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# Sustainable Urban Drainage Systems in Spain: Analysis of the Research on SUDS Based on Climatology

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**Abstract:** Sustainable urban drainage systems (SUDS), or urban green infrastructure for stormwater control, emerged for more sustainable management of runoff in cities and provide other benefits such as urban mitigation and adaptation to climate change. Research in Spain began a little over twenty years ago, which was later than in other European countries, and it began in a heterogeneous way, both in the SUDS typology and spatially within the peninsular geography. The main objective of this work has been to know through bibliographic review the state of the art of scientific research of these systems and their relationship with the different types of climates in the country. These structures have a complex and sensitive dependence on the climate, which in the Iberian Peninsula is mostly type B and C (according to the Köppen classification). This means little water availability for the vegetation of some SUDS, which can affect the performance of the technique. To date, for this work, research has focused mainly on green roofs, their capabilities as a sustainable construction tool, and the performance of different plant species used in these systems in arid climates. The next technique with the most real cases analyzed is permeable pavements in temperate climates, proving to be effective in reducing flows and runoff volumes. Other specific investigations have focused on the economic feasibility of installing rainwater harvesting systems for the laundry and the hydraulic performance of retention systems located specifically in the northeast of the Iberian Peninsula. On the contrary, few scientific articles have appeared that describe other SUDS with vegetation such as bioretention systems or green ditches, which are characteristic of sustainable cities, on which the weather can be a very limiting factor for their development.

**Keywords:** sustainable urban drainage systems; green infrastructures; stormwater green infrastructure; Mediterranean climate; arid climate; template climate; Spain



**Citation:** Abellán García, A.I.; Cruz Pérez, N.; Santamarta, J.C. Sustainable Urban Drainage Systems in Spain: Analysis of the Research on SUDS Based on Climatology. *Sustainability* **2021**, *13*, 7258. https://doi.org/10.3390/su13137258

Academic Editors: Margarita Martinez-Nuñez and Mª Pilar Latorre-Martínez

Received: 29 April 2021
Accepted: 25 June 2021
Published: 29 June 2021



## 1. Introduction

A new approach to urban stormwater management emerged in the 1980s and 1990s, introducing a holistic and environmentalist approach to urban hydrology, and which is increasingly spreading around all cities of the world [1]. This methodology reproduces, as faithfully as possible, the natural hydrological cycle to minimize the impact of urban development. It aims to reduce the negative impacts in terms of quantity and quality of runoff, as well as maximize the landscape integration and the social and environmental value of the elements involved in urban stormwater management [2]. This new way of treating urban stormwater took different names around the world. A very widespread one is Sustainable Urban Drainage Systems (SUDS), those elements of the infrastructure (urban–hydraulic–landscaping) whose mission is capture, filter, retain, transport, store, and infiltrate the urban runoff, trying to reproduce as close as possible the natural water cycle [3]. This definition is similar to green infrastructures in the United States: an approach to hydrological cycle that uses soils and vegetation to enhance and/or mimic the natural hydrologic cycle processes of infiltration, evapotranspiration, and reuse [4]. On the other hand, in Europe, the concept of green infrastructure is broader, encompassing all those elements that provide connectivity to ecosystems, provide ecosystem services, and contribute to the mitigation and adaptation to climate change; these are classified in different scales: the local level, municipal level, and regional or state level [5]. Therefore, the SUDS would be urban green infrastructures to be implemented at the local–municipal level. In addition, since some SUDS are characterized by the use of vegetation (for example: green roofs, bioswale, artificial wetlands, bioretention areas ... ), they can also be included within the so-called Nature-based Solutions (NbS), which include those elements in Nature that inspire facing new social challenges efficiently and responsibly with the environment [6].

SUDS cover a wide variety of elements or techniques such as [7] rainwater harvesting systems, green roofs, permeable surfaces, bioretention systems, vegetated swales, filter strips, infiltration systems, and detention–retention systems.

In Spain, SUDS appeared later than in other countries such as the UK or USA and were not as widely distributed or studied [8]. Thus, the objective of this article is to determine the state of the art in Spain and identify possible deficiencies in the research and/or experiences (if there are any of them); more specifically, it is to identify which techniques are the most analyzed and if they depend on the climate of the area or not.

*Study Area*

According to the Spanish State Agency of Meteorology (AEMET), in the Iberian Peninsula, there are mainly three types of climates in agreement with the Köppen classification [9]: (i) Dry climates (type B): BWh (warm desert) and BWk (cold desert), corresponding to the provinces of Almería, Murcia, and Alicante, where minimal rainfall occurs, and BSh (warm steppe) and BSk (cold steppe) for Extremadura and the Balearic Islands; (ii) Temperate climates (type C): Csa (temperate with dry and hot summer, known as Mediterranean climate) is found in approximately 40% of the surface of the Iberian Peninsula and the Balearic Islands, being the most common climate, it extends over almost all the southern half and much of the Mediterranean shoreline, Csb (temperate with hot and dry summer) in most of the northwest of the Peninsula and inland mountainous areas, Cfa (temperate without dry season with hot summer) in the northeast of the peninsula and in a strip of medium altitude in the Pyrenees, Cfb (temperate without dry season with mild summer) in the Cantabrian region; (iii) Cold climates (type D): Dsb (cold with dry and temperate summer) and Dsc (cold with dry and cool summer), Dfb (cold without dry season and mild summer) and Dfc (cold with dry summer and cool summer) in high mountain areas of the Pyrenees, the Cantabrian Mountains, and the Iberian System. Figure 1 shows the spatial distribution of the different climatic classes in Spain.

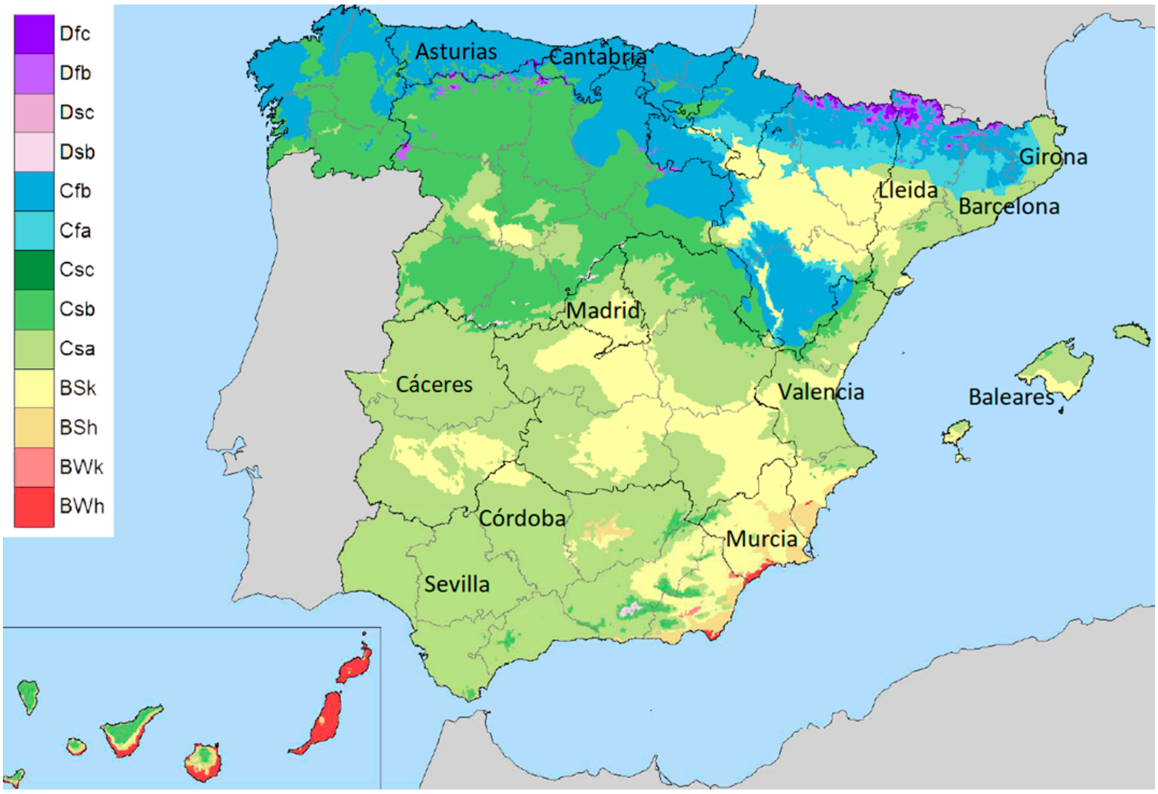


**Figure 1.** Köppen Climate Classification. The province's written names are the places where studies of real cases have been carried out. Source: Adaptation of Mapas climáticos de España (1981–2010) Y ETo (1996–2016) [10].

The weather in most of the country is characterized by temperate temperatures and rainfall regimes divided into two periods: one maximum in autumn and the other secondary in spring (except for the west and south of the peninsula, where the rainiest periods are autumn. and winter) [11]. This irregularity in the distribution can affect the development of plants [12] (many SUDS, such as bioretention areas or green roofs, have vegetation) and the performance of drainage elements as well [13]. So, the climate is a key element to consider in SUDS operation. Another characteristic of the rainfall in the Mediterranean and dry areas is the high intensity of rainfall events that are expected to increase in the future because of climate change [14].

SUDS are solutions for climate change adaptation and mitigation [15], and for this, they appeared as recommendations in publications for urban sustainability [16]. However, as we know the importance of the weather, doubts arise about the performance of these solutions in regions with different weather conditions, and therefore, there are concerns as to whether they are translatable. For this reason, this analysis intends not only to elucidate the state of the art of research on these techniques in Spain (if it is homogeneous throughout the national territory or not, if all the techniques arouse equal interest, what are the parameters, characteristics, or functionalities most analyzed) but also to find out the operation of the different sustainable drainage technologies under different climatic conditions.

So, although the main question to answer in this article was about the state of the art in scientific research on sustainable drainage systems in Spain, there have also been attempts to answer other questions in this regard, such as: Is there any relationship between climatology and the techniques studied? Since they are multifaceted structures, does the research focus on hydrological–hydraulic performance, or are other potential benefits evaluated?

## 2. Materials and Methods

The scientific publications compiled in SCOPUS on the sustainable treatment of urban runoff in Spain were the starting point for this analysis. SCOPUS was selected because it was a search engine that includes a greater number of journals compared to others such as Web of Science, and its citation analysis was faster [17]. Previously, we verified that the journals where researchers of specialized university centers (such as GITECO (https://www.giteco.unican.es/SUDSlab/inicio.shtml (accessed on 22 February 2021)) or IIAMA (https://www.iiama.upv.es/iiama/es/ (accessed on 22 February 2021)) published could be found indexed to SCOPUS.

In this bibliographic review, those publications made in scientific journals with DOI (and indexed in JCR or SJR) have been considered, looking for scientific evidence that shows the performance of these techniques in their different facets under the climatological characteristics of Spain [9].

The development of the methodology followed has had the corresponding steps: (i) Bibliographic search in SCOPUS, to find any paper about SUDS in Spain; (ii) Selection of the bibliography found, which was focused on obtaining the necessary data to answer the research question in this article (What is the state of scientific research on SUDS in Spain?); and (iii) Obtaining information from the selected documents focused mainly on knowing the temporal evolution of research in this field in Spain, if there were more theoretical studies than empirical cases, what techniques were most analyzed according to the different climates of the country or if there was some type of stormwater green infrastructure that has not been studied or monitored. Each of these points is detailed below.

### *2.1. Bibliographic Search in Scopus*

The search in the SCOOPUS database included publications of any nature, without a time limit and geographically affiliated with Spain that contain the following key concepts (Table 1), since one of the main objectives of this article was to know the status of the scientific research on sustainable urban drainage, the years of experience in this area, and the amount of research carried out.

**Table 1.** Keywords used in the search for articles related to SUDS in Spain. Source: Prepared by the authors.

| Keywords | Search String |
|---|---|
| Sustainable Urban Drainage | (TITLE-ABS-KEY (sustainable AND urban AND drainage) AND AFFILCOUNTRY (Spain)) |
| Stormwater Green Infrastructure | (TITLE-ABS-KEY (stormwater AND green AND infrastructure) AND AFFILCOUNTRY (Spain)) |
| Nature-Based Solutions Rainwater/Stormwater | (TITLE-ABS-KEY (nature AND based AND solutions) AND AFFILCOUNTRY (Spain) AND TITLE-ABS-KEY (stormwater OR rainwater)) |
| Permeable Pavement | (TITLE-ABS-KEY (permeable AND pavement) AND AFFILCOUNTRY (Spain)) |
| Green Roof | (TITLE-ABS-KEY (green AND roof) AND AFFILCOUNTRY (Spain)) |
| Soakaway | (TITLE-ABS-KEY (soakaway) AND AFFILCOUNTRY (Spain)) |
| Bioretention | (TITLE-ABS-KEY (bioretention) AND AFFILCOUNTRY (Spain)) |
| Infiltration Drainage/Sustainable/Urban Stormwater | (TITLE-ABS-KEY (infiltration) AND TITLE-ABS-KEY (drainage OR sustainable OR urban AND stormwater) AND AFFILCOUNTRY (Spain)) |
| Detention Drainage/Sustainable/Urban Stormwater | (TITLE-ABS-KEY (detention) AND TITLE-ABS-KEY (drainage OR sustainable OR urban AND stormwater) AND AFFILCOUNTRY (Spain)) |
| Retention Drainage/Sustainable/Urban Stormwater | (TITLE-ABS-KEY (retention) AND TITLE-ABS-KEY (urban AND drainage) AND AFFILCOUNTRY (Spain)) |

**Table 1.** *Cont.*

| Keywords | Search String |
|---|---|
| Artificial Wetland/Urban Drainage | (TITLE-ABS-KEY (artificial AND wetland) AND AFFILCOUNTRY (Spain) AND TITLE-ABS-KEY (stormwater OR rainwater OR drainage)) |
| Bioswale | (TITLE-ABS-KEY (bioswale) AND AFFILCOUNTRY (Spain)) |
| Vegetated Swale | (TITLE-ABS-KEY (vegetated AND swale) AND AFFILCOUNTRY (Spain)) |
| Filter Strips Drainage/Sustainable/Urban Stormwater | (TITLE-ABS-KEY (filter AND strips) AND TITLE-ABS-KEY (drainage OR sustainable OR (urban AND stormwater)) AND AFFILCOUNTRY (Spain)) |
| Rainwater Harvesting | (TITLE-ABS-KEY (rainwater AND harvesting) AND AFFILCOUNTRY (Spain)) |
| Urban Green Infrastructure Drainage/Rainwater/Stormwater | (TITLE-ABS-KEY (urban AND green AND infrastructure) AND TITLE-ABS-KEY (stormwater OR drainage OR rainwater) AND AFFILCOUNTRY (Spain)) |
| Blue Green Infrastructure | (TITLE-ABS-KEY (blue AND green AND infrastructure) AND AFFILCOUNTRY (Spain)) |

### 2.2. Selection of Bibliography

The initial search provided a total of 424 records, including articles, book chapters, lectures, and reviews. However, several articles with different keywords appeared with different search criteria, so there were some duplicate items. The screening process consisted in the elimination of duplicates, exclusion of publications without DOI, and we reviewed and read the papers to ensure that the practical cases were located within the Spanish geography (without include the work of Spanish researchers or Spanish entities in foreign locations). Thus, the number of documents to be analyzed became 137, of which 116 were articles, 5 were reviews, 9 were books or book chapters, and 7 were conference papers. This analysis considered the information contained in articles reviews and conferences. Most of the papers consulted belong to journals indexed in prestigious scientific databases, such as Journal Report Citation (JCR), SJR, and SCOPUS.

### 2.3. Extraction of Information

To answer the questions related to the state of SUDS research in Spain, which is one of the objectives of this study (Which techniques are the most analyzed? What are the most studied parameters and the main characteristics or functionalities? Is the study distributed evenly throughout the country? Does the study of these techniques arouse interest over time?), the minimum information collected included the following:

- Exposed drainage technique or techniques, according to a typical classification [3,7]: green roofs, rainwater harvesting, permeable pavement, detention systems, green channels, infiltration systems, retention systems, artificial wetlands, permeable pavements. The generalities have been included in a group called Sustainable Urban Drainage (SUDS in Figures).
- Year of publication.
- Type of study carried out: analysis of real cases (study of both structural and non-structural SUDS projects), laboratory tests (testing of a technique or any of its components in the laboratory), bibliographic review (studies of previous publications on the subject or comparisons of existing cases from other studies data) and application of models (use of hydrological, hydraulic, economic, or environmental models to simulate the operation of SUDS projected in a location but that do not exist in reality).
- Parameters analyzed in the articles: hydrological (in relation to flows and runoff volumes), structural (to evaluate the structure or typical structural components of each technique), ecological (to consider the biota involved in the performance of the techniques), energy (refer to the ability of SUDS to serve as an insulator or improve

urban thermal comfort), economic (cost–benefit studies and life cycle analysis of systems), social (citizens' perceptions about urban drainage and related urban policies), and planning (proposals for the inclusion of SUDS at the urban level, urban drainage design and management methodologies).

The information to delve into the analysis of the SUDS based on the weather included the following:

- The location of the study cases (included only those studies of SUDS or its components operating outdoors under the normal climatic conditions) to determine the climatology.
- Within the real cases of study were differentiated: testing new technologies (TNT), checking the performance of an alternative component or a novel structure; comparative (C), comparison of results between the performance of SUDS between variants or with gray infrastructures; data collection (DC), SUDS results monitored over time; model application (MA), creation of a model with previously obtained results; and survey (S), interviews on various aspects of SUDS.
- For the analysis of the case studies, the subject matter specified were: C, Component, or system layer (the article deals with one or more specific components of a SUDS); EP, Energy performance (the object of the research is to evaluate the potential energy benefits of a technique); EE, Economic study; ES, Ecosystem services (research to evaluate the potential ecosystem services of one or more techniques); HP, Hydrological performance (hydrological performance of SUDS or any of its components); HHP, Hydrological–hydraulic performance (hydrological performance and hydraulic operation of SUDS or any of its components); LCA, Life Cycle Analysis (economic–environmental analysis tool to analyze the suitability of a long-term technique); UP, Urban policies (article showing different policies and ways of managing urban water); RQ, Runoff quality (research focuses on runoff water quality and the ability of SUDS to manage it); SP, Social perception (how citizens perceive some of the sustainable drainage techniques); V, Vegetation (study focused on the plants that make up some of the SUDS).

## 3. Results

A total of 128 publications met the selection requirements. Figure 2 shows the total number of articles according to the technique analyzed and the evolution in the number of publications since the first explicit reference to the SUDS in the 1990s [18]. Under the title of several techniques are the articles that deal with projects that contemplated the operation (hydrological and quality of runoff) of several techniques simultaneously. With SUDS, we refer to those articles that deal with the sustainable management of urban runoff in a general way and not always using that term, also, green infrastructures.

Table 2 shows in a more concrete way the classification of the articles according to type of technique, type of study, and main subject studied in each case. The numbers indicate the number of publications found in this regard and in the last column of the table, the references of the classified articles.

Figure 3 schematically shows the articles grouped and counted according to the analyzed study parameters and also to the type of study (see Section 2.3).

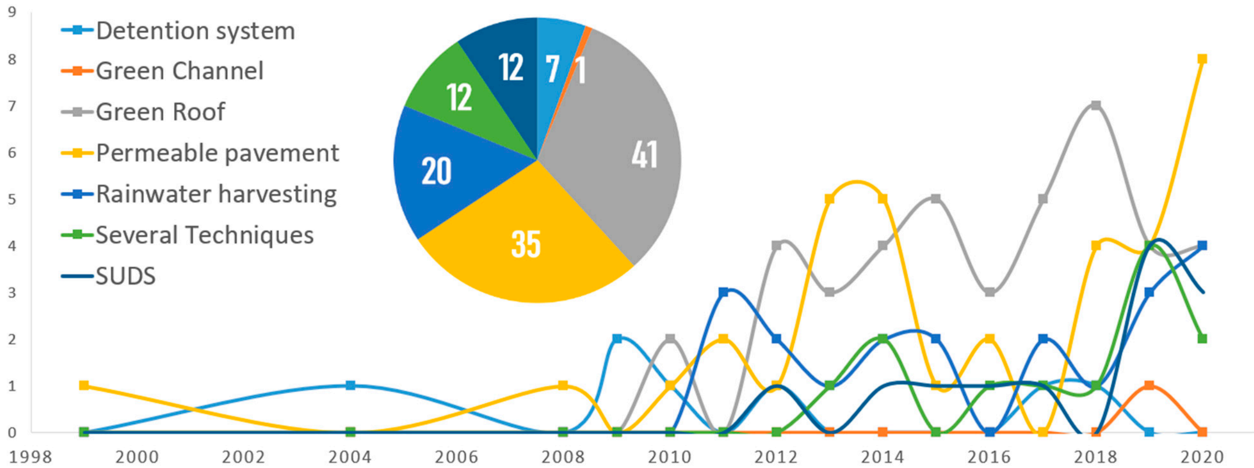


**Figure 2.** Number of articles according to the analyzed technique and temporal evolution of the number of publications. Source: Prepared by the authors.

**Table 2.** Types of studies and subjects analyzed according to the exposed drainage technique or techniques in the papers. Source: Prepared by the authors.

| Type of Sustainable Drainage Technique | Type of Study | Subject Studied | | References |
|---|---|---|---|---|
| Detention System (7) | Model application (5) | Hydrology | 5 | [19–23] |
| | Real case (2) | Hydrology | 1 | [24] |
| | | Runoff quality | 1 | [25] |
| Green Channel (1) | Laboratory test (1) | Energy | 1 | [26] |
| Green Roof (41) | Bibliographical review (4) | Ecology | 2 | [27,28] |
| | | Energy | 2 | [29,30] |
| | Laboratory test (2) | Ecology | 1 | [31] |
| | | Energy | 1 | [32] |
| | Model application (9) | Economy | 5 | [33–37] |
| | | Energy | 3 | [38–40] |
| | | Social | 1 | [41] |
| | Real Case (26) | Ecology | 7 | [42–48] |
| | | Economy | 1 | [49] |
| | | Energy | 13 | [50–62] |
| | | Hydrology | 2 | [63,64] |
| | | Runoff quality | 1 | [65] |
| | | Social | 2 | [66,67] |
| Permeable Pavement (35) | Bibliographical review (3) | Hydrology | 1 | [68] |
| | | Structural | 2 | [8,69] |
| | Laboratory test (21) | Energy | 1 | [70] |
| | | Hydrology | 5 | [71–75] |
| | | Hydrology/ Runoff quality | 1 | [76] |
| | | Runoff quality | 2 | [77,78] |

**Table 2.** *Cont.*

| Type of Sustainable Drainage Technique | Type of Study | Subject Studied | | References |
|---|---|---|---|---|
| | | Structural | 12 | [18,79–89] |
| | Model application (2) | Structural | 2 | [90,91] |
| | Real case (9) | Energy | 2 | [92,93] |
| | | Hydrology | 5 | [94–98] |
| | | Hydrology/ Runoff quality | 1 | [99] |
| | | Runoff quality | 1 | [100] |
| Rainwater Harvesting (20) | Model application (12) | Economy | 9 | [101–109] |
| | | Hydrology | 2 | [110,111] |
| | | Structural | 1 | [112] |
| | Real case (8) | Economy | 2 | [113,114] |
| | | Runoff quality | 2 | [115,116] |
| | | Social | 4 | [117–120] |
| Several Techniques (12) | Bibliographical review (1) | Energy | 1 | [121] |
| | Model application (7) | Economy | 2 | [122,123] |
| | | Hydrology | 5 | [124–128] |
| | Real case (4) | Hydrology | 2 | [129,130] |
| | | Hydrology/Runoff quality | 1 | [131] |
| | | Runoff quality | 1 | [132] |
| Sustainable Urban Drainage (12) | Bibliographical review (4) | Planning | 3 | [133–135] |
| | | Structural | 1 | [136] |
| | Model application (4) | Economy | 1 | [137] |
| | | Planning | 2 | [138,139] |
| | | Social | 1 | [140] |
| | Real case (4) | Planning | 2 | [141,142] |
| | | Social | 2 | [143,144] |

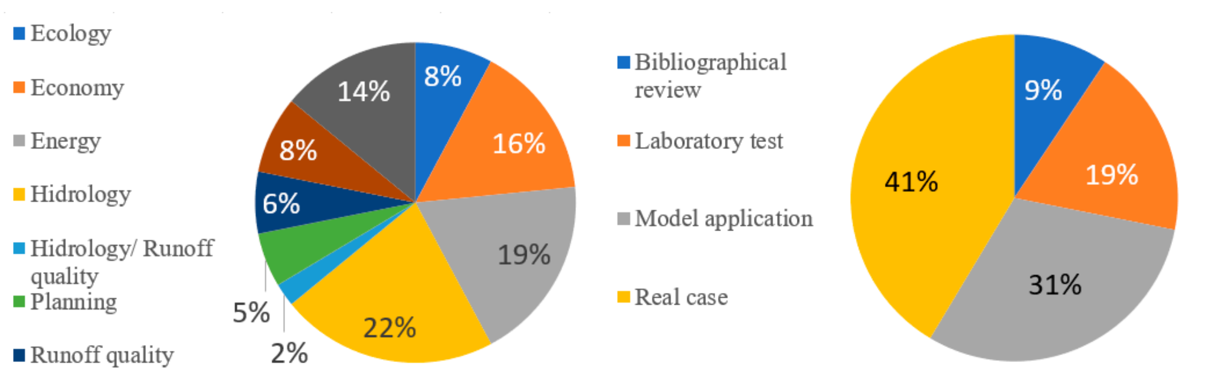


**Figure 3.** The graph on the left shows the percentage of study of the main subjects covered in the articles, and the graph on the right shows the proportion of papers according to type of study. Source: Prepared by the authors.

### 3.1. Sustainable Urban Drainage

This classification includes those articles that talk about sustainable drainage and green infrastructures in a global way, how they should be implemented, projects executed, and the benefits that these systems provide.

It also includes a recent bibliographic review of the SUDS in Spain from 2019: "The potential of sustainable urban drainage systems (SUDS) as an adaptive strategy to climate change in the Spanish Mediterranean" [136]. This paper is a compilation of some of the techniques implemented in Spain, particularly in Alicante.

Since these were not real case studies that could be affected by the weather, we did not delve further into the content of this classification.

### 3.2. Projects With Several SUDS

In addition to real cases of independent SUDS, publications that contemplated the simultaneous operation of different SUDS also appeared in the search: a pair referring to the AQUAVAL project [129–131] in Valencia province (Csa climate) and out in the north of the country (Cfb climate), whose conclusions appear in Table 3.

**Table 3.** Main conclusions of the studies on several SUDS together. Abbreviations used in Kind of Study: C, Comparative; DC, Data collection. Abbreviations used in Subject Studied: HHP, Hydrological–hydraulic performance; RQ, Runoff quality. Source: Prepared by the authors.

| Year | Title | Climate | SUDS Studied | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|---|
| 2013 | The sustainable management of surface water at the building scale: Preliminary results of case studies in the UK and Spain [129] | Csa | Green roof, permeable pavement, rainwater harvesting | C | HHP | Comparison of the hydrological performance of SUDS in the United Kingdom and Xátiva (AQUAVAL project). The monitored elements revealed good hydrological–hydraulic performance of these systems. |
| 2014 | Comparative analysis of the outflow water quality of two sustainable linear drainage systems [132] | Cfb | Green channel, French drain | C | RQ | The results of measurements of water quality parameters (dissolved oxygen, TSS, pH, electrical conductivity, turbidity, and total hydrocarbons) showed fewer pollutants at the outlet of SUDS than the outlet of conventional drainage systems. |
| 2014 | SuDS Efficiency during the Start-Up Period under Mediterranean Climatic Conditions [130] | Csa | Infiltration pond, green channel; green roof | C | HHP-RQ | AQUAVAL project in Benaguasil: The hydrological and water quality results for the infiltration pond and green channel showed a significant attenuation of flows, volumes, and pollutants. However, the water quality of the green roof was worse than the conventional one. |

**Table 3.** *Cont.*

| Year | Title | Climate | SUDS Studied | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|---|
| 2017 | The role of monitoring sustainable drainage systems for promoting transition towards regenerative urban built environments: a case study in the Valencian region, Spain [131] | Csa | Green channel; green roof, rainwater harvesting, detention and infiltration systems | DC | HHP-RQ | AQUAVAL project in Benaguasil: The results of the monitored SDUS proved good hydraulic performance in a typical Mediterranean climate and an improvement in water quality in green channels and infiltration systems. |

In addition to the real cases, there were also investigations that propose models to evaluate the suitability of the use of these techniques in flood control (giving positive results) [124–128], improving adaptation to change climate [122,125], and providing another environmental benefits [123].

### 3.3. Green Roofing

Green roofs, with 41 publications, were the most analyzed techniques, and 24 of these articles showed the results of monitored roofs. Table 4 summarizes the main conclusions obtained in investigations of real cases in Spain in a semi-arid climate (type B) and in a Mediterranean climate (type Csa).

**Table 4.** Main conclusions of the studies on green roofs. Abbreviations used in Kind of Study, TNT, Test new technologies and/or materials; S: Survey; C: Comparative; DC: Data collection; MA, Model application. Abbreviations used in Subject Studied: HP, Hydrological performance; EP, Energy performance; V, Vegetation; C, Component, or system layer; LCA, Life Cycle Analysis; ES, Ecosystem services; UP, Urban policies; SP, Social perception. Source: Prepared by the authors.

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2012 | Use of rubber crumbs as drainage layer in experimental green roofs [63] | BSk | TNT | HP | The use of rubber crumbs as a drainage layer material in extensive green roofs was feasible |
| 2012 | Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material [51] | BSk | TNT | EP | The use of rubber crumbs for the energy improvement of a building did not give better results than other typical green roof components |
| 2012 | Green roofs as passive system for energy savings when using rubber crumbs as drainage layer [50] | BSk | TNT | HP—EP | The use of these techniques using rubber crumbs showed an improvement in these yields compared to a normal ceiling during the monitoring period |
| 2013 | Green roof systems: A study of public attitudes and preferences in southern Spain [66] | Csa | S | SP | Sociodemographic characteristics and environmental background of childhood influenced the green roof type preferences of citizens. |
| 2014 | Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life Cycle Assessment [49] | BSk | TNT | LCA | The rubber crumbs produced less environmental impact than pozzolan, which is an element that can be substituted in green roofs. |

**Table 4.** *Cont.*

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2014 | Photovoltaic-green roofs: An experimental evaluation of system performance [53] | BSk | C | EP | The green roof systems (Gazania rigens and Sedum clavatum) with photovoltaic panels showed a considerably lower roof surface temperature compared to the photovoltaic panel–gravel configuration |
| 2015 | A critical analysis of factors affecting photovoltaic-green roof performance [54] | BSk | C | EP | The results revealed that the increase in photovoltaic production provided by photovoltaic green roofs depended on several factors, and among the plant species studied, Sedum clavatum showed the best interaction with photovoltaics and the building. |
| 2015 | Evaluating the growth of several Mediterranean endemic species in artificial substrates: Are these species suitable for their future use in green roofs? [42] | BSh | C | V | Study of the growth of Silene vulgaris, Silene secundiflora, Crithmum maritimum, Lagurus ovatus, Asteriscus maritimus, and Lotus creticus on three artificial substrates. S. vulgaris and L. ovatus showed greater germination and growth than the other species. |
| 2015 | Plant cover and floristic composition effect on thermal behaviour of extensive green roofs [55] | BSk | TNT | EP | Study of the thermal performance of an extensive green roof according to coverage and floristic composition (Sedum species) that compares the behavior of the system with low (10%) and high (80%) vegetation coverage. There were not significant changes between both. |
| 2015 | The inorganic component of green roof substrates impacts the growth of Mediterranean plant species as well as the C and N sequestration potential [43] | BSh | TNT | C: Substrate | Lotus creticus and Asteriscus maritimus were planted and evaluated for 10 months in four substrates with the same compost but several inorganic materials in different proportions. The study demonstrated that the composition of the substrate impacts on native plant growth and C and N sequestration. |
| 2015 | The thermal behaviour of extensive green roofs under low plant coverage conditions [56] | BSk | DC | EP substrate | The results of a monitored green roof study focused on analyzing the thermal behavior of the substrate layer with the growing plants (10% vegetation cover). Where plants provide little shade, the thermal performance of the roof depended on the characteristics of the lower layers, especially the substrate. |

**Table 4.** *Cont.*

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
| --- | --- | --- | --- | --- | --- |
| 2016 | The composition and depth of green roof substrates affect the growth of Silene vulgaris and Lagurus ovatus species and the C and N sequestration under two irrigation conditions [44] | BSh | C | C: Substrate | The authors analyzed the sequestration of C and N and their state with irrigation at 40% of the ETP values in two different substrates with Silene vulgaris and Lagurus ovatus and concluded that this irrigation allowed an adequate vegetal cover. |
| 2016 | Thermal assessment of extensive green roofs as passive tool for energy savings in buildings [58] | BSk | C | EP | Extensive green roof samples provided lower energy consumption than conventional roofs during hot periods, while they consumed higher energy during heating periods. |
| 2017 | Sustainable earth-based vs. conventional construction systems in the Mediterranean climate: Experimental analysis of thermal performance [59] | BSk | C | E | Seven cubicles with the same inner dimensions and orientation but different construction systems are thermally tested at a real experimental scale. Similar thermal behavior can be achieved by using sustainable and environmentally friendly construction systems instead of the current high embodied energy conventional ones. |
| 2018 | Performance evaluation of five Mediterranean species to optimize ecosystem services of green roofs under water-limited conditions [46] | BSk | C | V | An experiment evaluated the growth and coverage of Brachypodium phoenicoides, Crithmum maritimum, Limonium virgatum, Sedum sediforme, and Sporobolus pungens, with irrigation at 50% and 25% of the ET0 values. All species survived and showed an adequate aesthetic performance and plant cover, although not equally between them. |
| 2018 | Thermal regulation capacity of a green roof system in the Mediterranean region: The effects of vegetation and irrigation level [60] | BSk | DC | EP | Quantification of the contribution of the vegetation cover and the effect of the volume of irrigation water on the thermal efficiency of a green roof. The presence of vegetation reduced the thermal variations. Sedum sediforme behaved as a better insulator than Brachypodium phoenicoides during the experimental period (spring and summer). |

**Table 4.** *Cont.*

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2018 | Hydrological performance of green roofs at building and city scales under Mediterranean conditions [64] | Csa | C | HP | The authors monitored a green and a conventional roof for comparison and created hydrological models that were calibrated and validated. Green roofs provided a good hydrological performance. |
| 2018 | Mediterranean green roof simulation in Caldes de Montbui (Barcelona): Thermal and hydrological performance test of Frankenia laevis L., Dymondia margaretae Compton, and Iris lutescens Lam [45] | Csa | DC | HP-EP plants | The authors evaluated the thermal and hydrological behavior of Frankenia laevis, Dymondia margaretae, and Iris lutescens with a minimum irrigation contribution and a dry land treatment. The results showed that the most influential factors recorded were the relationship between air and water in the substrate and the interaction between the green layer and the substrate. In particular, D. margaretae conserved more water than the other species in both summer and winter. |
| 2018 | Risk assessment by percolation leaching tests of extensive green roofs with fine fraction of mixed recycled aggregates from construction and demolition waste [65] | Csa | S | C: Substrate | The aim of this study was the environmental risk of contaminant release in leachates from different substrate mixtures based on recycled construction waste aggregates. Records were lower compared to laboratory test data, showing how laboratory conditions may overestimate the potential contaminating effect of these materials. |
| 2019 | Evaluating the establishment performance of six native perennial Mediterranean species for use in extensive green roofs under water-limiting conditions [47] | BSk | C | V | The authors cultivated Asteriscus maritimus, Brachypodium phoenicoides, Crithmum maritimum, Limonium virgatum, Sedum sediforme, and Sporobolus pungens under good irrigation and water deficit conditions to evaluate the effects of water deficit on their growth. Sedum sediforme appeared to be the species best adapted to water deficit and Brachypodium phoenicoides and Limonium virgatum showed a satisfactory aesthetic performance in water deficit conditions. |

**Table 4.** *Cont.*

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2019 | Long-term experimental analysis of thermal performance of extensive green roofs with different substrates in Mediterranean climate [61] | Csa | C | EP substrate | The thermal performance over two years of three green roofs with different types of substrates (commercial and recycled materials) and a traditional ballasted gravel roof. The results of a comparison between the thermal performance over two years of three green roofs with different types of substrates (commercial and recycled materials) and a traditional ballasted gravel roof indicated that for hot and dry weather conditions, the greater capacity to retain water in the substrate provided a greater cooling capacity. |
| 2020 | Evaluation of the development of five Sedum species on extensive green roofs in a continental Mediterranean climate [48] | BSk | C | V | The paper reflected the growth and development patterns of Sedum album, S. sediforme, S. sexangulare, Sedum spurium, and Sedum spurium and concluded that Sedum album, S. sediforme, and S. sexangulare were species recommended for use in extensive green roofs, while S. spurium presented some limitations for their use. |
| 2020 | Creating urban green infrastructure where it is needed—A spatial ecosystem service-based decision analysis of green roofs in Barcelona [67] | Csa | S | ES | The authors created a decision tool for the implementation of green roofs based on their potential ecosystem services from models and the opinions of the participants in workshops held within the Naturvation (https://naturvation.eu/ (accessed on 25 February 2021)). |
| 2020 | Study of the improvement on energy efficiency for a building in the Mediterranean area by the installation of a green roof system [62] | Csa | MA | EP | A model created with TRNSYS and calibrated with experimental data from a monitored green roof resulted in a substantial improvement in the building's cooling energy demand, a 30% reduction in energy demand for a standard summer day, and 15% for a winter day. |

Given the importance of climate in the development and maintenance of vegetation and that the climate of much of the national territory is characterized by long periods of drought, an important part of the research carried out has focused on the functioning of species such as *Brachypodium phoenicoides*, *Crithmum maritimum*, *Limonium virgatum*, *Sedum sediforme*, *Sporobolus pungens*, [46,47] and *Asteriscus maritimus* [47], which were studied in the Balearic Islands; Sedums such as *lbum, sexangulare,* and *spurium* [48], which were observed in Lleida; and *Silene vulgaris, Silene secundiflora, Crithmum maritimum, Lagurus ovatus, Asteriscus maritimus*, and *Lotus creticus* in Murcia [42].

### *3.4. Permeable Pavements*

Permeable pavements were the second technique with the most publications, with a total of 35 papers. Nine of them reflected the results of experimental installations, and 20 were laboratory tests. Table 5 shows the most representative conclusions of the study cases in locations with a temperate mesothermal climate (type Cfb) and in places with a Mediterranean climate (Csa).

**Table 5.** Main conclusions of the studies on permeable pavements. Abbreviations used in Kind of Study: C, Comparative; DC, Data collection. Abbreviations in Subject Studied: HP, Hydrological performance; EP, Energy performance; LCA, Life Cycle Analysis; S, Survey; RQ, Runoff quality; C, Component. Source: Prepared by the authors.

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2010 | Performance of pervious pavement parking bays storing rainwater in the north of Spain [94] | Cfb | C | HP | The comparison of the performance of three types of permeable pavements, two with geotextiles (Inbitex and One Way) and another without it, did not show differences in the storage capacity of the SUDS. |
| 2011 | Analysis and contrast of different pervious pavements for management of stormwater in a parking area in Northern Spain [95] | Cfb | C | HP | The materials of the surface layer of the permeable pavements tested had a greater effect than the geotextile layer in their storage capacity; although the behavior was different in the three types of permeable pavements identified, the differences in their ability to retain water were not significant. |
| 2011 | Design and construction of an experimental pervious paved parking area to harvest reusable rainwater [99] | Cfb | C | HP-RQ | The materials of the surface layer of the permeable pavements tested had a greater effect than the geotextile layer in their storage capacity; although the behavior was different in the three types of permeable pavements identified, the differences in their ability to retain water were not significant. The quality of the stored water was suitable, although in the conditions of the first flush, it did not give good results and neither did it comply with some parameters of the Spanish legislation. |
| 2013 | Monitoring and evaluation of the thermal behavior of permeable pavements for energy recovery purposes in an experimental parking lot: Preliminary results [92] | Cfb | C | EP (Ground Source Heat Pumps) | The temperature of the subbase was different from the air temperature during the study period, which showed that the subbase is less affected by air temperature than the pavement bedding because of the insulating capacity of the permeable pavements. |
| 2013 | Temperature performance of different pervious pavements: Rainwater harvesting for energy recovery purposes [93] | Cfb | C | EP (Ground Source Heat Pumps) | The temperature of the subbase was different from the air temperature during the study period, which shows that the subbase was less affected by air temperature than the pavement bedding because of the insulating capacity of the permeable pavements. The rainwater tank did not represent a health risk associated with the appearance of Legionellae (in case the permeable pavement worked in geothermal air conditioning). |
| 2014 | Water quality and quantity assessment of pervious pavements performance in experimental car park areas [100] | Cfb | C | RQ | The results of three field studies demonstrated important correlations between sub-base materials and outlet water quality parameters. The polymer-modified porous concrete surface course in combination with limestone aggregate performed better than basic oxygen furnace slag. |

**Table 5.** *Cont.*

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2018 | The long-term hydrological performance of permeable pavement systems in Northern Spain: An approach to the "end-of-life" concept [97] | Cfb | DC | C | Despite suffering a significant reduction in permeability after 10 years of operation, the permeable pavements analyzed showed a high rate of infiltration, although there were spatial variations in the reduction of infiltration capacity due to static loads from vehicles. |
| 2018 | A study of the application of permeable pavements as a sustainable technique for the mitigation of soil sealing in cities: A case study in the south of Spain [96] | Csa | C | HP | The efficiencies of the maximum flow reduction of the monitored pavements exceed 95% and, in relation to the volumetric efficiencies, they were higher than 80%. |
| 2020 | Middle-term evolution of efficiency in permeable pavements: A real case study in a Mediterranean climate [98] | Csa | DC | C | The pavements tested did not suffer from obstructions in the medium term, and the variability in efficiency could be due to the Mediterranean climate, the variations in the behavior of the pavement seemed to be more influenced by the initial saturation of the soil than by possible obstructions in the first years of operation. |

Regarding the use of this technique for adaptation to climate change, the Life CERSUDS project [91] has investigated the capacity of these forms of permeable surfaces made from ceramic elements systems to mitigate the expected effects.

### *3.5. Rainwater Harvesting*

There were also several studies of rainwater harvesting and potential uses (Table 6), which were all located in places with Mediterranean climatology (Barcelona and Girona).

**Table 6.** Main conclusions of the studies on rainwater harvesting. Abbreviations used in Type of Study: S, Survey; C, Comparative; DC, Data collection; MA, Model application. Abbreviations used in Subject Studied: UP, Urban policies; RQ, Runoff quality; EE, Economic study; SP, Social perception.

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2011 | A comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the Metropolitan Area of Barcelona (Spain): Social experience, drinking water savings, and economic costs [113] | Csa | C | SP | Rainwater was rarely used for flushing toilets and cleaning clothes despite giving favorable results in the Metropolitan Area of Barcelona. The perception about these systems was that the environmental benefit exceeded the pecuniary. The main drawback identified was the long payback period of these systems. |
| 2011 | Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods [114] | Csa | C | EE | The strategies for collecting and reusing rainwater in dense urban areas of the Mediterranean were economically advantageous only if they were carried out at an appropriate scale allowing economies of scale and considering the expected evolution of water prices. |
| 2011 | Roof selection for rainwater harvesting: Quantity and quality assessments in Spain [115] | Csa | C | RQ | The quality of rainwater runoff in the study area appeared to be better than the average quality found in the literature review. Smooth sloping roofs have performed better in terms of runoff quality and therefore may be preferable for stormwater catchment. |

**Table 6.** *Cont.*

| Year | Title—Reference | Climate | Kind of Study | Subject Studied | Main Conclusions |
|---|---|---|---|---|---|
| 2015 | Watering the garden: Preferences for alternative sources in suburban areas of the Mediterranean coast [117] | Csa | MA | SP | The analysis of the sizes of rain collection tanks for irrigation, in suburban areas of Girona, concluded that many had been oversized. |
| 2017 | Urban rainwater runoff quantity and quality—A potential endogenous resource in cities? [116] | Csa | DC | RQ | The study of the quantity and quality of runoff collected from different urban surfaces according to use (pedestrian or motorized mobility) and materials (concrete, asphalt and slabs) showed that precast concrete slabs provided a better-quality runoff. |
| 2020 | Diverse pathways-common phenomena: Comparing transitions of urban rainwater harvesting systems in Stockholm, Berlin and Barcelona [119] | Csa | C | UP | Urban planning could be decisive in the development of urban rainwater harvesting systems. Its socio-environmental benefits could bring sustainability and resilience to cities. |
| 2020 | A breakthrough in urban rain-harvesting schemes through planning for urban greening: Case studies from Stockholm and Barcelona [118] | Csa | DC | UP | The lack of inclusive and democratic procedures, of a long-term commitment in the implementation of these systems (which require proper design and monitoring) could cause significant challenges in a fairer and more sustainable stormwater management. |
| 2020 | Non-conventional resources for the coming drought: the development of rainwater harvesting systems in a Mediterranean suburban area [120] | Csa | S | UP | The rainwater harvesting systems in Catalonia and Spain turned out to be very marginal. The article concluded that important changes in water policies were needed for the implementation of rainwater harvesting systems, such as determining their obligation or offering subsidies. |

A large portion of the articles are economic analyses on the use of rainwater among this type of analysis, including the creation of a software, Plugrisost [105], to evaluate the profitability and environmental impact of rainwater tanks, which has been used to estimate water prices (for different uses) from which it is economically profitable to install a rainwater harvesting system [106] and to carry out an environmental and economic analysis of rainwater storage systems that supply water for laundry [109].

### 3.6. Green Channel

There was hardly exhaustive research on green channels, although it is necessary to mention a laboratory investigation [26] focused on the temperature variations in the different layers of a green channel.

The hydrological behavior of green channels was effective from the hydrological point of view [129–131] and improving the runoff quality [131,132].

### 3.7. Detention Systems

The studies of detention systems observed were mainly hydrological–hydraulic models applied in Barcelona [24], Granada [19,20], and Valencia [21,22,25], cities with a Csa climate, and Cantabria [21] with a Cfb climate.

### 3.8. Research by Climate

The studies found from the end of the 1990s to the end of the year 2020, although they were not homogeneously distributed throughout the Spanish geography, they cover a large part of the national territory based on the climate. In more arid climates (type B), it seems that research (there are 16 articles of empirical studies carried out in arid climate) has focused more on energy performance (eight papers of 16) and optimizing vegetation selection (six papers of 16), while in temperate climates (type C), it has focused more on hydrology (eight papers of 29 based on C climate). Figure 4 graphically shows the amounts of articles dedicated, on the one hand, to each subject of study and on the other to each type of specific technique.

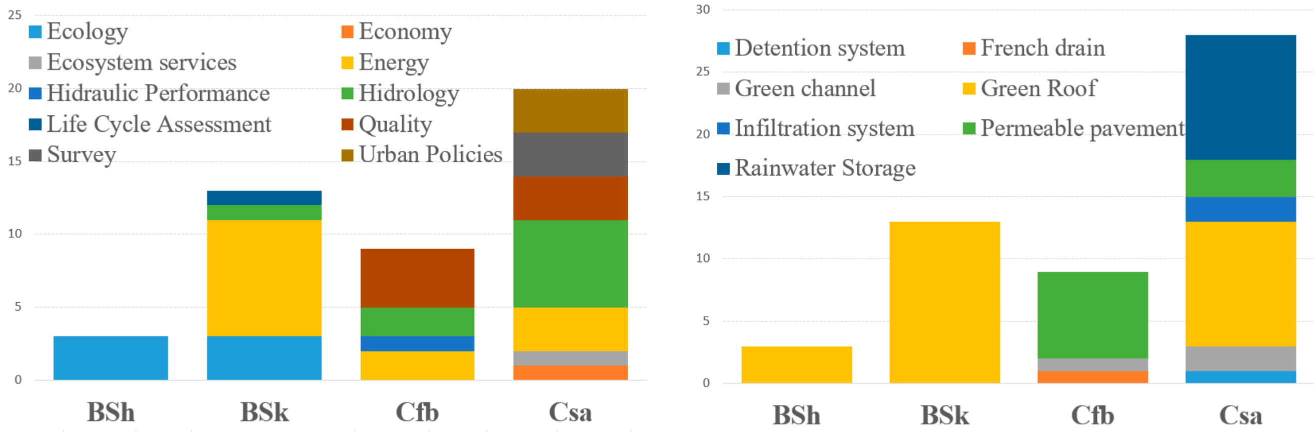


**Figure 4.** The graph on the left shows the number of studies of the main subjects covered in the articles about real cases according to climate, and the graph on the right shows the techniques studied in the papers. The authors have separately accounted for each of the techniques reflected in the articles that contemplated several simultaneously. Source: Prepared by the authors.

## 4. Discussion

A difference between the recent bibliographic review [136] (that compares the implementation of SUDS in other countries with respect to Spain) and the recent publication Sustainable Urban Drainage Systems in Spain: A Diagnosis [145] (an exhaustive compilation of implemented techniques) is that this paper only considers those cases in which a scientific investigation process had been carried out.

The usefulness of SUDS as effective and sustainable management of urban runoff in different climatic regions of Spain is widely demonstrated in several papers [64,96,129–131] analyzed in this review, as well as their potential in other fields such as mitigation of climate change in cities [136,139], but the success rates of local–regional SUDS in Spanish different climatology are still not validated.

By far, the most studied techniques are green roofs and permeable surfaces (Figure 2), followed by rainwater harvesting and detention systems. In contrast, typical green street techniques [146] such as bioswales, bioretention areas, or filtering strips providers of several ecosystem services [147] have hardly been analyzed.

The study of SUDS is unequally distributed throughout the Spanish geography; Catalonia and Cantabria are the regions with the greatest number of studies of these techniques, their components, and their operation. In Cantabria, the GITECO research group has carried out a large number of investigations [8], but these have almost entirely focused on permeable surfaces and their hydraulic–hydrological performance. In Catalonia, research centers with different objects of study, such as ICTA (https://www.uab.cat/web/icta-1345819904158.html (accessed on 8 February 2021)) or CREAF (http://www.creaf.cat/es (accessed on 9 February 2021)) have investigated mainly green roofs and rainwater harvesting systems from different points of view (not only dealing with the hydrological and hydraulic performance, but energy, biological, and economic).

The establishment of vegetation is essential for the correct long-term operation of a green infrastructure [148], and it depends directly on the weather. Since some areas of Spain are predominantly dry [9], one of the main concerns could be the selection of species that can withstand water scarcity. Perhaps this is the reason why the regions where vegetative growth and development have been most investigated are the Balearic Islands, Lleida, and Murcia, which are characterized by their low rainfall [9]. The deductions that can be drawn after observing Table 4 is that for the prevailing dry climate in the country, it is advisable to use a mixture of perennial and annual plants with porous and light substrates [42]; the presence of vegetation is decisive for the functions of thermal insulation [56] and water retention with the characteristic rainfall regime of dry areas [45]. However, not all vegetation is equally effective [48]; species such as Sedum sediforme [60] give better results than others [47,48,60]. Regarding the hydrological operation, the effectiveness of green roofs has been demonstrated, but the results of improving the quality of runoff are not satisfactory [130], so further tests in real facilities are recommended, since the results differ from those obtained in the laboratory.

However, more interest seems to focus on the condition of insulation against the heat of these techniques due to the number of publications in this regard (see Table 2).

Permeable pavements work well hydrologically regardless of the climate in which they have been analyzed (see Table 5); although their performance in quality management depends largely on the composition [77–79], there are no records of its operation in arid climates.

Although bioretention systems and green channels or bioswales are some of the green infrastructure solutions recommended at the urban level due to their multifunctionality [149], there are not plentiful investigations, as occurs with other techniques. Its multifunctional performance depends largely on the biota [150], which derives from factors such as location and climate (predominantly dry and with little precipitation in Spain [9]); plant selection and plant conditioning factors can be a limiting factor [151]. Therefore, it would be advisable to investigate further which plant elements and components are the ones that would work best under long-term peninsular climatic conditions, since ecosystem services will depend on plants, such as urban biodiversity or $CO_2$ reduction, and maintenance costs, among others [152].

## 5. Conclusions

The SUDS study includes different disciplines, hydrology, edaphology, ecology, economics, etc. [7]. However, in Spain, the study is highly polarized; that is, the papers with various techniques and those about permeable surfaces deal with the hydrology, while green roofs papers are focused on the improvement of the energy efficiency of buildings, and rainwater harvesting investigations show their economic performance. This can be associated with the fact that the studies are carried out by specialists who tend to prioritize their own fields without considering the important impacts of other fields [153].

There are many more types of SUDS than those found in this research, such as filter strings, trenches or infiltration wells, artificial wetlands, etc. However, although there is evidence that they have been implemented in the Spanish geography, there are no studies that evaluate its operation: neither the hydrological–hydraulic performance nor its potential components or possible secondary benefits.

It is interesting to mention that the most analyzed techniques in Spain are "in situ" control. That means there is too much to investigate about local and regional control SUDS—in other words, techniques that manage runoff from streets, municipalities, or large areas. This may be because it is easy to install a green roof or a permeable pavement in a university building or research centers, but it is more complicated to follow and monitor techniques located in the public space. In this case, it is necessary to have a collaboration between the researchers, the public administration, and citizens.

It would be advisable to carry out more interdisciplinary studies or a holistic analysis of these techniques in their operation in urban areas. Especially SUDS such as bioswales or bioretention systems that develop populations of living beings are limited in their growth by the rainfall regimes of the country.

**Author Contributions:** Conceptualization, J.C.S.; methodology, A.I.A.G.; formal analysis, N.C.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

**Acknowledgments:** To all the scientists and researchers whose contribution to research into a new approach to runoff management has made this article possible.

**Conflicts of Interest:** The authors declare no conflict of interest.

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