides Germination Study

In each treatment, 18 cells were seeded with 3 Solidago Ptarmicoides seeds equaling 54 seeds per treatment. The Cleveland sample had the highest germination at 50% at Week 7 (9/16/2017.) Second was Maumee, and lastly, Rooflite®. By harvest date, week 10 (9/25/2017,) all treatments had a significant amount of seedlings perish. Week 7-10 was extremely hot and the seedlings were drying out even though they were being watered daily.

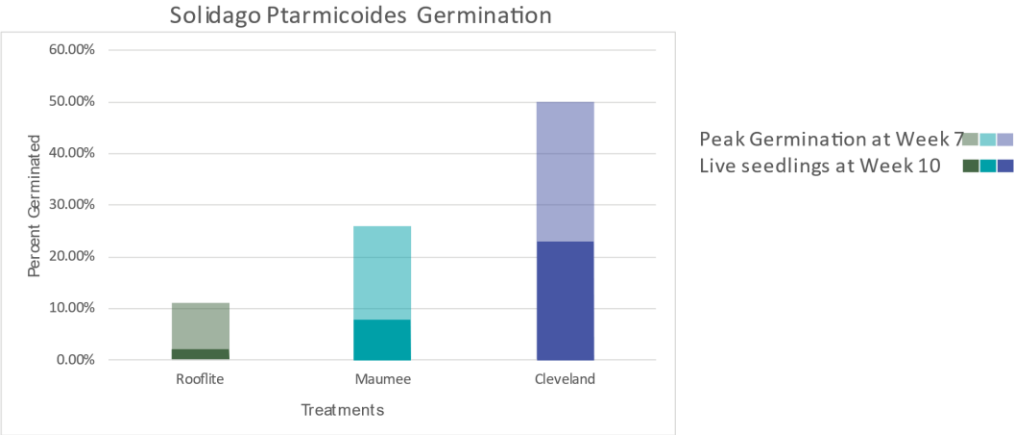


Figure 26 Germination Study

4.2.3 Biomass

After plants were harvested, they were taken to the Kent State University Biology Lab where they were dried in their oven for one day. After they were pulled out, they were weighed.

The Cleveland sample results (Figure 27) showed that *Sedum Kamchaticum* had the highest biomass, next *Sedum Album*, and lastly *Solidago Ptarmicoides*. Both the *Sedum Album* and *Sedum Kamchaticum* had similar ranges.

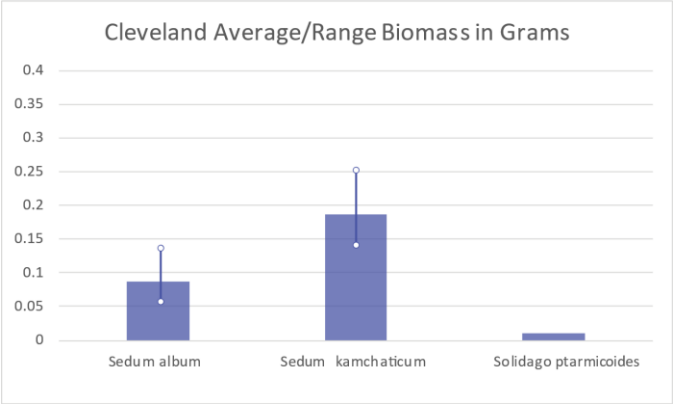


Figure 27 Biomass in Grams from Cleveland Sample

The Toledo sample was similar to the Cleveland sample with *Sedum Kamchaticum* having the highest biomass, then *Sedum Album*, then *Solidago Ptarmicoides*.

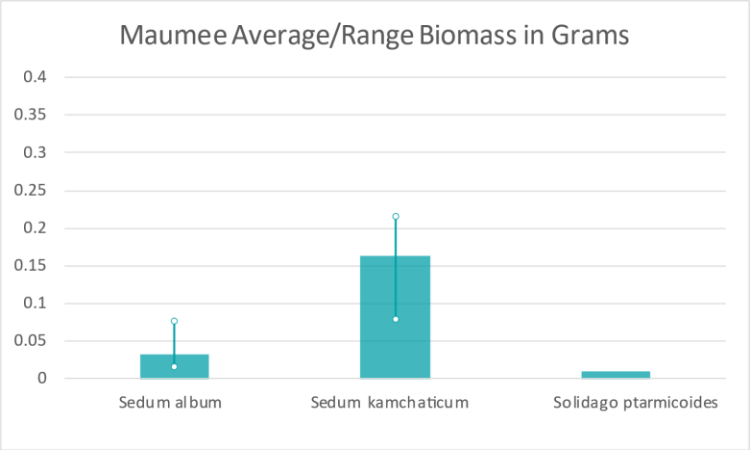


Figure 28 Biomass in Grams from Toledo Sample

The Rooflite® sample had a significant difference with the *Sedum Kamchaticum* having much higher biomass than the other samples. The *Sedum Album* was similar to the others, and the *Solidago Ptarmicoides* the same.

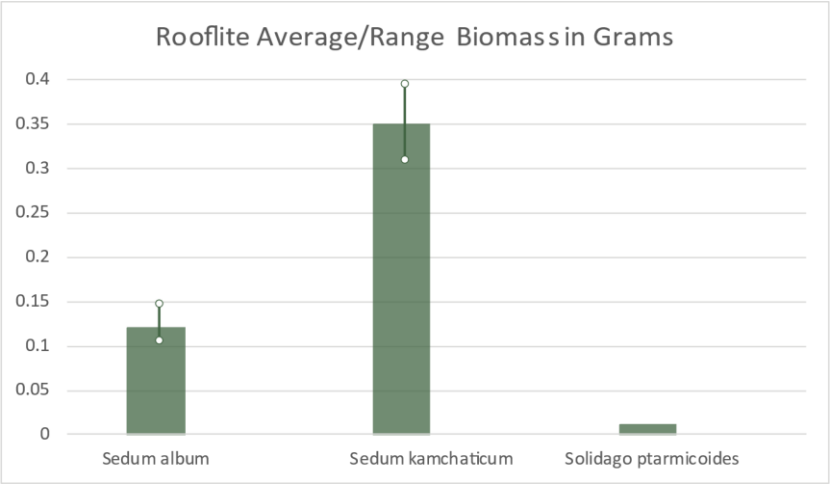
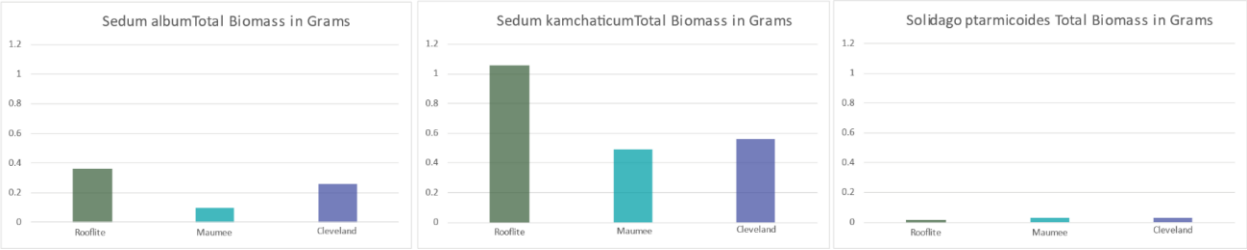


Figure 29 Biomass in Grams from Rooflite® sample

Figure 30 compares the total biomass of three plants from different growth media. For *Sedum Album*, Rooflite had the most biomass, with Cleveland following not too far behind (Figure 30A). Figure 30B indicates *Sedum Kamchaticum* had the most biomass from the Rooflite sample The Maumee and Cleveland samples were very similar in biomass. Biomasses of *Solidago Ptarmicoides* are compared in Figure 30C. The Maumee and Cleveland were just about the same total biomass, with the Rooflite being the lowest. This could mean that the Maumee and Cleveland samples are better to germinate seeds into. One thing to note is that the *Sedum Kamchaticum* cuttings were larger than the *Sedum Album* cuttings at the beginning of the study.



(a) Sedum Album (b) Sedum Kamchaticum (c) Solidago Ptarmocoides

Figure 30 Total Biomasses from Different Growth Media

4.3 Summary

The results of a comprehensive experimental plan were presented and discussed in Chapter 4. The LWA made from dredged material was incorporated in the green roof material. The dredged

material was successfully used as a component in developing plant growth media. The lab and field testing show it has a great potential to be used for plants development.

5. Market Research

The research team partnered with the College of Business Administration, Kent State University to research the possibility of using the LWA as a commercially available product for use in green infrastructure especially as a growth media for green roofing. Supervised by Professor Christopher Groening from the Department of Marketing and Entrepreneurship, four groups, a total of 14 senior students majored in Marketing took this study as their cap-stone projects. The main findings are summarized in this chapter and their presentations are attached in the Appendix A. In addition, the LauchNET directed by Professor Julie Messing at Kent State University provides the research team with a Startup Canvas to develop a business model and commercialize the product. The tool used is included in this chapter.

5.1 Findings from Market Research

The following findings were excerpted from a report authored by Matt Bianco, Megan Henrich, and Sydney Shepherd.

Through primary and secondary research, trends in the industry were identified that helped shape understanding of the green roof market and the LWA as a whole. Green roofing is projected to account for 8% of all roofing installed in 2017, and there is a natural trend towards sustainable architecture overall. We also found that this product does better in larger cities where government incentives are being provided to help lower the cost of green roofing. Our survey of architects gauges opinions of green roofing and preferences for green roof media, and provided insight of what these decision makers were looking for when selecting which materials to use in a green roof project.

Based on the total area of green roofing installed the firm was able to identify five major areas to target. Washington D.C., Philadelphia, Chicago, New York, and Baltimore have the largest green roof markets in the U.S. making them the most attractive cities. Aside from these top regions, the firm is suggesting to additionally target Northeast Ohio, because it is home to the product.

Three segments were identified through our research and "Industry Insiders" is the group that will be the focus of the promotions plan. Industry insiders are primarily architects and green roofing designers. This group has a direct hand in designing a building with a green roof, and they are the ones who decide which materials are used in a finished green roof. It is important to note that the product is only green roof media, and we are not promoting the green roof as a

whole. This is an important distinction because green roof media and total green roofs would have completely different promotional strategies.

Through the information gathered about our target segment and market, the firm created a comprehensive promotional plan….. This includes but is not limited to appearances at trade shows, advertisements in top trade publications, on-line advertising, direct email, and other promotional strategies. The firm will recommend two different approaches for the top five major markets and Northeast Ohio. The goal of the promotions plan is to gain market penetration in the target cities……

5.2 Business Model Canvas

The following tools provided by the LauchNET were used to develop a business model to promote using dredged material in green infrastructure. They could be referenced by others to develop their own business models. More research results have been revealed by Marketing students in the Appendix A.

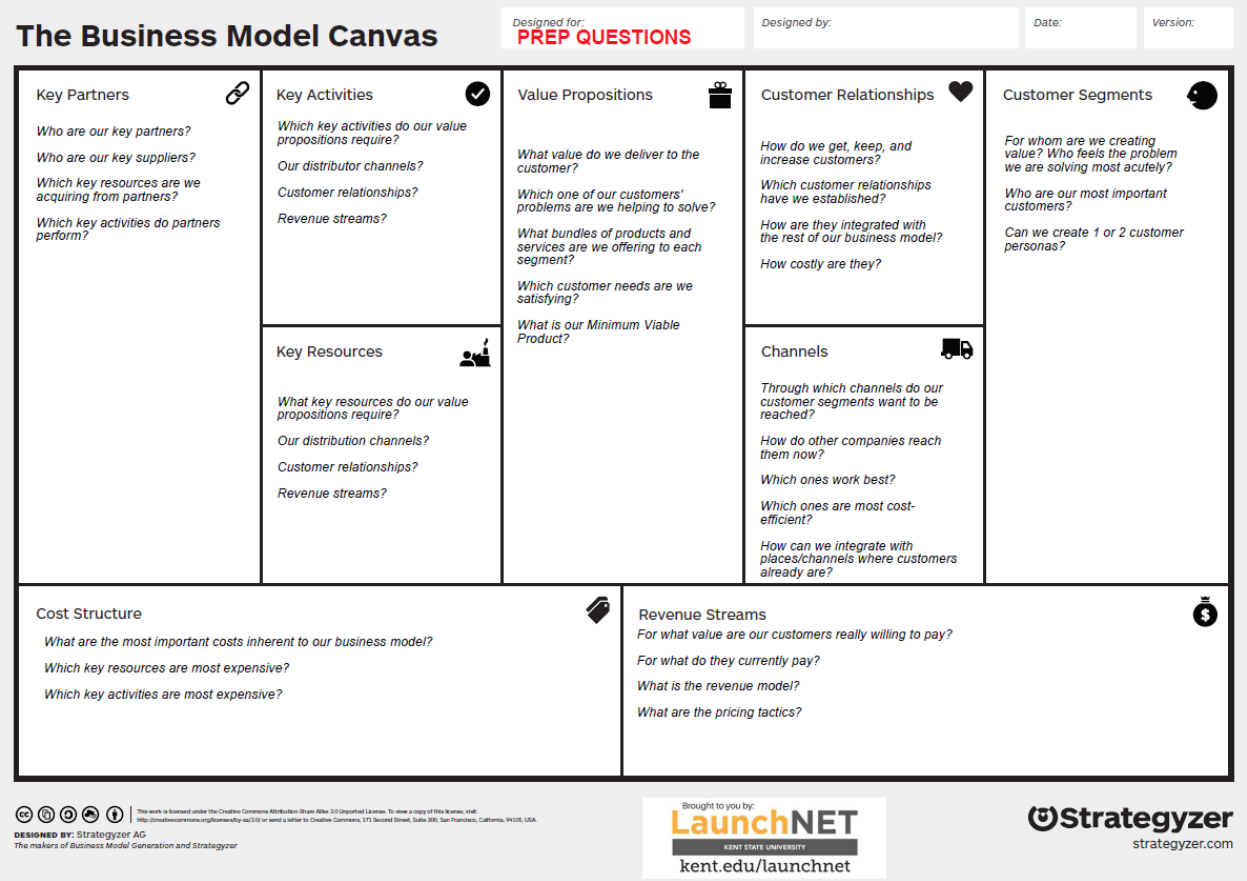
Table 9 Startup Canvas

LaunchNET
KENT STATE UNIVERSITY
kent.edu/launchnet

LaunchNET Lean Startup Canvas

1. Problem to Solve Reducing the amount of dredged material in the Great Lakes and repurposing the dredge into a lightweight aggregate material that will be used as an alternative RoofLite material	**2. People with Problem** This problem is nation wide and affects the quality of the worlds largest bodies of fresh water.	**3. Current Solution(s)** Dredged Material Disposal Facilities (DMDF) Confined Disposal Facilities (CDF) What's wrong with them? Unexpected overuse Expensive	**4. Channels** One of the best ways for us to advertise is by signing up for local design conventions and setting up a booth for advertising we can then create our start up website with Launch NET **5. Need to Succeed** We will need a more efficient and time effective way of producing the material we are hoping that through various sponsers we will be able to move out of our current lab and consider moving to a bigger more equip facility	**6. Unfair Advantage(s)** All designers are in a race to be the ones to resolve this on going issue with dredge material. By re-purposing the dredge material into a sustainable design strategy instead of designing new landfill solutions we have the advantage. We also have the advantage that our material holds a structural advantage for green infrastructure and drainage.
7. Revenue Streams		**8. Cost Structure**		

Table 10 Business Model Canvas



The Business Model Canvas

Designed for: PREP QUESTIONS | Designed by: | Date: | Version:

Key Partners

Who are our key partners?

Who are our key suppliers?

Which key resources are we acquiring from partners?

Which key activities do partners perform?

Key Activities

Which key activities do our value propositions require?

Our distributor channels?

Customer relationships?

Revenue streams?

Key Resources

What key resources do our value propositions require?

Our distribution channels?

Customer relationships?

Revenue streams?

Value Propositions

What value do we deliver to the customer?

Which one of our customers' problems are we helping to solve?

What bundles of products and services are we offering to each segment?

Which customer needs are we satisfying?

What is our Minimum Viable Product?

Customer Relationships

How do we get, keep, and increase customers?

Which customer relationships have we established?

How are they integrated with the rest of our business model?

How costly are they?

Channels

Through which channels do our customer segments want to be reached?

How do other companies reach them now?

Which ones work best?

Which ones are most cost-efficient?

How can we integrate with places/channels where customers already are?

Customer Segments

For whom are we creating value? Who feels the problem we are solving most acutely?

Who are our most important customers?

Can we create 1 or 2 customer personas?

Cost Structure

What are the most important costs inherent to our business model?

Which key resources are most expensive?

Which key activities are most expensive?

Revenue Streams

For what value are our customers really willing to pay?

For what do they currently pay?

What is the revenue model?

What are the pricing tactics?

This work is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported License. To view a copy of this license, visit: http://creativecommons.org/licenses/by-sa/3.0/ or send a letter to Creative Commons, 171 Second Street, Suite 300, San Francisco, California, 94105, USA.

DESIGNED BY: Strategyzer AG
The makers of Business Model Generation and Strategyzer

Brought to you by: LaunchNET KENT STATE UNIVERSITY kent.edu/launchnet

Strategyzer strategyzer.com

6. Conclusions

This study examined the issue of dredge material management, which is one of the current challenges facing Lake Erie and surrounding communities. In addition, algal blooms due to the eutrophication especially increasing phosphorus content due to non-point pollution in the lake could be addressed by constructing green infrastructure to manage stormwater runoff. This report strategically proposed how to use raw dredged material and LWA sintered from dredged material in GI constructions. Here, the quality of the raw dredged material was examined in the lab through chemical and physical testing, its suitability for lightweight aggregate production and GI construction for industrial and residential use. Then, the dredged material was used to develop the engineered filter media for bioretention systems and growth media for green roofs.

The growth media made from dredged material were successfully developed in the lab, with excellent water retention capabilities to manage the storm water. However, the growth media had high wet unit weights, due to the heterogeneous nature of the substrate and different densities of LWA, sand, silt, and clay. Hence, there is a need to develop a lightweight growth media composition with a high-water retention capacity that would help retain high volume of storm water. Further, the leachate test results demonstrated the water quality of engineered Type 1 and Type 2 substrates, comparable with the drained water from commercial product Rooflite®

The study investigated Viola Pedatifida because of its difficulty to establish and persist in disturbed and engineered soils. A two-sample unequal variance t-test with two-tailed distribution was performed to compare the differences of the plants harvested from the Type 1 growth media developed using dredged material and Rooflite®. The results showed the plant coverage area comparison for the substrates were statistically insignificant.

Field testing plots for additional green roof microcosms have be constructed at the Cleveland Industrial Innovation Center (CIIC) through an existing memorandum of understanding between CIIC and Kent State University. Native, exotic, and rare plants including Sedum Album, Sedum Kamchaticum, and Solidago Ptarmicoides have been investigated for their potential applications in the newly developed growing media made from the dredged material. The Rooflite® sample had the highest average growth. The Maumee (Toledo) and Cuyahoga (Cleveland) samples average growth were very similar. The ranges of growth for both the Maumee and Cleveland samples reached the average inches grown in the Rooflite® sample. The Sedum Kamchaticum

cuttings was larger than the Sedum Album and Solidago Ptarmicoides cuttings. All three species have comparable performances in the three growth media tested in the field in this study.

To beneficially use the dredged material in GI construction, several challenges must be addressed: (1) Determine the contamination of the dredged material and its suitability to be used in the built environment; (2) evaluate the performance of the dredged material as a GI construction material; (3) investigate the cost and sustainability issues; and (4) evaluate regulatory issues and public acceptance. This study proposed solutions to the first two challenges. The research team is developing a business model that determines market relevance of the technology through partnerships with industry and manufacturing involving direct, indirect, and life cycle cost analysis. In addition, the research team is collaborating with Ohio EPA to evaluate regulatory issues and to promote its beneficial uses in the built environment. The research team will also investigate other ecosystems benefits of green infrastructures made from dredged material and strategies to install these infrastructures in the urban area to improve the resilience of Lake Erie and its local communities in the future.

7. References

[1] U. S. Army, “Army Low Impact Development Technical User Guide,” 2013.

[2] N. R. Francingues, D. W. Thompson, and F. L. Hamons, “Exploring Innovative Reuse of Dredged Material From Baltimore Harbor,” pp. 271–280, 2011.

[3] J. P. Kreitinger, R. A. Price, T. D. Borrowman, A. J. Kennedy, D. L. Brandon, and M. Bourne, “Project Report Evaluation of Beneficial Use Suitability for Cleveland Harbor Dredged Material : Interim Capacity Management and Long-Term Planning Environmental Laboratory,” no. August, 2011.

[4] K. Hamer and V. Karius, “Brick production with dredged harbour sediments. An industrial-scale experiment,” *Waste Manag*., vol. 22, no. 5, pp. 521–530, 2002.

[5] R. Liu and R. Coffman, “Lightweight Aggregate Made from Dredged Material in Green Roof Construction for Stormwater Management,” *Materials*, vol. 9, no. 8, p. 611, 2016.

[6] Hula, R. C. (2012). Reclaiming Brownfields: A comparative analysis of adaptive reuse of contaminated properties. Routledge. Pg 263.

[8] Curtis Hinman. (2005). Low Impact Development, (February).

[9] E. Oberndorfer et al., “Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services,” Bioscience, vol. 57, no. 10, pp. 823–833, 2007.

[10] Hopkins, G., & Goodwin, C. (2011). Living architecture: green roofs and walls. Csiro Publishing.

[11] Peck, S. 2012 The Rise of Living Architecture, Green Roofs for Healthy Cities

[12] Kadas, G. (2006). Rare invertebrates colonizing green roofs in London. Urban habitats, 4(1), 66-86.

[13] Coffman, R.2009 "Elevating Habitat:Creating biodiversity through quasi-traditional green roof design." Landscape Architecture Magazine, Vol 99, No1, Jan pgs 72-77

[14] Loder, A. (2014). 'There's a meadow outside my workplace': A phenomenological exploration of aesthetics and green roofs in Chicago and Toronto. Landscape and urban planning, 126, 94-106.

[15] Moreno-Garcia, MC. 1994. “Intensity and Form of the Urban Heat Island in Barcelona”. International Journal of Climatology, 14 (6), 705–710.

[16] Bolund, P., & Hunhammar, S. 1999. “Ecosystem Services in Urban Areas”. Ecological Economics, 29 (2), 293–301.

[17] Hardin, PJ, and Jensen, RR. 2007. “The Effect of Urban Leaf Area on Summertime Urban Surface Kinetic Temperatures: A Terre Haute Case Study”. Urban Forestry and Urban Greening, 6, 63–72

[18] Nowak, DJ, and Crane, DE. 2000. The Urban Forest Effects (UFORE) Model: Quantifying Urban Forest Structure and Functions. In: Hansen, Mark; Burk, Tom, eds. Integrated tools for natural resources inventories in the 21st century. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. 714-720.

[19] McPhearson, T. 2011. Toward a Sustainable New York City: Greening through Urban Forest Restoration. In E. Slavin (Ed.), Sustainability in America’s Cities: Creating the Green Metropolis (pp. 181–204). Island Press: Washington, DC.

[20] Aylor, D. 1972. “Noise Reduction by Vegetation and Ground”. Journal of the Acoustical Society of America, 51 , 197–205.

[21] Kragh, J. 1981. “Road Traffic Noise Attenuation by Belts of Trees”. Journal of Sound and Vibration, 74 (2), 235–241.

[22] Fang, C, & Ling, D. 2003. “Investigation of the Noise Reduction Provided by Tree Belts”. Landscape and Urban Planning, 63 (4), 187–195.

[23] Ishii, M. 1994. “Measurement of Road Traffic Noise Reduced by the Employment of Low Physical Barriers and Potted Vegetation”. Inter-noise, 29–31, 595–597

[24] Pathak, V, Tripathi, BD, and Mishra, VK. 2007. “Dynamics of Traffic Noise in A Tropical City Varanasi and Its Abatement through Vegetation”. Environmental Monitoring and Assessment, 146 (1–3), 67–75.

[25] Nowak, DJ. 1994. Air Pollution Removal by Chicago’s Urban Forest. In Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project (McPherson et al. ed.). General Technical Report NE-186. United States Department of Agriculture.

[26] Nowak, DJ. 1996. “Notes: Estimating Leaf Area and Leaf Biomass of Open-grown Deciduous Urban Trees”. Forest Science, 42 (4), 504–507.

[27] Dzierzanowski, K, Popek, R, Gawrońska, H, et al. 2011. “Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Waxes of Urban Forest Species”. International Journal of Phytoremediation, 13 (10), 1037–1046.

[28] Farber, S. 1987. “The Value of Coastal Wetlands for Protection of Property against Hurricane Wind Damage”. Journal of Environmental Economics and Management, 14, 143–151.

[29] Danielsen, F, Sørensen, MK, Olwig, MF, et al. 2005. “The Asian Tsunami: A Protective Role for Coastal Vegetation”. Science, 310 (5748), 643.

[30] Depietri, Y, Renaud, FG, and Kallis, G. 2012. “Heat Waves and Floods in Urban Areas: A Policy Oriented Review of Ecosystem Services”. Sustainability Science, 7, 95–107.

[31] Kerr, AM, & Baird, AH. 2007. “Natural Barriers to Natural Disasters”. BioScience, 57 (2), 102–103.

[32] Villarreal EL, Bengtsson L. 2005. “Response of a Sedum Green roof to Individual Rain Events”. Ecological Engineering. 25: 1–7

[33] Pataki, DE, Carreiro, MM, Cherrier, J, et al. 2011. “Coupling Biogeochemical Cycles in Urban Environments: Ecosystem Services, Green Solutions, and Misconceptions”. Frontiers in Ecology and the Environment, 9 (1), 27–36.

[34] Clausen, JC. 2007. Jordan Cove Watershed Project 2007 Final Report. Department of Natural Resource Management and Engineering, University of Connecticut

[35] Shuster, W, Morrison, M, and Webb, R. 2008. “Front-loading Urban Stormwater Management For success: A Perspective Incorporating Current Studies on the Implementation of Retrofit Low Impact Development”. Cities and the Environment (CATE), 1 (2), Article 8.

[36] Maher, AW, Douglas, S., Jafari, F., and Pecchioli, J. 2013. The Processing and Beneficial Use of Fine-Grained Dredged Material, A Manual for Engineers. Centre for Advance Infrastructure and Transportation. Accessed on 6/21/2016 from http://www.state.nj.us/transportation/airwater/maritime/documents/PDM_FINAL_4.24.13-cs.pdf

[37] Rulkens, W. 2005. “Introduction to the Treatment of Polluted Sediments”. Reviews in Environmental Science and Biotechnology. 4 (3): 213–21. doi:10.1007/s11157-005-2167-6.

[38] U.S. Environmental Protection Agency. 2005. Contaminated Sediment Remediation Guidance for Hazardous Waste Sites. Office of Solid Waste and Emergency Response, 236. Accessed on 7/30/2016 from https://nepis.epa.gov/Exe/ZyNET.exe/P1000R7F.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C00thru05%5CTxt%5C00000015%5CP1000R7F.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

[39] BMP. (2014). BMP Standard specification, (December).

[40] Prince George’s County. (2002). Bioretention Manual. Programs & Planning Division.

[41] Ecommendations WSU. (2009). Bioretention Soil Mix Review and Recommendations for Western Washington, 2456(choice 7).

[42] Santa Clara Valley Urban Runoff Pollution Prevention Program. (n.d.).

[43] BIORETENTION GUIDANCE Lake County , Ohio. (2005).

[44] Wulliman, J., Erikson, S., Kroeger, C., Yager, J., Thomas, P., Frey, M., … Student, J. (n.d.). Ultra Urban Green Infrastructure Guidelines. Retrieved from http://water.epa.gov/infrastructure/green

Appendix A – Marketing Studies and Business Model