

Sustainable urban drainage: delineation of a scientific domain of knowledge production

ABSTRACT

Sustainable Urban Drainage emerged and gained prominence during the late 90s. Despite this progress, there is little uniformity in subjects and definition of terms within the overall sustainability theme. This tends to create a duplication of objectives and confusion about the correct use of techniques and procedures. This paper seeks to identify, map and evaluate 'Sustainable Urban Drainage' as a scientific domain, using relationships between underlying subthemes. We analyzed 3,805 publications by 8,237 authors with relation to 11,957 citations using sociometric and bibliometric techniques. The results confirm the existence of the knowledge domain with one main nucleus and 20 independent networks. Core subthemes such as stormwater management, low impact development, integrated urban water management, bioretention, and best management practices are distinguishable as the main domain.

Keywords: scientific domains, low impact development, integrated urban water management, bioretention, best management practices.

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INTRODUCTION

Questions related to urban drainage have occupied professionals and researchers in different contexts. Over the last decades, practical results, adaptations, experiences and techniques have been the object of scientific literature originating mainly from Europe, the United States of America (USA), and Australia. Research within the vast area of natural hydrological cycles represents a point of convergence within this theme.

A central concept in the urban drainage literature is the knowledge generated in networks involving intellectual, social, physical, chemical, and biological processes. Studies focusing upon the theoretical development and the practical application of new methods are chiefly concerned with the reduction of negative impacts from urban development, as well as the development of the respect for the natural environment limitations.

From this perspective, studies of urban drainage range from those that are strictly technical in nature - e.g. induced infiltration, retention and (bio) filtration – to multidisciplinary socio-technical studies whose aim is to avoid downstream transfer of impacts, and reinforce environmental education as well as social participation. In this range of approaches ranging from the technical scope to the political one, the increasing concern on understanding how to operationalize socio-technical solutions capable of assuring significant levels of success based on the sustainable development principles become more relevant.

This paper seeks to identify, relate and analyze a group of research areas united by a sustainable urban drainage theme. This study maps and explains the relationships between authors and subthemes related to urban drainage in an international context. The work seeks answers to the following questions: Which are the main subthemes that emerge under the sustainable urban drainage theme? Which are the major countries and authors that establish relationships among the subthemes? Which are the most active subthemes in the scientific community?

THEORETICAL PERSPECTIVES ON URBAN DRAINAGE

As communities build improved responses to urban drainage problems, social research that explains how scientists interact and how they reach consensus on methods is conducted. Scientific enterprise depends, to a large extent, on the community's ability to adopt assumptions and dedicate themselves to the implementation of specific practices until new scientific knowledge becomes available. New investigations will consequently lead the community to a new set of practices. While it is theoretically possible to repeat this process indefinitely, in reality it tends to degrade over time, eventually leading to the emergence of new methods, which, as they propagate, repeats the process. Within the sustainable urban drainage theme, the fundamental questions currently in discussion pertain mainly to general methods as well as philosophical principles (Kuhn, 2000, pp. 23-25).

In the case of conventional urban drainage systems, efforts to expand knowledge tend to concentrate on internal components (Geldof, 1995). For example, reducing runoff volume through infiltration removes this source of flow

to downstream areas more or less permanent. This influence is perceived on the amount of technical developments and theoretical framework about drainage based on conduits for the construction of stormwater sewers and actions to increase the flow capacity of rivers and canals (Pompêo, 2000; Procopiuck & Rosa, 2015). Although this perspective on development of knowledge about urban drainage is important in the scope of technological development as well as fast responses to emergency problems, it came short of bearing fruit in offering more aligned solutions to the sustainable development.

Since the 60s, municipal master plans have adopted protection of natural resources as a policy goal, indicating a broader focus of urban drainage. Research are now focused on aspects other than the flooding of streams to overcome problems caused by the development of integrated methods as well as measures to mitigate urbanization effects (Geldof, 1995, p. 16; Pompêo, 2000).

The development of techniques to reduce flows by temporary storage in the soil through infiltration was created out of necessity in order to prioritize planning actions (Pompêo, 2000). While originating in the broad strategies of environmental management, urban drainage can be understood as a network of relationships between intellectual, social, physical, chemical, and biological processes (Geldof, 2005).

On a constant development process marked by new demands of sustainable urban development, the technical paradigm was replaced by a new perspective focused on multifunctional adaptive structure for managing natural resources. Integrated management emerges as a multidisciplinary approach to face uncertainties on how to handle natural resources (Jeffrey & Gearey, 2006). This change of perspective has contributed significantly to the rise of a new concept of urban drainage, sustainable urban drainage (SUD).

SUD research can be classified into: alternative techniques (Tim D. Fletcher et al., 2014), best management practices (Davis, Hunt, Traver, & Clar, 2009; Tim D. Fletcher et al., 2014; Zhou, 2014), bioretention systems (R. A. Brown & Hunt III, 2010; Davis, 2008), compensatory techniques (Tim D. Fletcher et al., 2014), design stormwater (Park, Chung, Yoo, & Kim, 2012), diffuse pollution control (Panagopoulos, Makropoulos, & Mimikou, 2013), green infrastructure (Tim D. Fletcher et al., 2014), integrated urban water management (Tim D. Fletcher et al., 2014), low impact development (Tim D. Fletcher et al., 2014; T. J. Scott et al., 2014; Zhou, 2014), low impact urban design and development (Tim D. Fletcher et al., 2014; Zhou, 2014), management of urban drainage (Tim D. Fletcher et al., 2014), management of urban water (R. Brown, 2005; Lee & Yigitcanlar, 2010), source control (Tim D. Fletcher et al., 2014), stormwater control measures (Tim D. Fletcher et al., 2014), stormwater management (Davis et al., 2009; Roseen et al., 2009; T. J. Scott et al., 2014; Zakaria, Ab Ghani, Abdullah, Mohd. Sidek, & Ainan, 2003), stormwater quality improvement devices (Begum, Rasul, & Brown, 2008), stormwater quality studies (T. D. Fletcher, Andrieu, & Hamel, 2013; Newman, Aitken, & Antizar-Ladislao, 2013; Zakaria et al., 2003), stormwater quantity studies (R. Brown, 2005; Zakaria et al., 2003), stormwater treatment efficiency (Zhang, Zhou, Li, & Yu, 2010), sustainable drainage systems (Lee & Yigitcanlar, 2010), sustainable urban drainage systems (Tim D. Fletcher et al., 2014; Zhou, 2014), and water Sensitive Urban Design (Davis et al., 2009; Tim D. Fletcher et al., 2014; Lee & Yigitcanlar, 2010; Sharma, Gray, Diaper, Liston, & Howe, 2008).

The increase and spread of different approaches to better understand a given phenomenon tends to demonstrate its importance and dynamic. However, in this case, it complicates effectively the proper grasp of the domain and its central themes. In this study, we investigate the direction of SUD research.

METHODOLOGICAL APPROACH TO THE COMPREHENSION OF THE THEORETICAL FIELD OF URBAN DRAINAGE

Considering this complexity, we contend that both clarity and direction of the research themes within SUD can be enhanced through domain analysis. According to Argas-Quesada and de Moya-Anegón (2007), domain analysis is one of the novel fronts of research emerging from advancements in information visualization of networks and, consequently, this approach helps reveal the essence of scientific knowledge, especially in multidisciplinary fields with intense changes.

Domain analysis is based upon the concept that the best way to comprehend a knowledge field is through analysis of speech patterns, and identifying the networks that provide structure to knowledge areas. Knowledge domains contain unique structures and organization, standards of cooperation, language as well as communication means (Argas-Quesada & de Moya-Anegón, 2007; Hjørland & Albrechtsen, 1995). Based on sociometric criteria, domain mapping generates images that express the networks, relationships, and roles that scientific communities play in society (Argas-Quesada & de Moya-Anegón, 2007; Hood & Wilson, 2000).

In addition, bibliometric analysis reduces subjectivity by informing statistics such as the number of authors, of publications, and of countries of origin in the citations of a domain category (Price, 1976, p. 39). Bibliometric studies use statistical and mathematical methods to identify historical trends in the literature and assess emerging standards, mainly through analysis of the relationship between authors and the use of domain knowledge and themes. In these studies, a sociometric technique known as the Social Network Analysis (SNA) perspective is often used. SNA views the researcher as a socially interconnected actor. Advancing science and producing knowledge requires interactions, associations and the union of abilities according to common views. This is especially the case with collaborative works.

The central-periphery model provides an important tool for SNA, facilitating the evaluation of cohesion between nodes in a network. This evaluation algorithm calculates the proximity values in relation to the center and, from that, the correlation between the empirical matrix and the theoretical one. The evaluation was conducted with continuous method to attribute a score to the relationships of each node to the center (Borgatti & Everett, 1999).

MATERIALS AND METHODS

The bibliometric analysis was conducted in two phases. First, it was performed under a qualitative method through the choice of expressions from a body of text comprised of 50 papers that address different perspectives of SUD studies; the papers served as a basis for the construction of a research project under the theme. The objective was to make a systematic survey of the most relevant terms

and expressions. That survey resulted in 22 expressions, which are listed in Table 1.

In the second phase, the bibliometric analysis was conducted using a quantitative method, exploring research papers and reviews that contained high information credibility and authored by prominent researchers in the SUD field. The data was compiled in August 2015, from the Web of Science database, covering all complete papers and reviews registered since the year 1864. The software VantagePoint (Search Technology, 2006) was used to house and structure the data and assist in further analysis.

Initially, 18,662 documents were identified, which reduced to 3,805, in the second phase. A filter was used in the following areas: Environmental Science Ecology, Engineering, Water Resources, Agriculture, Geography, Architecture, Science technology and other topics, Urban Studies, Biodiversity Conservation, Physical Geography, Chemistry and Public Administration. This refinement was necessary because many expressions have multiple meanings outside the interest of SUD research.

The queries in the 'Web of Science' were based on the expressions in the first column of Table 1. The searches included each expression altogether in quotation marks. Thus, abbreviations and acronyms were omitted.

The data in the last column of Table 1 was condensed, for each expression, in a matrix of co-citation in the software called VantagePoint. These databases were converted into edglist1 files through Visual Basic for Applications (VBA) codes run inside Microsoft Excel, to be imported by the software Ucinet. The visualization of the networks was made with the NetDraw software.

Finally, the evaluation of the centrality of countries, institutions, themes and authors occurred using the Core/Periphery model of Ucinet (Borgatti, Everett, & Freeman, 2002), with 1,000 interactions processed based on continuous method. Centrality was evaluated using the Gini index, where 0 stands for complete equality and 1 stands for complete inequality.

RESULTS ANALYSIS

In the following topics, there is a first characterization of the body of analysis comprised by the documents resulting from the search on Web of Science. Subsequently, it is presented the global result based on the centrality relationships between authors relative to locations. Then, the centrality and peripheral relationships of universities or research centers, to which the authors are affiliated were characterized, as well as the themes reviewed in this research; and finally, the relationship between authors without an institutional mediation.

Characterization of the analysis

All documents selected by the search terms from the first phase, i.e., without any filter are contained in column (b) of Table 1. There are the numbers of documents in the research fields with affinity with the theme in column (c). Finally,

the remaining documents used in body of analysis of this paper are provided in column (d).

Table 1 – Expressions searched in the Web of Science base

(a) Searched expression	Number of publications resulted from the search		
	(b) Found	(c) Refined	(d) Used
1) Alternative techniques	2025	249	239
2) Best management practices	5388	1156	1122
3) Bioretention	362	263	259
4) Compensatory techniques	32	3	2
5) Design storm water	5	4	4
6) Diffuse pollution control	31	26	24
7) Green infrastructure	453	309	288
8) Integrated urban water management	86	69	66
9) Low impact development	349	249	215
10) Low impact urban design and development	6	4	3
11) Management of Urban Drainage	12	11	11
12) Management of Urban Water	51	28	26
13) Source control	8107	319	298
14) Storm water control measures	40	38	37
15) Storm water management	1140	809	774
16) Storm water quality improvement devices	3	2	2
17) Storm water quality	298	210	207
18) Storm water quantity	34	27	25
19) Storm water treatment efficiency	5	5	5
20) Sustainable drainage systems	64	59	59
21) Sustainable urban drainage systems	65	57	57
22) Water Sensitive Urban Design	106	82	82
TOTAL	18662	3979	3805

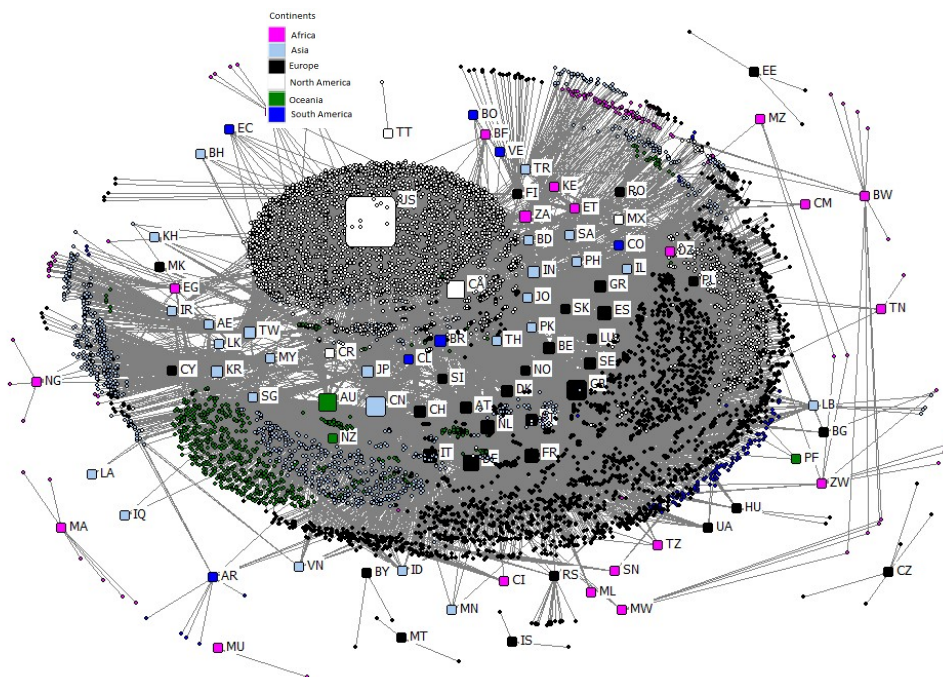
Source: The authors, 2018.

There are disparities among the results in Table 1 regarding the number of documents found, refined and used for each searched term. That happens because some terms are considered as techniques or a set of techniques in a global scope – for example, Alternative techniques, Best management practices, Source control and Stormwater management – and others can be applied in different knowledge fields.

Global network of authors and countries

The global network showed in Figure 1 express the relational logic of the community studying SUD. This community is comprised of 8,237 authors from 82 countries. The authors relate to each other through 11,957 bonds established by their location.

Figure 1 – Global network



Source: The authors, 2018.

Figure 2 – Relationships between authors and Source: The authors, 2018.

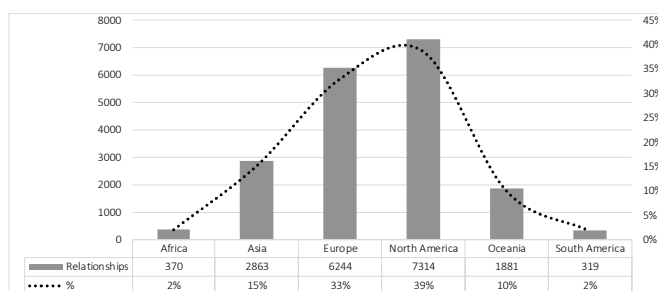
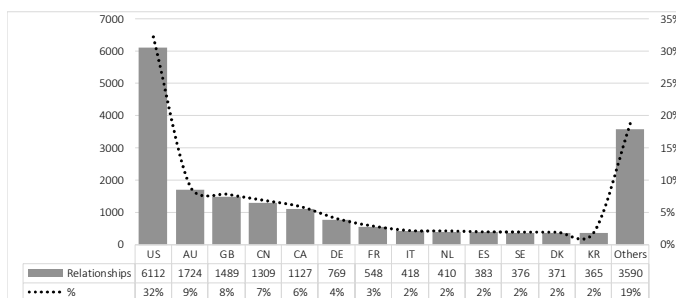


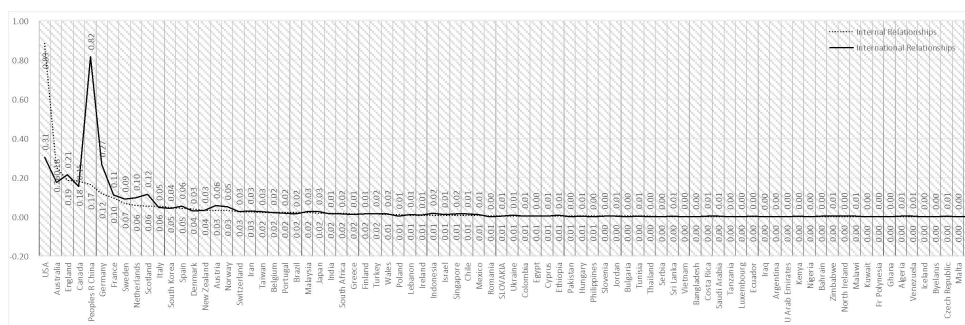
Figure 3 – Relationships between authors and countries



Source: The authors, 2018.

In the global network, 32% of authors are from the USA. An intermediary group formed by 12 countries sums up 49% of authors. Finally, a last group of 80 countries gathers 19% of the authors. This distribution is verified in detail in figure 3. When author locations are consolidated from country to continent, it is apparent that 71% comes from North America and Europe, 25% from Asia and Oceania, and 4% from South America or Africa Figure 2. When internal and external relationships of the authors are considered, the central countries in the SUD research network are the USA, Australia, Canada, England, and Germany, as marked by a dashed line in figure 4.

Figure 4 – Centralization of countries' Source: The authors, 2018.



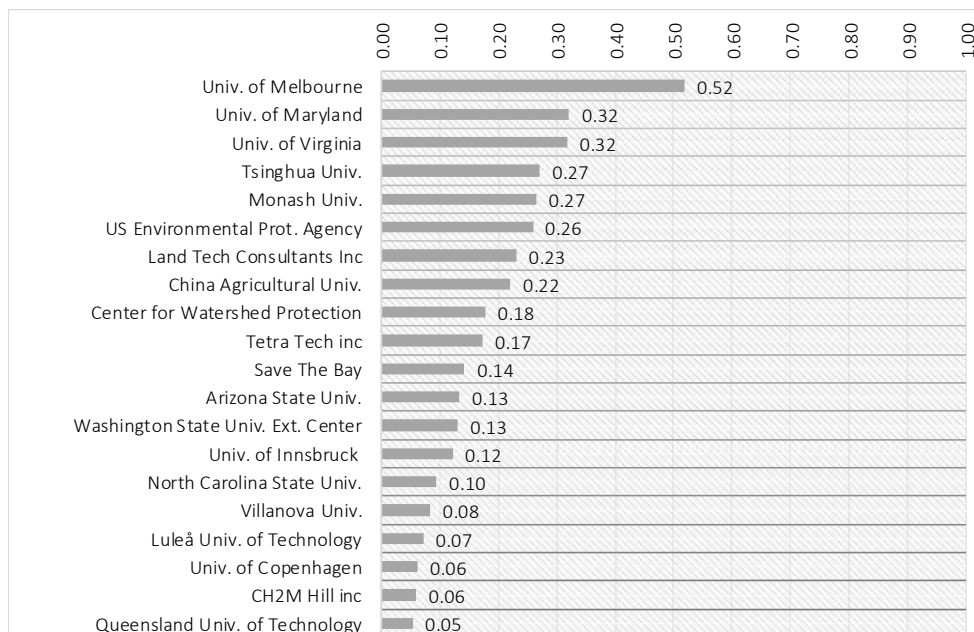
In figure 4, the solid line represents the centrality of authors exclusive of their external relationships, i.e., international relationships. In this perspective, there is a shift of the order of the countries in terms of centrality. In order of importance, the sequence becomes the Peoples Republic of China (PRC), USA, Germany, England, Australia, and Canada. The centrality index considering internal and external relationships are 0.786, considering only international relationships, the centrality index is 0.770.

Relationship between research institutes

Regarding the relation between centrality and peripheral of institutions to which the authors are affiliated, in the universe of 2,027, 12 are from the USA, 3 from Australia, 2 from China, 1 from Sweden, 1 from Austria and 1 from Denmark. In figure 5, the first 14 institutions were classified as central by the central-periphery model. From North Carolina State University onwards, the following 2,020 institutions are considered peripheral.

With the application of the core-periphery model considering the internal relationships of the authors from the institutions, the correlation coefficient was 0.197 and the Gini index, 0.909. The model reclassified as core members the first 14, with a concentration correlation coefficient of 0.879. When only external relationships were considered, the correlation coefficient was 0.236. The Gini index was the same, as well as the number of core authors. In both evaluations there was no alteration in the centrality indices of the institutions. The 20 most central institutions are shown in figure 5.

Figure 5 – Institutions Centrality



Source: The authors, 2018.

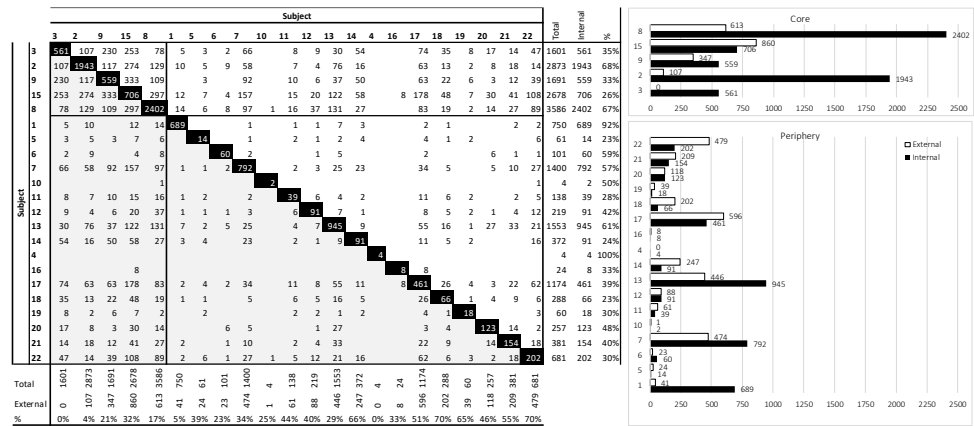
The Australian universities took the 1st position (Melbourne), 5th (Monash) and 20th (Queensland). In this list prevail, in quantitative terms, the universities and institutes from USA as 2nd position (Univ. of Maryland), 3rd (University of Virginia), 6th (U.S. Environmental Protection Agency), 12th (Arizona State University), 15th (North Carolina State University), and 19th (CH2M Hill Inc.). Although the literature does not place PRC with a history of publications, Tsinghua University got 4th place and China Agriculture University got 8th. Among the European universities, the Austrian University of Innsbruck stands in 14th, the Swedish Lulea University of Technology in 17th, and the Danish University of Copenhagen in 18th.

Relationship between research themes

The 22 themes assessed in terms of the internal and external relationships are shown in figure 6. The relationships built on similar themes are quantified in the diagonal, highlighted in black in the matrix. These relationships are important to evaluate a discussion concentration levels within each theme.

On the upper right frame of the matrix (Figure 6) lies the five most densely related themes. Faced with the set of relationally evaluated themes, the subgroup – formed by (3) Bioretention, (2) Best management practices (BMPs), (8) Integrated urban water management, and (15) Stormwater management – is considered core in the discussions about SUD. The themes (2) Best management and (8) Integrated urban water stand out as internal cohesive elements in the discussion, while (15) Stormwater management stands out as the most important intermediate topic in the central themes set.

Figure 6 – Core and peripheral themes



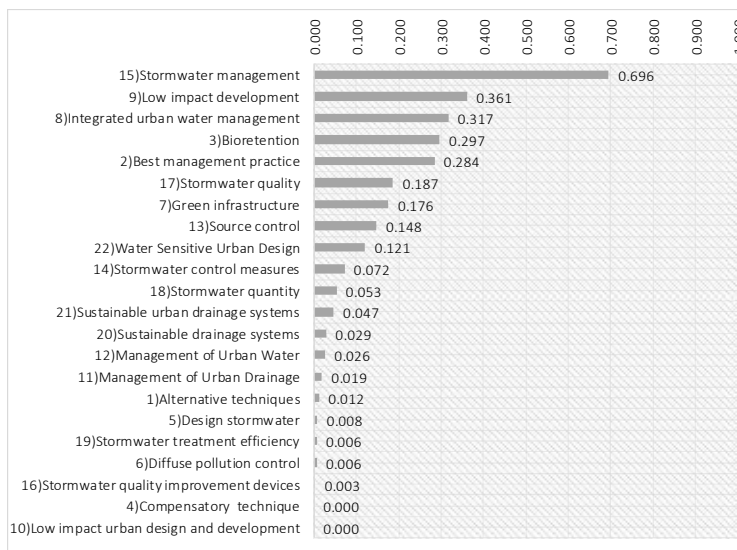
Source: The authors, 2018.

In the above matrix, the data found above and below the diagonal are symmetric; thus, in terms of the analysis, the location on either side of the diagonal does not make a difference. The data assists in the evaluation of diversity of terms. This evaluation helps identify research gaps in the reviewed literature.

Some of the peripheral themes include: (7) Green infrastructure and (13) Source control; and these themes assume a leading role in discussions for they concentrate the number of intra-thematic relations. The themes (17) Stormwater quality and (22) Water Sensitive Urban Design are both easily identified as nodal elements of the external thematic relationships, and in effect, serve as focal points in the network for important themes.

The core-periphery model, using the continuous method, indicated a correlation coefficient of 0.971 and Gini index of 0.625. The model re-concentrated as core members the first five themes, with a correlation of 0.838. When only external relationships of the institutions were considered, correlation was reduced to 0.236. The Gini index remained similar to the previous evaluation, as did the number of core authors. The centralization indices of the themes were not changed in both evaluations. A diagram of the classification of themes is provided in Figure 7.

Figure 7 – The mescentrality



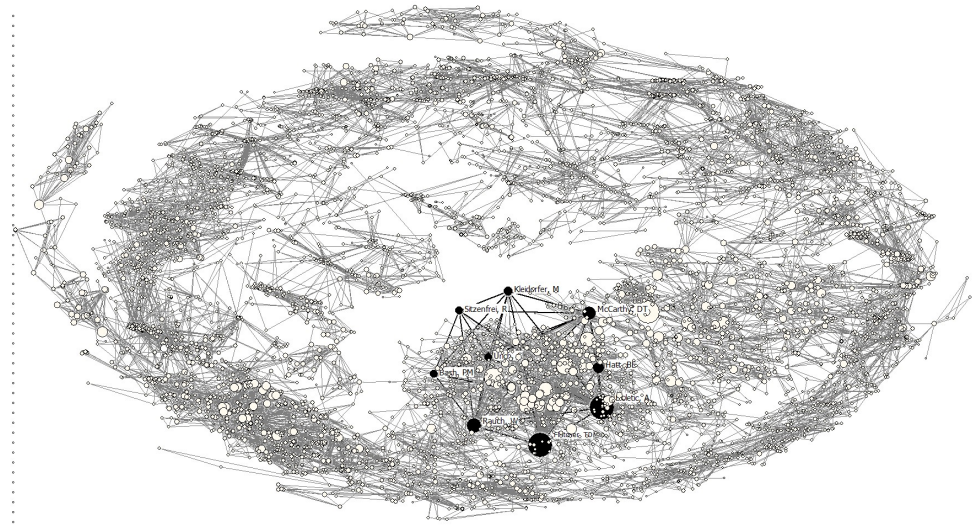
Source: The authors, 2018.

Historically, SUD research has focused upon hydraulic treatment to conduct superficial flow, resulting in the conception of drainage systems based on conduits (Pompêo, 2000). That started to change in the 90s, when experience and adaptation of compensatory techniques received more attention by research groups from Europe, USA and Australia. Currently this new approach has led to reflections and pointed to a paradigm shift in the urban drainage area. Figure 7 brings a ranking of themes that takes prominent position related to urban drainage management practices, techniques and technologies of adaptive methods. This set of novel concepts has the same principles and types of solution in common, being those structural and/or non-structural. Generally, the principles are the same, the goal is to maintain the natural water cycle and improve sustainability.

Relationships of centrality among authors

The global network of researchers in the SUD is shown in Figure 8. The network formed by the core authors is highlighted in black. According to the results of the Core/Periphery model, using the categorical method, the core authors network is comprised by Fletcher, TD; Deletic, A; Rauch, W; McCarthy, DT; Hatt, BE; Kleidorfer, M; Sitzenfrei, R; Bach, PM; and Urich, C. The density of relationships between the core authors was of 7.083 while for the peripheral model, it was 0.001.

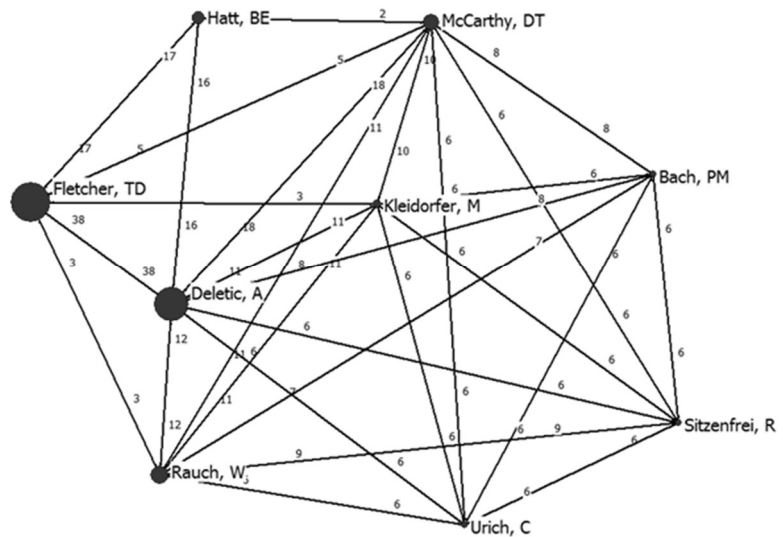
Figure 8 – Global authors network



Source: The authors, 2018.

The relationships between core authors shown in Figure 8 are detailed and quantified in Figure 9. In these two networks, the node size is proportional to the degree of centrality of each author.

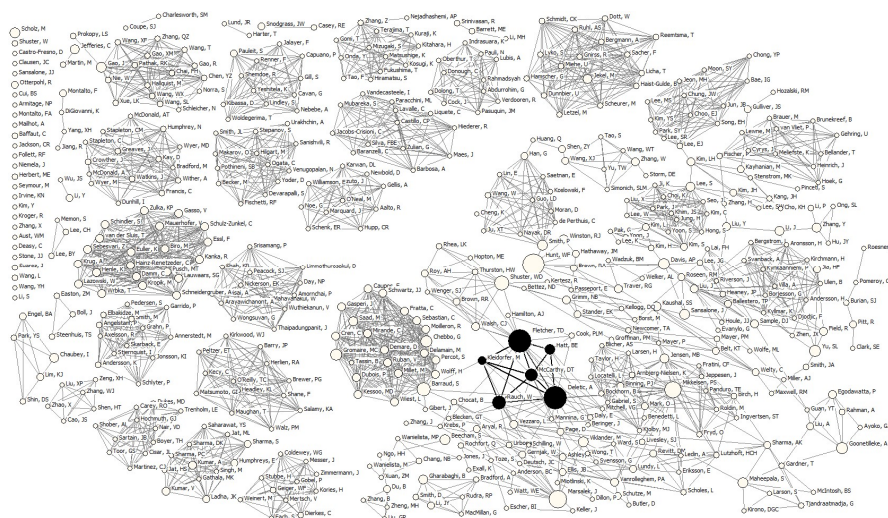
Figure 9 – Core authors network



Source: The authors, 2018.

Table 2 complements the data presented in Figure 9 with data from the affiliation and publication history. This set of authors that takes a core position in the network belongs to four universities, which also stood out in Figure 5. The majority of the authors have a publication history of approximately two decades.

Figure 11 – Networks of authors with degree higher than 10



Source: The authors, 2018.

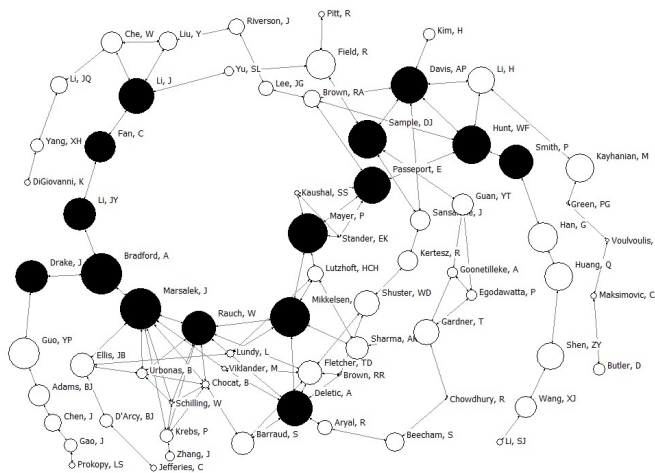
In Figure 11, it is worth noting that the broad network located in the bottom right corner is dominated by the core authors. Regarding the other smaller networks, interesting perspectives arise for investigations into which methods or interests structure the relationship between authors. The diversity of groups of authors represented in Figure 11 presents opportunities for future studies to understand what the particularities of such communities are. From an intra-group perspective, is it important to understand, for example, what kind of technology has been studied by each of these groups? What are the theoretical approaches used? What are the empirical problems that these groups are dedicated to solving? In what regions do they work? What are the factors that motivate the research? From an extra-group perspective, are equally important questions about, for example, what factors determine group differentiation? What are the reasons why groups are isolated? Are current trends pointing to the formation of a global network of researchers or, on the contrary, to further fragmentation?

Relationships of intermediation capacity

The betweenness centrality index considers a network as a whole and is an expression of the capacity of each author to establish relationships between other two non-neighboring authors in the network. The relationship between the two non-neighboring authors depends on the intermediary authors, which implies that the latter has a greater influence over the social network. The authors with higher level of intermediation are considered core connectors because they provide the connection for a large number of authors in the network.

This metric enables the evaluation of importance of a particular author as a function of the flow passing by that author. The 70 authors with the highest intermediate centrality index in 2,012 relationships are shown in the network of Figure 12, with indices ranging from 249.2 to 2341.6.

Figure 12 – Betweenness Centrality



Source: The authors, 2018.

The 15 most relevant authors in terms of intermediation centrality are Marsalek, J (2,341.6), Bradford, A (2,291.2), Meyer, P (2,078.3), Mikkelsen, PS (1,901.4), Hunt, WF (1,770.8), Sample, DJ (1,677.3), Pesseport, E (1,650.6), Davis, AP (1,509.8), Li, J (1,505.1), Deletic, A (1,482.3), Rauch, W (1,374.8), Smith, P (1,254.9), Drake, J (1,242.0), Li, JY (1,225.9), Fran, C (1,205.7). In the intermediation network, the authors are identified as strategically located in a central position within the network; and they have an important role in the flux by their capacity to concentrate and make directly available information of other authors. They are authors that facilitate direct contact with many others without the necessity of intermediates, and exert important influence in the network information flux.

CONCLUSIONS

The sociometric and bibliometric techniques described in this paper helped identify, map and objectively evaluate the domain formed by scientific publications related to a set of 22 themes related to SUD, involving researchers from 82 countries, 2,027 research centers, and 8,237 authors interacting through 11,857 citation relationships. In this domain, 72% of the relationships occurred between authors from European and North American countries.

The research supporting SUDs has drawn attention from a large number of countries. From the results, it can be inferred that the central locations, in terms of relationships between researchers and research centers, are USA, Australia, Canada, England, and Germany. When the internal relationships of each author of each location are considered, the PRC takes the second place among the core countries. Considering the great number of authors that articulate themselves in a large international, it is difficult to generalize tendencies in the area guided only by the geographical location of the authors of seminal texts. On the other hand, the domain shows that, if there are such pretensions, research should be expanded to capture local and regional nuances to fully explore SUD. From that expanded domain, generalizations would become more realistic.

Among the 8,237 authors, the ones considered as core authors in terms of density of citation relationships with authors from other countries are Fletcher, TD; Deletic, A; Rauch, W; McCarthy, DT; Hatt, BE; Kleidorfer, M; Sitzenfrei, R; Bach, PM; and Urich, C. Although these pose as references to the domain due to their relationships in the central network, there are other authors that stand out with relevant levels of leadership in 20 smaller networks. Moreover, if the evaluation is accomplished under the perspective of intermediation, the 15 most relevant authors are Marsale, J; Bradford, A; Meyer, P; Mikkelsen, OS; Hunt, WF; Sample, DJ; Pesseport, E; Davis, AP; Li, J; Dedetic, A; Rauch, W; Smith, P; Drake; Li, JY; and Fran, C. While authors from the first core group dominate in terms of strong relationships among each other, mainly because they belong to a selective group of 4 universities, the second group stands out because their publications broaden the reach of SUD knowledge produced by other authors.

The great majority of the research conducted on SUD has been carried out in developed countries. That probably derives from the investment capability of these countries as well as their concerns with alternative solutions based on the SUD perspective, assigning greater importance to the environmental issues. The low participation of African and South-American countries, which provided only 2% of the citation relationships, can be explained by the lower priority environmental issues may have in developing countries. On the other hand, this relatively small number of studies may represent promising opportunities to move forward to develop new locally appropriate technologies as well as to move forward in attempts to transfer sustainable drainage technologies to these countries.

The most active themes in the academic community included: Stormwater management, Low impact development, Integrated urban water management, bioretention and best management practice. The nuclear position of these themes may indicate interesting paths to future research regarding SUD and may suggest analytical efforts to try to unify the nomenclature and form a domain of scientific research. The formation of a domain would facilitate, on the one hand, a deepening of research, and on the other hand, bring benefits to policymakers so that they may understand and justify public policies based on a more consistent theoretical diagnosis about how important it is to follow up such references on SUD.

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