infrastructures

Article

Beneficial Uses of Dredged Material in Green Infrastructure and Living Architecture to Improve Resilience of Lake Erie

Shruti Bhairappanavar, Rui Liu * and Reid Coffman

College of Architecture and Environmental Design, Kent State University, Kent, OH 44242, USA; sbhairap@kent.edu (S.B.); rcoffma4@kent.edu (R.C.)

* Correspondence: rliu5@kent.edu; Tel.: +1-330-672-0611

Received: 2 July 2018; Accepted: 24 September 2018; Published: 27 September 2018

Abstract: To maintain the navigational depth, 1.15 million cubic meters (1.5 million cubic yards) of sediment is dredged out from the federal harbors every year from Lake Erie, Ohio Coast. Treating this huge amount of dredged material is a major challenge due to the mobilization of potential contaminants causing depreciation in water quality and depletion of valuable land. Rather than treating the dredged material as a waste, we suggest investigating alternative ways to recycle and reuse the material within Green Infrastructure (GI) and living architecture applications. This study identifies potential applications of the dredged material in bioretention and vegetative roof systems, and examines the role of dredged material in these edaphic conditions. The paper discusses the beneficial uses of dredged material in GI by investigating the quality of dredged material and performances of GI built using dredged material through laboratory and field-testing. Preliminary results of a growth media using dredged material for the vegetative roof have been developed in lab/field studies that possess the performance values comparable to the current commercial product. The growth media containing lightweight aggregate, made from the dredged material, is observed to have high water retention capacity and high unit weight in comparison to a commercial product. The growth media leachate water test demonstrated the water quality to be comparable to the drained water from the commercial product. The growth media overwintered and advanced a rare plant species, *Viola pedatifida*, which is similar to conventional media. The beneficial uses of dredged material in the GI will help maintain the economic viability of harbors and ports along the shoreline of Lake Erie in Ohio and GIs, which were built using dredged material that can help address storm water management issues in urban areas due to extensive impervious surfaces.

Keywords: dredged material; green infrastructure; resilience

1. Introduction

In the United States, the Army Corps of Engineers is responsible for maintaining over 30,578 km (19,000 miles) of navigable waterways in over 1000 harbors and ports. These navigation activities in the ports are currently managed by dredging the bottom sediments (annually, which accounts for 300 million cubic yards or 230 million cubic meters) and transporting it elsewhere for disposal. The water bodies accumulate upstream sediments in the bottom of the lakes or river channel beds as a natural process of aggradation that is intensified in urbanized watersheds [1,2]. The disposal of the dredged material is executed either through open water disposal (OWD) or placed in confined disposal facilities (CDF) [1].

The dumping of dredged material in a CDF or OWD in the prolonged duration is recognized to have environmental impacts on the areas of disposal and its immediate surroundings [3]. As illustrated in Figure 1, the dredged material disposal leads to three main concerns. First, the migration of contaminants is caused by the transportation of heavy metals like arsenic, cadmium, chromium, copper, lead, manganese, mercury, etc. For example, in the case of OWD, the exchange of nutrients in sediments and organometallic interaction results in the release of toxic substances into the water column [4]. In case of CDF, the leachate leaches through the underlying soil into the groundwater [3]. Second, the environmental concerns on OWD question the quality of water and its effect on aquatic life [4]. The disposition of dredged material in the CDF raises a red flag due to the deterioration of a groundwater table and contamination of underlying soil, which causes health hazards to the surrounding neighbourhood [3]. Third, the dredged material management poses difficulties in the disposal of a huge quantity of material annually in the existing CDFs; resulting in a requirement for new CDFs. However, due to urbanization surrounding the ports and harbors, the new CDFs are forced to be located at a greater distance from the dredging site, increasing the disposal cost due to transportation [1,5,6].

An alternative to disposal is to reuse the dredged material in the built environment like construction and landscaping [7–9]. Moreover, 90 percent of the dredged material is considered acceptable for alternative reuses [1,5–10] as the dredged material primarily consists of natural sediments such as gravel, sand, silt, clay, and organic particles [1,7–9]. However, these sediments could be contaminated by municipal or industrial wastes or by runoff from terrestrial sources such as agriculture land [4]. Therefore, the examination of contaminants like heavy metals, fertilizers, sewer waste, pesticides, and petroleum products is recommended to evaluate and treat the material before re-use [11–13], along with testing on physical characteristics (grain size distribution and plasticity); engineering characteristics (compaction, consolidationm and shear strength), and chemical characteristics (cation exchange capacity, nitrogen content, and sulfur content), depending on the structural or non-structural application of dredged material [1,11]. See Table 1.

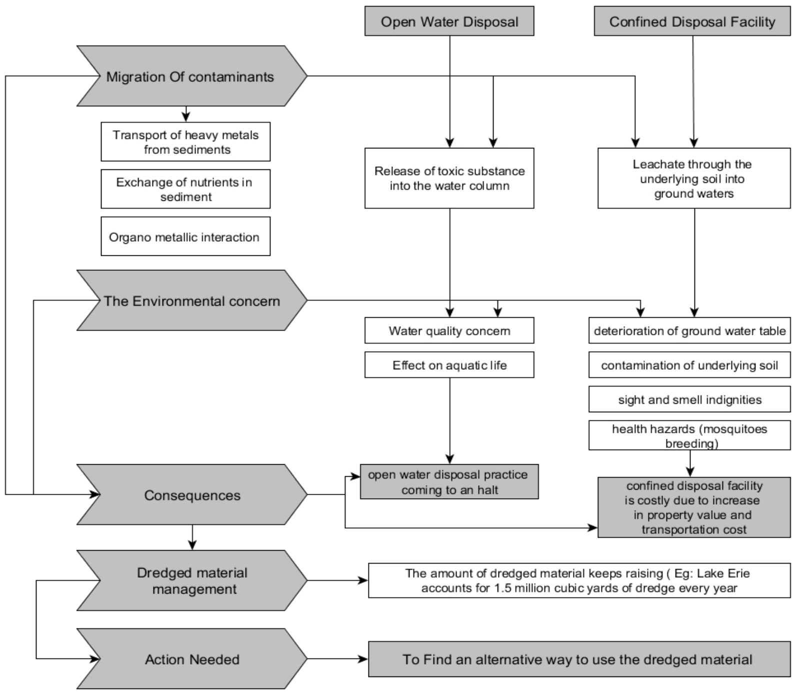

Figure 1. Challenges of Dredged Material Management (Ref: [1–3,6]).

Table 1. Appropriate tests for determining physical, engineering, chemical, and biological properties of dredge material to evaluate its suitability in the built environment (Ref: [5,11]).

Analysis	Appropriate Tests	Standards	Application
Physical Analysis	Grain Size—Standard Sieve test and Hydrometer test	ASTM D422	Structural and Non-structural applications
	Particle Shape/Texture	ASTM D2488	
	Water Content/% Moisture	ASTM D2216	
	Permeability	ASTM D2434, ASTM D5084	
	Atterberg Limit	ASTM D4318	
	Organic content/organic matter	ASTM D2487	
	Unit weight	ASTM D29, ASTM D854, ASTM D1556, ASTM D2922	
Engineering properties	Compaction Tests Standard Compaction Test Modified Compaction Test 15 Blow Compaction Test	ASTM D698 ASTM D1557 ASTM D5080	Structural application
	Consolidation tests	ASTM D2435	
	Bearing capacity	ASTM D1883	
	Shear Strength	ASTM D2850, ASTM D3080, ASTM D4767	
	Compressive Strength	ASTM D2166, ASTM D4219	
Chemical properties	pH	ASA 1996: Ch 16	Structural and Non-structural applications
	Calcium Carbonate Equivalent	ASA 1996: Ch 16	
	Cation Exchange Capacity	ASA 1996: Ch 40	
	Salinity	ASA 1996: Ch 14	
	Sodium	ASA 1996: Ch 19	
	Chloride	ASA 1996: Ch 31	
	Electrical Conductivity	ASA 1996: Ch 14	
	Total Organic Carbon	ASTM D2974; D2974-87; ASA 1982: 29-4.2	
	Ammonium Nitrogen	EPA-CRL-324	
	Nitrate-nitrogen; Nitrite-nitrogen	EPA-SW846-9200	
	Total Phosphorus	EPA-CRL-435	
	Ortho-phosphorus	EPA-CRL-435	
	Potassium	ASA 1996: Ch 19	
	Total Metals	EPA-SW846-200.9; ASA 1996: Ch 18-30	
	Pesticides (chlorinated)	EPA-SW846-8080	
	Polynuclear Aromatic Hydrocarbons (PAHs)	EPA-SW846-8270	
	Dioxins	EPA-SW846-8290 and 1630	
Biological Properties	Animal Bioassay	ASTM 1998	Structural and Non-structural applications
	Elutriate Bioassay	EPA 1991 (Method 11.14)	

Note: ASTM = American Society for Testing and Materials; ASA = American Society of Agronomy/Soil Science Society of America; EPA = U.S. Environmental Protection Agency.

The use of dredged material is a widely used methodology resulting in nearly 2000 man-made islands and 1100 habitat development projects [1]. As illustrated in Figure 2, the environmental enhancement using dredged material generally refers to formation and management of relatively perpetual and biologically productive manmade plant and animal habitats, such as enhancements of harbor and port facilities, strip mine reclamation and solid waste landfill, parks and recreation enhancement, and beach nourishment, where the dredged material feasibility is employed. The utilization of dredged material in agriculture, horticulture, and forestry is primarily used to enhance marginal soil to elevate the productivity of the vegetables, fruits, ornamental plants, orchards, sod farms, and trees with its rich mineral contents for commercial uses. Lastly, one of the unique beneficial uses of the dredged material, identified by U.S. Army Corps of Engineers, is to produce lightweight aggregate (LWA) that can be used in subsequent constructions [1], which are formed by sintering the dredged material with or without mineral admixtures (e.g., calcium and magnesium carbonates and/or silicates) [1,6]. The applications of dredged material in the habitat development, agriculture, and engineering use, such as a land creation, land improvement, berm creation, shore protection, capping, construction material, topsoil, fisheries improvement, and wetland restoration demonstrates the feasible alternatives that are more economical, social, and environmentally beneficial to the surrounding environment, in comparison to the traditional OWD and CDF disposals [1].

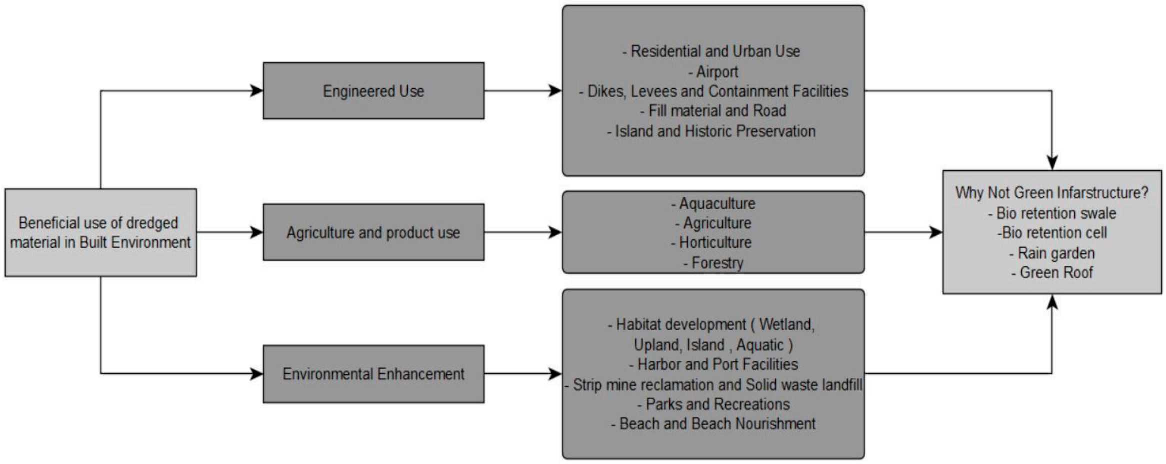

Figure 2. Benefits of dredged material (Ref: [1,6]).

As recognized by the United States Environmental Protection Agency (US EPA), green infrastructure (GI), which includes bioretention, rain gardens, rain barrels, swales, permeable pavement, and constructed wetlands [14,15], is an approach using vegetation and growth media (natural process in the built environment) that urban dwellers can choose to maintain healthy water, provide multiple social, economic and environmental benefits, and support sustainable community development [16]. GI restores dwindling green spaces available in urban and suburban areas, with major functions of reducing the volume of stormwater runoff and peak flow [17–19] and providing a broad range of ecosystem services, e.g., reduction of concentrations of nutrients and metals in nearby water bodies [20], mitigation of urban heat island effect [17,21–28], carbon sequestration [29–31], improvement of aesthetics, noise reduction [32–36], and community livability [20].

Living architecture (LA), in the form of vegetated roofs and walls, provides an array of ecological services in hydrology [14,19,37,38], air temperature [17,22], biological diversity [15,39,40], human wellness and it separates itself as a field of study focusing on structural and mechanical building adaptions using soil and vegetation [20,41,42]. Conceived mainly as rainfall interceptors to reduce storm water runoff [18], roofs are now being designed as novel ecosystems possessing suites of ecosystem services ranging from providing habitat for rare wildlife species [15,39,40] to nature access for human restoration and wellness [43].

The high-water absorption rate (10.96–23.40%) and low specific gravity (SG) of the LWA made by dredge material samples (SG 1.46–1.74) [6] demonstrates a potential beneficial use in green infrastructure and living architecture to enhance its hydraulic soil performance, by increasing infiltration and permeability preventing site stormwater runoff.

The LA/GI rely on soil-plant interactions where the soil provides an environment to anchor plants to the site while containing essential plant nutrients, and in turn, the plant roots prevent soil erosion and utilize soil nutrients and organic matter for growth and defense. However, most forms of LA/GI use engineered soil in the place of natural soil to retain greater volumes of water and nutrients that improve storm water runoff quantity and quality [44,45]. The plants use physical, chemical, and biological processes to filter and clean the storm water, improving the water quality [14,46–51]. The benefits of GI, especially in stormwater management and the urban heat island effect, is successfully obtained by cautiously choosing the engineered growth media as it influences the plant growth by providing nutrients and enhances the GI performance due to peak flow reduction, improvement in water quality, thermal insulation, and sound insulation in case of green roofs [44,45].

The engineered growth media is heterogeneous in nature, consisting of coarse aggregate (lightweight and porous), fine aggregate (sand), and organic matter [52]. Currently, there are numerous commercial engineered growth media available in the market, manufactured using naturally available LWA like lava, pumice, expanded slate, clay, and shale. However, they are costly due to the utilization of finite natural resources, which are mostly available in few locations resulting in increased substrate cost. Hence, there is a need for additional investigation for alternative lightweight material to use in growth media, which is locally available to lower the construction cost of GI [45]. One such attempt is made in this study and discusses the strategy of how dredge material could be used in the construction of GI. The study discusses the beneficial uses of dredged material in GI by investigating the quality of dredged material and the performances of GI built using dredged material through laboratory and field-testing. The paper also discusses the initial performance criteria that can be achieved and acknowledges the sustainability achieved using the dredged material.

2. Site Description

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 3). 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), recreational, or both [5].

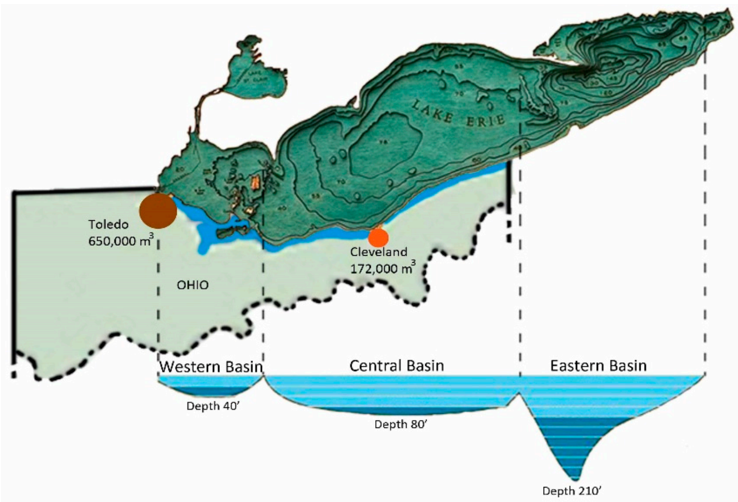

Figure 3. Map of Lake Erie: physical features and areas with immediate action required (Toledo brown large circle and Cleveland red small circle indicate immediate actions required due to huge amounts of sediments dredged in these harbors) (Reference [5]).

To maintain economic viability and the sustainable development of harbors and ports built along the coast of Lake Erie, 1.15 million cubic meters (1.5 million cubic yards, CY) of dredged material needs to be removed annually. Landfill of the dredged material is costly and occupies valuable land space, while OWD has the potential to deteriorate water quality through siltation, increased turbidity, and mobilization of potential contaminants, therefore increasing the risk of algal bloom [4]. The OWD of dredged material in Lake Erie will be banned in the State of Ohio after 1 July 2020 [53]. In Cleveland, dredged material is disposed off in a 42.1-hectare (104-acre) CDF, maintained by the Cleveland-Cuyahoga County Port Authority.

Nevertheless, additional capacity is needed to accommodate the 172,000 m^3 (225,000 CY) of sediment that needs to be disposed off 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 influence on the surroundings and the water table below. An alternative to disposal is to reuse the dredged material in the built environment like construction and landscaping material [6,9,10].

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 [1,5,7,8], and sintered products [6]. 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 [1,6]. The application of raw dredge is most common and occurs within the categories of beneficial uses discussed above [1]. 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 sintered dredged material taken from the Harbor of Cleveland [6], which could potentially create an ecologically beneficial product, as well as an economical alternative compared to the currently produced LWA.

The suitability of using the dredged material from the Harbor of Cleveland in the built environment was evaluated by Liu and Coffman [6]. The paper in Reference [8] demonstrated the contents of the major heavy metals (Arsenic, Cadmium, Chromium, Copper, Iron, Lead, Manganese and Mercury) to be lower than the Risk Screen Levels specified by U.S. EPA (EPA SW846 6010B, EPA SW846 7471A, EPA 335.2 and EPA SW846 7196A) for residential and industrial uses. In addition, the research group completed the leaching test to examine leaching potentials of heavy metals from the sintered lightweight aggregate made from dredged material taken from the CDF in Cleveland. 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 in this study.

Many cities in the Lake Erie region are transitioning away from industry and manufacturing economies in the hope of reclaiming urban cores lost later in the 20th century, as a part of global trade and suburbanization [54]. This has resulted in new core architecture growth and dispersed remnant vacant post-industry lands. In some cases, the combination of concentrating development in urban centers, while planning for distributed urban green infrastructure could be mutually beneficial. For example, the City of Cleveland, being the manufacturing and industrial center for Cuyahoga County, hosted many industries back in the day, which resulted in dense residential neighborhoods. After the 1980's, the City observed a period of high unemployment due to the shutdown of industries. Most of these industrial sites, which were heavily polluted, turned out to be brownfields (5666 hectares/14,000 acres) with almost 90 percent of impervious surfaces [10]. These impervious surfaces adversely contribute to the water quality impairment of urban waterways due to the reduction in volume of soil infiltration, resulting in the increase of the rate and volume of storm water runoff in nearby water bodies [55]. In addition, these un-remediated brownfields devalue and destabilize neighborhoods around this area, and the impervious surface increases flooding concerns in combined sewer overflow areas where many brownfields are located [54].

The growth media in GI could help emphasize infiltration and hydrological retention, whereas, plants using biological processes could potentially provide a flexible and affordable solution to reduce stormwater runoff in the urban brownfields 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 dredged material in GI and living architecture would help improve the resilience of Lake Erie, on the one hand, and mitigating the issue of infiltration on the other, a seemingly inevitably circular economy [56–59] solution. The dredged material may supply nutrients to plant growth in GI, and raw mineral materials to produce LWA, which has a high hydrological retention capacity for GI construction. This study discusses the potential applications of dredged material in the construction of GI by investigating the water quality and hydraulic performances of two types of substrate mix using dredged material through laboratory and field testing to reduce storm water runoff, which affects people residing on the coast of Lake Erie.

3. Materials and Methods

3.1. Experimental Design

Two types of green roof growth media, Type 1 and Type 2, were developed using the raw dredged material and LWA made from dredged material taken from the Harbor of Cleveland (The LWA made from the dredged material was produced in the material testing lab, College of Architecture and Environmental Design, Kent State University, using the same procedure as specified in Reference [6]). 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. Water Retention Capacity, Unit Weight and Leachate Quality

A testing device (see Figure 4) 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/m^3) 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 4. 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.

3.3. 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 on May 2016 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 inche depth growth media (i.e., one iteration per substrate mix) and were irrigated manually every week for the entire summer of 2016 (Figure 5). In that summer, plant growth was recorded by hand-held NDVI (Normalized Difference Vegetative Index, GreenSeeker® Crop Sensing System, Trimble®, Sunnyvale, CA, USA) 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 [60–62]. 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 mm^2 resolution. See Figure 6.

Figure 5. Vegetated (*Viola pedatifida*, Prairie Violet) green roof media. Growth media with the dredged material (**left**) and Rooflite® growth media (**right**).

Figure 6. L1-3100C Area Meter (**left**), used to measure the leaf coverage area (**right**).

4. Results

4.1. Water Retention Capacity, unit weight and Leachate Quality

The water retention capacity and wet unit weight of substrate testing results are summarized in Table 2. 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 7). 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 7.

Table 2. Water retention capacity and wet unit weight of substrate (Lab Testing Results).

Specimens	Dry Material wt. (kg)	Water Adsorbed (mL)	Wet wt. of Sample (kg)	Water Retention (%)	Wet Unit Weight (kg/m^3)
			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

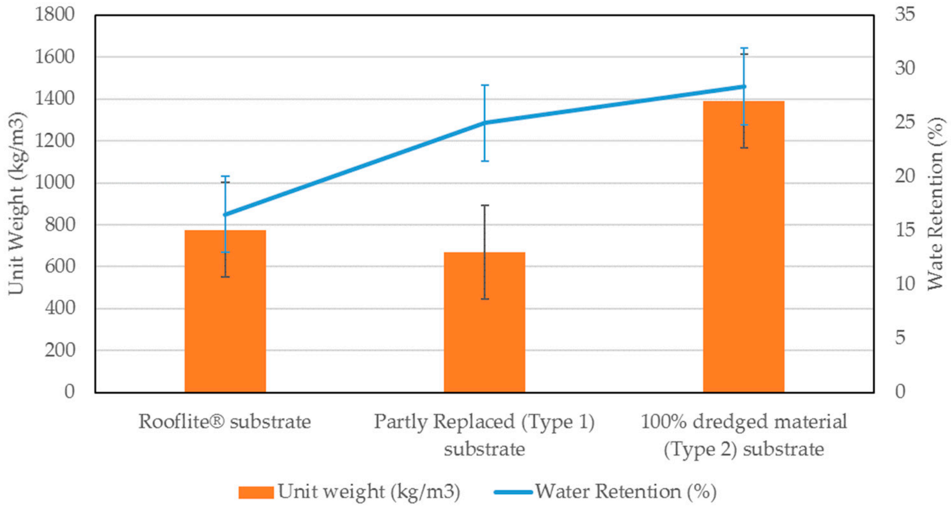

Figure 7. Relationship between water retention capacity and wet unit weight of substrates.

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 3. 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

4.2. 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 5).

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 8) 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 4 indicates the differences of biomass harvested at the end of growing season are not statistically significant between the dredged material-based media and Rooflite®.

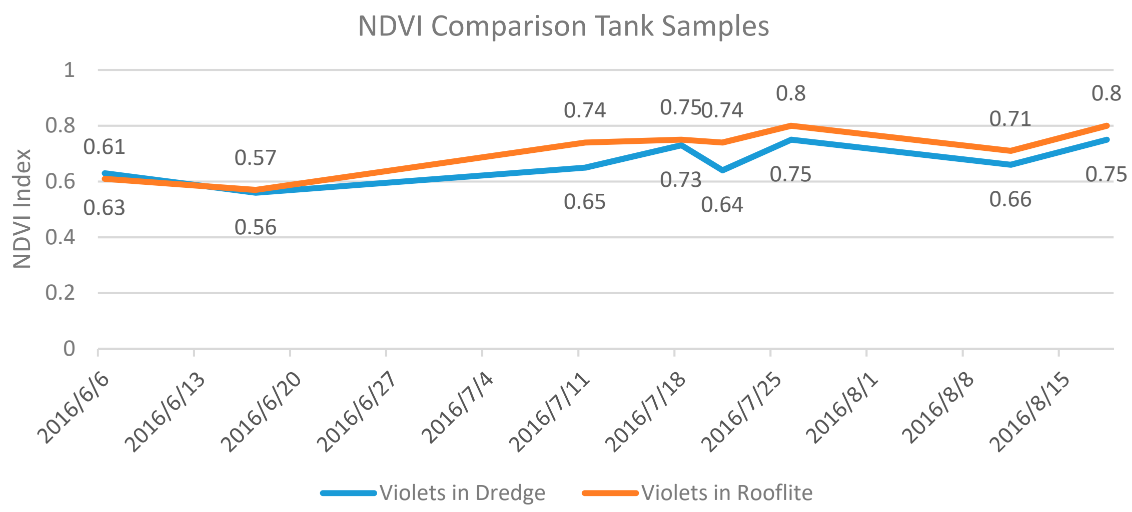

Figure 8. NDVI comparison graph, Violets in Dredge vs. Violets in Rooflite®.

Table 4. Plant Coverage Area value.

Sample No.	Plant Cover Area (cm^2) Dredged Material	Plant Cover Area (cm^2) 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 (cm^2)	320.323	372.547
Standard Deviation (cm^2)	123.786	114.561
Probability (*t*-test)	0.198 > 0.05 (Statistically insignificant)	

4.3. 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 7, 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/m^3) differ from the Rooflite® material (whose bulk density was observed to be 0.304 kg/m^3). 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 4).

5. Conclusions

This study examined the current challenges facing Lake Erie and surrounding communities: Algal blooms due to the eutrophication especially increasing phosphorus content in the lake, and dredged material management. To manage stormwater runoff is the necessary step to address the issue of non-point phosphorus pollution in Lake Erie. This article 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 two types of growth media (type 1 and type 2) made from dredged material were successfully developed in the lab, with excellent water retention capabilities to manage the storm water. However, the two engineered 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 Type 1 and Type 2 substrates, comparable with the drained water from commercial product Rooflite®

The study only investigated *Viola pedatifida* because of its difficulty to establish and persist in disturbed and engineered soils. 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* are under investigation for their potential applications in the newly developed growing media made from the dredged material.

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.

Author Contributions: S.B., R.L. and R.C. conceived and designed the experiments; S.B. performed the experiments; S.B., R.L. and R.C. analyzed the data; R.L. contributed reagents/materials/analysis tools; S.B. drafted the paper, which was edited and improved by R.L. and R.C.

Funding: The project was funded by the Ohio the Lake Erie Protection Fund (LEPF) grant number TG507-2016.

Acknowledgments: The LEPF is supported by the citizens of Ohio through their purchase of the Lake Erie License Plate. Special thanks to Pamela Allen, Kurt Princic, and David Emerman from Ohio Environmental Protection Agency, James White from Harbor of Cleveland, and Jason Ziss from Kurtz Brothers, Inc. who advised the research team and helped acquire the dredged material samples from a confined disposal facility in Cleveland. The authors would also like to thank many undergraduate and graduate students in Kent State University who contributed to this research study: Emily Appelbaum, Zachary Karto, Brandon Sanchez, Jennifer Rufener, Khue Trinh, and Keely Mager from College of Architecture and Environmental Design, and Anna Droz, Department of Biological Sciences.

Conflicts of Interest: The authors declare no conflict of interest

References

1. U.S. Army Corps of Engineers. Beneficial Uses of Dredged Material. USACE Engineer Manual No. 1110-2-5026. 1987, p. 284. Available online: https://www.publications.usace.army.mil/portals/76/publications/engineermanuals/em_1110-2-5025.pdf (accessed on 22 June 2018).
2. Walling, D.E.; Webb, B.W. *Erosion and Sediment Yield: Global and Regional Perspectives: Proceedings of an International Symposium Held at Exeter, UK, from 15 to 19 July 1996*; IAHS Press, Institute of Hydrology: Wallingford, UK, 1996; pp. 3–19. ISBN 0-947571-89-2.
3. Chen, K.Y.; Eichenberger, B.; Mang, J.L.; Hoeppel, R.E. *Confined Disposal Area Effluent and Leachate Control (Laboratory and Field Investigations)*; University of Southern California: Los Angeles, CA, USA, 1978; Available online: https://emrrp.el.erdc.dren.mil/elpubs/pdf/trd78-43.pdf (accessed on 15 May 2017).
4. Truitt, C.L. Dredge Material Behavior During Open Water Disposal. *J. Coast. Res.* **1988**, *4*, 489–497.
5. Brandon, D.L.; Price, R.A. Summary of Available Guidance and Best Practices for Determining Suitability of Dredged Material for Beneficial Uses. Engineer Research and Development Center Vicksburg Ms Environmental Lab, 2007. Available online: http://www.dtic.mil/dtic/tr/fulltext/u2/a474463.pdf (accessed on 19 August 2017).
6. Liu, R.; Coffman, R. Lightweight Aggregate Made from Dredged Material in Green Roof Construction for Stormwater Management. *Materials* **2016**, *9*, 611. [CrossRef] [PubMed]
7. Francingues, N.R.; Thompson, D.W.; Hamons, F.L. Exploring Innovative Reuse of Dredged Material from Baltimore Harbor. In Proceeding of the 2011 WEDA Technical Conference and Texas A&M Dredging Seminar, Nashville, TN, USA, 5–8 June 2011; pp. 271–280.
8. Kreitinger, J.P.; Price, R.; Borrowman, T.D.; Kennedy, A.J.; Brandon, D.L.; Bourne, M. *Evaluation of Beneficial Use Suitability for Cleveland Harbor Dredged Material: Interim Capacity Management and Long-Term Planning*; ERDC/EL Project Report; US Army Corps of Engineers: Washington, DC, USA, 2011; Available online: http://www.lrb.usace.army.mil/Portals/45/docs/Cleveland/Army_ERDC_Cleveland_BU_Final_Report.pdf (accessed on 24 September 2018).
9. Hamer, K.; Karius, V. Brick production with dredged harbour sediments. An industrial-scale experiment. *Waste Manag.* **2002**, *22*, 521–530. [CrossRef]
10. Hula, R.C. *Reclaiming Brownfields: A Comparative Analysis of Adaptive Reuse of Contaminated Properties*; Routledge: Abingdon, UK, 2016; p. 263.
11. Maher, A.W.; Douglas, S.; Jafari, F.; Pecchioli, J. The Processing and Beneficial Use of Fine-Grained Dredged Material, A Manual for Engineers. Centre for Advance Infrastructure and Transportation, 2013. Available online: http://www.state.nj.us/transportation/airwater/maritime/documents/PDM_FINAL_4.24.13-cs.pdf (accessed on 21 June 2016).
12. Rulkens, W. Introduction to the Treatment of Polluted Sediments. *Rev. Environ. Sci. Biotechnol.* **2005**, *4*, 213–221. [CrossRef]
13. U.S. Environmental Protection Agency. Contaminated Sediment Remediation Guidance for Hazardous Waste Sites. Office of Solid Waste and Emergency Response, 2005; p. 236. Available online: 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 (accessed on 30 July 2016).

14. U.S. Army Corps of Engineers. Army Low Impact Development Technical User Guide. January 2013. Available online: https://www.usace.army.mil/Portals/2/docs/Sustainability/Hydrology_LID/Army_LID_Technical_User_Guide_January2013.pdf (accessed on 15 May 2017).
15. Maes, J.; Liquete, C.; Teller, A.; Erhard, M.; Paracchini, M.L.; Barredo, J.I.; Grizzetti, B.; Cardoso, A.; Somma, F.; Petersen, J.E.; et al. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosyst. Serv.* **2016**, *17*, 14–23. [CrossRef]
16. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.L.; et al. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
17. Bolund, P.; Hunhammar, S. Ecosystem Services in Urban Areas. *Ecol. Econ.* **1999**, *29*, 293–301. [CrossRef]
18. Villarreal, E.L.; Bengtsson, L. Response of a Sedum Green roof to Individual Rain Events. *Ecol. Eng.* **2005**, *25*, 1–7. [CrossRef]
19. Pataki, D.E.; Carreiro, M.M.; Cherrier, J.; Grulke, N.E.; Jennings, V.; Pincetl, S.; Pouyat, R.V.; Whitlow, T.H.; Zipperer, W.C. Coupling Biogeochemical Cycles in Urban Environments: Ecosystem Services, Green Solutions, and Misconceptions. *Front. Ecol. Environ.* **2011**, *9*, 27–36. [CrossRef]
20. Oberndorfer, E.; Lundholm, J.; Bass, B.; Coffman, R.R.; Doshi, H.; Dunnett, N.; Gaffin, S.; Köhler, M.; Liu, K.K.; Rowe, B. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *Bioscience* **2007**, *57*, 823–833. [CrossRef]
21. Moreno-Garcia, M.C. Intensity and Form of the Urban Heat Island in Barcelona. *Int. J. Climatol.* **1994**, *14*, 705–710. [CrossRef]
22. Hardin, P.J.; Jensen, R.R. The Effect of Urban Leaf Area on Summertime Urban Surface Kinetic Temperatures: A Terre Haute Case Study. *Urban For. Urban Green.* **2007**, *6*, 63–72. [CrossRef]
23. Nowak, D.J.; Crane, D.E. The Urban Forest Effects (UFORE) Model: Quantifying Urban Forest Structure and Functions. In *Integrated Tools for Natural Resources Inventories in the 21st Century*; General Technical Report NC-212; Hansen, M., Burk, T., Eds.; U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 2000; pp. 714–720.
24. McPhearson, T. Toward a Sustainable New York City: Greening through Urban Forest Restoration. In *Sustainability in America's Cities: Creating the Green Metropolis*; Slavin, E., Ed.; Island Press: Washington, DC, USA, 2011; pp. 181–204.
25. Farber, S. The Value of Coastal Wetlands for Protection of Property against Hurricane Wind Damage. *J. Environ. Econ. Manag.* **1987**, *14*, 143–151. [CrossRef]
26. Danielsen, F.; Sørensen, M.K.; Olwig, M.F.; Selvam, V.; Parish, F.; Burgess, N.D.; Hiraishi, T.; Karunagaran, V.M.; Rasmussen, M.S.; Hansen, L.B.; et al. The Asian Tsunami: A Protective Role for Coastal Vegetation. *Science* **2005**, *310*, 643. [CrossRef] [PubMed]
27. Depietri, Y.; Renaud, F.G.; Kallis, G. Heat Waves and Floods in Urban Areas: A Policy Oriented Review of Ecosystem Services. *Sustain. Sci.* **2012**, *7*, 95–107. [CrossRef]
28. Kerr, A.M.; Baird, A.H. Natural Barriers to Natural Disasters. *BioScience* **2007**, *57*, 102–103. [CrossRef]
29. McPherson, G.E.; Nowak, D.J.; Rowntree, R.A. *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*; Gen. Tech. Rep. NE-186; US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Radnor, PA, USA, 1994.
30. Nowak, D.J. Notes: Estimating Leaf Area and Leaf Biomass of Open-grown Deciduous Urban Trees. *For. Sci.* **1996**, *42*, 504–507.
31. Dzierzanowski, K.; Popek, R.; Gawrońska, H.; Sæbø, A.; Gawroński, S.W. Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Waxes of Urban Forest Species. *Int. J. Phytoremed.* **2011**, *13*, 1037–1046. [CrossRef] [PubMed]
32. Aylor, D. Noise Reduction by Vegetation and Ground. *J. Acoust. Soc. Am.* **1972**, *51*, 197–205. [CrossRef]
33. Kragh, J. Road Traffic Noise Attenuation by Belts of Trees. *J. Sound Vib.* **1981**, *74*, 235–241. [CrossRef]
34. Fang, C.; Ling, D. Investigation of the Noise Reduction Provided by Tree Belts. *Landsc. Urban Plan.* **2003**, *63*, 187–195. [CrossRef]
35. Ishii, M. Measurement of Road Traffic Noise Reduced by the Employment of Low Physical Barriers and Potted Vegetation. *Inter-Noise* **1994**, *29–31*, 595–597.
36. Pathak, V.; Tripathi, B.D.; Mishra, V.K. Dynamics of Traffic Noise in A Tropical City Varanasi and Its Abatement through Vegetation. *Environ. Monit. Assess.* **2007**, *146*, 67–75. [CrossRef] [PubMed]

37. Clausen, J.C. *Jordan Cove Watershed Project, Final Report*; Department of Natural Resource Management and Engineering, University of Connecticut: Hartford, CT, USA, 2007.
38. Shuster, W.; Morrison, M.; Webb, R. Front-loading Urban Stormwater Management for success: A Perspective Incorporating Current Studies on the Implementation of Retrofit Low Impact Development. *Cities Environ. (CATE)* **2008**, *1*, 8.
39. Kadas, G. Rare invertebrates colonizing green roofs in London. *Urban Habitats* **2006**, *4*, 66–86.
40. Coffman, R. Elevating Habitat:Creating biodiversity through quasi-traditional green roof design. *Landsc. Archit. Mag.* **2009**, *99*, 72–77.
41. Hopkins, G.; Goodwin, C. *Living Architecture: Green Roofs and Walls*; Csiro Publishing: Clayton, Australia, 2011.
42. Peck, S.W. *The Rise of Living Architecture*; Green Roofs for Healthy Cities: Toronto, ON, Canada, 2012; ISBN 0988051702, 9780988051706. Available online: https://books.google.com/books?hl=en&lr=&id=DbjmOWakmYYC&oi=fnd&pg=PA32&dq=The+Rise+of+Living+Architecture&ots=TiG1AXdpss&sig=iP-KrV37UnPEXqeR19H12fjeAt0#v=onepage&q=The%20Rise%20of%20Living%20Architecture&f=false (accessed on 24 September 2018).
43. Loder, A. 'There's a meadow outside my workplace': A phenomenological exploration of aesthetics and green roofs in Chicago and Toronto. *Landsc. Urban Plan.* **2014**, *126*, 94–106. [CrossRef]
44. Graceson, A.; Adams, H. Characterising the components of green roof growing media. In Proceedings of the 1st National Green Roof Student Conference, London, UK, 16–17 May 2011; pp. 15–16.
45. Eksi, M.; Rowe, D.B. Green roof substrates: Effect of recycled crushed porcelain and foamed glass on plant growth and water retention. *Urban For. Urban Green.* **2016**, *20*, 81–88. [CrossRef]
46. Virginia Approved Stormwater BMP Standards and Specifications. Available online: https://www.vwrrc.vt.edu/swc/StandardsSpecs.html (accessed on 15 January 2018).
47. Prince George's County. *Bioretention Manual*; Programs & Planning Division Department of Environmental Resources: Landover, MD, USA, 2002.
48. Hinman, C. Bioretention Soil Mix Review and Recommendations for Western Washington. 2009. Available online: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=9D3D66D721A26FBCE87DAEFDD17C8020?doi=10.1.1.431.4124&rep=rep1&type=pdf (accessed on 30 January 2018).
49. Santa Clara Valley. Urban Runoff Pollution Prevention Program. Available online: http://scvurppp-w2k.com/ (accessed on 15 January 2018).
50. Biohabits. Bioretention Guidance. Lake County, Ohio. 2005. Available online: http://www.lakecountyohio.gov/portals/21/Final%20Report%203-17-06.pdf (accessed on 15 January 2018).
51. Anderson, S.; Piza, H. Ultra Urban Green Infrastructure Guidelines. Available online: https://www.denvergov.org/content/dam/denvergov/Portals/705/documents/ultra-urban-green-infrastructure-guidelines.pdf (accessed on 12 March 2018).
52. Ampim, P.; Sloan, J.J.; Cabrera, R.I.; Jaber, F. Green Roof Growing Substrates: Types, Ingredients, Composition and Properties. *J. Environ. Hortic.* **2010**, *28*, 244–252.
53. Ohio EPA, Lake Erie Dredged Material Program. Available online: http://epa.ohio.gov/dir/dredgehttp://epa.ohio.gov/dir/dredge (accessed on 12 March 2018).
54. Wright, J.G. *Risks and Rewards of Brownfield Redevelopment*; Lincoln Institute of Land Policy: Cambridge, MA, USA, 1996.
55. Arnold, C.L., Jr.; Gibbons, C.J. Impervious surface coverage: The Emergence of a key Environmental Indicator. *J. Am. Plan. Assoc.* **1996**, *62*, 243–258. [CrossRef]
56. Korhonen, J.; Leskinen, P.; Matthies, B.D.; Toppinen, A. Green, circular, bio economy: A comparative analysis of sustainability avenues. *J. Clean. Prod.* **2017**, *168*, 716–734.
57. Reike, D.; Vermeulen, W.J.V.; Witjes, S. The circular economy: New or Refurbished as CE 3.0?—Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resour. Conserv. Recycl.* **2017**, *135*, 246–264. [CrossRef]
58. Kalmykova, Y.; Sadagopan, M.; Rosado, L. Circular economy—From review of theories and practices to development of implementation tools. *Resour. Conserv. Recycl.* **2017**, *135*, 190–201. [CrossRef]
59. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]

60. Liew, O.W.; Chong, P.C.; Li, B.; Asundi, A.K. Signature optical cues: Emerging technologies for monitoring plant health. *Sensors* **2008**, *8*, 3205–3239. [CrossRef] [PubMed]
61. Jackson, R.D.; Huete, A.R. Interpreting vegetation indices. *Prev. Vet. Med.* **1991**, *11*, 185–200. [CrossRef]
62. Govaerts, B.; Verhulst, N. *The Normalized Difference Vegetation Index (NDVI) Greenseeker (TM) Handheld Sensor: Toward the Integrated Evaluation of Crop Management Part A: Concepts and Case Studies*; CIMMYT: Mexico, 2010.