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Review

A Systematic Review of the Scientific Literature on Pollutant Removal from Stormwater Runoff from Vacant Urban Lands

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Abstract: Even though the common acknowledgment that vacant urban lands (VUL) can play a positive role in improving stormwater management, little synthesized literature is focused on understanding how VUL can take advantage of different stormwater control measures (SCMs) to advance urban water quality. The project aims to provide urban planners with information on the remediation of vacant lands using urban runoff pollutant removal techniques. To find the most effective removal method, relevant scholarly papers and case studies are reviewed to see what types of vacant land have many urban runoff pollutants and how to effectively remove contaminants from stormwater runoff in the city by SCMs. The results show that previously developed/used land (but now vacant) has been identified as contaminated sites, including prior residential, commercial, industrial, and parking lot land use from urban areas. SCMs are effective management approaches to reduce nonpoint source pollution problems runoff. It is an umbrella concept that can be used to capture nature-based, cost-effective, and eco-friendly treatment technologies and redevelopment strategies that are socially inclusive, economically viable, and with good public acceptance. Among these removal techniques, a bioretention system tends to be effective for removing dissolved and particulate components of heavy metals and phosphorus. Using different plant species and increasing filter media depth has identified the effectiveness of eliminating nitrate nitrogen (NO_3-N). A medium with a high hydraulic conductivity covers an existing medium with low hydraulic conductivity, and the result will be a higher and more effective decrease for phosphorus (P) pollutants. In addition, wet ponds were found to be highly effective at removing polycyclic aromatic hydrocarbons, with removal rates as high as 99%. For the removal of perfluoroalkyl acid (PFAA) pollutants, despite the implementation of SCMs in urban areas to remove PFAAs and particulate-related contaminants in stormwater runoff, the current literature has little information on SCMs' removal of PFAAs. Studies have also found that VUL's size, shape, and connectivity are significantly inversely correlated with the reduction in stormwater runoff. This paper will help planners and landscape designers make efficient decisions around removing pollutants from VUL stormwater runoff, leading to better use of these spaces.

Keywords: stormwater runoff; vacant urban land; stormwater control measure (SCM); pollutant removal

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1. Introduction

Urban stormwater runoff is generally known as a major transport medium for contaminants released into urban environments [1]. It has been known as a major source of nonpoint source pollutants (NPS) during rain [2]. The literature has shown that many pollutants exist in stormwater runoff, which contains total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), heavy metals (Cu, Zn, and Pb), perfluoroalkyl acid (PFAA), and polycyclic aromatic hydrocarbons (PAHs) [3].

There are three factors that contribute to stormwater runoff and increase the pollutant load: First, the potential causes of frequent stormwater runoff mainly include the increased rainfall intensities due to climate change and increases in urbanization and industrialization [4]. Second, the aging of the urban infrastructure and insufficient infrastructure capacities also contribute [5]. Cities may need additional action to deal with an inadequate system capacity, broken pipes, and sewer overflows. Third, it would also be worth mentioning the impact of the time between rainfall on the pollutant load. Capturing and slowing just an inch of rainfall can have greater than expected benefits for water quality related to the first inch of stormwater runoff—sometimes called a "first flush." After a long time without rainfall, the concentration of pollutants in the first flush is higher because the rain washes the contaminants off the ground.

First, impervious surfaces in urban areas, such as industrial, commercial, and residential areas as well as parking lots, replace areas that previously allowed stormwater to infiltrate (i.e., vegetation area), thereby reducing the area where infiltration to the groundwater can occur. Therefore, more stormwater runoff occurs, which may act as a medium that transports contaminants. This action is used to receive water bodies. It is a major cause of the deterioration of the water quality in cities [1]. Second, Barkasi et al. (2012) revealed frequent problems related to infrastructure aging for sanitary sewers and stormwater collection and treatment systems within some older industrialized cities, particularly in the Rust Belt [6]. The issues for earlier or older industrial cities in the United States (USA) and their outdated water infrastructure have continued to date [7] (Vahedifard, 2017). Significant investments were made in stormwater treatment systems from 2005 to 2012, but in 2013, the "American Institute of Civil Engineers' American Infrastructure Report Card" rated the drinking water, stormwater, and wastewater treatment systems at a 'D' level [8]. This poor assessment was mainly caused by failed pipes, broken water lines, and sewer overflows when the storms had broken the original sewage [9]. In the US, 772 cities and 40 million people are serviced by combined sewer systems (CSS) [10]. There are approximately 43,000 combined sewer overflows (CSOs) that occur each year, resulting in 3.2 billion cubic meters of overflow [8]. This severe overflow phenomenon easily brings more contaminants into the water body, thereby increasing the load of toxic pollutants. Excess pollutants can seriously affect the urban water quality if the soil and water containing harmful contaminants rush into nearby waters or infiltrate the groundwater.

Cities within the US have already been looking for effective measures to improve stormwater management for a long time. Among these measures, if the infiltration of stormwater runoff into the on-site area is considered, it can actually bring various economic and ecological benefits, including reducing the cost of the stormwater infrastructure and the pollutant load of the stormwater runoff and increasing the groundwater recharge [11] (Dhakal, 2017). In these sites, with the increases in demolition and the abandonment of residential, commercial, and industrial areas and parking lots, the vacant and underutilized land [12] has become a common feature of contemporary urban landscapes. The penetration of rainwater brings both opportunities and challenges.

The EPA (2013) reported that vacant, underutilized, or abandoned land is the most promising place for stormwater runoff to implement on-site infiltration measures for stormwater runoff [13]. However, the infiltration of stormwater runoff in places where contaminants are present may cause diversions based on the existing pollutants on-site pollutants and may increase the possibility of urban groundwater pollution. Thus, it is important to reconcile the removal of contaminants, including brownfields, to achieve sustainable stormwater management and reduce the pollutant load. The history of prior land use activity can illustrate the potential for vacant or underutilized or abandoned land contamination. Figure 1 clearly shows the relationship between the history of land-use activities and the associated contamination probability.

Low probability of a contaminated site → High probability of a contaminated site
Park – Farm – Residential – Retail – Commercial – Service Station or Dry Cleaners – Industrial
Past and present property use

Figure 1. The general relationship between the property use, site history, and the associated probability of contamination. Source: [13].

Pollutant removal from runoff has become a significant issue in stormwater management. Vacant urban land (VUL) presents valuable stormwater management and mitigation opportunities. However, the premise is that these runoff pollutants from unattended vacant land areas need to be removed with appropriate procedures to ensure the quality of the urban runoff. In other words, VUL does not always need to be viewed as a problem if people manage or repurpose it appropriately. It presents valuable opportunities for stormwater runoff mitigation. VUL can further even contribute to stormwater management. In general, stormwater pollutant removal from urban runoff is an important ecosystem service that provides vacant or underutilized land with a more potential value for reuse, such as for ecological and social purposes [14].

Therefore, this paper aims to provide planners or decision-makers with detailed information regarding the remediation of vacant land areas using urban runoff pollutant removal techniques. To find the most effective removal method, we review relevant scholarly papers and case studies to see which types of vacant land contain many urban runoff pollutants and to determine how to remove contaminants from stormwater runoff in the city by stormwater control measure (SCM). This research aims to evaluate stormwater management practices that decrease the load on a city's sewer and storm drain system and also decrease the negative effects of a vacant properties. Meanwhile, the paper will help planners and landscape designers make efficient decisions around removing pollutants from VUL stormwater runoff, leading to better, forward-looking utilization of these spaces.

2. Methods

An important first step in this research was a literature review of what types of VUL exist within US cities, and what types of VUL are contaminated. The second step was to review the types of pollutants from urban runoff in VUL. The third step was to see if VUL can be used to implementing different ecological interventions in order to remove contaminants from urban runoff. Two electronic journal databases were used to conduct this literature review: Scopus and Web of Science (WoS). Scopus has more social science journals than WoS, but at the same time, WoS covers more historical papers than Scopus [15]. The next step was to develop the search terms in order to maximize the chances of finding reference papers, but with the trade-off of trying to capture a manageable number of new "hit" papers on each search platform. The keywords used in Scopus were based on the title, abstract, and keyword, while the keywords in WoS were only based on the title due to the absence of an abstract and keyword option (see the Methods section of the Supplementary Materials).

By reading the titles, abstracts, and full papers where necessary, the studies and articles considered to fall outside the scope of studying vacant land (including urban land) and its definition, characteristics, and classification, were excluded. At the same time, papers that were not in English or not available from the author's university library were also excluded. The list of papers identified for review consisted of 140 items, which is based on the initial 1033 articles. Of particular note is that there are no or few articles on the removal of polycyclic aromatic hydrocarbons and perfluoroalkyl acids in these two electronic journal databases. The study expanded its search using Google Scholar and discovered an additional six relevant papers. In summary, a total of about 146 potentially relevant articles were identified for this review based on predetermined search criteria (Figure S1).

3. Results

3.1. Defining and Characteristics VUL

3.1.1. VUL Definitions

Even though there is no internationally recognized definition of vacant urban land (VUL), up to the present, there have been a series of definitions of VUL, which are summarized in (Table S1). There are three sections in the table—categories, definitions or brief descriptions, and reference(s). The word vacant land is expansive and diversified, but it often breaks down into two broad categories. First, VUL is defined as "previously undeveloped or unused lands" [16] that does not contain residential, commercial, or industrial structures. In addition, it also comprises no remnants of structures [17]. Under the second broad category, VUL is "previously developed land" that was previously used for different activities purposes but is now vacant [18]. Compared with previously undeveloped land, a previously developed property is more suitable for future land development. The utilization may help to protect urban ecosystem services [19].

3.1.2. VUL Characteristics

There are relatively few studies on the conditions and characteristics of VUL. Comprehensive research and analyses of the conditions and characteristics of VUL in the US were conducted by investigating relevant urban planners in 99 cities [20]. The research survey outcomes represented that the vacant land had various characteristics. Among these characteristics, most of the vacant parcels had the characteristics of being small in size, of different shapes, and in the wrong location [20]. Later, depending on its definition, VUL was divided into "previously undeveloped land" and "previously developed land" as two broad categories (Table S2). Based on those categories, Kim et al. (2018) further developed the most recent comprehensive study on the conditions and characteristics of vacant land areas in US cities [17]. These characteristics were identified based on their similarities and differences. The relevant findings from the characteristics of VUL are summarized in Table S2. Three categories are defined in the table—categories, characteristics or brief descriptions, and references.

3.2. Classification of VUL

To date, vacant urban land (VUL) has been subjected to various taxonomic studies. First, previous research classified vacant land areas as "temporary" or "permanently" abandoned lands [21]. Second, Berger (2006) used the term "drosscape" to distinguish between "waste landscapes" and "wasted landscapes" and "wasteful landscapes" in urban areas [22]. Third, based on recent research, Kim et al. (2018) used and explored the online tool named "i-Tree Eco" to conduct a sampling survey of vacant land areas in Roanoke City, Virginia, USA. The research further analyzed aerial photographs in order to classify existing vacant land areas according to ecosystem services [17].

The existing literature gives a clear classification of VUL, but there is not a classification scheme of for VUL that has been proposed from the perspective of stormwater runoff contaminations so far, and there are few comprehensive studies exploring how VUL can contribute to stormwater management, particularly for city-level areas. Furthermore, due to the lack of a classification of these areas, despite the vacant land occupying an important position in the city, it is often overlooked as part of the process of assisting stormwater management. Studies have indicated that vacant land areas may be a promising place to implement stormwater infiltration practices. However, infiltrating stormwater in vacant land areas where there are pollutants may mobilize the contaminants and increase the potential for groundwater pollution [13]. Hence, the classification of vacant land areas is a prerequisite to minimize the possibility of mobilizing pollutants to promote stormwater infiltration.

As noted in Table S2, previously developed or used land areas have been identified as contaminated sites within US cities [23]. According to the definitions of existing VUL and their prior land uses, previously developed or used land areas can be divided into industrial, residential, commercial, and parking properties or other combinations in urban areas [24]. These previous land use uses, and the types of on-site activities, often predict the presence of contaminants or waste in the soil [13]. In particular, if stormwater infiltrates areas where pollutants exist, the water may transfer existing pollutants into the soil and increase the possibility of urban groundwater contamination [13]. In other words, removing pollutants from these unattended vacant land areas is necessary to enhance the urban groundwater quality. Table S3 outlines the characteristics of the various subtypes of previously developed or used land areas derived from the literature review.

3.2.1. Prior Industrial Land

Prior industrial land contains abandoned and damaged industrial sites. These land areas have been abandoned for a long time. While being suitable for development, they still require significant rehabilitation work before they can be reused. "Brownfield" is a type of vacant industrial land. In particular, it is contaminated properties that often cause the deterioration of the surrounding environment, which seriously affects the value of the surrounding property and the safety, health, and quality of life of the nearby residents [25]. These vacant industrial properties are the product of industrial decline, regional policy changes, and abandoned infrastructure. Some sites may not contain structures but often exist on impervious surfaces. These surfaces are anthropogenic in feature and the water cannot penetrate the soil through them, including through asphalt, concrete, and so on [23]. In addition, Table S3 outlines the idea that former industrial land also contains different physical and biological characteristics.

3.2.2. Derelict Land

In recent years, the definition of derelict land has still not been clear. Gardiner et al. (2013) noted that derelict land is vacant land formed after the urban demolition of houses and infrastructure [26]. However, some derelict sites may still have vacant or unused buildings or houses. According to the definition of NLUD, a derelict site contains "developable" land [27]. Kivell and Hatfield (2018) further represented that derelict land refers to land previously used by humans and which has been severely damaged due to industrial or other development but has been unused for a while [28]. This includes abandoned industrial, residential, and commercial properties as well as parking lots [29]. These sites are wasted, underutilized or undervalued compared to other types of VUL [17]. Kim et al. (2015) identified that derelict land areas are not contaminated [30]. However, many studies have shown that different types of pollutants existed in former residential, commercial, and parking areas [31,32]. This paper attributes derelict land to contaminated properties.

In this type of VUL, some more intuitive indicators can better define the derelict urban land areas derived from the literature review, such as the shape, size, and physical and biological indicators (shown in Table S3). In addition, Table S3 describes the derelict land and contains some of the physical and biological characteristics. Among these characteristics, only the size and pattern of the land and the contamination conditions are different from the vacant industrial land use, while the other physical characteristics are similar.

3.2.3. Unoccupied Vegetation Sites

The unoccupied vegetation sites are natural areas dominated by vegetation. Such areas must have once been used for urban natural forests, protected areas, and land uses related to nature and transportation but are now vacant and not suitable for development or contain vacant areas awaiting to be developed. Unoccupied vegetation sites represent one of the previously developed or used land types. Such sites are not contaminated and contain no building structures [17]. Unoccupied vegetation sites are areas that formerly contained residential single-family homes, but which contain open spaces, gardens, or parks after the demolition of the infrastructure. The unoccupied vegetation land contains certain physical characteristics, such as high plant quality or a spontaneous vegetation structure, including a large number of trees or very well covered tree canopy, e.g., more than five trees per 0.04 ha [33] (Table S3).

Numerous definitions and taxonomies for vacant urban land (VUL) exist. Such classifications have been adjusted based on the existing VUL taxonomies from the perspective of the previously developed or used land runoff contamination. While there are some similarities and overlaps in some definitions and classifications, each classification level generally has distinctive characteristics. The classification studies presented that previously developed/used land (but now vacant) has been identified as contaminated sites, including former residential, commercial, industrial, and parking lot land use from urban areas. Next, a comprehensive literature analysis focused on understanding how four previously developed land areas can take advantage of different SCMs to remove contaminants from vacant properties and urban runoff. This does not include unoccupied vegetation land because it is not contaminated and can be developed without special treatment [17].

3.3. Stormwater Pollutants from Former Industrial Land Areas

Among these common pollutants, prior industrial land use has been targeted as a contributing source of many contaminants to urban catchments, especially heavy metals, total suspended solids (TSS), and polycyclic aromatic hydrocarbons (PAHs) (Table S5). These contaminants enter urban runoff in two different ways, which are [1]: (1) via atmospheric deposition, which helps transfer atmospheric pollutants to urban runoff; and (2) via direct urban surface runoff from prior industrial land use. Former industrial land use areas contribute more contaminants than commercial areas, parking lots, and residential land use areas [34]. Since 1992, compared to other types of vacant land, industrial land has been subject to the “National Pollutant Discharge Elimination System” (NPDES) regulations authorized by the “Clean Water Act” (CWA), as well as the state and the permitting requirements from the federal regulations designed to reduce the pollutant loads in urban runoff [35]. Therefore, pollutant removal after prior industrial land use has become a significant concern in stormwater management.

Heavy metals and PAHs are two kinds (or categories) of runoff pollutants found in urban stormwater runoff from former industrial land use areas [36]. Because of the prevalence of these two runoff pollutants in urban environments, they are of particular concern in urban stormwater management [37]. Among these two pollutants, heavy metals are the most common contaminants, and former industrial sites tend to produce higher concentrations of heavy metals [38]. Several studies have identified this result; for instance, Liu et al. (2018) noted that compared to the previous residential and commercial sites, the former industrial sites produced higher concentrations of heavy metals in urban runoff [39]. In particular, Zn is the substance with the highest concentration of heavy metals. Special attention should be paid to Zn removal when dealing with urban runoff. Furthermore, the results also note that the sources of metals in atmospheric sediments are diversified, including “the resuspension of previously deposited heavy metals” [39]. Secondly, polycyclic aromatic hydrocarbons (PAHs) are considered to be persistent organic pollutants (POPs) from stormwater runoff from former industrial land use areas [40]. Lawal (2017) found that PAHs are harmful and long-lasting organic runoff contaminants, and the “high-molecular-weight” (HMW) PAHs among them cause serious damage to the urban environment and to human health [41].

Perfluoroalkyl acids (PFAAs) are industrially produced compounds which are mainly used for industrial and commercial purposes, including in aqueous fire-fighting foam (AFFF) [42]. Environmentalists have become increasingly concerned about removing PFAAs due to their persistence, toxicity, and prevalence in urban runoff [42]. In addition, the components of total suspended solids (TSS) also mainly come from industrial stormwater runoff. The main phases of pollutant discharge are dissolved nitrogen (NO_3-N), particle phosphorus (NH_4-N), and TSS [43]. Commonly, many industrial land areas in cities are large plots containing hundreds of acres of unpaved property. The suspended solids concentration in unpaved rainwater is usually higher in stormwater because stormwater runoff captures the erosion material from loose iron-bearing soil between storm events [44]. These pollutants are very harmful to the health of humans and urban ecosystems. It is very important to implement strategies to remove toxic substances from urban runoff for purification, and stormwater runoff may be used as an alternative water source in urban areas.

3.4. Source of Stormwater Pollutants on Previously Developed or Used Land

Stormwater runoff in cities can carry a variety of pollutants from urban areas. As the Introduction explained above, infiltrating stormwater in places with contaminants may transfer the pollutants and increase the potential for urban groundwater contamination [13]. The EPA (2013) further noted that prior land use and activities are good predictors of contaminants in urban land soils [13]. The relevant findings for the typical stormwater pollutants loaded in different previously developed land areas are summarized in Table S4. The mean contaminant concentration values, such as for heavy metals, total suspended solids (TSS), polycyclic aromatic hydrocarbons (PAHs), and oil and grease, for each previously developed land category are summarized in (Table S5) and discussed in detail below.

Of these pollutants, the urban stormwater runoff contains many heavy metals. The heavy metal release mechanism is also complicated, and many researchers have found a large amount of pollutant mass loads of heavy metals (Zinc (Zn), copper (Cu), and lead (Pb)) are from the stormwater runoff in urban areas [31]. Most heavier metals present in urban runoff are from industrial, commercial, and residential lands [45], especially from areas for prior industrial land uses (Table S5). Of these, the Zn, Cu, and Pb concentrations were significantly higher at industrial sites than at the other two types of sites (i.e., commercial and residential land areas). For Zn, the event means concentrations (EMCs) in the industrial land areas averaged 599.1 mg/L compared to 362.2 mg/L and 87.1 mg/L for residential and commercial properties, respectively [36] (Table S5).

The total suspended solids (TSS) are linked to contaminants from urban runoff. The TSS from stormwater can reflect the source of various pollutants in the urban catchment [46]. In particular, they describe particles from various sources, such as phosphorus (P or NH_4-N), organic compounds, and some heavy metals [47]. The sources of TSS include road surfaces, vehicle exhaust emissions, vehicle parts, building materials, particulate matter deposition in the atmosphere, and so on. The TSS mainly results from former industrial, residential, commercial, and parking lot areas where concentrations of pollutants [48]. The research results indicated that the EMCs of TSS at the industrial properties averaged 130 mg/L compared to 105 mg/L and 100 mg/L for the residential and parking areas, respectively (Table S5). Moreover, for these sites, the mean polycyclic aromatic hydrocarbons (PAHs) from the industrial site were significantly greater than for all other sites [36]. It is estimated that total PAH EMCs were 1.5 ng/L (Table S5).

In addition to these typical pollutants, perfluoroalkyl acids (PFAAs) are another significant contributor to water quality degradation. These are industrially produced compounds that are now distributed in urban environments, where the concentrations are usually higher near industrial land areas [49]. Hence, it is important to control and remove PFAA contaminants and prevent them from entering urban domestic water resources. However, it is worth considering that many SCMs have been adopted in urban areas to remove and reduce the contaminants and particulate-matter-related pollution concentrations in stormwater runoff, but there is currently no information available on SCMs to remove PFAA.

In addition, several pollutants from urban runoff are also important. Among these pollutants, petroleum hydrocarbons in urban runoff come from prior commercial land use [50]. Previous studies have indicated that on former commercial land, the primary source of hydrocarbons in urban runoff in automotive crankcase oil, which probably drips onto the parking lot surfaces [50]. Meanwhile, oil and grease (O&G) pollutants are some of the most important ingredients in the pollutant load from urban stormwater runoff.

Residual oil is mainly deposited on impervious surfaces in urban areas, especially where cars are widely used, such as roads, parking lots, and commercial sites [51]. This section concludes that different types of urban runoff pollutants exist on previously developed or used land. This phenomenon is also indeed related to the previous land use and activity conditions.

3.5. Removing Stormwater Pollutants from Former Industrial Land Areas by Nature-Based Technologies

Two factors caused by pollutants necessitate their removal from former industrial sites: First, these pollutants often deteriorate the environment around the city, thereby affecting the value of the surrounding properties and affecting the safety, health, and quality of life of the surrounding residents. Second, stormwater infiltration at sites where no contaminants are present may reduce the transfer of pollutants and decrease the potential harm from the urban groundwater pollution. The aim of the next part of this review is to provide useful information to help communities and stakeholders to determine the appropriateness of implementing appropriate stormwater control technologies to promote the removal of runoff from different pollutants from vacant land areas and brownfields, in order to reduce on-site stormwater runoff, particularly for land areas previously used for industrial purposes.

3.5.1. Heavy Metal Removal

In order to minimize the impact of heavy metals on the urban water environment, it is necessary to undertake water quality monitoring [52]. Stormwater control measures (SCMs) are common urban water quality management methods used to help meet water quality regulatory requirements. Up to the present, various SCMs have been used for the removal and control of runoff pollutants. These structures include the bioretention systems, constructed wetlands, sand filters, permeable pavements, dry swales, grass channels, and grass filters [52]. Past studies have concluded that installing stormwater retrofits and stormwater SCMs in land areas previously used for industrial purposes lands is the most effective strategy for reducing heavy metals in urban water environments [53] (Table S6). Among these practices, bioretention systems (also called biofiltration systems, biofilters, and rain gardens) are very effective in decreasing the heavy metal concentrations from stormwater runoff [54].

Heavy Metal Removal Processes

Bioretention systems process urban stormwater through mechanical filtration, sedimentation, absorption, and the absorption of plants and microorganisms [55]. The pollutants in the urban runoff enter the biological retention unit. They then are physically filtered and adsorbed into the soil organic matter and clay (i.e., metal retention in the soil medium) for purification to remove the heavy metals in the runoff [56]. The past research results showed that most particulates of heavy metals from urban runoff are trapped on the surfaces of the bioretention media [57]. Schueler et al. (2015) further provided a comprehensive method to remove heavy metals to the maximum extent within a bioretention system [53]. They concluded that even shallower media depths could produce higher removal rates of heavy metals (Table 1), but if more organic matter is added to the bioretention medium formulation to increase the metal-binding sites, this can increase the removal rate of heavy metal pollutants [58]. Among these practices, the bioretention systems have primarily examined a single medium. It has been observed that the vegetation growth and contaminant removal are affected due to the lack of a carbon source in the single medium in the bioretention system. Furthermore, it is worth noting that only the solid or particulate fractions of metals are removed through interception, and only a fraction of it will or can be removed [59].

Design Features That Enhanced the Heavy Metals Removal

Optimizing the media and structure in bioretention systems is an essential role in removing heavy metals from urban runoff. However, the removal efficiency of a bioretention system is affected by changes in the filter media [53]. Some recent studies have investigated and explored the design and improvement of various filter media to improve the removal of heavy metals within bioretention areas and sand filters. Blecken et al. (2009) reported that the removal rate of Zn, Cu, and Pb in the mesocosm of the bioretention system was as high as 95% and pointed out that this method did not negatively affect the denitrification process [60]. Reddy et al. (2014) studied the ability and potential of biochar to improve the removal of heavy metals in the settling column test [61]. However, it was found that in addition to Cu, the addition of biochar in the sand filter cannot significantly improve the removal rate of heavy metal pollutants. As can be seen in Table 1, Wang et al. (2017) pointed out that a cylindrical reactor was used to study four mixtures of biofilter media (sand, zeolite, sandy loam, and quartz sand) mixed with lignin [59]. In the 7-day rainfall event, the average removal efficiency of the four medium mixtures for the three heavy metals (Zn, Cd, and Pb) was higher than 97%. These three heavy metal removal results were similar to those Li and Davis (2010) found [62]. Regarding the composition of the media, they used sand clay loam, about 54% sand, and 46% fines (on a per-volume basis) [57] to retain more than 98% of the heavy metals in the bioretention systems. In addition, compared with previous similar studies, the combination of quartz sand and zeolite as a filter medium in a bioretention system significantly improved the removal efficiency to 18% for Pb and 20% for Zn [63].

Table 1. The design details and comparative efficiency levels from studies of bioretention systems used for heavy metal removal from the literature.

Bioretention System Characteristics					**Heavy Metal Removal (%)**			
Location	**Media Composition**	**Media Depth (cm)**	**Bioretention Surface Area (m^2)**	**Ponding Depth (cm)**	**Zn**	**Cu**	**Pb**	**Reference(s)**
Greensboro, NC	Organic sand	120	10	NA	>98	>98	>80	[64]
Charlotte, NC	6% fines and loamy sand	120	229	NA	60	77	32	[64]
College Park, MD	80% sand, 20% fines, and sandy loam	50–80	181	15	92	65	83	[62]
Silver Spring, MD	54% sand, 46% fines, and sandy clay loam	90	102	30	99	96	100	[62]
N/A	N/A	N/A	N/A	>30	98	98	80	[65]
N/A	Four media mixes, sand, zeolite, sandy loam, and quartz-sand	N/A	N/A	N/A	>97	>97	>97	[59]

3.5.2. Removal of Total Suspended Solids

The total suspended solids (TSS) are the solids in the stormwater runoff that can be captured by filters [66]. They also represent a commonly found category of prior industrial land use stormwater pollutants. In a primary treatment system, the removal efficiency of suspended solids (SS) is around 50%. The low removal efficiencies are mainly due to the insufficient removal of finely divided suspended particles that account for a large portion of the SS. Previous research pointed out that the removal of small particles (<50 µm) is almost impossible in a primary sedimentation tank [67]. Hence, to improve the removal of SS from sewage in primary treatment systems, particle agglomeration through chemical coagulation or flocculation is necessary [68]. It should be noted that such chemically enhanced primary sewage treatment systems impose high operational costs incurred from the use of coagulants and the treatment and disposal of a large amount of chemical sludge.

The research shows the effect of the alum sludge dosage on the removal efficiency of SS. The SS removal efficiency rates were increased to up to 72–90%, compared to efficiency rates of 52–66% in a primary treatment system [69].

In addition, the main phases of pollutant discharge are dissolved nitrogen (NO_3-N), and phosphorus (P) [43]. Among these TSSs, NO_3-N is the pollutant with the highest nutrient content in urban runoff, and its concentration mainly depends on the previous land use activities [52]. Commonly, there are many vacant industrial land areas in cities, comprising hundreds of acres of unpaved property. The suspended solids concentration in unpaved rainwater is usually higher than in stormwater due to stormwater runoff capturing the erosion material from loose iron-bearing soil between storm events [44]. These pollutants are very harmful to human and ecosystem health. Implementing strategies to remove harmful substances from urban runoff is very important to realize the potential of stormwater runoff as an alternative water source in urban areas.

Nitrogen Removal Processes

Nitrogen (NO_3-N) removal is a key step in controlling the urban stormwater quality. Nitrogen is highly soluble and difficult to remove [54]. Studies have shown that the nitrogen removal process is usually slower than for other runoff pollutants [70]. Previous research has focused on nitrogen removal in bioretention systems [71]. The removal of nitrogen in the bioretention system mainly depends on factors such as the vegetation, soil filter media, influent concentration, and hydraulic power [72]. In addition, other studies have noted that the effective removal of nitrogen depends to a large extent on the physical processes, biological processes, and chemical reactions [73]. The main processes of removal include nitrogen absorption, ammoniation, nitrification, and denitrification [74,75]. For NO_3-N removal to occur, there are two possible processes. One is NO_3-N capture via activated carbon or some other mechanism or substance. The other is nitrification or denitrification, which is a two-step biological process that requires an anoxic zone and a carbon source.

Design Features That Enhanced the Total Nitrogen Removal

NO_3-N removal is usually achieved in the subsurface (or top layer) of the bioretention medium [52], similar to the treatment method for removing heavy metals. However, past studies have pointed out the problem of poor nitrogen removal in bioretention systems. For example, Brown (2012) stated that their water quality results were unsatisfactory due to the influx of groundwater in bioretention tanks and the lack of denitrification conditions in bioretention tanks or permeable concrete systems [76]. As a result, nitrogen removal has become the focus of recent research. Several studies have noted that the effect of nitrogen removal effect is better in bioretention systems modified by carbon sources [77]. In addition, the absorption of nitrogen by plants can be significantly improved by increasing the growth of the plants [52]. Previous studies have also shown that the nitrogen removal rates are higher in soil media containing greater amounts of organic matter [78]. For instance, the removal efficiency rates of NO_3-N from sandy loam range between 60% and 80%, while soils with lower permeability have better removal efficiency rates of about 83%, and the use of different plant species and an increased depth of the filter media can greatly improve the removal rate of the NO_3-N, meaning the highest removal rates can reach 93% [65]. Table 2 summarizes the relevant findings from studies involving improvements in bioretention design to improve nitrogen removal.

Table 2. Summary of the relevant findings from studies from the literature on improvements in bioretention design to improve nitrogen (NO_3-N) removal.

Different Design to Improve Nitrogen Removal	NO_3-N (%)	Ranking	Reference(s)
Designed of bioretention columns with lower-permeability soil layers	84	High	[79]

Table 2. *Cont.*

Different Design to Improve Nitrogen Removal	NO_3-N (%)	Ranking	Reference(s)
Design of saturation zones with different depths	62	Medium–high	[80]
Designed for plant bioretention with saturated areas	67	High	[81]
Designed with a two-layer biological retention system, modified with wood chips	80	High	[82]
Design of a saturated zone with wood chips	82.4	Medium–high	[83]
Design for the use of biochar to correct bioretention	30.6–95.7	Low–high	[84]
Design of the treatment method for combining carbon sources in saturated zones	85–94	High	[85]
The use of different plant species and increased depth of the filter media	93	High	[65]
Design to revise the saturated zone where bioretention and biochar are combined	50–60	Low–medium	[81]

3.5.3. Phosphorus Removal in Total Suspended Solids

The main processes for removing phosphorus (P or NH_4-N) in bioretention systems are precipitation, adsorption, filtration, and plant absorption [57]. Laboratory studies and on-site monitoring results have shown that can effectively remove heavy metals and nitrogen can be effectively removed from industrial stormwater runoff through the use of bioretention systems, but it is reported that the bioretention systems have inconsistent effects in terms of P removal. Some research reports indicate that using bioretention systems results in the leaching of phosphorus [64]. Table 3 summarizes the reductions in P concentrations obtained from the field monitoring of different designs of bioretention systems.

Table 3. Summary of the relevant findings taken from the literature for bioretention designs for phosphorus (P or NH_4-N) removal.

Location	Different Design Features	P or NH_4-N Reduction (%)	Reference(s)
Garden, Haddam, CT	Bioretention system enclosed in an impermeable membrane lining.	−117	[88]
Cell, College Park, MD	Setting up a saturation zone under the drain to promote the anaerobic process.	79	[89]
Cell, Louisburg, NC	Bioretention system enclosed in an impermeable membrane lining.	10	[90]
Rocky Mount, NC	Planting grass. Setting up a saturation zone under the drain to promote the anaerobic process.	67	[91]
North Cell, Graham, NC	Planting grass.	53	[92]
South Cell, Graham, NC	Planting grass.	68	[92]
N/A	A hydraulic conductivity media.	85	[86]
N/A	The mixed filter media of sand and local soil, with or without vegetation.	>90	[93]
N/A	Bioretention depth range: 60 to 80 cm.	70–85	[94]
N/A	Constructed biofiltration mesocosms (vegetated sand and vegetated sandy loam).	85–94	[87]
N/A	Sandy media.	<20	[95]
N/A	Landscaped bioretention.	60	[57]

Hsieh et al. (2007) found that a medium with a high hydraulic conductivity covers an existing medium with low hydraulic conductivity, and the result is a higher and more effective decrease in P pollutants [86]. Approximately 85% of the introduced P was removed. Furthermore, studies have noted that specific bioretention processes can significantly affect the P removal in biofilters. Henderson et al. (2007) suggested that plants play an essential role in removing P within biofilters [57,87]. Obvious P leaching was observed on a non-vegetation column, while the P absorption in the vegetation column was good.

However, the removal of P varies greatly within bioretention systems, and leaching is often observed (Table 3). Bratieres et al. (2008) observed that when the existing soil is used for organic matter correction, this results in the leaching of P pollutants from the bioretention column [65]. Moreover, the biofilters enclosed in the impermeable membrane liner will cause a large amount of P leaching (approximately −117%) (Table 3).

3.5.4. Polycyclic Aromatic Hydrocarbons Removal

Polycyclic aromatic hydrocarbons (PAHs) contain a high concentration of persistent organic chemical pollutants generated by industrialization's anthropogenic activities [40]. As noted in Table S5, the mean PAHs from the industrial site was significantly greater than all other prior land uses [96]. PAHs are used in large quantities in industrial activities and then discharged into various water bodies, causing severe health and environmental issues [97].

Based on the existing research and the basic features of PAHs, most urban stormwater control measures (SCMs) are considered to remove PAHs from the runoff in cities [53]. However, there are only a few studies that have assessed whether the SCMs can remove PAH pollutants, which may be related to the high costs of such compounds and the difficulty of the sampling process. Table 4 summarizes the reductions in PAH concentrations included from the field monitoring of different designs of biofiltration systems.

Table 4. Summary of the relevant findings taken from literature for bioretention design studies of polycyclic aromatic hydrocarbon (PAHs) removal.

Location	Different Design Features	PAHs Reduction (%)	Reference(s)
College Park, MD	90 cm of soil, sand, and organic matter, and plant appropriate vegetation.	31–99	[98]
N/A	The construction of a bioretention system consisting of rain gardens and a bioswale.	97	[99]
N/A	Combination of phytoremediation and bioretention system.	Enhanced by 18–115	[102]
N/A	Different permeable inorganic materials as filter medium (sand, calcite, zeolite, and iron filings).	90	[100]
N/A	Bioretention soil mixtures.	84–100	[101]

DiBlasi et al. (2009), who found that a bioretention system was very effective in reducing the concentration of PAH pollutants in urban runoff and in an on-site study in a bioretention area in College Park, MD, reported that the PAH removal rate was more than 87% [98]. Meanwhile, DiBlasi et al. (2009) identified that the bioretention system contained a mixture of approximately 90 cm of sand, soil, and organic matter and was planted with appropriate vegetation. The average concentration of PAH events means concentration (EMC) of PAHs decreased from 99% to 31% [98]. David et al. (2015) further calculated the pollutant loading rate of PAHs by constructing a bioretention system, including a rain garden and a bioswale, showing that the PAHs in the stormwater runoff were reduced by about 97% [99]. Reddy et al. (2014) studied the effectiveness of different permeable inorganic materials as filter media to remove PAHs from stormwater runoff, and the removal rate reached 90% [100]. In addition, Jay et al. (2019) suggested that using a soil mixture (BSM) in the bioretention system can effectively remove PAHs, with the removal rates ranging between 84% and 100% [101].

However, recent studies have shown that bioretention systems cannot promote the degradation or removal of PAHs. On the contrary, they can promote the accumulation of PAHs in the soil [102]. Weerasundara and Vithanage (2016) indicated that if a combination of phytoremediation and bioretention systems is used, the removal rate of the PAHs can be enhanced by 18–115% [102] (Table 4).

In addition, Crabtree et al. (2006) evaluated the impacts of other SCMs on reducing the concentrations of PAH contaminants in stormwater runoff [103]. The study found that the wet ponds are also very effective in removing PAHs, with a removal rates of up to 99%. In turn, dry ponds are not very effective in removing PAHs (only 22%), and they cannot remove PAHs from storm drain inlets. Sebastian (2014) further studied the effectiveness of dry retention ponds in removing the concentrations of PAH pollutants in French industrial sites [104]. They observed that dry ponds were more effective in reducing PAH concentrations with higher molecular weights than PAHs with lower molecular weights. During 10 storm events, the daytime ponds removed 24% to 67% of the high-molecular-weight (HMW) PAHs, but only 4% to 31% of the low-molecular-weight (LMW) PAHs. Generally, the removal rate of the PAHs was less than that of the TSS throughout the study.

3.6. Considerations of Economic Efficiency

From an economic perspective, there have been attempts to find the average costs of several practices using the price ranges of different stormwater management practices provided by the US Army Corps of Engineers [105]. Among these SCMs, planting trees is probably the cheapest option, with an average cost of USD 4.45 per square foot or USD 2200 per acre. The average price of permeable pavement is USD 8.24 per square foot. The cost for the planting of vegetation to control rainwater is between USD 10.30 and USD 11.50 per square foot. The pricier options may be for biological retention systems and rain gardens, with an average price of USD 25.55 per square foot [105]. In addition, Xu et al. (2017) noted that constructed wetland areas demonstrate a high economic burden that plays an essential role in the costs of the graded gravel and cushion plants among constructed in wetland areas [106].

However, Mateleska (2016) gave a different economic cost approach by using the method named the “Opti-Tool.” [107]. Table 5 summarizes the proposed SCM cost estimates for the “Opti-Tool.” This table does not include the cost of tree planting practices. These fees may vary depending on the specific location and availability. In general, the overall best option for installing SCMs may be a bioretention system based on the ability to remove stormwater pollutants, whereas the overall best option for installing SCMs may be planting trees, depending on the installation cost. This method is the cheapest one, along with having low maintenance costs.

Table 5. Summary the proposed SCM cost estimates for the “Opti-Tool” [107].

SCM (From Opti-Tool)	Cost (USD/ft^3) [1]	Cost (USD/ft^3)—2016 Dollars [6]
Bioretention (includes rain garden)	13.37 [2,4]	15.46
Dry pond or detention basin	5.88 [2,4]	6.80
Enhanced bioretention (biofiltration practice)	13.5 [2,3]	15.61
Infiltration basin (or other surface infiltration practice)	5.4 [2,3]	6.24
Infiltration trench	10.8 [2,3]	12.49
Porous pavement—Porous asphalt pavement	4.60 [2,4]	5.32
Porous pavement—Pervious concrete	15.63 [2,4]	18.07
Sand filter	15.51 [2,4]	17.94
Gravel wetland system (subsurface gravel wetland)	7.59 [2,4]	8.78
Wet pond or wet detention basin	5.88 [2,4]	6.80
Subsurface infiltration/Detention system (infiltration chamber)	54.54 [5]	67.85

[1] Footnote: Includes 35% add-on for design engineering and contingencies. [2] Costs in 2010 US dollars. [3] From CRWA cost estimates. [4] From UNHSC cost estimates; most of original costs were from 2004 and converted to 2010 US dollars using the U.S. Department of Labor (USDOL). (2012). Bureau of Labor Statistics consumer price index inflation calculator. [5] From cost estimates from the MA TT Rizzo Project (2008 US dollars). [6] 2010 costs were converted to 2016 values to adjust for inflation. The ENR Cost Index Method was used for this conversion.

In addition, understanding the maintenance costs of SCMs is also an important factor in the use of SCM technologies. Houle et al. (2013) examined the maintenance costs of seven different types of SCMs [108]. The annual maintenance cost of the wet ponds are USD 7830/ha and USD 2280/ha/year for a vegetated swale. In terms of reducing large loads of runoff pollutants, the maintenance costs for porous asphalt pavement, bioretention systems, and vegetated swale range from USD 4–8/kg/year to USD 11–21/kg/year [108]. Previous research also pointed out the complexity of the maintenance of SCMs through investigations. The study used different grades from 1 to 4, with 1 indicating the least complexity and 4 indicating the greatest complexity (i.e., requiring stormwater professionals or consultants). As shown in Table S7, for most SCM categories, most of them indicate that the maintenance is simple and the systems are easy to operate. However, for wetland areas and porous pavements, approximately 50% of the responses indicate that the maintenance work is moderately difficult or complicated.

3.7. Other Considerations

The spatial distribution of VUL areas ranges from large to small, from clustering to dispersion [109]. In these distributions, it is impossible to construct a wet pond or retention basin in a small VUL area for the removal of runoff pollutants—in other words, using the above SCM technologies in a small VUL area to reduce the concentration of urban runoff pollutants. However, these small-sized VUL areas can play an active role in controlling stormwater runoff, which can also help to reduce the concentration of runoff pollutants in the VUL areas. As was frequently found in previous research, the less fragmented the VUL areas and the higher the proximity index (PROX) values, the more effective the system is in reducing the peak runoff [110]. Meanwhile, studies have also found that the size, shape, and connectivity of VUL areas are significantly inversely correlated with the reduction in stormwater runoff [110]. It is shown that larger VUL areas, higher shape, and connectivity indices were not significantly associated with a reduction in stormwater runoff. That is to say, if the cost of installing an SCM is higher than the cost of using the VUL itself, then the community stakeholders could consider not installing an SCM but rather using the VUL itself, which could provide opportunities for the reconstruction or reuse of the VUL and could also bring about great economic value. The research indicated that the more VULs are re-greened, the more it can help the city form a larger, less fragmented, and more interconnected green network, which is more likely to positively impact urban runoff and contamination levels [111].

3.8. Results Summary

This section summarizes the recent studies that have introduced various potential strategies for vacant land areas—and especially those that were previously used for industrial purposes—to minimize the potential movements for mobilizing contaminants. The various studies have indicated that prior industrial land use often results in contaminated properties. SCMs are effective management approaches to reduce runoff and non-point source pollution problems.

Among these measures, bioretention systems tend to be effective in the removal of heavy metals (zinc (Zn), copper (Cu), lead (Pb)), and nutrients (nitrogen (NO_3-N) and phosphorus (P or NH_4-N)). However, several studies have reported that the removal efficiency of a bioretention system is affected by the use of various filter mediums. In particular, advanced heavy metal removal in SCMs can be achieved using a four-medium biofiltration system mixes, including sand, zeolite, sandy loam, and quartz sand. The use of different plant species and increasing the filter media depth have been identified as effective steps in removing NO_3-N. A medium with high hydraulic conductivity covering media with low hydraulic conductivity will result in higher P removal efficiency (with a mass removal rate of 85%). In addition, wet ponds were found to be highly effective in removing polycyclic aromatic hydrocarbons (PAHs), with removal rates of 99%. For the removal of perfluoroalkyl acid (PFAA) pollutants, despite the implementation of SCMs in urban areas to remove PFAAs and particulate-related pollutants from stormwater runoff, the current literature has little information on the removal of PFAAs using SCMs.

In order to better optimize the SCMs, it is necessary to consider a relationship between various design factors and their combined impacts on the removal of different pollutants. In addition, for the proposed action plan above, we need to consider the types of vacant land to determine which remedy is the most appropriate. For instance, for safety and feasibility considerations, it is not recommended to use bioretention tanks for individual vacant land areas in residential areas, but it would be appropriate to apply this method to larger vacant industrial areas. The installation of SCMs for all vacant land areas is not recommended based on many factors. Instead, the overall best ability of an SCM to remove stormwater pollutants, the cost of its installation, and its maintenance costs should be considered.

4. Conclusions

Vacant or under-utilized parcels may appear promising places to locate stormwater infiltration practices. Vacant and abandoned attributes can provide a useful canvas to add to the removal of pollutants and promote the penetration of stormwater runoff while establishing stormwater management strategies. By reintroducing stormwater management strategies into the urban environment, urban planners can reduce some of the negative impacts of deindustrialization, thereby creating a more beautiful environment. Literature reviews suggest that the word vacant land is expansive and diversified, but it is often broken down into two broad categories, including previously undeveloped land and previously developed land. This paper summarizes recent studies that have introduced various potential strategies on vacant lands—especially those previously used for industrial purposes—to minimize the potential for mobilizing contaminants. As a potential redevelopment opportunity, vacant urban land can be redefined as an essential resource. The relationship between VUL and contaminants is not only cost-efficient but is in line with the United Nations (UN) Sustainable Development Goals (SDG). In the context of the UN's SDG blueprint for a more sustainable future for all, SDG planners should be commended for expanding the scope of global water and sanitation (W&S) monitoring, including a new emphasis on environmental sustainability, comprehensive water resource management, and participation from local communities. This literature review is expected to help relevant stakeholders better understand the vacant land in urban areas and thus promote better use of these areas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141912906/s1, Figure S1: Search logical framework for articles for review; Table S1: Definitions of VUL used in literature; Table S2: Characteristics of VUL used in literature; Table S3: Classification of VUL used in the literature; Table S4: Summary of the typical stormwater pollutants loading on different previously developed lands from the literature; Table S5: Comparison of event mean concentrations (EMCs) for specific previously developed lands from the literature; Table S6: The comparative ability of SCMs to remove efficiencies heavy metals from the literature; Table S7: Research on maintenance complexity for different stormwater SCMBMPs. References [15,17,19–21,24,31,34,36,45,47–53,56,58,59,62,63,65,72,109,112–118] are cited in the supplementary materials.

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