Review

Scientific Evidence behind the Ecosystem Services Provided by Sustainable Urban Drainage Systems

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Abstract: Urban green infrastructure such as sustainable urban drainage systems are potential providers of ecosystem services. This paper reviews the field studies that empirically verify the potential benefits of SUDS. The cultural, provisioning, supporting, and regulating ecosystem services investigated in real cases have been studied and classified according to climatology (except for the control of urban hydrology, which has been widely corroborated). Although successful cases of runoff decontamination are numerous, there is heterogeneity in the results of the systems beyond those associated with climatic differences. The other ecosystem services have not been as widely studied, giving very variable and even negative results in some cases such as climate change control (in some instances, these techniques can emit greenhouse gases). Installations in temperate climates are, by far, the most studied. These services derive from the biological processes developed in green infrastructure and they depend on climate, so it would be advisable to carry out specific studies that could serve as the basis for a design that optimizes potential ecosystem services, avoiding possible disservices.

Keywords: ecosystem services; sustainable urban drainage systems; urban green infrastructure; climate change; urban biodiversity; urban ecology; stormwater quality

1. Introduction

Sustainable urban drainage systems (SUDS) are part of the so-called green infrastructure and, as such, can provide a series of ecosystem services (ES). This article reviews scientific evidence to identify whether the ecosystem services attributed in the literature have been empirically demonstrated.

In the last decades of the 20th century, new approaches to the management of urban stormwater emerged, which introduced a holistic and environmental approach to urban hydrology and are spreading more and more around cities around the world [1]. SUDS capture, filter, retain, transport, store, and infiltrate urban runoff, trying to reproduce the natural water cycle as closely as possible; the objective of these systems is to reduce the negative impacts in terms of the quantity and quality of runoff, as well as to maximize landscape integration and the social and environmental value of the elements involved in stormwater management in cities [2].

The SUDS contemplated in this review (ordered according to the location in the drainage chain from local control to regional control) are rain barrels, pervious pavements, soakaways, infiltration trenches, bioretention systems, green swales, filter strips, infiltration ponds, detention ponds, retention ponds, and artificial wetlands. These techniques are urban green infrastructures (UGIs).

UGIs encompass all those components that provide connectivity to ecosystems, provide ecosystem services, and contribute to mitigation and adaptation to climate change at the local municipal level [3].
Ecosystem services are benefits gained from ecosystems that support people’s survival and quality of life. These benefits are classified (see Table 1) into cultural services (nonmaterial benefits), provisioning services (products obtained from ecosystems), supporting services (services necessary for the production of all other ecosystem services), and regulating services (benefits obtained from regulation of ecosystem processes) [4].

Table 1. Main ES provided by SUDS according to bibliography; table adapted from [5–9].

| ES                | Benefits                                                                 | SUDS                                                                 |
|------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------|
| Cultural services| Improvement of the urban landscape                                       | Wetlands, bioretention systems, retention and detention ponds, green swales |
|                  | Recreation and health: Multifunctional open spaces for physical and mental wellbeing | Superficial and/or visible SUDS                                     |
|                  | Cognitive development and knowledge preservation, educational value, and encouragement of environmental awareness |                                                                      |
| Provisioning services | Water supply for different uses                                         | Rain barrels and SUDS with water storage that facilitate the recharge of aquifers used for human consumption |
|                  | Food production                                                          | Retention ponds, bioretention systems, and wetlands                 |
| Supporting services | Groundwater recharge                                                    | Infiltration SUDS                                                   |
|                  | Noise reduction                                                          | SUDS with vegetation and some permeable pavements                   |
|                  | Air quality improvement                                                  |                                                                     |
|                  | Carbon reduction and sequestration                                       |                                                                     |
| Regulating services | Water regulation: Maintenance of the hydrological cycle and stormwater mitigation* | All SUDS                                                           |
|                  | Water purification: Improve water quality                                | All SUDS (but to a different degree)                                |
|                  | Habitat and biodiversity: Pollination, creation of new urban habitats, increase of urban species | Vegetated SUDS                                                     |
|                  | Climate regulation: Reduction of the urban heat island effect and mitigation of the effects of climate change | Vegetated SUDS or those that store a surface sheet of water         |
|                  | Reduction of erosion processes produced by runoff                        | All SUDS (the volume and speed of runoff is reduced)                |

* SUDS are drainage elements and, as such, this is their main function.

In recent years, trends have emerged aimed at increasing green infrastructure in cities [10] (they provide multiple potential benefits and help to achieve the 11th goal of the UN’s 17 Sustainable Development Goals: “make cities inclusive, safe, resilient and sustainable” which includes providing access to green and public spaces for all strata of society [11]) and also towards a comprehensive urban water management, in which all the components of the urban water cycle are integrated with the urban development of the city and the management of basins, focused on maximizing the economic, social, and environmental benefits in an equitable manner in cities [12].

Hydrological-hydraulic control of these techniques has been extensively studied with positive results [13]; therefore, this work does not consider the ES related to flood control and restoration of the hydrological cycle of these drainage systems. However, the effectiveness of SUDS providing ES may vary for the same technique, depending on its shape, size, and/or composition [14]. Therefore, can it be said that each of the SUDS techniques will always give the same benefits? There are also studies that show differences between the benefits identified in the bibliography and what is observed in practical cases. In addition, ES depend on the type of ecosystem developed [3] and this, in turn, depends on climate [15], so the question arises as to whether the contributions of the SUDS will be the same under different climatic conditions.

Although climatic conditions on Earth vary widely from one place to another, they can be divided into categories based on temperature and rainfall ranges. According to the world Köppen climate classification (Figure 1), which was used in this study, there are five main types of climate, each of which is further divided into thirty classes denoted by letters (Table 2, 2nd letter refers to pluviometry and 3rd letter to temperature) that refer to the temperatures and amounts of rainfall that define each climate and specify the kind of vegetation that is present [16].
| Climate Subtypes | Description | Criteria ** |
|------------------|-------------|-------------|
| **A** Tropical   | T<sub>cold</sub> ≥ 18°C |
| f Rainforest    | P<sub>dry</sub> ≥ 60 mm |
| m Monsoon       | Not (Af) and P<sub>dry</sub> ≥ 100–MAP/25 |
| w Savannah      | Not (Af) and P<sub>dry</sub> < 100–MAP/25 |
| **B** Arid      | MAP < 10 × P<sub>threshold</sub> |
| W Desert        | MAP < 5 × P<sub>threshold</sub> |
| S Steppe        | MAP ≥ 5 × P<sub>threshold</sub> |
| h Hot           | MAT ≥ 18°C |
| k Cold          | MAT < 18°C |
| **C** Temperate | T<sub>hot</sub> > 10°C and 0°C < T<sub>cold</sub> < 18°C |
| s Dry Summer    | P<sub>sdry</sub> < 40 mm and P<sub>sdry</sub> < P<sub>wwet</sub>/3 |
| w Dry Winter    | P<sub>wdry</sub> < P<sub>wwet</sub>/10 |
| f Without dry season | Not (Cs) or (Cw) |
| **D** Cold      | T<sub>hot</sub> > 10°C and T<sub>cold</sub> ≤ 0°C |
| s Dry Summer    | P<sub>dry</sub> < 40 and P<sub>dry</sub> < P<sub>wwet</sub>/3 |
| w Dry Winter    | P<sub>wdry</sub> < P<sub>wwet</sub>/10 |
| f Without dry season | Not(Ds)or(Dw) |
| **E** Polar     | T<sub>hot</sub> ≤ 10 |
| T Tundra        | T<sub>hot</sub> > 0 |
| F Frost         | T<sub>hot</sub> ≤ 0 |

** Meaning of acronyms and abbreviations: MAP = Mean Annual Precipitation; MAT = Mean Annual Temperature; T<sub>hot</sub> = Temperature of the hottest month; T<sub>cold</sub> = Temperature of the coldest month; T<sub>mon10</sub> = number of months where the temperature is above 10; P<sub>dry</sub> = precipitation of the driest month; P<sub>sdry</sub> = precipitation of the driest month in summer; P<sub>wdry</sub> = precipitation of the driest month in winter; P<sub>wwet</sub> = precipitation of the wettest month in summer; P<sub>threshold</sub> = varies according to the following rules: if 70% of MAP occurs in winter (the cooler six consecutive month), then P<sub>threshold</sub> = 2 × MAT, but if 70% of MAP occurs in summer (the warmer six consecutive month), then P<sub>threshold</sub> = 2 × MAT + 28, otherwise P<sub>threshold</sub> = 2 × MAT + 14). Therefore, the purpose of this review is to show which of the ecosystem services attributed to SUDS have been empirically demonstrated and if their performance for different ES varies according to climate, a determining factor in the development of ecosystems.

2. Materials and Methods

This article is a systematic review of the academic literature on the empirical evidence of the ecosystem services offered by SUDS that follow the principles of the PRISMA 2020 Declaration [18]. The platform used to search for the articles was the Library Archive of the Polytechnic University of Madrid. This archive gives access to numerous databases,
including Journal Citation Report (JCR), ProQuest Central, Scopus, Science Direct, and the American Society of Civil Engineers ASCE Journals. To ensure the quality of the results, the selected publications had been peer-reviewed, and only articles and conferences were included. The search included all files up to mid-February 2021, with no geographical limits and with D.O.I. (Digital Object Identifier).

To better manage the results, the searches were initially divided by the type of SUDS and, within each one of them, by the class of ecosystem service studied. In addition, search words related to rainfall, runoff, and drainage were included to delimit the search for sustainable urban drainage in the field. The search criteria used were: the abstract or description of the publications should contain each of the different techniques contemplated in this study (to ensure that it was the object of the study and not a simple mention); the rest of the search fields had to include keywords to refer to each of the potential ecosystem services offered by the SUDS, as well as keywords related to runoff and drainage, to limit the results to the objective of the study.

The keywords and Boolean operators used for each of the techniques were for artificial wetland, (“urban wetland**” OR “artificial wetland**”); for bioretention systems, (bioretention); for retention pond, (“retention pond**” OR “retention basin**”); for detention pond, (“detention pond**” OR “detention basin**”); for green swale, (“vegetated swale**” OR “green swale**” OR “green channel**” OR “bioswale**”); for rain barrel, (“rain barrel**” OR “rain tank**”); for pervious pavement, (“pervious pavement**” OR “permeable surface**” OR “porous surface**” OR “porous pavement**”); for infiltration trench, (“infiltration trench**”); for soakaway, (“infiltration well**” OR “soakaway**”); for infiltration pond, (“infiltration pond**” OR “infiltration basin**”); and for filter strip, (“filter stri**”).

The keywords used to search for ecosystem services have been used for cultural ecosystem services, which include amenity, aesthetic benefits, recreation, health, traffic calming, educational value, cultural identity: (landscape OR amenity OR “aesthetic” OR “visual impact” OR recreation OR health OR “mental well-being” OR cultural OR “spiritual value*” OR education OR social); for provisioning ecosystem services, including freshwater supply, urban agriculture, rainwater harvesting: (“freshwater supp*” OR food OR “urban agriculture” OR “rain-water harvesting” OR resource); for supporting ecosystem services, including groundwater recharge, noise reduction, air quality, carbon reduction and sequestration: (“groundwater Recharge” OR noise OR “air quality” OR “air purification” OR “carbon reduction” AND “carbon sequestration” OR CO2); for regulating ecosystem services that includes Water Quality: (“water quality” OR “water puri*” OR “pollutant*” OR “treatment system” OR “treatment plant” OR “heavy metal**”); for erosion control: (“erosion control” OR “erosion management**” OR “soil control” OR “soil management**” OR erosion); for the increase of biodiversity: (“seed dispersal” OR “ecological diversity” OR “urban ecology” OR “plant divers**” OR “plant diversity” OR “pollin*”). OR Biodiversity OR Habitat OR “urban ecosystem” OR “ecolgic benefit”*), to refer to climate change: (“climate regulation**” OR “temperature regulation” OR “climate change” OR “energy savings” OR Energy OR “urban heat island” OR “thermal control**” OR cool*) and finally: (“stormwater” OR “rainwater” OR “drain*”).

As an example, the search for publications on regulation services related to the improvement of water quality by action on bioretention systems would be: Summary/Description contains (bioretention) AND Any field contains (“Water Quality” OR “water puri*” OR “pollutant*” OR “phosphorous OR nitrogen OR “stormwater treatment**” OR “stormwater pollution**” OR “heavy metal**”); for erosion control: (“erosion control” OR “erosion management**” OR “soil control” OR “soil management**” OR erosion); for the increase of biodiversity: (“seed dispersal” OR “ecological diversity” OR “urban ecology” OR “plant divers**” OR “plant diversity” OR “pollin*”). OR Biodiversity OR Habitat OR “urban ecosystem” OR “ecologic benefit”), to refer to climate change: (“climate regulation**” OR “temperature regulation” OR “climate change” OR “energy savings” OR Energy OR “urban heat island” OR “thermal control**” OR cool*) and finally: (“stormwater” OR “rainwater” OR “drain*”).

We listed and reviewed the titles and authors of the publications found to eliminate duplicates and articles from other subjects that could be included in the results. After
this first screening, we checked in the results lists of searches by technique, which articles appeared in more than one urban drainage technique, and which articles appeared in the search for two or more different ecosystem services, to avoid double counting of records.

After removing all duplicates and nonurban drainage publications, we selected publications that recorded empirical studies (both reviews and articles) of techniques under development or pilot projects located outdoors (in urban settings (cities and highways)) and citizen surveys on SUDS (to estimate cultural ecosystem services). Outdoor tests of small elements with short duration were excluded, as they are not really influenced by possible seasonal changes.

After this second sieve, we classified the results by climatology. For this, we reviewed the summary and methodology of each of the articles and found the location of the studies. Their climatology was defined based on the maps with the Köppen classification (Figure 1) [17] that differentiates the climates: Af, tropical rainforest; Am, tropical monsoon; Aw, tropical savanna; BWh, hot desert climate; BWk, cold desert climate; BSk, cold semi-arid climate; Csa, hot summer Mediterranean climate; Csb, warm summer Mediterranean climate; Cwa, warm oceanic climate/humid subtropical climate; Cwb, subtropical highland climate or temperate oceanic climate with dry winters; Cwc, subtropical cold subtropical highland/subpolar oceanic; Cfa, humid subtropical climate; Cfb, temperate oceanic climate; Cfc, subpolar oceanic climate; Dsa, humid continental climate with dry warm summer; Dsb, humid continental climate with dry cool summer; Dsc, continental subarctic with cold dry summer; Dsd, continental subarctic with dry summer and very cold winter; Dwa, humid continental hot summers with dry winters; Dwb, humid continental mild summer with dry winters; Dwc, subarctic with cool summers and dry winters; Dwd, subarctic with cold winters and dry winters; Dfa, humid continental hot summers with year-round precipitation; Dfb, humid continental mild summer, wet all year; Dfc, subarctic with cool summers and year-round rainfall; Dfd, subarctic with cold winters and year-round rainfall; ET, tundra climate; EF, ice cap climate. In this way, we categorized the publications according to climatology.

![World Map of Köppen Climate classification](image)

When reading the abstracts and methodologies of the publications, we realized that in many cases the search criteria for ecosystem services were not related to those stated in the article. Therefore, we reviewed the results to reclassify the publications according to the type of observed ecosystem service. For example, an article that appeared as a result in searches for ecosystem services related to temperature control, water quality, and landscape improvement, in its content only studied and analyzed parameters related to water quality. So, we rate that item solely on water quality.
To carry out the basic statistics of the results, we took the following into account: the publications that contained more than one type of SUDS of study were classified by each one of the techniques for the counts of the classes of SUDS studied; the results deal with the types of SUDS analyzed per publication, not the number of techniques studied; and, in the publications that contemplate different locations, the location of all SUDS (except laboratory tests) studied has been considered to determine the present climatologies.

3. Results

The total number of results found is 2841 articles and conferences, but they contain duplicates and some articles from other unrelated research areas, such as optics. As the subject of the analysis was empirical evidence for the contribution of SUDS ecosystem services beyond hydrological control, we only considered those articles with field tests and measurements and eliminated the small ad hoc scale (hours or days), which resulted in a total of 250 articles. Figure 2 shows the different screening processes.

Figure 2. Scheme of the search process used in this research work.

In this section, we present the ecosystem services for each SUDS study, based on the climatology of the site where the test or data collection was performed.

Each SUDS listed in the bibliography that was consulted is treated as a record and counted as such because several of the study papers considered two or more categories of SUDS. One of the publications, for instance, investigated the thermal performance of permeable pavements and green gutters in temperate climates. As a result, we counted the analysis of two distinct methodologies for the same article. The same was done with articles that looked at the same type of SUDS in several places with various climates.

Figure 3 displays the registered SUDS in accordance with the local climate categorization. As the graph shows, the largest number and types of techniques studied are in mesothermal climate zones. More notably in oceanic or temperate regions, where there is never a dry season because the rains are evenly distributed throughout the year (climates Cf). The D or continental cold is the following climate zone (with a significant divergence from the temperate region) in terms of the number of SUDS investigated. However, as is the case with climate C, the examined SUDS are situated in areas with regular and continuous precipitation (Df). More harsh climates, in terms of pluviometric regimes, are far behind in terms of the volume of techniques evaluated (A, rainy with ETP higher than precipitation, or conversely, B, dry climates with low rainfall).
The main conclusions of the ES analyzed in the bibliography selected by type of SUDS technique and climatic region are shown below.

In Figure 4, there is a wide variety of ES in the columns on the left (those that correspond to the number of ESs tagged per paper in the databases). It might be easy to think that the benefits of SUDS are much more widely studied than they really are. For example, according to search labels, there are articles that contemplate provision, cultural, support, and thermal regulation services in infiltration trenches, which suggests that several benefits of these techniques have been studied, but only the improvement of water quality (columns on the left). This figure highlights the difference between the ES expected in papers according to the search labels and the ES found.
Figure 4. Number of articles dealing with ecosystem services in the SUDS by climatology. The column on the left shows the number of articles according to the search, and the one on the right shows the identified ecosystem services.
3.1. Rain Barrel

3.1.1. Cultural Services

Cfa. The results of the survey show that the installation of rain barrels by private individuals is an opportunity to educate and train residents about the management of water resources on their properties [20]. Installing this SUDS in schools, in addition to promoting outdoor activities and interaction between students, can be the seed of future professional interests of interest to society [21].

Dfa. Public participation in hydrographic management, and knowledge of the operation of these techniques and their benefits can be an effective tool in encouraging pro-environmental behavior in people [22].

3.1.2. Provisioning Services

Dwa. The use of rainwater tanks in apartment buildings allows for the use of a considerable amount of rainwater, making this urbanization more sustainable [23].

Dfa. Rain barrels are useful to save much of the water used in irrigation [24].

3.1.3. Regulation Services: Biodiversity

Dfa. Combined use with rain gardens produces a significant effect of treatment on several habitat and water quality parameters [24].

3.1.4. Regulation Services: Water Quality

Cwa. Rain barrels help remove chemical oxygen demand (COD), ammonia, and total nitrogen from the water [25].

3.2. Pervious Pavement

3.2.1. Regulation Services: Biodiversity

Dwa. The permeable pavement allows the growth of plant species in its vicinity, unlike the impermeable pavement that shows limitations [26]. Instead, the creation of bacterial habitats under the subsoil is similar in both cases [27].

3.2.2. Regulation Services: Climate Change and Thermal Control

Cfa. Porous concrete bricks and porous asphalt had, on average, a lower surface temperature compared to regular concrete, which could help mitigate impacts from heat islands in urban settings [28].

3.2.3. Regulation Services: Water Quality

Cfa. The porous lot shows less concentration of turbidity, pollutants, calcium, zinc, silica, and total phosphorus than the asphalt lot, whereas total nitrogen concentration was higher [29].

Cfb. The quality of the runoff water improves in relation to pH, oxygen demand, and turbidity [30], but they can modify the chemical characteristics and humidity of the soil [31] as well by the elimination of suspended solids and heavy metals [32–34] some of which are retained in the porous surface and/or geotextile [35], but the rest is dragged into the subsoil with the infiltration water [36].

Csa. Permeable pavements have high potential to reduce the sodium adsorption ratio (SAR) of water [37].

Dfa. The porous pavement can retain copper but does not affect conductivity, total phosphorus, and chloride [38].

Dfb. The water quality treatment performance for petroleum hydrocarbons, zinc, and total suspended solids is exceptional but not for phosphorus, and the treatment for nitrate is negative [39].

3.3. Soakaway

Regulation Services: Water Quality
Am. Soakaways capture sediments with different grain sizes from different urban surfaces [40].

Cfa. Soakaways can retain different heavy metals such as zinc, lead, cadmium [41], lead [42], nickel, or copper, but the amount retained depends on several factors such as the presence of organic matter or the interaction between metals [43].

3.4. Infiltration Trench

Regulation Services: Water Quality

Csb. When there are anoxic conditions, denitrification and nitrate removal processes could occur [44].

Dfa. Performance of these techniques varies seasonally, and it is possible to improve the mobility of the metal [45].

Dfb. This facilitation provided diminutions in the concentration of total suspended solids, COD, total nitrogen, and total phosphorous [46].

Dwa. Infiltration trenches improve the quality of infiltrated water [23].

3.5. Bioretention System

3.5.1. Cultural Services

Csa. [47] Aesthetic services and sense of place in Southern California are regulated by different plant traits (leaf color for aesthetic services and maximum plant height for sense of place) and participant characteristics, particularly psychosocial characteristics such as environmental worldview (defined as an individual’s perception of their environmental role in the world), which significantly influences aesthetic services but not sense of place. Reflecting these differences, only 4 of the 15 plant species evaluated were found to provide both cultural services.

Dfa. Encouraging public participation in watershed activities, raising awareness of how these systems work, and emphasizing the functional benefits of practice can be effective in promoting acceptance of these technologies [22].

3.5.2. Supporting Services

Csa. Bioretention basins can sequester and store carbon throughout the ponding area [48].

3.5.3. Regulation Services: Biodiversity

Cfa. Alisma parviflora, Caltha palustris, Iris ‘Black Gamecock’, Lysimachia punctata ‘Alexander’, Oenanthe javanica ‘Flamingo’, Mentha aquatica, Phalaris arundinacea ‘Picta’, and Typha laxmannii have good survival and growth, and A. parviflora and M. aquatica help reduce pollutant [49]. Bioretention systems support a robust community of invertebrate fauna, despite their physical isolation [50].

Cfb. Bioretention basins and urban green spaces are different in their habitat properties, the first having more positive impacts on urban biodiversity compared to the green spaces they have replaced [51]. The invertebrate communities in these systems are affected by vegetation coverage, the number of plants in flower, pH, and the slope [52].

Dfa. Rain gardens with only native plant taxa can contribute to increases in native flora and wildlife habitat in the neighborhood [24].

3.5.4. Regulation Services: Climate Change and Thermal Control

Cfa. Nitrous oxide emissions are greater in summer than in fall, which may be due to the connection between warmer temperatures and high rates of nitrous oxide gas emissions from nitrification and denitrification [53].

3.5.5. Regulation Services: Water Quality

Af. The discharge quality of the catchments with bioretention ponds is better than those without them [54].
BSk. Total nitrogen and phosphorus retention in bioretention is likely driven by soil microbes and it may be that high plant density improves treatment [35].

Cfa. Bioretention systems, even small ones [56], are effective devices for the reduction of a variety of pollutants [57–60]. For example, suspended solids and total nitrogen [61] (for different processes: filtration, microbial activity [62] as denitrification [63,64]), and vegetal metabolism [65], nearly all total Kjeldahl nitrogen outflow is dissolved organic nitrogen [66]. Other retained contaminants are total phosphorus and phosphates [67], but this is variable [68]; sometimes bioretention cells can increase these elements in outflow [69,70]. These systems can also eliminate E. coli and enterococci [71,72] (soil depth and hydraulic loading are important to sequester microbes [73] and different vegetation show different efficiencies removing bacteria in descending order: no vegetation, shrubs, and grass [74]), metals [75–77], COD [78]. Bioretention areas are able to reduce stormwater runoff temperature [79]. However, bioretention performance can fluctuate [80] and can even increase the concentrations of pollutants [81] and nutrients [33]. Operativity can improve with age [82] and some modifications [83]; fly ash amendments improved microbial removal in bioretention cells [84] and are an effective option for phosphorus removal [85], as a retrofitted upflow filter [86]. Bioretention acts as both a nitrogen source and sink (by infiltration and plant uptake mainly) [87]. To improve nitrogen removal, it is useful to enrich microflora such as chloroflexi and nitrospirae [88], and installing soil medium with low sand content provides denitrifies activity [89]. However, no significant improvement is observed with the addition of the green technology called floating treatment wetlands [90].

Cfb. These systems have strong retention capacity after long-term operational time; heavy metals accumulate more at the inlet [91] and in the first centimeters of the soil mixture of bioretention systems [76].

Csa. Bioretention systems are effective in reducing salts [37], nitrogen [92], phosphate, and total organic carbon [93].

Csb. These systems can be effective for removing mercury, polychlorinated biphenols (PCBs), dioxins, heavy metals, suspended solids, polycyclic aromatic hydrocarbons (PAH) [94], motor oil [95], copper and zinc, without significant differences in performance or effluent concentration with time [96]. However, sometimes, levels of nitrate and orthophosphate increase in outflow [97], so changes in soil mix design are needed to reduce high levels of orthophosphates [98].

Dfa. These devices retain metals [99] (although not all with the same efficiency [75]), suspended solids and nutrients [100], but sometimes they can produce nitrates and component phosphorus [101]. Denitrifying bacterial communities are altered by the surrounding soil physiochemistry [102].

Dfb. Bioretention cells are able to retain suspended solid, COD, total nitrogen, and total phosphorous [46] (in some cases a special treatment is necessary [103]), naphthalene [104], microplastics [105], benzotriazole (depending on temperature, and salinity can be desorbed) [106], and metals [91].

Dfc. Metal retention is high, mainly by adsorption and mechanical filtration through the mulch and soil column, but there is plant uptake too [107]. Microplastics are efficiently removed [108].

3.6. Green Swale

3.6.1. Cultural Services

Csb. These techniques are a tool for raising awareness in the management of rainwater, but the citizen does not recognize them as natural spaces [109]. They can also be perceived as an inconvenience due to maintenance needs or the accumulation of garbage [110].

3.6.2. Supporting Services

Cfa. These devices have the potential capacity to sequester carbon, similar to that of grasslands [111].
3.6.3. Regulation Services: Biodiversity

Cfa. Engineered soils used in bioswales can serve as effective reservoirs of functional microbial biodiversity [112], which can be affected by the type of planted vegetation [113].

3.6.4. Regulation Services: Climate Change and Thermal Control

Cfb. Vegetated swales can act as temperature regulators because they can provide a higher surface temperature than air temperature in winter and the opposite in summer, providing a lower temperature than air [114].

3.6.5. Regulation Services: Water Quality

Af. The event mean concentrations of total suspended solids, total phosphorous, and total nitrogen are lower in catchments with green swales than without SUDS [54].

BWk. Bioswales achieve high removal rates of contaminant particles, but performance is poor and highly variable, in terms of dissolved contaminants, even though the effluent concentration is typically higher than influent. This SUDS itself appears to be the source of orthophosphate [115].

Cfa. Green swales reduce the concentration of total suspended solids in stormwater [116], while reducing heavy metals [117], turbidity, and bacteria [118,119]. The rate of reduction in nutrients is variable, usually favoring nitrogen but sometimes increasing phosphorus levels in effluents, as well as turbidity, heavy metals, and bacteria. The rate of nutrient reduction is variable [58], generally good for nitrogen [120,121] but sometimes increases phosphorus levels in the effluent [122].

Cfb. Reductions in total suspended solids and high particulate contaminants are high but not in dissolved phase pollutants [123]. Green swales produce higher nitrogen concentrations than untreated stormwater [70]. Swales with macrophytes are more capable of retaining soil particles and trace elements such as lead, zinc, copper, and PAHs [124]. The performance of these techniques retaining heavy metals is good [78] and increases over time [125].

Csa. Bioswale reduce nitrogen, phosphate, total organic carbon loading [93], Zn, Pb, Co, Cu, and Mn [126].

Csb. These systems can be effective for reducing copper and zinc, but changes to the soil mix are needed to reduce high levels of phosphorus in the effluent [98].

Dfa. In these types of techniques, denitrification can occur under appropriate conditions [102].

3.7. Filter Strip

3.7.1. Supporting Services

Cfa. These devices have the capacity to sequester carbon and reach a density similar to that of grasslands [111].

3.7.2. Regulation Services: Water Quality

Cfa. Filter strips retain some pollutants such as suspended solids [59,127] and metals [70], but they are not very effective in retaining phosphorus [70]. With respect to nitrogen, in some cases they can produce improvements in the quality of runoff water [128], but in others increased concentration may occur; the performance depends on the slope [129].

Cfb. Concentration reductions of total suspended solids and highly particulate contaminants are high but not the treatment of dissolved pollutants [123].

Dwa. The amount of pollutants retained in these techniques seems to depend on external factors such as the intensity of rainfall [130].

3.8. Infiltration Pond

3.8.1. Cultural Services

Dwa. The infiltration tank of a residential area serves as a playground for children in the dry season [23].
3.8.2. Supporting Services

Cfb. Infiltrated stormwater does not always reach a baseflow with high temperatures and is evapotranspired by the vegetation downslope of the basin [131].

3.8.3. Regulation Services: Biodiversity

Cfb. Rumex sp., Taraxacum sp., and Artemisia sp. are the most represented types of trees; these can be used as bioindicators [132]. Amphipoda, Gammarus pulex, and Niphargus rhenorhodanensis can be used as bioindicators to assess toxic disturbance [133].

3.8.4. Regulation Services: Water Quality

BWh. Infiltration basin can reduce nitrogen concentrations, fecal coliform concentrations, viruses, suspended solids, and total organic carbon [134].

Cfa. This device retains metals and hydrocarbons, providing low groundwater impact [41]. The mean removal efficiency for total phosphorus and total Kjeldahl nitrogen is representative [135] but variable between season [136] and soil texture properties [137]. Infiltration basins can achieve better performance after some time [78] and can be retrofitted with activated biosorption media to improve nutrient removal [138,139].

Cfb. In this climatology, the retention of contaminants [140,141] such as hydrocarbons [142] and heavy metals [143] or bacterial contamination [144] has also been proven, although not all contaminants behave in the same way; some are not retained in high concentrations [145,146], and components such as carbendazim, diuron, fluopyram, imidacloprid, and lamotrigine reach the groundwater [147]. The use of vegetation such as Phalaris arundinacea and Typha latifolia can absorb or modify the mobility of heavy metals [148].

Csa. Greater or lesser aeration of the infiltration ponds affects the chemistry of the soil [149].

Csb. These systems can be effective for copper and zinc but not always for phosphorus [98].

Dfa. The reduction of pollutants (chloride, copper, nitrogen, and phosphorus) in stormwater is greater than 90% [38].

Dfb. The infiltration ponds help to retain a large part of the salts that thaw drags, protecting the groundwater [150].

3.9. Detention Pond

3.9.1. Cultural Services

Cfa. People value the benefits of pond water quality, and improving its characteristics could generate large community benefits [151].

3.9.2. Supporting Services

Cfa. The relatively high volume of water infiltrating through detention ponds may serve to dilute some contaminants, but it may increase the concentration of others in the aquifers [152].

Csa. Rainwater stored in detention ponds serves to recharge an aquifer, reduce its saline load, and allow the later use of that water for irrigation [153].

3.9.3. Regulation Services: Biodiversity

Cfa. The mowing of invasive cattails (Typha spp.) and phragmites (Phragmites australis) in dry ponds increases the risk of transmission vectors of the West Nile virus (WNV) [154].

Cfb. These techniques have a higher concentration of heavy metals than natural lakes, but the bioaccumulation of metals did not affect the biodiversity of the water bodies. Stormwater ponds can play a biodiversity role similar to that of natural lakes [155,156]. In another study, most detention ponds are shown to be dominated by pollutant-tolerant taxa, indicating low biological quality [157].
Dfa. The survival of the crustacean Gammarus minus varies between the entrance and exit of a detention pond, and the concentration of pollutants [158].

Dfb. When comparing biodiversity, there is no clear difference between detention ponds and shallow lakes; only mollusks are more abundant in detention ponds [155].

3.9.4. Regulation Services: Climate Change and Thermal Control

Dfa. The average temperature in stormwater ponds is somewhat higher than that of the surrounding areas [158].

3.9.5. Regulation Services: Water Quality

Af. Not all ponds meet quality targets on their own, although the TSS value is low; in some cases, they would increase, raising the temperature while reducing the oxygen concentration and endangering aquatic species and ecosystems [159].

Aw. The detention basins have a positive impact over pollution control, with reduction of biological oxygen demand and suspended solids [160].

Cfa. Detention ponds are effective in reducing loads of suspended solids, suspended metals [161] (those in commercial areas have higher levels of zinc and lead in the sediments compared to other ponds [162]), turbidity, and nutrients [163] and help to remove fecal coliform [72]. Contaminant retention appears to be higher in green detention ponds than in grays [164]. The decomposition of detritus differs with plant species and decaying time, the effects of plant species being greater on mass loss than decaying time [165]. Sedimentation may be an important microbe removal mechanism, but it is not enough to achieve water quality objectives [166]. Controlling cyanobacteria in stormwater detention ponds, with the technology denominated floating treatment wetlands, could have an issue due to the residual algal toxin impact [167]. However, it may help to reduce nitrogen and phosphorus in some cases [168,169], though not in all [170]. Sediment burial rates of nutrients and carbon in detention pond sediments are like those observed in natural lake systems [171]. Unmaintained dry detention basins can provide improved water quality; eliminating routine maintenance improves carbon sequestration [172]. Differences in influent pollutant concentrations cause significant differences in water quality and pollutant removal efficiency between detention ponds [173].

Cfb. Wet detention ponds are more polluted by metals than lakes [155], but comparing potentially toxic metal concentrations with standards, the average sediment quality should not affect aquatic ecosystems [174]. Plants bioaccumulate metals in their roots, Typha sp. and Juncus sp., and they have high efficiency in metal retention [175]. Concentrations of suspended solids and total nitrogen decrease in these ponds [176], PAHs [177,178], nutrients, and DOC [179]. Although there are differences in pollutant removal, particle-associated pollutants are effectively removed, while dissolved pollutants are not [180]. At some detention ponds, fecal bacteria and other human pathogens [181] arrive, and these fecal bacteria can cause a slight drop in the device [182]. Pesticides, rather hydrophilic, are not trapped in the detention basin, but alkylphenols and alkylphenol ethoxylates, as well as bisphenol A [183] settle, suggesting these sediments should be managed with precautions [184], to avoid contamination of the environment. Maintenance and cleaning of the detention ponds are necessary, especially on highways [157].

Csa. There are significant differences in metal content in comparison of non-vegetated and vegetated areas in highway detention ponds; metal concentrations appeared particularly accumulated in the rhizosphere of macrophytes, and vegetation helps to prevent aeolian dispersion of particles [185].

Csb. Removal efficiencies are better in ponds designed primarily for water quality treatment, being more effective for suspended solids and metals and less effective for phosphorus [186].

Dfa. In detention ponds, petroleum hydrocarbons are maintained in the sediments, and it is not possible to determine whether or not the hydrocarbons are degraded or pose a migration threat [187]. Pollution in detention ponds can reach values that negatively
influence the survival of macroinvertebrates [158]. Soil bacteria from these techniques can perform denitrification under the right conditions [102]; the efficiency of nitrate removal in detention deposits varies seasonally [188].

Dfb. Wet detention ponds are more polluted by metals than lakes [155]. They can retain a high concentration of total metal content, nutrients, and COD [189] and, adding specific devices, the kind and concentration of retained pollutants increases [190,191]. Underground stormwater detention chambers provide similar levels of stormwater treatment as wet detention ponds and avoid thermal contamination of aquatic habitats [192]. The use of a train of stormwater infrastructure (including detention ponds) can be more effective in removing total suspended solids, COD, total nitrogen, and total phosphorous, but only if the infrastructure is sequenced properly [46]. The concentration of suspended solids and total nitrogen also decrease in these ponds because of their sedimentation [176]. These sediments may contain several trace metals and PAHs that, together with chlorides (from winter road deicing), cause depauperate benthic communities due to their ecotoxicity; therefore, they can be used as bioindicators [193]. Ecotoxicological evaluations reveal that toxicity may or may not be detected, depending upon site, storm conditions and the toxicity test system chosen [194]. N$_2$O emissions were low in all stormwater detention ponds studied, and wet detention basins had higher CH$_4$ emissions but also higher denitrification [195].

Dsb. The average suspended solid and metal removal efficiency is high [196].

3.10. Retention Pond

3.10.1. Cultural Services

Csb. There are common issues affecting resident acceptance of SUDS such as environmental attitudes, awareness, understanding of purpose and function, and plant choice and maintenance. Increased public engagement, localized maintenance strategies, or customized facilities might improve acceptance [110].

3.10.2. Provisioning Services

Cfb. Although these techniques are currently used for the reuse of rainwater, it is advisable to carry out a risk analysis for bacterial contamination [197].

3.10.3. Supporting Services

Af, Cfa, Cfb, Dfc. Stormwater wet retention ponds can sequester carbon across these four different climate zones, with annual rainfall and length of growing season being important general factors for carbon accumulation [198].

3.10.4. Regulation Services: Biodiversity

Cfa. The analysis of bacterial communities and their capacity to degrade pollutants can be done using genetic studies; it is recommended to evaluate the quantification of RNA in the measurement of the ecological functioning of bacteria [112].

Cfb. Stormwater ponds play an important role in biodiversity conservation in urban areas, because they can sustain a high species richness of plant species (inclusive threatened vegetation) [199]. The abundance and kind of amphibians varies with pond area, depth, vegetation, and operating time. These devices are useful as riparian corridors in urban settings [200], as well as in roadsides, where they can contribute to enhancing the biodiversity of the pond network at a regional scale [201]. Comparing nine amphibian species in a retention pond and a natural pond, the species richness and frequency of each species did not differ [202]. Something similar happens with aquatic macroinvertebrates [203], although roadside detention ponds differ in abiotic conditions, and they support rich and diverse communities. For some of them, as for the endangered species *Libellula depressa* and *Ischnura pumilio*, a temporary hydroperiod is necessary [204]. Stormwater retention ponds can support an invertebrate ecosystem without greater bioaccumulation of PAHs in organisms than in shallow lakes in the same region [205].
Csa. Ponds with natural bottoms show more dragonfly richness than those with an artificial bottom. Amphibian richness is more sensitive to the structure of the surrounding landscape [206].

Csb. No significant risks to benthic organisms are posed from Zn concentrations in sediments and pore water in this technique [207].

Dfb. Roadside ponds are different from ponds serving residential and industrial areas. There are no significant differences between the latter two in terms of diatom abundance, although different biocide applications by pond type cannot explain the taxonomic variability of diatoms [208]. Between *Juncus effusus* L., *Schoenoplectus tabernaemontani*, *Palla*, *Pontederia cordata* L., and *Carex comosa*, the last one has the best performing and is more suitable for this climate [209]. Some stormwater retention ponds can sustain an invertebrate ecosystem without the organisms experiencing higher bioaccumulation of PAHs, but then what is the case in shallow lakes of the same region [205]?

3.10.5. Regulation Services: Climate Change and Thermal Control

Cfa. Harvesting in retention basins and the use of herbicides to remove aquatic vegetation result in poorer water quality and stimulate greenhouse gases emissions [210].

Dfb. A better design is necessary, one that reduces sediment methanogenesis to avoid the hypothesized potential greenhouse gas emissions from unvegetated stormwater retention ponds [211].

3.10.6. Regulation Services: Water Quality

Af. Retention ponds can have high organic pollution levels and, in some cases, cyanobacteria, which produce a toxin that is harmful to the environment, aquatic animals, and public health [212].

BWh. In retention ponds, denitrification rates decrease from inlet to outlet and with soil depth, and the denitrification in these devices can affect the whole-city nitrogen cycling [213].

Cfa. Retention ponds have good performance in retaining suspended solids and nutrients but can produce orthophosphates that exit from the effluent [70]; better performance in phosphate elimination can be reached with special filters [86, 214]. They can remove *Escherichia coli*, enterococci [71], and fecal coliform (however, it is not always so effective with *Escherichia coli* elimination [72]), probably by settlement in both [215]. These systems can vary their performance, removing pollutants [216] and nutrients [217] with a special device (floating treatment wetland) with different species of plants, although they are not always effective in total nitrogen treatment [90]. This component can be eliminated with another technology filter-based [218]. The effectiveness of the devices in water quality treatment increases in warm seasons, probably caused by more active biological activities during the warmer months [219]. An undersized retention pond can still improve stormwater quality, reducing nutrients and suspended solid concentrations [220]. Infiltration through this system can serve to lower the concentrations of certain constituents in groundwater by dilution, while increasing concentrations of other compounds are more readily found in stormwater than in groundwater [152]. Stormwater pond biota can accumulate Cu and Zn [221], other organisms; false dark mussels can be bioindicators for PAH contamination in these devices [222]. Possible disadvantages of these drainage systems are the increase in microplastics in wet periods [223], (they can be a source of dissolved and particulate organic carbon) [224], and without stormwater runoff treatment, there is a potential for introducing and concentrating Erwinia soft-rot bacteria populations [225].

Cfb. Total PAH levels are similar in retention ponds and natural lakes; however, higher molecular weight PAH concentration in sediments is higher in retention ponds [205]. These devices are also effective in eliminating metals [226] and have the potential to remove some, but not all, pharmaceuticals contained in the effluent through faulty connections, sewer leaks, and overloading [227], nor pesticides belonging to the dissolved fraction [228] nor sodium from deicing salt on the roadway [229]. Some technologies such as floating treat-
ment wetlands offer higher treatment efficiency, especially for particulate pollutants [230] and metals [231]. They can improve nitrogen removal [232] and increased phosphorus sedimentation [233]. Regarding dissolved oxygen and pH, photosynthesis plays an important role for most of the year [234]. Microplastics are highly concentrated in retention pond sediments and accumulate in vertebrates [235], but studies show the absence of acute and chronic ecotoxicity in the sediment of retention ponds that treat stormwater from a road [236]. There is low bioavailability of some elements such as nickel and copper [237]. Retention facilities provide good elimination of pollutants but, in the case of some substances, appropriate management is necessary to prevent contamination of outflow water [238].

Csa. There are complements for retention ponds to improve their solid removal efficiency [239].

Csb. Zn concentrations were temporally quite variable in retention ponds, but there is no significant risk to benthic organisms from zinc concentration in sediments and pore water [202].

Dfa. Wood filters help with removal efficiency in retention ponds [240].

Dfb. There are several kinds of polymers in retention ponds in function of catchment land use [241] and metals in sediments [242]. Levels of total PAHs are similar in retention ponds and lakes; however, retention pond sediments tended to have higher concentrations of high-molecular-weight PAHs [205]. There are variations between summer and winter in the settlement of some salt components [243]. Retention ponds are effective in reducing the mean concentrations of total suspended solids, COD, total nitrogen, and total phosphorous [46], but removal of vegetation in stormwater retention ponds degrades water quality [211].

3.11. Artificial Wetland

3.11.1. Regulation Services: Biodiversity

Cfa. Macroinvertebrate abundance was highly variable between study sites, and taxon richness was low across all sites. Oligochaetes, nematodes, ostracods, and chironomids were the most common taxa found [244]. Over time, artificial wetlands stop attracting different species of bats [245,246]. When assessing mosquito risk, they should not be considered collectively, as that does not reveal links with urban wetland habitats or measures of aquatic diversity.

Cfb. Oligochaetes and midge larvae are the main invertebrate communities in stormwater wetlands [247]. There is homogenization of macroinvertebrate communities across the study wetlands, with some dependency between receiving wetland conditions and the degree of urbanization of the catchment, but other factors may be important too [248].

Csa. Hydrological and vegetation management with continuous inspections are essential to maintain the habitat diversity of the site [249].

Dfa. Artificial wetlands are dominated by an overall macrophyte community indicative of human disturbance; thus, any rehabilitation efforts need to take into account anthropogenic stressors [250]. Six identified wetland community types have aggressively spread non-natives amongst the most common plant species. Anthropogenic drivers have resulted in profound and pervasive changes, creating novel habitats and community types [251].

Dfb. Constructed stormwater wetlands frequently serve as breeding habitat for amphibians, but the levels of occurrence and abundance are lower than in natural wetlands. Terrestrial habitat surroundings should be restored for increasing biodiversity [252]. Correlations between land use, water chemistry, and biological communities suggest that urban run-off is likely a major factor in structuring biological communities [253].

Dwa. The studied wetland showed high removal efficiency. In addition, local plant and animal species (3 amphibian species, 3 reptile species, 17 benthic macroinvertebrate species, and 18 avian species) seemed to successfully settle [254].
3.11.2. Regulation Services: Climate Change and Thermal Control

Cfb. Large benthic invertebrates increase in average methane and CO₂ flux, so urban wetlands without control may make greater contributions to the total greenhouse gas budget in cities [247].

Dfb. Stormwater wetlands can have a climate warming effect, contributed to by methane and radiative forcing, so it is recommended to design and establish wetlands with large patches of emergent vegetation and to limit the areas of open water to the minimum necessitated by other desired ecosystem services [255].

3.11.3. Regulation Services: Water Quality

Aw. Stormwater wetland may lose its nutrient retention capacity because resuspension reintroduces them to the water column from sediments [256].

BSk. The presence of PAHs in wetlands can be estimated from its bioaccumulation in odonates [257].

Cfa. Artificial wetlands have high effectiveness in eliminating heavy metals [258,259], nitrogen [260], suspended solids [70,261], and nutrients absorbed by vegetation [262]. They can improve their effectiveness in removing substances such as phosphorous over time [78], so generally, they have better water quality performance than detention ponds [263].

Wetlands can remove fecal coliform [72], *Escherichia coli*, and enterococci [71].

Cfb. Stormwater wetlands can reduce high concentrations of pollutants [264], but in some cases, settled pesticides can limit fish life [265].

Dfa. Denitrification rates in the analyzed soils matched or exceeded atmospheric nitrate deposition and stormwater nitrate loading; thus, brownfields may play an important role in nitrate removal from urban stormwater [266].

3.12. ES Provided by the SUDS according to Climatic Region

Runoff quality regulation services are the most studied ES in all climate types. In fact, they are the only corroborated function (without considering the hydraulic performance) for SUDS in dry climates and almost the only one in tropical climates. As a summary, the main conclusions obtained from the analysis of the ES of the SUDS are (by type of climate) (Figure 5):

![Figure 5. ES provided by SUDS identified by climate type.](image-url)
3.12.1. Climate A

Type A climates are hot and rainy or with more precipitation than evapotranspiration losses [17].

Regulation Services, Water Quality: SUDS seem to be an ideal technique to improve the quality of runoff [40,54,160], but sometimes, given the high temperatures that characterize it, problems of a lack of oxygen in the waters [159] or eutrophication [212] in the stormwater green infrastructure may appear.

Supporting Services: SUDS can sequester carbon thanks to frequent rainfall and length of growing season being important general factors for carbon accumulation [198].

3.12.2. Climate B

Climate B includes the arid and semi-arid climates, characterized by having little annual precipitation. Precipitation and humidity are lower than evaporation and transpiration [17].

Regulation Services, Water Quality: The only ES recorded in the search has been the quality of the water. In general, the vegetated SUDS give a good performance improving the quality of the runoff [55,115,134,213], and some of the microfauna present naturally can serve as a bioindicator [257].

3.12.3. Climate C

Climate C is characterized by being moderate, with variable winters and summers but never extremes. The most common subtypes are f (with constant rainfall without a dry period) and s (dry summers). Figure 4 shows that most studies have been conducted in areas with constant rain.

Cultural Services:

The perception of the SUDS and its potential have been contrasted through various surveys and participatory actions [47,109,110,151].

Supporting Services: SUDS can be used to sequester carbon [48,111,152,198] and to recharge an aquifer, reduce its saline load, and allow the later use of that water for irrigation [153], but it is advisable to carry out a risk analysis for bacterial contamination [197].

Regulation Services. Biodiversity: The expansion of biodiversity and its potential benefits rank second among ecosystem services in terms of research. SUDS can support habitats and life [112,199], despite their physical isolation [50], and can sometimes play a biodiversity role similar to that of natural lakes [155,156,202,203], but their biota depends on materials and plants [113] used in the infrastructure.

Regulation Services. Climate Change and thermal control: Green swales and permeable pavement can act as temperature regulators [28,114], but other SUDS can emit greenhouse gases due to warmer temperatures [53], the benthic invertebrates metabolism [247], or the use of herbicides to remove aquatic vegetation [210].

Regulation Services. Water Quality:

The performance of SUDS in this type of climate has been measured, assessed, and compared in more than 200 studies, with positive outcomes as decontamination techniques.

3.12.4. Climate D

It is characterized by freezing winters with precipitation exceeding evaporation [17].

Cultural Services: Surveys of neighbors showed that knowledge of the operation of SUDS and their benefits can be an effective tool in encouraging pro-environmental behavior in people [22].

Supporting Services: SUDS multifunctionality have been probe in a residential area [23], as well as carbon sequester [198].

Regulation Services. Biodiversity: SUDS produce a significant effect of treatment on several habitat and water quality parameters [24]. They sometimes provide a biodiversity similar to the natural one [155,208,209,254], but the habitats created in these infrastructures
are highly conditioned by the anthropic presence [205,250,251], which can influence the biota present in the environment [158,252,253].

Regulation Services. Climate Change and thermal control: Large surface water storage SUDS have a warming effect [158,255] on their immediate surroundings and can sometimes emit greenhouse gases [211].

Regulation Services. Water Quality: Pervious pavement [38,39], infiltration trenches [23], bioretention systems [46,75,91,99,100,104–108], green swale [102], infiltration pond [38,150], detention pond [102,155,158,187,189–192] (although their efficiency of nitrate removal in detention deposits varies seasonally [188]), retention pond [46,205], and artificial wetland [266] have demonstrated good efficacy at removing pollutants. However, the absence of vegetation in some techniques can degrade water quality [211].

4. Discussion and Conclusions

We found only some empirical evidence of the ES that, according to the bibliography, have SUDS. It may be because the benefits extrapolated to the SUDS from natural spaces do not always work as expected since, although they may seem to, they do not really have a developed and established ecosystem. Table 3 discusses the main findings according to the ES classification.

Table 3. Notes to the main ES provided by SUDS.

| ES                | Benefits                              | Remarks on Review                                                                 |
|-------------------|---------------------------------------|-----------------------------------------------------------------------------------|
| Cultural services | Urban landscape improvement            | The studies are focused more on environmental education [20–22] (the population does<br>not always have a positive perception of these techniques [109,110]) than on checking if<br>they really help improve health or if they are really used for recreational purposes [23]. |
|                   | Recreation and health                  |                                                                                    |
|                   | Educational value                      |                                                                                    |
| Provisioning services | Water supply                          | The use of stored water may be limited by bacterial contamination [197], so to take<br>advantage of this service, it is necessary to adopt complementary measures.<br>Plants bioaccumulate heavy metals [75–77] and, although there are no field studies on<br>the production of edible vegetables, it has been shown in the laboratory that they<br>would not be suitable for consumption [267]. |
|                   | Food production                        |                                                                                    |
| Supporting services | Groundwater Recharge                  | Water stored in ponds serves to recharge an aquifer, reduce its saline load, and allow<br>later use of that water for irrigation [153] but not always. In some cases, the<br>concentration of other contaminants in aquifers may increase [152]. |
|                   | Noise reduction                        | There are no empirical studies that record these capabilities of SUDS in the consulted<br>databases. |
|                   | Improved air quality                   | Bioretention [48] and green swales have the potential capacity to sequester carbon,<br>similar to that of grasslands [111]. |
|                   | Carbon reduction                       |                                                                                    |
| Improve stormwater quality | All SUDS contemplated are efficient in the retention of contaminants (suspended, not dissolved [115,123]) but, in some cases, they can produce and mobilize pollutants [81]. The techniques that have the most biodiversity studies are retention ponds, artificial wetlands, and detention ponds in temperate and cold climates. Although in some cases the fauna they support can be similar to natural environments [155,156] and can contribute to increases in native flora and wildlife habitat in the neighborhood [24], runoff contamination can limit the taxa present [157] and can increase disease vectors [154]. |
| Habitat and biodiversity |                                                                                    | |
| Regulating services | Climate regulation                     | Although vegetated swales [114] and some permeable pavements can act as temperature buffers [28] in temperate climates, other SUDS can increase greenhouse gas emissions: Urban runoff carries a high concentration of nitrogen that, in the processes of nitrification and denitrification in vegetated systems, can be converted into nitrous oxide [53]; the degradation of organic matter washed by the stormwater in small and deep retention ponds without vegetation produces CO2 and CH4, so that, these kind of systems can contribute substantially to climate forcing [210]; the combined treatments (herbicides and harvesting) applied to the conventional stormwater retention basins to remove aquatic vegetation result in poorer water quality and appear to stimulate methane emissions resulting in noticeably higher cumulative fluxes of greenhouse gases from these basins [211]; pollution-tolerant wetland invertebrates have been shown to enhance greenhouse flux CH4 and CO2 [247]; artificial wetlands can sometimes have a water-warming effect in cold climates [158], open water and green areas of artificial wetlands are potential sources of carbon and may even have a net climate warming effect in boreal regions [255]. We do not find specific empirical studies that contemplate SUDS as urban runoff erosion control techniques in the consulted databases. |
| Erosion control   |                                        |                                                                                    |
The difference between the search results for each type of ecosystem service and those identified by reading the articles is notable; most of them deal with improving the quality of runoff, but no other ecosystem services that they performed appear in the search parameters.

Some publications can be very optimistic in attributing SE to SUDS [5–9], but more research is needed, especially regarding the improvement of citizen well-being, urban biodiversity, and climate regulation. This last point especially has turned out to be more controversial than expected.

The studies collected in this report show that SUDS can have a negative impact regarding thermal regulation and greenhouse gas emissions [53,210,211,247] (contrary to what is stated in other articles, based on evidence in the natural environment or in models). These undesirable emissions come from the decomposition of the organic matter present in the runoff [247], in high quantities due to the contamination dragged [53], so that if this decomposition does not occur in the SUDS, they could do so in the water masses where they occur [255]. They can be reduced with the correct design [210] and selection of plant growth substrates [53] used in SUDS, so it is advisable to include the analysis of this ecosystem service in the selection and implementation of SUDS, especially at the urban level where they can have a negative impact on thermal comfort. Therefore, it is essential to continue researching the optimization of the design, focused on the provision of services beyond hydraulics.

The intended goal of this review was to be able to examine the differences that could arise in the performance of the SUDS in several sites due to the different climatologies, but after reviewing the available literature, we concluded that we lacked the essential and adequate knowledge to do so for two main reasons:

− Few ES studies (apart from those pertaining to water quality).
− Predominance of research in temperate and cold climates with regular precipitation (Cf and Df climates found mainly in the northern hemisphere and Australia). In climatologies with little rainfall, where variables such as biodiversity or the rise in temperature with climate change may be affected, the prospective regulation services (apart from hydrological management) have scarcely been proven.

The conclusions drawn from this assessment therefore focus more on the information that is lacking than what is present.

While it seems that carbon sequestration is simple in warm regions, some SUDS can produce methane and other greenhouse gases through biological modification in cold climates. Although there may be an increase in temperatures in the areas nearby the SUDS in the near future, these gases cause an increase in temperature that is predicted to rise much further because of climate change, especially in the frigid cold of the northern hemisphere (areas with D climates).

It is important to note that all of the research works discovered were only concerned with raising water quality in type B regions, which are known for having minimal precipitation. It is odd that there has not been any research on the potential multiuse and services that may be provided to infrastructures that are dry virtually all year round since many SUDS are defined by being multifunctional environments.

Limitations and Future Considerations

This research is limited to scientific publications that must have a series of quality requirements, so it is possible that non-peer-reviewed publications that study real experiences of ES provided by SUDS are left out. Considering the number of articles reviewed, we realize that the percentage of studies that analyze and verify ES (those not related to hydrological control and excluding the improvement of water quality) is low. In addition, the biological portion offered by these services varies depending on the climate, so the same species will not be available in areas with marked climatic differences. A selection of plant species that optimizes the retention of pollutants in a rainy climate is very likely not to survive under conditions of extreme aridity.
The design of the SUDS focuses mainly on the hydraulic point of view since they are drainage elements. However, to be a multifunctional urban green infrastructure, the parameter design needs to be broadened. Additionally, the requirements of citizens to live in a comfortable and healthy environment (apart from reducing the risk of urban flooding) and the bioclimatic stage where it is located must be considered in each urban environment, as this will determine and limit development of the biological processes that provide ES. Expansion of the analysis in the design of these drainage techniques should not only be carried out to avoid problems such as the increase in greenhouse gas emissions or the generation of runoff with a high load of nutrients but also to be able to optimize all potential associated benefits of SUDS in places with high human concentration and little free space (cities).

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