

Supplementary research methods, figures, and tables

- **Research methods**

An important **first step** in reviewing the literature was reviewing just 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 could take advantage of implementing different ecological interventions to remove pollutants in urban runoff. Two electronic journal databases were used to conduct this literature review: “*Scopus and Web of Science*” (WoS). Scopus has more social sciences journals than WoS, but at the same time, WoS covers more historical papers than Scopus [15]. The next step was to develop 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 on Scopus were based on the title, abstract, and keyword, while the keywords on WoS were only based on title due to the absence of an abstract and keyword option.

By reading the titles, abstracts, and full papers where necessary, studies and articles considered to fall outside the scope of vacant land, including urban land, its definition, characteristics, and classification, were excluded. At the same time, papers that were non-English or not available from the author’s university library were also excluded. The list of papers identified for review consisted of **140 items** based on the title of the initial **1033 articles**. Among these 140 papers, by reading the full papers where necessary, **55 of them** cover the definitions, conditions, characteristics, and classifications of vacant land. However, during the review of the papers identified, **14 relevant papers** were discovered that did not appear in the search results based on these two databases. Hence, these papers were included in the list of articles for review, increasing the total to **69 papers** (Figure S1).

Based on the first step, previously developed land (but now vacant) was identified as contaminated sites. Thus, the **second step** summarizes the types of runoff pollutants in previously developed land. The types of pollutants in stormwater runoff depend largely on the activities that eventually cause land waste. Németh and Langhorst (2014) noted that previously developed property could be zoned as industrial, residential, commercial, or parking lots [24].

As in the first step, articles considered outside the scope of search keywords were excluded by reading the titles, abstracts, and full papers. The list of papers identified for review consisted of **134 items**, which is based on the title of the initial **495 articles**. Of these 134 articles, there are 27 overlapping articles. By reading the full papers where necessary, 43 papers cover the relevant content of search keywords. However, during the review of the papers, an additional 20 relevant papers were discovered that did not appear in the search results based on these two databases. Thus, these papers were included in the list of articles for review, increasing the total number to **63 papers**. Up to the present, there is a total of **125 papers** identified for review in the first two steps (Figure S1).

The **third step** was to identify if VUL can be taken advantage of by adapting different ecological interventions to remove pollutants from urban runoff. Based on the results of the first two steps, it was confirmed that prior-industrial land use contributes more pollutants than commercial, parking lots, and low-density residential land use [34]. That is, the third step of the review search further

focused on the removal of pollutants from prior industrial land use, so that focused on the following pollutants in particular. Heavy metals, polycyclic aromatic hydrocarbons (PAHs), perfluoroalkyl acids (PFAAs), and total suspended solids (TSS) have been identified in stormwater runoff from post-industrial lands [31].

As in the first and second steps, articles that were considered to be outside the scope of the search keywords were excluded by reading the abstracts and full papers. The specific screening process is as follows. The list of papers identified for review consisted of **15 items**, which is based on the title of the initial **127 articles**. Of these 15 articles, there is a total of 7 overlapping articles. Of particular note is that there are no or few articles on the removal of polycyclic aromatic hydrocarbons and perfluoroalkyl acids on these two electronic journal databases. The research expanded the search using Google Scholar, and 6 relevant papers were discovered. Thus, these papers were included in the list of articles for review, increasing the total number to **21 papers** (Figure S1). In summary, **about 146 potentially relevant articles** were identified for this review based on predetermined search criteria.

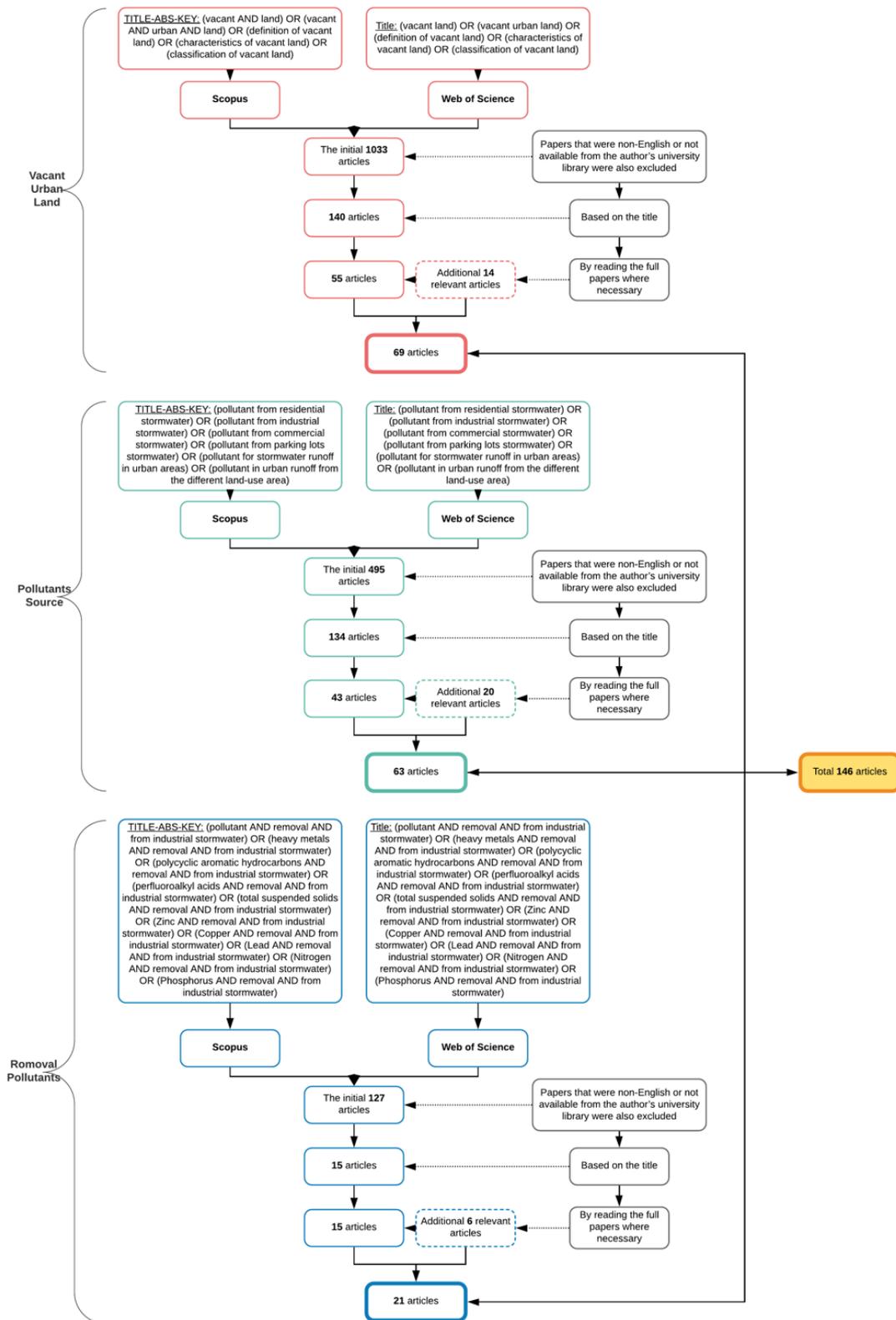


Figure S1. Search logical framework for articles for review.

Table S1. Definitions of VUL used in literature.

Categories	Definition/Brief Descriptions	Reference(s)
Previously Undeveloped/Unused Land	Non-underwater land of undeveloped.	[112]
	Unused or abandoned land for a long time.	[113]
	"Bare soil."	[20]
	"Derelict land" (or landscape) with wildly grown vegetation.	[114]
	"Semi-wild nature" – "green space" or "greenbelts."	[19]
	Unused or marginal cultivated land and cultivated or farmland that has been razed.	[17]
	The land has also been termed city "cracks" and "lost space."	[17]
Previously Developed/Used Land	The land is limited by the physical aspects of the environment – drainage area, wetlands, hillsides, riverbanks, and river floodplains.	[115]
	"Dead space."	[116]
	The land as a brownfield; "brownfield" has been adopted to describe land which has previously been subjected to development, and notably "brownfield" is a prior land property that makes reconstruction or reuse very complex due to the existence (or possible existence) of pollutants.	[117]
	The land is frequently linked to the term "contaminated."	[118]
	Prior developed land use, but it is now vacant.	[117]
	The land can be divided into residential, commercial, industrial or other different combinations according to the prior different land activities.	[24]
	The emergence of vacant lands may occur at any location, such as the spatial distribution of scattered or continuously on the edge of transport corridors, and others.	[24]
	The land may temporarily or permanently contain some unused public structures and buildings.	[17]
	The property is more suitable for land development in the future.	[17]

Table S2. Characteristics of VUL used in literature.

Categories	Characteristics/Brief Descriptions	Reference(s)
Previously Undeveloped/Unused Land	Not contaminated.	[17]
	Not any structure present.	[17]
	Different shapes (rectangular, irregular, or linear).	[112]
	Bare “derelict land.”	[119]
	Different sizes for parcels (i.e., size < 0.8 ha or > 0.8 ha).	[17]
	“Pervious surface.”	[109]
	High vegetation quality or low vegetation quality, roughly vegetated wastelands.	[116]
Previously Developed/Used Land	Land having physical limitations to development (i.e., unbuildable). <ul style="list-style-type: none"> • Slopes in excess of 10%–15%. • Flood hazards. • Unstable subsurface materials. 	[115]
	Contaminated.	[118]
	Contains structure or no structure present.	[17]
	Different shapes (rectangular, irregular, or linear).	[112]
	Different prior land use. <ul style="list-style-type: none"> • Commercial. • Residential. • Industrial. • Parking lots and others. 	[24]
	Different sizes (i.e., size < 0.8 ha or > 0.8 ha).	[17]
	“Impervious surface” (pavement, asphalt, and buildings).	[114]
	Different slopes (i.e., slope < 5% or > 5%).	[115]
	Different temporary or permanent use functions, such as material dumps, landfills, and construction sites.	[21]
	Abandonment of old transportation networks or factories.	

Table S3. Classification of VUL used in the literature.

Overall Categories		Sub-Categories					
		Types	Build Types		Natural Factors		
			Land Former Use	Blank Pattern Typologies	Overall Physical Characteristics	Biological Characteristics	
						Land Cover Types	Indicators
Previously Developed/Used Land, but now Vacant	Type 1: Prior-Industrial Land/Brownfield	Prior Industrial Land Use		- Pattern: Mass majority blank pattern - Shape: Square or rectangle or irregular	- Construction: Structure present – public amenities/structures - Hard surface: >25% asphalt, concrete, or gravel [114] - Size: Large or small – large: 648 acres, small: 10-15 acres - Soil: permeable or impermeable - Sites with poor ground conditions - Semi-wild state - Contaminated properties	- Low plants quality - Scattered wild vegetation - Wetlands - Dry ground	- A few trees or bare soil – <5 trees per 0.04 ha - Featureless landscape of soil or sand cover - Sporadic distribution shrub layer - Existed water birds – rarely confined to artificial wetlands - Existed rare or endangered species - Poor water retention
		Prior-Commercial Land Use		- Pattern: Mass majority blank pattern - Shape: Square or rectangle or irregular OR - Pattern: Interval blank	- Construction: Structure present – public amenities/structures - Hard surface: >25%	- Permeable – semi-bare soil, and grass or impervious surface – asphalt, buildings, or mixed use	- Permeable surface: 40% or others - Impervious surface: 60% or others

		<ul style="list-style-type: none"> pattern or cross distribution - Shape: Square or rectangle OR - Pattern: Scattered blank pattern or cross distribution - Shape: Square 	<ul style="list-style-type: none"> asphalt, concrete, or gravel - Size: Larger or medium or small – large: 50-60 acres, median: 40 acres, small: 10-15 acres - Contaminated properties [113] 	<ul style="list-style-type: none"> - Low plants quality - Soil conditions 	<ul style="list-style-type: none"> - Sporadic trees or bare soil – less than 5 trees per 0.04 ha - Featureless landscape of soil or sand cover - The underlying subsoil is compacted to a density approaching that of concrete.
	Prior Parking Lots Use	<ul style="list-style-type: none"> - Pattern: Mass majority blank pattern - Shape: Square or rectangle or irregular 	<ul style="list-style-type: none"> - Construction: No structure present - Hard surface: >50% asphalt, concrete, or gravel - Size: median or small, – median: 40 acres, small: 10-15 acres - Soil: Permeable or impermeable - Sites with poor ground conditions - Contaminated properties 	<ul style="list-style-type: none"> - Pavement: Impervious hard surface (pavement, asphalt, buildings) - Low plants quality 	<ul style="list-style-type: none"> - Impervious surface: 90% or other - A few trees or bare soil – <5 trees per 0.04 ha - Featureless landscape of soil or sand cover

Overall Categories		Sub-Categories			
Previously Developed/Used	Types	Build Types		Natural Factors	
	Type 2:	Land Former Use	Blank Pattern Typologies	Overall Physical Characteristics	Biological Characteristics

Land, but now Vacant	Derelict Land –abandoned industrial/residential/commercial properties/or others				Land Cover Types	Indicators
	Abandoned Industrial Site	<ul style="list-style-type: none"> - Pattern: Mass majority blank pattern - Shape: Square or rectangle or irregular 	<ul style="list-style-type: none"> - Construction: Structure present or not - Size: large or medium, e.g., large: 50-60 acres, median: 40 acres - Mixed surface: >25% hard surfaces, and >500 ft² of contiguous open grass or bare soil - Soil: Impermeable - Contaminated properties 	<ul style="list-style-type: none"> - Scattered wild vegetation - Soil quality 	<ul style="list-style-type: none"> - Sporadic distribution shrub layer - Low fertility - Contaminated - Soil unused 	
	Abandoned Residential (Single-Family) District	<ul style="list-style-type: none"> - Pattern: Interval blank pattern and cross distribution OR - Pattern: Scattered blank pattern and cross distribution - Shape: Square or rectangle 	<ul style="list-style-type: none"> - Construction: Structure present. - Hard surface: >25% asphalt, concrete, or gravel - Size: Median or small – median: 40 acres, small: 10-15 acres - Soil: Permeable or impermeable - Sites with poor ground conditions - Contaminated properties 	<ul style="list-style-type: none"> - Low plants quality - Low tree number per ha - Low tree canopy cover 	<ul style="list-style-type: none"> - A few trees or bare soil (< 5 trees per 0.04 ha) - Featureless landscape of soil or sand cover - Tree number: 21-22 per ha - Tree canopy cover rate: 13%-14% 	
	Abandoned Commercial Properties	<ul style="list-style-type: none"> - Pattern: Corner blank pattern and symmetrical 	<ul style="list-style-type: none"> - Construction: Structure present. 	<ul style="list-style-type: none"> - Low plants 	<ul style="list-style-type: none"> - Grass 55%-75% 	
				<ul style="list-style-type: none"> - Fragmented and larger vacant lots 	<ul style="list-style-type: none"> > 500² 	

		<ul style="list-style-type: none"> distribution - Shape: Square OR - Pattern: Interval blank pattern and cross distribution - Shape: Square or rectangle OR - Scattered neighborhood commercial 	<ul style="list-style-type: none"> - Hard surface: >25% asphalt, concrete, or gravel - Size: Median or small – median: 40 acres, small: 10-15 acres - Soil: Permeable or impermeable - Contaminated properties - Sites with poor ground conditions 	<ul style="list-style-type: none"> quality - Low tree number per ha - Low tree canopy cover - Impervious surface (pavement, asphalt, buildings) - - Ground cover 	<ul style="list-style-type: none"> - Water 0% - Bare soil 3.5%-4.5% - Cement 0%-1% - 15% impervious surface within 300 feet - A few trees or bare soil (< 5 trees per 0.04 ha) - Featureless landscape of soil or sand cover
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Overall Categories		Sub-Categories				
Previously Developed/Used Land, but now Vacant	Types	Build Types		Natural Factors		
	Type3: Unoccupied Vegetation Land, e.g., Previously Garden Site, Unimproved Natural Forests, Perimeter Agricultural, and Conservation Areas	Land Former Use	Blank Pattern Typologies	Overall Physical Characteristics	Biological Characteristics	
					Land Cover Types	Indicators
		Residential/Commercial/Open Space/Garden/Park District	<ul style="list-style-type: none"> - Pattern: Scattered blank pattern and cross distribution - Shape: Square or line or irregular 	<ul style="list-style-type: none"> - Construction: No structure present - Size: Small or large 	- High plants quality	- Several trees, very well covered tree canopy (more than 5 trees)

	- Dense vegetation: >25% vegetation or plants and <500 ft ² of contiguous open grass	per 0.04 ha)
		- Landscape of deciduous trees and evergreen trees
	- Soil: Permeable or impermeable	- Tree number per ha
	- Not contaminated	- 35-62 per ha
		- Tree canopy cover
		- Grass 55%-75%
		- Water 0%
		- Bare soil 3.5%-4.5%
	- Ground cover	- Cement 0%-1%
	- Plantable space	- 72%-80%
	- Scattered trees	- Mostly pervious surfaces (a few plants or bare soil)
	- Scattered shrub	- Bushes, shrubs, and woody trees

Table S4. Summary of the typical stormwater pollutants loading on different previously developed lands from the literature.

Categories	Land Former Use	Pollutant Types	Reference(s)
Previously Developed/Used Land	Prior industrial lands (Brownfields)	Heavy metals	[45]
		Total suspended solids (TSS)	[47]
		Polycyclic aromatic hydrocarbons (PAHs)	[36]
		Perfluoroalkyl acids (PFAAs)	[49]
		Heavy metals	[31]
		<ul style="list-style-type: none"> • Nitrogen (NO₃-N) • Phosphorus (P) 	[47]
	Commercial properties	Polycyclic aromatic hydrocarbons (PAHs)	[36,115]
		Perfluoroalkyl acids (PFAAs)	[49]
		Petroleum hydrocarbons	[50]
		Trace organic contaminants	[51]
		Heavy metals	[59]
	Residential properties	<ul style="list-style-type: none"> • Nitrogen (NO₃-N) • Phosphorus (P) 	[48]
		Polycyclic aromatic hydrocarbons (PAHs)	[36]
		Organic materials	[58]
		Pesticides	[59]
		Herbicides	[63]
Parking lots	Heavy metals	[31]	
	<ul style="list-style-type: none"> • Nitrogen (NO₃-N) • Phosphorus (P) 	[47]	
	Oil and grease	[51]	

Table S5. Comparison of event mean concentrations (EMCs) for specific previously developed lands from the literature.

Previously Developed/Used Land	Mean event means concentration (EMCs)												Reference(s)
	Total Zinc (Zn)		Total Copper (Cu)		Total Lead (Pb)		Total TSS		Total PAHs		Oil and Grease		
	mg/L	sd	mg/L	sd	mg/L	sd	mg/L	sd	ng/L	sd	mg/L	sd	
Prior industrial lands (Brownfields)	599.1	197.0	70.3	18.0	24.1	10.9	92.2	50.9	1.5	8.6	N/A	N/A	[36]
	583.0	N/A	31.0	N/A	18.0	N/A	130.0	N/A	N/A	N/A	N/A	N/A	[36]
	290.0	N/A	32.0	N/A	4.0	N/A	81.0	N/A	N/A	N/A	N/A	N/A	[65]
Commercial properties	362.2	135.6	38.1	18.4	20.4	14.0	49.6	67.8	1.2	5.8	N/A	N/A	[36]
	133.0	N/A	12.0	N/A	4.0	N/A	15.0	N/A	N/A	N/A	N/A	N/A	[36]
	290.0	N/A	32.0	N/A	4.0	N/A	81.0	N/A	N/A	N/A	N/A	N/A	[72]
Residential properties	87.1	60.7	29.9	18.1	6.0	8.4	105.0	142.9	1.4	6.0	N/A	N/A	[36]
	59.0	N/A	17.0	N/A	4.0	N/A	22.0	N/A	N/A	N/A	N/A	N/A	[36]
	116.0	N/A	12.0	N/A	3.0	N/A	33.0	N/A	N/A	N/A	N/A	N/A	[51]
Parking lots	200.0	N/A	50.0	N/A	15.0	N/A	100.0	N/A	N/A	N/A	N/A	N/A	[52]
	290.0	N/A	43.0	N/A	23.0	N/A	48.0	N/A	N/A	N/A	N/A	N/A	[53]
	205.0	N/A	50.0	N/A	11.0	N/A	348.3	N/A	N/A	N/A	N/A	N/A	[56]
	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.4-11.7	N/A	[109]

Table S6. The comparative ability of SCMs to remove efficiencies heavy metals from the literature.

Design SCMs	Heavy Metals – Concentration Removal (%)			Ranking	Reference(s)
	Zinc (Zn)	Copper (Cr)	Lead (Pb)		
Bioretention system	80–100	80–100	80–100	Very High	
Constructed wetland	26–50	50–75	26–50	Moderate	
Sand filter	50–75	26–50	76–100	High	
Permeable pavement	76–100	26–50	76–100	High	
Dry swale	76–100	50–75	N/A	High	[53,59]
Grass channel	26–50	0–25	0–25	Low	
Grass filter	26–50	26–50	0–25	Moderate	
Dry pond	26–50	0–25	26–50	Moderate	
Wet pond	50–75	50–75	50–75	High	

Table S7. Research on maintenance complexity for different SCMs [112].

SCM Category	Maintenance Complexity*			
	Minimal (%)	Simple (%)	Moderate (%)	Complicated (%)
Wet ponds	55	32	5	9
Dry ponds	65	30	0	5
Constructed wetlands	40	13	40	7
Surface sand/soil filters	63	0	25	13
Infiltration basins/trenches	33	40	13	13
Bioretention practices	38	31	13	19
Porous pavements	42	8	42	8
Filter strips/swales	62	31	0	8
Underground sed. devices	40	33	7	20
Underground filt. devices	50	20	10	20