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基于CiteSpace知识图谱分析的城市内涝问题研究述评

A REVIEW OF RESEARCH ON URBAN WATERLOGGING BASED ON CITESPACE MAPPING KNOWLEDGE DOMAINS

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摘要

内涝问题持续困扰城市发展，对中英文文献中有关“城市内涝”问题的研究进行梳理与总结有助于系统剖析该问题的研究进展，从而探究缓解中国城市内涝问题的科学途径。本文以Web of Science核心合集数据库和中国知网数据库的文献为研究对象，运用科学计量分析工具CiteSpace的知识图谱绘制功能，客观地呈现了中英文文献在“城市内涝”问题上的学科结构、研究重点和研究热点。通过数据分析与解译得出：“城市内涝”问题研究整体保持较高热度，涉及大部分学科并出现学科交叉现象，且近年在城乡规划学、地理学、风景园林学等领域的研究热度持续升高；所涉及的代表性学科在内涝问题上的主要研究内容各有侧重；中英文文献已从规划理念、基础设施、排水系统、空间调控、管理方法、微观措施6个角度呈现多样的调控途径探索；当前学界研究热点主要集中在内涝调控的理念与措施、水文学规律、内涝成因、风险评估与管理等方面；目前研究偏向微观尺度，从宏、中观尺度探寻雨洪管控的理想空间格局与规划实现途径的研究相对欠缺，对于城市水文过程、内涝形成机制与雨洪调控途径的空间类型之间的关联性研究不足。最后，针对目前的研究局限提出：研究理论上应深入探讨各类内涝调控途径的产生背景、核心目的、应用场景等，研究尺度上可对宏、中观层面空间规划途径的空缺进行弥补，研究广度上应注重与水文学进行学科融贯探究，为进一步拓展中国城市内涝调控途径提供方向指引。

关键词

城市内涝；研究述评；研究热点；知识图谱；CiteSpace

ABSTRACT

Cities have suffered from long-time waterlogging problems. A review of English and Chinese literature on “urban waterlogging” can help analyze the research progress and further explore methods and approaches to alleviate such problems in Chinese cities. By examining the literature from the Web of Science Core Collection database and CNKI database with CiteSpace, a Mapping Knowledge Domains tool, this paper aims to scientifically review the disciplinary structure, major research interests, and research hotspots of the issues of urban waterlogging. Through data analyses, it concludes that: 1) urban waterlogging is a hot topic that has been studied in a great number of subjects, with interdisciplinary studies and a continuous growth in Urban and Rural Planning, Geography, Landscape Architecture, etc. in recent years; 2) the research on waterlogging in representative subjects varies; 3) English and Chinese literature explores stormwater management and control measures from the perspectives of planning concepts, infrastructure, drainage systems, spatial regulation, management methods, and micro-measures; 4) research hotspots cover the concepts and measures of waterlogging control, hydrological processes and patterns, causes of waterlogging, and risk assessment and management; 5) the existing research mainly focuses on micro scales, and there is an absence of studies on ideal spatial patterns and planning approaches at macro and medium scales, or on the correlation between urban hydrological processes and waterlogging formation mechanisms with spatial deployment of stormwater regulation approaches. Finally, according to existing research limitations, the paper proposes that: 1) future theoretical studies should explore the backgrounds, objectives, and application scenarios of various waterlogging control approaches; 2) studies are expected to explore spatial patterns and planning approaches at macro and medium scales; and 3) scholars should expand the territory of research by integrating with Hydrology.

KEYWORDS

Urban Waterlogging; Research Review; Research Hotspot; Mapping Knowledge Domains; CiteSpace

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EDITED AND TRANSLATED BY Tina TIAN

① 本文使用的CiteSpace是5.0.R1 SE（64-bit）版本。

① The 5.0.R1 SE (64-bit) version of CiteSpace was used in this research.

1 引言

随着城镇化进程的不断推进，中国特大规模的城市内涝灾害日益频发。近年来，海绵城市建设逐渐成为学界和地方政府关注的热点，相关理论研究与实践成果快速涌现，理论缺陷与实践乱象也随之凸显[1]。国内外对于“城市内涝”问题的研究涉及环境科学、生态学、水资源、地理学、城乡规划学等众多学科。国外研究起步较早并已取得较为成熟的经验，国内学者亦常予以引用和借鉴，然而鲜有研究基于学科角度对这些经验进行系统梳理，也未形成明确的理论框架来支撑中国“城市内涝”问题的实际调控途径。因此，亟需对当前涉及“城市内涝”的学科的研究体系进行述评。

总体来看，国内外各学科关于“城市内涝”问题的研究文献数量巨大，若使用传统的文献分析方法，则必须查阅几乎所有的相关文献，费时费力且容易掺杂过多主观判断。针对此问题，“知识图谱”（MKD）方法可以帮助研究人员从海量数据中更为全面、精准地提取各学科结构、学科热点和主题分布信息。本研究选取了CiteSpace①这一知识图谱分析工具，并基于Web of Science（WOS）核心合集数据库和中国知网（CNKI）数据库对中英文文献所反映出的各学科在“城市内涝”问题上的相关研究进行了可视化分析，通过领域共现与关键词共现，清晰地展示了“城市内涝”问题研究的学科分布、前沿动态、研究短板及发展趋势，以期为中国“城市内涝”问题的调控提供构建理想空间格局的理论依据。

2 分析工具与数据

2.1 分析工具

MKD是一种有效的知识管理手段[2]，自2005年引入中国以来已得到广泛应用。MKD具体指以知识域（knowledge domain）为对象，对科学知识的结构、规律和发展进程进行可视化分析后所获得的图形[3]。2004年，美国德雷克塞尔大学计算机与情报学学院的陈超美教授使用Java语言开发了信息可视化软件CiteSpace，其随后一跃成为最具特色和影响力的MKD绘制工具之一[4]。但是，目前CiteSpace在中国的应用主要集中在图书馆与档案管理、管理科学与工程，以及教育学方面，在城乡规划学和风景园林学领域的应用还较少。

CiteSpace能够进行合作网络、共现、共被引、文献耦合和研究基金的分析，处理的数据源包括WOS、Scopus、Derwent、CNKI、CSSCI、

1 Introduction

Along with the aggressive urbanization process, China’s mega cities are facing increasingly frequent and severe storm and waterlogging problems. In recent years, sponge city construction has become a widely-discussed topic among researchers and local governors, with productive research outcomes and practice efforts. However, it has also seen a number of problems in both theoretical and practice explorations[1]. Since issues of “urban waterlogging” have already been broadly studied by international academia in Environmental Sciences, Ecology, Water Resources, Geography, Urban and Rural Planning, etc., Chinese scholars have often introduced such proofed experiences, but neither in a systematical way nor establishing any theoretical frameworks that could adapt to China’s waterlogging problems. It thus urgently needs to review the existing literature of research on urban waterlogging issues among related disciplinary fields.

The amount of existing research on urban waterlogging is too huge to be examined with traditional, manual literature review methods. As a more efficient and scientific analysis alternative, the Mapping Knowledge Domains (MKD) method is adopted in this research to comprehensively and accurately extract subject structures, hotspots, and topics from massive data in varied fields. This study employed CiteSpace①, a MKD tool, to examine the existing literature on urban waterlogging from the Web of Science (WOS) Core Collection database and China National Knowledge Infrastructure (CNKI) database through a visualized analysis of the research network of various subjects. By analyzing co-category and co-keyword occurrence, subject relations, new interests, deficiencies, and trends were reviewed to provide a theoretical basis for building ideal spatial patterns in order to respond to China’s urban waterlogging issues.

2 Analysis Tool and Data

2.1 Analysis Tools

MKD is an effective tool of knowledge management[2] and has been widely applied since it was firstly introduced into China in 2005. By analyzing individual knowledge domains, MKD supports visualizing disciplinary structure and development pattern and trajectory of a certain kind of scientific knowledge[3]. In 2004, Professor Chen Chaomei in the College of Computing and Informatics at Drexel University, the United States developed CiteSpace, an information visualization Java software, which has soon become one of the most popular

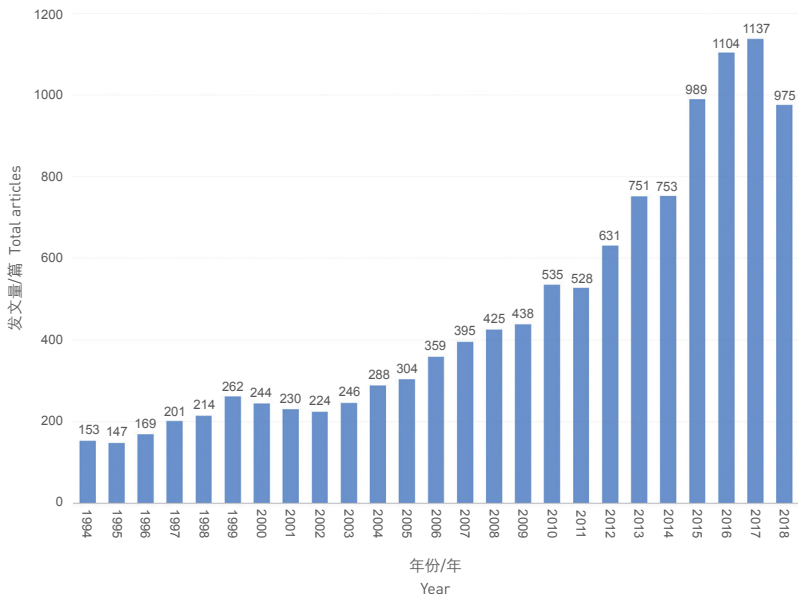
CSCD、RCI和KCI，其中来自WOS数据库的文献的可用功能最为全面，来自CNKI数据库的文献则只能进行作者合作网络分析、机构合作网络分析和关键词共现分析。运用CiteSpace分析得到的知识图谱主要以节点②与连线的方式呈现，其中节点大小反映了分析对象（如作者、机构、国家）的发文量，主题、关键词、领域出现的频次，或者代表文献、作者、期刊的被引次数，连线粗细反映了合作关系强度、共现强度或共被引强度，连线颜色则对应节点第一次共现或共引的时间[5]③。

2.2 数据来源

为较为全面地反映国内外的研究概况，分别选取WOS核心合集数据库和CNKI数据库作为数据来源。其中，WOS核心合集数据库中的英文文献涵盖了国内外学者的重要研究成果，但以国外学者为主，主要反映国外学者的研究情况；为避免文献重复，CNKI数据库仅选取中文文献进行分析，主要反映国内学者的研究情况。④

WOS核心合集数据库的英文文献采集于2018年11月4日，以所有年份的“TS=（waterlogging）OR TS=（stormwater）⑤进行检索，经过CiteSpace的除重功能，共得文献12 460篇，时间跨度为1974~2018年。借助WOS数据库自带的文献分析功能对近20余年的论文发表总数进行统计，发现近年针对“城市内涝”相关话题的英文文献数量逐年上升，2015年增速最快，并于2017年到达顶峰（图1）。

CNKI数据库的文献采集于2018年11月7日，以所有年份的“主题=城市内涝 OR 主题=雨洪 OR 主题=洪涝灾害 OR 主题=暴雨灾害 OR 主题=雨洪管控 OR 主题=雨水调蓄”⑥进行检索，剔除报刊、刊首语等无效文献，共得中文文献5 471篇，时间跨度为1988~2018年。



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and influential MKD tools in the world[4]. However, in China, CiteSpace now is mainly used in Sciences of Library and Archive Management, Management Science and Engineering, and Pedagogy. Few applications are found in fields of Urban and Rural Planning and Landscape Architecture.

CiteSpace supports the analyses of cooperation, co-occurence, co-citation, literature coupling, and research fund. It is also used to process data from different sources including WOS, Scopus, Derwent, CNKI, CSSCI, CSCD, RCI, and KCI, wherein WOS supports relatively comprehensive analyses, while the CNKI database only supports co-author, -institution , and -keyword analyses. Knowledge network graphs generated by CiteSpace mainly consist of nodes② and linking lines, wherein the node size represents the amount of published articles by author / institution / country, occurrence of topics / keywords / domains, or the total cited times of a literature / author / journal, and the thickness of linking lines represents the strength of cooperation / co-occurrence / co-citation while different colors represent the time when the first co-occurrence or co-citation occurred[5]③.

2.2 Data Sources

This study examined both the WOS Core Collection database and the CNKI database. The English literature in the WOS Core Collection database covers important research findings of scholars around the world, especially overseas scholars; the CNKI database basically collects Chinese scholars' studies, wherein, to avoid duplication, only Chinese literature was examined④.

The data of English literature from the WOS Core Collection database was retrieved on November 4, 2018 through a search by “TS = (waterlogging) OR TS = (stormwater)”⑤ for all years of the collection span. After duplication screening with CiteSpace, a total of 12,460 articles were found, spanning from 1974 to 2018. Using the built-in counting module in WOS database for the literature published in the past 25 years, the statistics reveals that the total number of English articles on the topic of urban waterlogging has increased year by year. The fastest growth is observed in 2015, with a peak in 2017 (Fig. 1).

Data of Chinese literature from the CNKI database was retrieved on November 7, 2018 through a search by “主题=城市内涝 OR 主题=雨洪 OR 主题=洪涝灾害 OR 主题=暴雨灾害 OR 主题=雨洪管控 OR 主题=雨水调蓄” [“TS=(urban waterlogging) OR TS=(stormwater flooding) OR TS=(flood disaster) OR TS=(rainwater disaster) OR TS=(stormwater management and control) OR TS=(stormwater regulation and storage)”]⑥ for all years of the collection span. After screening newspaper reports, editorials, etc., a total of 5,471 articles were found, spanning from 1988 to 2018.

② CiteSpace运行生成的可视化图谱为网络图，分析对象所形成的网络节点会因分析项目的不同而代表不同含义。在分析施引文献（也称原文献，通常是指直接检索到的文献）时，节点可代表文章作者、机构、国家、标题、关键词、学科类别、基金等。在分析被引文献（施引文献中的参考文献，通常具有较高的学术价值）时，节点可代表作者、标题、期刊、年份等内容。

③ 节点圈层的厚度与该年的发文频次（或引文频次）成正比，圈层颜色对应图谱上方的时间轴，便于直接识别具体圈层所代表的年份。

② The network graphs generated by CiteSpace visualize varied information according to specific analysis purposes. In the analyses of citing literature (also known as original literature that is directly retrieved), the nodes represent the author(s), institution(s), country, title(s), keywords, subject categories, fund(s), etc. When cited literature (the references / citations in citing literature that usually enjoys high academic value) is examined, the nodes can represent the author(s), title(s), journal(s), year(s), etc.

③ The thickness of the circle layer(s) is proportional to the total amount of published articles (or the total citation counts) of a certain year. The color of circle layer(s) represents the corresponding published year(s) in the timeline on the top of the graph.

④ 为较全面地反映国内外研究概况，本文选取了WOS核心合集数据库和CNKI数据库进行文献分析，但仍旧无法完全避免疏漏。由于WOS核心合集数据库涵盖了全世界各个国家学者所发表的文献，按文献总体数量占比来看，中国学者仅占其中一小部分，故可认为WOS核心合集的英文文献主要反映的是国外研究概况。

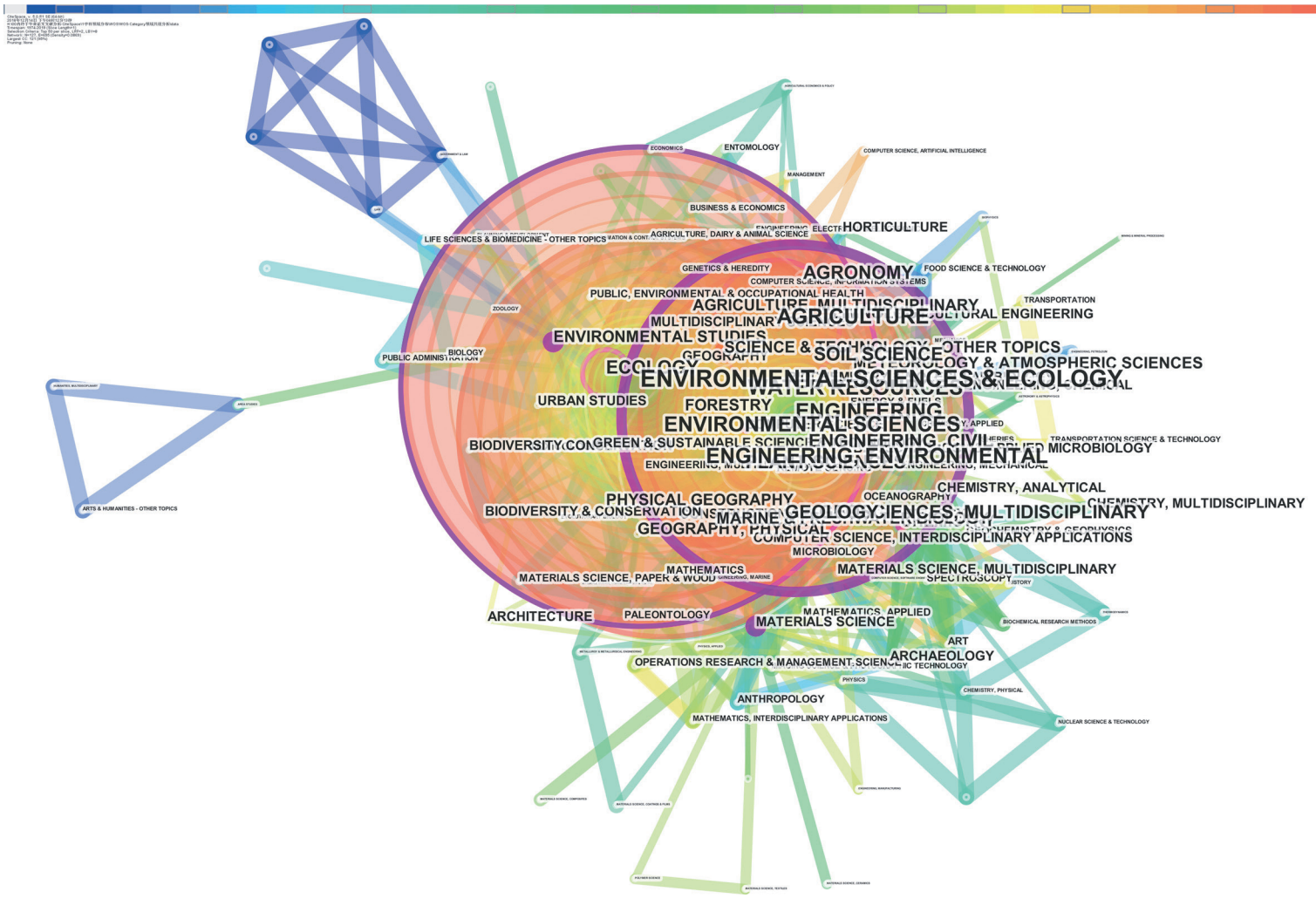
⑤ 按照主题词（TS）检索时，WOS核心合集数据库的主题词限定越少，检索得到的文献越全面。本研究基于前期文献阅读与研究，尝试了多个主题词的搜索（包括“waterlogging”“stormwater”“surface runoff”“rainfall”等），并通过比较各自的文献数量与主题相关性，最终确定使用“waterlogging”和“stormwater”这两个代表性主题词。其中，国外研究中对于“waterlogging”的表述出现较少，且研究多与作物涝渍耐受性有关，但为与国内研究主题词检索有所对应，保留该词；出现最多的是“stormwater”，其原因可能与早期形成的“低影响开发”“绿色雨水基础设施”“最佳管理措施”等理念的英文表述有关。

⑥ 由于CiteSpace对于CNKI数据库的文献仅能根据关键词本身识别其主要研究内容，而不似WOS数据库综合了标题、作者关键词、扩充关键词、摘要等文献信息，因此，CNKI数据库的文献主题词越多，检索得到的文献越全面。中国学者在“城市内涝”问题的研究中所使用的关键词较为多样（如“暴雨洪水”“暴雨洪涝”“暴雨灾害”等相似性极高的表述），这与国内学者在“城市内涝”研究中尚未使用统一术语有关。本研究从20余个关键词中筛选出6个核心关键词，因其所能代表的文献较多且研究内容与“城市内涝”问题贴合性最高。

④ In order to cover the existing research in China and abroad as much as possible, this research examines all the literature from the databases of WOS Core Collection and CNKI. However, there is still a possibility of omission. Since the WOS Core Collection covers the literature written by scholars all around the world, where the literature by Chinese scholars only accounts for a small part, the English literature from the WOS Core Collection can represent the existing research by foreign scholars.

⑤ When searching by topics (TS) in the WOS Core Collection, the fewer topics used, the more documents retrieved. Based on literature review, the authors selected topics "waterlogging," "stormwater," "surface runoff," "rainfall," etc., and compared the amount of literature and the topic relevance by each. Finally, the topics "waterlogging" and "stormwater" were identified. The authors found that the topic "waterlogging" is less mentioned in foreign studies and most of the research on waterlogging focuses on studying crops' resistance to waterlogging. However, the topic "waterlogging" is much more mentioned in Chinese literature. The topic "stormwater" is most frequently mentioned among the existing literature, probably due to the long time promotion of concepts such as "Low Impact Development," "Green Rainwater Infrastructure," and "Best Management Practices."

⑥ The main research topics of the literature in CNKI database can only be learned by examining keywords — in WOS the research topics can be learned by examining article titles, author keywords, keywords plus, abstracts, etc. — which means that the more topics searched, the more articles retrieved. A variety of keywords were found in Chinese scholars' research on urban waterlogging (such as "Stormwater Flooding," "Stormwater Waterlogging," and "Storm Disaster" that share a high similarity), resulting from the terminology divergence among Chinese scholars' research on urban waterlogging. In this research, the authors selected six keywords out of over 20, which can cover the most of literature of a high relation with the issues of urban waterlogging.



1. WOS核心合集数据库内关于“城市内涝”话题的英文文献数量的年度变化（1994~2018年）
2. WOS核心合集数据库内关于“城市内涝”话题的学科领域分布网络图谱

1. Annual changes in the number of published English articles on urban waterlogging in WOS Core Collection database (1994 ~ 2018)
2. Disciplinary networks of published articles on urban waterlogging in Web of Science Core Collection database

表1：“城市内涝”问题相关英文文献中出现频次排名前10与中介中心性排名前10的学科领域类别
Table1: The top 10 subject categories by citation counts and the ones by centrality of foreign urban waterlogging studies in English literature

出现频次排名前10的学科领域类别 Top 10 subject categories by citation counts			中介中心性排名前10的学科领域类别 Top 10 subject categories by centrality		
排名 Ranking	出现频次 Citation counts	学科领域 Subject categories	排名 Ranking	中介中心性 Centrality	学科领域 Subject categories
1	5,291	环境科学与生态学 Environmental Sciences & Ecology	1	0.24	材料科学 Materials Science
2	4,645	环境科学 Environmental Sciences	2	0.21	环境研究 Environmental Studies
3	3,862	工程学 Engineering	3	0.20	环境科学与生态学 Environmental Sciences & Ecology
4	3,825	水资源 Water Resources	4	0.20	工程学 Engineering
5	2,413	环境工程 Engineering, Environmental	5	0.16	计算机科学 Computer Science
6	1,994	农业 Agriculture	6	0.16	生态学 Ecology
7	1,365	土木工程 Engineering, Civil	7	0.14	农业 Agriculture
8	1,266	植物学 Plant Sciences	8	0.13	化学 Chemistry
9	1,035	地质学 Geology	9	0.09	土木工程 Engineering, Civil
10	1,015	生态学 Ecology	10	0.07	林学 Forestry

3 英文文献的学科分布情况

WOS核心合集数据库基于SCI、SSCI和A&HCI将学科划分为252类，并以字段WC记录。因此，可以直接分析WOS数据库英文文献的学科领域分布情况。

3.1 领域共现网络分析结果

运用CiteSpace的领域共现分析功能，绘制出针对这12 460篇英文文献的学科分布知识图谱，共得到127个关键节点⑦和695条关系连线（图2），并分别获得出现频次前10名和中介中心性⑧前10名的学科领域列表（表1），表明这些学科在“城市内涝”问题上的研究具有代表性，且进行了广泛探索。利用CiteSpace的突发性检测功能⑨又得出56个突发学科领域，其中突发强度排名靠前的为植物学、农业与多学科、规划与发展学等学科。另外，分析结果显示，近年来学科领域出现频

⑦ 将TOP N参数设置为默认值50，提取每个时间切片（以年为单位）内出现频次排名前50的学科类别，由此得到关键节点。

⑧ 中介中心性是CiteSpace中发现和衡量文献在网络中的重要性的指标，并用紫色外圈对该类文献（或作者、期刊以及机构等）进行重点标注，中介中心性在0~1间取值，带有紫环的节点中介中心性不小于0.1。具有高中介中心性的文献通常是连接两个不同领域的关键枢纽，在CiteSpace中也称其为转折点。

⑨ 突发性检测是CiteSpace用于考察研究对象（本文为学科和关键词）在短期内出现频次突然增加的重要功能，可揭示其变化动态。在CiteSpace中，某个聚类所包含的突发节点越多，表示该领域越活跃，可能是研究的新兴趋势。

3 Disciplinary Networks in English Literature

The WOS Core Collection database that covers SCI, SSCI, and A&HCI classifies subjects into 252 categories which are recorded in the field WC, making it possible to directly examine the disciplinary networks of the English literature from the WOS database.

3.1 Co-category Network Analysis Results

Through the co-category analyses of the 12,460 English articles by CiteSpace, a knowledge network graph of disciplinary network was generated that is composed of 127 key nodes⑦ and 695 linking lines (Fig. 2). The top 10 subject categories by citation counts and by centrality⑧ (Table 1) were also obtained, revealing the representative subject categories in urban waterlogging study with productive research findings. Besides, through the burst detection⑨ by CiteSpace, 56 burst subjects were identified, out of which the ones of the highest burst intensity include Plant Sciences, Agriculture (Multidisciplinary), and Planning &

⑦ By setting up the TOP N parameter as the default value of 50, the top 50 subject categories in each time slice (/year) were identified, which are shown as key nodes.

⑧ In CiteSpace, centrality is a key indicator of the importance of a literature / author / journal / institution in the network, which is represented with an outer ring in purple. The centrality of a literature values between 0 and 1, and the value of a purple-ring node is not less than 0.1. Literature of high centrality is considered disciplinary pivots (or "turning points" in CiteSpace) that connect different domains.

⑨ Burst detection is an important module in CiteSpace to examine the surge of occurrence of a certain research object (that is subject or keyword in this research) in a short time period, in order to reveal the shifts and trends of related research interests. In CiteSpace, the more burst nodes a cluster includes, the more active it is, where emerging research interests are suggested.

表2：“城市内涝”问题相关英文文献中近年持续突发的学科领域
Table2: Subject categories that see continuous bursts of foreign urban waterlogging studies in English literature in recent years

学科领域 Subject categories	突发强度 Burst strength	突发起始年份 Beginning year	突发结束年份 Ending year	突发情况时间轴（1974~2019年） Timeline of study burst (1974 to 2019)
城市研究 Urban Studies	7.72	2015	2017	
地理学 Geography	6.5509	2015	2018	
绿色可持续科学与技术 Green & Sustainable Science & Technology	48.9386	2015	2018	
环境研究 Environmental Studies	18.1422	2015	2018	
施工和建筑技术 Construction and Building Technology	5.2498	2016	2018	
能源与燃料 Energy and Fuels	7.8938	2016	2018	
泛科技类学科 Science and Technology — Other Topics	63.3609	2016	2018	
多学科科学 Multidisciplinary Sciences	19.2279	2016	2018	
艺术 Art	5.6681	2017	2018	

注释
“突发情况时间轴”中的红色部分代表突发出现的年份。
NOTE
The burst years are marked in red.

次明显处于持续增多状态的有9个（表2）。然而，在这些代表性学科中却未包含公共、环境与职业健康，以及区域研究这两个与“城市内涝”问题相关度较高的学科，但本研究对这两个学科也进行了补充分析。

3.2 英文文献学科分布情况及研究重点解译

通过对以上数据进行初步统计与分析，得到如下结论：

1）在WOS核心合集数据库中关注“城市内涝”话题的代表性英文文献覆盖了WOS默认分类中的127个类别。其中，发表英文文献数量最多的三大学科为环境科学与生态学、环境科学和工程学，其次为水资

Development. In addition, the analyses show that nine subjects have continued a burst of occurrence in recent years (Table 2). Although the subject categories of Public, Environmental, & Occupational Health and Area Studies were not retrieved, both of them are considered closely related to the issues of urban waterlogging. Therefore, this research examined the two categories as well.

3.2 Disciplinary Network and Major Research Interests in English Literature

The preliminary statistics and data analyses reveal that:

1) The representative English literature on urban waterlogging covers 127 subject categories in the WOS Core Collection database, out of which the top three categories in the amount of publications are Environmental Sciences & Ecology, Environmental Sciences, and Engineering, followed by Water Resources, Engineering (Environmental), Plant Sciences, Geology, Ecology, etc., indicating that these disciplinary fields have made a great contribution to the issues of urban waterlogging and

表3：各代表性学科在“城市内涝”问题上的主要研究内容[6]-[14]
Table 3: Main research topics among representative disciplines on urban waterlogging[6]-[14]

代表学科 Representative disciplines	主要研究内容 Main research topics
环境科学与生态学 环境科学 生态学 环境研究 工程学 土木工程 环境工程 Environmental Sciences & Ecology Environmental Sciences Ecology Environmental Studies Engineering Engineering, Civil Engineering, Environmental	• “低影响开发”“绿色基础设施”“水敏性城市设计”“最佳管理措施”“可持续排水系统”的理念落实、空间布局和环境经济效益 • 微观措施：绿色屋顶（研究热点）、透水路面、生物滞留池 • 城市河流的生态问题与修复对策 • 城市水文过程 • 水文模型的应用 • 水污染问题与净化方法（研究热点）、空气污染问题 • 雨洪淹没风险评估 • 暴雨事件 • 作物涝渍耐受性 • The application, physical construction, and economic-environmental benefits of “Low Impact Development,” “Green Infrastructure,” “Water Sensitive Urban Design,” “Best Management Practices,” and “Sustainable Drainage Systems” • Micro measures: green roofs (hot topic), permeable pavement, and bioretention • Urban river's ecological problems and restoration solutions • Urban hydrological process • Application of hydrological models • Water pollution and cleaning methods (hot topic) and air pollution • Stormwater and flood inundation risk assessment • Storm event • Waterlogging tolerance of crops
水资源 Water Resources	• “低影响开发”的理念 • 城市化对流域生态系统的破坏和对雨水径流的污染 • 城市水文过程的特征 • 水资源综合管理 • Concept of “Low Impact Development” • Deterioration of watershed ecosystem and runoff pollution by urbanization • Characteristics of urban hydrological process • Integrated water resource management
农业 林学 植物学 Agriculture Forestry Plant Sciences	• “低影响开发”“最佳管理措施”的理念 • 微观措施：绿色屋顶、生物截流池、树木 • 作物涝渍耐受性 • 土壤渍水环境下的碳循环和酶活性 • Concepts of “Low Impact Development” and “Best Management Practices” • Micro measures: green roofs, biofilters, and trees • Waterlogging tolerance of crops • Carbon cycle and enzyme activity of soil in waterlogging environment
地质学 Geology	• “最佳管理措施”“可持续排水系统”的理念 • 从水文模型、水文分析、地表水文、湿地水文等方面关注城市水文过程 • 水系统退化和径流污染问题 • 城市化影响下的土地利用变化和规划应对方法 • 土壤磁化率与气候变化和年降雨量之间的关系 • 土壤有机碳 • 泥炭地的形成原因与演变规律 • Concepts of “Best Management Practices” and “Sustainable Drainage Systems” • Study on urban hydrological process from the aspects of hydrologic model, hydrologic analysis, surface hydrology, and wetland hydrology • Water system degradation and runoff pollution • Changes in land use and planning solutions under the background of urbanization • The relationship between soil magnetic susceptibility with climate change and annual precipitation • Soil organic carbon • The formation and evolution mechanisms of peatland
绿色可持续科学与技术 施工和建筑技术 能源与燃料 泛科技类学科 Green & Sustainable Science & Technology Construction & Building Technology Energy & Fuels Science & Technology — Other Topics	此类学科研究内容与区域研究、城市研究、地理学基本相同，此外还包括： • 各类雨洪调控措施的生命周期评价 • 下水道、透水混凝土、木材和垂直绿化墙体的工程结构 • 植物涝渍耐受性 • 泥炭地的形成原因与演变规律 These disciplines share the same research interests with the ones in Area Studies, Urban Studies, and Geography. Besides, they also study: • Life cycle assessment of all kinds of stormwater control measures • Engineering structures of sewers, permeable concrete, timber, and green walls • Waterlogging tolerance of plants • Formation and evolution mechanisms of peatland

续表见下页 / continued

⑩ CiteSpace中的节点支持单独查看其频次（被引或出现频次）在时间上的变化。若为共被引网络，查看结果为某文献被引用的时序图及其施引文献信息；若为共现网络，查看结果为某个词汇出现频次随时间的变化及其详细论文信息；若为合作网络，查看结果则为作者发文的时序分布及其详细论文信息。

⑩ CiteSpace allows users to check the change of occurrence or cited times of the nodes over a certain time period. When users check a co-citation network, the result represents a cited-timeline of a certain document and all the citing articles; when users check the co-occurrence network, the result reveals the occurrence change of a term over a certain time period and the detailed literature information; when users check a cooperative network, the result represents the timeline of an author's publication and the detailed literature information.

源、环境工程、植物学、地质学和生态学等，表明这些学科在“城市内涝”“城市雨洪”等相关问题上已进行了广泛的、具有较高学术价值的研究。

2）以紫色外环标注的中介中心性大于0.1的学科包括材料科学、环境研究、环境科学与生态学、工程学、计算机科学、生态学、农业和化学，表明这些学科与其他学科的联系更为紧密，发挥了加强跨学科研究的枢纽作用。

3）近年对于“城市内涝”相关问题关注度大幅提升的学科包括城市研究、地理学、绿色可持续科学与技术、环境研究、施工和建筑技术等。这与近年中国出现在地理、规划与景观学界的涝灾研究热潮相符。

通过阅读出现频次前10和中介中心性前10的各个学科领域内被引量排名前10[10]，和近年仍在持续突发的学科领域在突发年份内，以及公共、环境与职业健康和区域研究领域的英文文献标题、摘要、作者关键词、扩展关键词等信息，初步获知这些代表性领域的大致研究内容。再通过研读与剖析这些重要英文文献，总结得出各个代表性学科在“城市内涝”问题上的主要关注点（表3）。

3.3 英文文献反映的研究热点

基于上述步骤，笔者归纳出当前国外针对“城市内涝”问题的主要研究主题如下：

（1）雨洪管理的理念探索

这包括了目前已被国内学者广泛探讨的理念（如“低影响开发”“绿色基础设施”“水敏性城市设计”“最佳管理措施”等），以及很多较少被讨论的理念，包括基础设施层面的“水基础设施”“蓝绿基础设施”[15]“灌溉基础设施”等，排水层面的“排水基础设施”[16]“城市雨水排水系统”“市政独立雨水管道系统”[17]等，雨水管理层面的“城市雨水管理”“雨水管理系统”“雨水管理计划”等，设施层面的“暴雨控制措施”[18]“气候变化水管理工具”“雨水生物过滤

"urban stormwater and flooding" in publication quantity and academic value.

2) Subjects with centrality higher than 0.1, as outlined in purple, include Materials Science, Environmental Studies, Environmental Sciences & Ecology, Engineering, Computer Science, Ecology, Agriculture, and Chemistry, which have a higher connectivity with other subjects and thus serve as disciplinary pivots that help strengthen cross-disciplinary research.

3) Subjects that see a sharp growth of research on issues of urban waterlogging in recent years include Urban Studies, Geography, Green & Sustainable Science & Technology, Environmental Studies, and Construction & Building Technology. This is in line with the increasing focus on flooding and waterlogging problems in Chinese academia of Geography, Planning, and Landscape Architecture in the past decade.

The research interests of representative literature were roughly reviewed by examining the titles, abstracts, author keywords, keywords plus, etc. of the top 10 most cited English literature in the top 10 subject categories by citation and by centrality⑩, in the burst subjects during the time span of continuing burst years, and in the fields of Public, Environmental, & Occupational Health and Area Studies. Then through thorough analyses of these representative literature, the major research interests among the studies on urban waterlogging are summarized (Table 3).

3. 3 Research Hotspots in English Literature

Through the above steps, the authors summed up the research hotspots on urban waterlogging among the existing English literature:

(1) Theoretical Exploration on Stormwater Management and Control

Such concepts include both the ones extensively discussed by Chinese and overseas scholars (such as "Low Impact Development," "Green Infrastructure," "Water Sensitive Urban Design," and "Best Management Practices") and the less explored ones, including "water infrastructure," "blue and green infrastructure"[15], and "irrigation infrastructure," and other concepts on stormwater infrastructure; "drainage infrastructure"[16], "urban stormwater drainage systems," "municipal separate storm sewer system"[17], and other concepts on stormwater drainage; "urban stormwater management," "stormwater management system," "stormwater management program plan," and other concepts on stormwater management; "stormwater control measures"[18], "weather shift water tools,"

表3：各代表性学科在"城市内涝"问题上的主要研究内容（续）[6]-[14]
Table 3: Main research topics among representative disciplines on urban waterlogging (continued)[6]-[14]

代表学科 Representative disciplines	主要研究内容 Main research topics
材料科学 化学 Materials Science Chemistry	• 透水路面和浸水木材的结构特征 • 地下水和雨水径流的污染 • 作物涝渍耐受性 • Structural characteristics of permeable pavement and waterlogged woods • The pollution of groundwater and rainwater runoff • Waterlogging tolerance of crops
计算机科学 Computer Science	• 运用多媒体技术预警城市暴雨洪涝灾害 • Warnings of urban floods and storm disasters with multimedia technologies
公共、环境与职业健康 Public, Environmental & Occupational Health	• "可持续排水系统""绿色雨水基础设施""最佳管理措施""低影响开发理念"的水文性能评估与建成效果反馈 • 城市内涝应急措施 • 雨涝缓解方法：提高雨水管网设计标准、基于水文模型进行土地利用规划 • 流域、河流等水系统以及雨水、径流等的污染问题成因与防治措施 • 城市化对土地利用变化的影响：流域退化、城市水文过程改变、土壤微生物特性变化 • 公共健康与卫生，特别是发展中国家的基础设施建设状况 • Hydrological performance assessment and built-up evaluation of applications of "Sustainable Drainage Systems," "Green Stormwater Infrastructure," "Best Management Practices," and "Low Impact Development" • Emergency solutions to urban waterlogging • Waterlogging mitigation methods: improvement of design standards of rainwater drainage pipe networks, land use planning based on hydrological models • Pollution causes and control solutions of water systems (e.g., watersheds, basins, and rivers) and stormwater and runoff • The impact of urbanization on urban land use: watershed degradation, urban hydrological process changes, and changes of soil microbial characteristics • Public health and sanitation, especially the infrastructure development in developing countries
区域研究 城市研究 地理学 Area Studies Urban Studies Geography	• "绿色基础设施""水基础设施""绿色雨水基础设施""雨水基础设施""分布式雨水管理基础设施""蓝绿基础设施""最佳管理措施""暴雨控制措施""韧性城市""适应性规划"等在内的20余项理念的规划落实途径，涉及空间结构的布局、选址、设计过程、实施策略等层面，包括缓解雨洪灾害、净化水质，并开始研究更多的扩展功能 • 微观措施：对树木、绿色屋顶、雨水调蓄池、绿色街道、雨水花园、雨水桶、生物滞留池、透水路面、人工湿地和排水设施等进行了细致全面的研究，尤其对绿色屋顶的扩展功能（如屋顶农场的水文平衡、水分利用效率）展开探讨，另外对于绿色屋顶的作用、结构、问题与推广也有较多研究 • 理念应用与措施实施过程中的跨部门工作小组间的合作、政府部门与公共或私人利益相关者的合作、公众参与及认知和经济效益评估 • 从流域、城市到微观措施层面关注了水文循环、水文动力学、水文功能、水文模型等水文学话题 • 洪涝风险评估与灾害应对机制 • 水体修复、景观格局、生态系统服务、动植物栖息地与可持续发展 • Planning and implementation approaches of more than 20 concepts including "Green Infrastructure," "Water Infrastructure," "Green Stormwater Infrastructure," "Stormwater Infrastructure," "Distributed Stormwater Management Infrastructure," "Blue and Green Infrastructure," "Best Management Practices," "Stormwater Control Measures," "Urban Resilience," and "Adaptive Planning," covering spatial structure and layout, site selection, design process, implementation strategies, etc., with an interest shift from mitigating stormwater and purifying water quality towards broader uses • Micro measures: a great number of subdivisions of studies on trees, green roofs, rainwater retention ponds, green streets, rain gardens, rain barrels, bioretention, permeable pavement, constructed wetlands, and drainage facilities, especially including research on the broader uses of green roofs (such as hydrologic balance and water use efficiency of roof farms) and on the functions, structures, problems, and promotion of green roofs • Cross-department collaborations, collaborations between governments and public or private institutions, public engagement and awareness, and economic benefit evaluation of related applications and practices • Hydrologic cycles, dynamics, functions, models, and other aspects at scales of watershed, city, and micro measures • Flood risk assessment and disaster responding mechanism • Water restoration, landscape pattern, ecosystem services, animal and plant habitats, and sustainability
艺术 Art	• "可持续排水系统""低影响开发"的理念 • 微观措施：绿色屋顶、透水路面 • 木材吸湿性 • Concepts of "Sustainable Drainage Systems" and "Low Impact Development" • Micro measures: green roofs and permeable pavement • Hygroscopicity of timber

注释
鉴于学科太多，此表将关注点相似的学科进行了合并。
NOTE
Due to the huge amount of examined disciplines, in this research the ones with similarities are merged.

器”[19]等，另外还有城市空间规划层面的“适应性规划”“绿色开放空间网络规划”[20]“土地利用规划”等。

（2）各类雨洪管控措施的结构与布设

对于微观雨洪管控设施的研究主要涵盖绿色屋顶、透水路面、雨水花园、雨水滞蓄池、雨水净化池、洼地、沼泽地、人工湿地、浮床、雨水桶、绿色街道、绿色建筑、排水管网，以及洪泛平原等临时蓄洪空间，尤为关注绿色屋顶和透水路面。其中，学者不仅针对绿色屋顶的主要功能（如净化水质、减少径流、收集雨水、减少能耗、降低热岛效应）和结构（如植物和生长介质的选择）进行了专项研究，还研究了其特定类型（如扩展型绿色屋顶、农业屋顶[21]、芳香植物屋顶等），同时还包括水文性能、效益评估、自身污染问题分析等；透水路面则主要研究了其结构与水文性能。

（3）水质变化

水质变化方面主要从水质污染和水质净化两个角度研究了城市化对流域、河流等水系统以及雨水、径流等的污染问题，并尝试利用湿地系统等生态处理途径净化水质。

（4）水文学

对于水文学的关注主要体现在两个尺度上，一是流域、城市等宏观尺度，从生态水文学[22]、自然水文学[23]、流域水文学、河流水文学、城市水文学和地表水文学出发探讨径流机制（包括产生、蒸发、下渗等过程）的变化，从空间上划定出城市集水区[24]，尤其关注城市水文过程的水文平衡问题；二是微观尺度的各种雨洪管控措施，关注其水文性能[25]、水文功能与水文效益等，探索雨洪管控措施自然水循环过程的建立。另一方面，探究了SWMM[26]、SWAT[27]、SCS-CN等水文模型与工具如何进行宏观与微观尺度的雨水管理。

（5）内涝成因研究

在WOS核心合集数据库中几乎没有以“内涝成因”或“雨洪成因”为题的英文文献，但众多文献都涉及了对成因的描述，总结起来

“stormwater biofilters”[19], and other concepts on management and control measures; “adaptive planning,” “green open spaces planning”[20], “land use planning,” and other concepts on urban spatial planning.

(2) Structural and Spatial Deployment of Various Measures of Stormwater Management and Control

Studies on micro stormwater management and control measures cover topics of green roof, permeable pavement, rain garden, stormwater retention pond, stormwater treatment pond, swale, marsh, constructed wetland, floating bed, rain barrel, green street, green building, drainage network, and temporary flood storage spaces (such as floodplain), among which green roof and permeable pavement are hotspots. For example, scholars have studied the main functions of green roofs (e.g., water purification, runoff reduction, stormwater collection, energy saving, and heat island effect mitigation), structures of green roofs (e.g., the selection of plants and medium), specific types of green roofs (e.g., extended green roof, roof farm[21], and roof of aromatic plants), as well as related hydrological performance, efficiency evaluation, and self-pollution problems; Studies on permeable pavement concentrate on related structures and hydrological performance.

(3) Water Pollution and Water Quality Improvement

Water pollution and water quality improvement are the two research hotspots. Such literature has studied not only the pollution problems of watersheds, basins, rivers, and other water systems, as well as stormwater and runoff, caused by urbanization, but also ecological measures of water quality improvement such as wetland systems.

(4) Hydrology

Studies in Hydrology cross scales. At watershed, city, or other macro scales, such literature studies the changes of runoff mechanisms (e.g., processes of formation, evaporation, and infiltration) from the perspectives of Ecological Hydrology[22], Natural Hydrology[23], Watershed Hydrology, River Hydrology, Urban Hydrology, and Surface Hydrology, helping identify catchments in urban areas[24] with a particular focus on the balance of urban hydrological processes. At micro scales, studies of various stormwater management and control measures often focus on hydrological performance[25], functions, and benefits, helping establish natural water cycles through constructed approaches. In addition, such studies also explore the application of hydrological models and tools such as SWMM[26], SWAT[27], and SCS-CN for stormwater management across scales.

(5) Research on the Causes of Waterlogging

In WOS Core Collection database, despite of little English

主要包括气候变化、极端暴雨事件、城市化、排水系统、政策法规等方面的内容，其中城市化又主要涉及土地利用变化、河道硬化、城市下垫面变化等对水文循环过程的破坏。

（6）城市规划途径

土地利用规划、城市规划和景观设计被广大学者认为是能够实现雨洪管控的空间途径。土地利用规划方面提出为缓解内涝风险应控制城市中的不透水地表面积并优化其空间配置，并从土地利用类型政策和管理上寻找优化方法[28]；城市规划方面强调了蓝绿空间对于雨洪管控的重要性，提出了诸如绿色开放空间网络规划、综合农业系统模型设计等空间途径以将雨洪管控融入城市规划中；景观设计层面主要涉及具体设施的结构设计与布置，如低影响开发的设施单元设计。

（7）风险评估与管理

风险评估主要包括对洪涝灾害发生的风险及其所造成的经济损失进行的评估，风险管理则注重讨论洪涝灾害的适应机制。

（8）效益评估

效益评估的相关研究主要出现在英文文献中，主要评估具体的雨洪管控措施（如绿色屋顶、透水路面）等的经济效益[29]，另外还有诸多研究生态系统服务的货币价值的文献。

（9）政策与公众参与

政策研究主要涉及法规制定、雨水管理决策支持工具等；公众参与方面则探讨了政府主导、社区主导和公私合作等模式的适用场景与实施路径，注重社会资本等市场力量的加入，鼓励利益相关者如社区民众的积极参与。

（10）作物的涝渍耐受性[30]

主要涉及小麦、水稻、玉米、棉花、豌豆等作物的细胞通气组织、内涝胁迫响应模式等涝渍耐受性的相关研究。

literature with a title of “waterlogging causes” or “stormwater causes,” the causes of waterlogging or flooding are broadly discussed among such literature, being summarized into climate change, extreme storm events, urbanization, drainage system, policies and regulations, etc., among which urbanization is often considered the causes to damages of natural hydrology by land use changes, river canalization, impervious pavement, etc.

(6) Urban Planning Approaches

Land use planning, urban planning, and landscape design are commonly considered spatial approaches to stormwater management and control. Land use planning approaches focus on reducing the use of impervious surfaces in urban areas and optimizing spatial deployment to enhance urban resilience to waterlogging through planning policies and management measures[28]; Urban planning emphasizes the importance of blue-green spaces to stormwater management and control and focuses on combining the approaches of green open space network planning and integrated agricultural system modeling with urban planning; Landscape design approaches concentrate on the structural design and spatial deployment in implementation such as Low Impact Development unit design.

(7) Risk Assessment and Management

Literature on risk assessment of waterlogging and flooding mainly focuses on assessing the economic loss by such disasters, and that on risk management studies the adaptive mechanism to such impacts.

(8) Benefit Evaluation

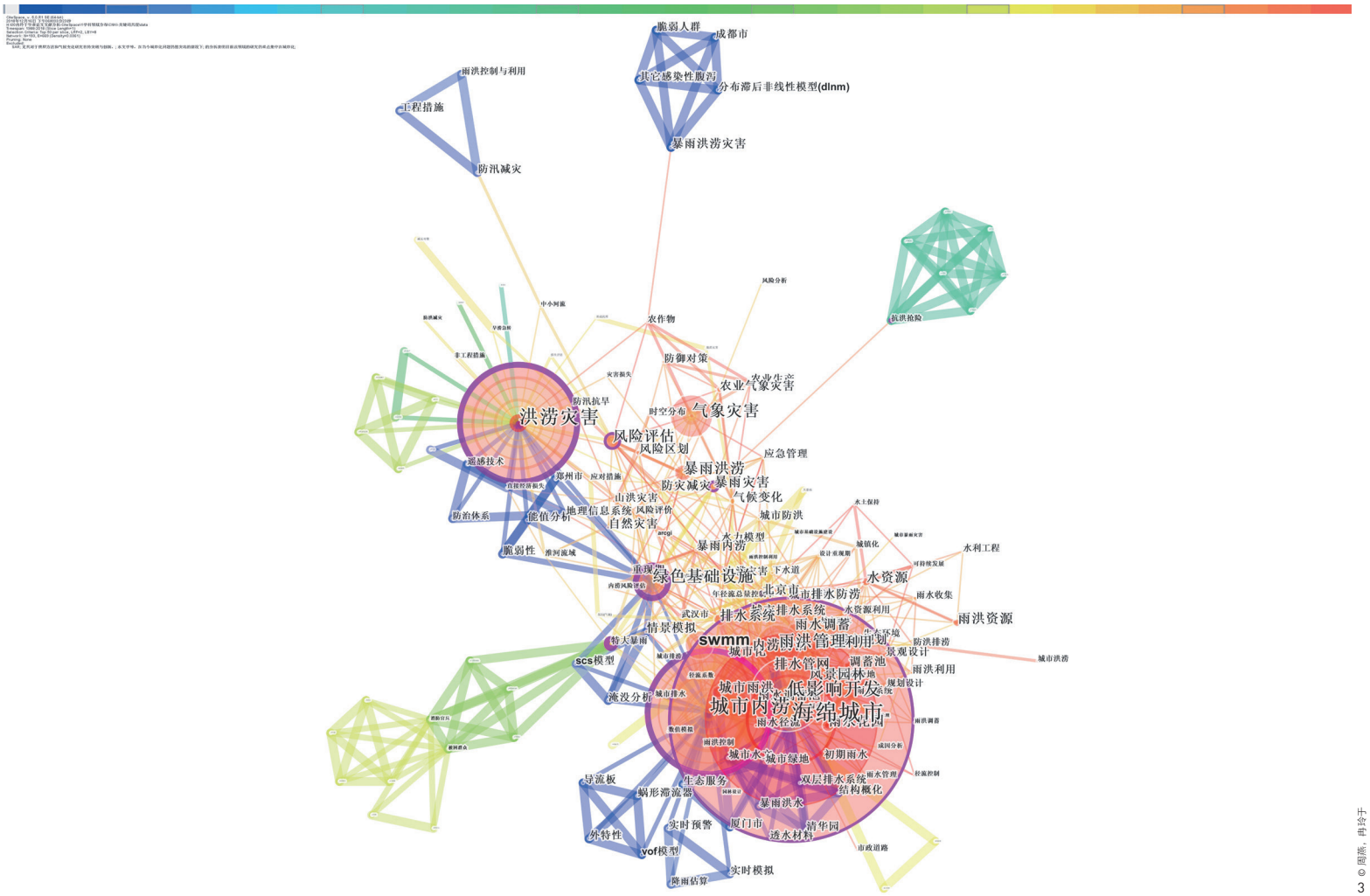
Research on benefit evaluation is more found in English literature, which evaluates the economic benefits of specific cases of stormwater management and control measures (such as green roof and permeable pavement), as mentioned previously[29]. It also sees a number of articles that demonstrate the monetary value of ecosystem services.

(9) Policies and Public Participation

Policy studies include the formulation of laws and regulations, as well as decision-making tools for stormwater management. Public participation studies discuss the scenarios and roadmaps of collaborative initiatives led by governments or local communities, or in a public-private form, stress the access of social capital, and encourage the engagement of stakeholders such as community residents.

(10) Waterlogging Tolerance of Crops[30]

Such research covers topics like cell aeration tissue and response patterns to waterlogging impacts of wheat, rice, corn, cotton, pea, and other crops.



3. 通过CiteSpace的关键词共现分析功能获得CNKI数据库中出现频次最高的关键词网络图谱，其中以“海绵城市”为中心的关键词呈现出较强的聚集性，反映出中国在“城市内涝”问题上的主要研究热点。

3. The most cited keywords in the CNKI database are obtained through co-keyword analysis with CiteSpace. The keywords related to "sponge city" show a strong aggregation that reveals the main research hotspot on the topic of urban waterlogging in China.

表4：“城市内涝”问题相关中文文献发文量排名前10的关键词与中介中心性排名前10的关键词
Table 4: The top 10 keywords by amount of published articles and by centrality of urban waterlogging study in Chinese literature

发文量排名前10的关键词 Top 10 keywords by amount of published articles			中介中心性排名前10的关键词 Top 10 keywords by centrality		
排名 Ranking	发文量 Amount of published articles	关键词 Keywords	排名 Ranking	中介中心性 Centrality	关键词 Keywords
1	1,129	海绵城市 Sponge city	1	0.34	洪涝灾害 Flood disaster
2	644	城市内涝 Urban waterlogging	2	0.24	城市内涝 Urban waterlogging
3	574	洪涝灾害 Flood disaster	3	0.23	绿色基础设施 Green infrastructure
4	357	低影响开发 Low Impact Development	4	0.20	特大暴雨 Extreme storm events
5	221	雨洪管理 Stormwater management	5	0.18	海绵城市 Sponge city
6	210	气象灾害 Meteorological disaster	6	0.16	暴雨灾害 Storm disaster
7	200	绿色基础设施 Green infrastructure	7	0.16	北京市 Beijing City
8	171	SWMM	8	0.10	风险评估 Risk assessment
9	95	暴雨洪涝 Rainstorm and flood	9	0.10	抗洪抢险 Flood resistance and emergency rescue
10	93	风险评估 Risk assessment	10	0.09	防灾减灾 Disaster prevention and mitigation

表5：“城市内涝”问题相关中文文献中突发强度排名前10的关键词
Table 5: Top 10 keywords of the strongest citation bursts of urban waterlogging studies in Chinese literature

关键词 Keywords	突发强度 Burst strength	突发起始年份 Beginning year	突发结束年份 Ending year	突发情况时间轴（1988~2018年） Timeline of study burst (1988 to 2018)
海绵城市 Sponge city	85.7876	2016	2018	
洪涝灾害 Flood disaster	18.6043	2013	2014	
城市水文 Urban hydrology	12.3082	1988	2012	
清华园 Tsinghua Campus	12.0158	1988	2011	
MIKE模型 MIKE model	12.0158	1988	2011	
分析复核系统 Analysis and rechecking system	12.0158	1988	2011	
厦门市 Xiamen City	12.0158	1988	2011	
淹没分析 Submergence analysis	12.0158	1988	2011	
农田灌溉 Farmland irrigation	12.0158	1988	2011	
沂源县 Yiyuan County	12.0158	1988	2011	

注释
“突发情况时间轴”中的红色部分代表突发出现的年份。
NOTE
The burst years are marked in red.

4 中文文献的学科分布情况

由于CNKI数据库下载的文献不包含学科类别信息，故而主要通过对CNKI文献进行关键词共现分析来间接获取学科分布情况。关键词共现分析也叫共词分析，用以在文献信息中提取能够表达文献核心内容的关键词频次的高低分布，以此来分析该领域的研究热点和发展动向。其中，新兴领域的研究较为分散，而成熟领域则会呈现出较强的中心聚集性。

4.1 关键词共现分析结果

将节点设置为“关键词”，得到关键词共现网络，剔除报刊、刊首语、资讯等非研究内容，合并同义关键词（如“LID”和“低影响开发”、“SWMM”和“SWMM模型”）后得到193个关键节点和669条关系连线（图3），可见其网络以关键词“海绵城市”为中心呈现出较强的聚集性。表4统计了发文量前10名的关键词和中介中心性指数前10

4 Disciplinary Network of Chinese Literature

Since the retrieved documents from the CNKI database do not include subject category information, the disciplinary network was indirectly reviewed through a co-keyword analysis (also known as co-word analysis), which is used to count the occurrence of keywords of literature, helping scholars learn research hotspots and trends. In a co-keyword analysis, emerging fields can be identified by a scattered network pattern while developed fields by a strong centrality.

4.1 Co-Keyword Analyses

By setting up the nodes to “keywords,” a co-keyword network graph was generated; then by screening newspaper reports, editorials, briefs, and other non-research documents and merging the synonymous keywords — for example, “LID” and “Low Impact Development”; “SWMM” and “SWMM model” — 193 key nodes and 669 linking lines were obtained (Fig. 3), forming a network of a strong centrality on the keyword “sponge city.”

表6：“城市内涝”问题相关中文文献中近年持续突发的关键词

Table 6: The keywords of continuous bursts of urban waterlogging studies in Chinese literature in recent years

关键词 Keywords	突发强度 Burst strength	突发起始年份 Beginning year	突发结束年份 Ending year	突发情况时间轴（1988~2018年） Timeline of study burst (1988 to 2018)
水力模型 Hydraulic model	4.6913	2015	2018	
雨水花园 Rain garden	5.8777	2016	2018	
农业生产 Agricultural production	6.0528	2016	2018	
景观设计 Landscape design	5.8683	2016	2018	
海绵城市 Sponge city	85.7876	2016	2018	

注释

“突发情况时间轴”中的红色部分代表突发出现的年份。

NOTE

The burst years are marked in red.

名的关键词，这20个关键词共同反映了当前国内学者在“城市内涝”问题上的主要研究热点。突发强度最高且远高于其他关键词的是“海绵城市”（表5），这与近年来国内学术界对“海绵城市”的高度关注态势相吻合。近年仍在持续突发的关键词包括“水力模型”“雨水花园”“农业生产”“景观设计”“海绵城市”，表明近年来在“城市内涝”问题上国内学者的研究重心开始转向这些方向（表6）。

4.2 中文文献学科分布情况及研究重点解译

在对上节所提到的代表性关键词统计与相应中文文献阅读的基础上，综合所有关键词，总结得出基于CNKI数据库的中文文献在“城市内涝”话题下主要涉及了八大学科，分别是城乡规划学、风景园林学、水文学、给排水科学与工程、气象学、农学、林学，以及医学，具体研究重点解译如下：

1）城乡规划学主要研究了“海绵城市”[31]和“绿色基础设施”[32]的理念与建设，而规划设计实践则主要关注城镇化建设、市政道路优化、遥感技术辅助、可持续发展等议题，也尝试从城市规划的空间与政策角度解析“城市内涝”的成因。

The top 10 keywords by amount of published articles and by centrality are listed in Table 4. These 20 keywords together reflect the current research hotspots in Chinese academia on urban waterlogging, out of which “sponge city” has the highest burst strength (Table 5), consistent to China’s research upsurge on “sponge city” in recent years. Besides, the keywords of continuous bursts in recent years include “hydraulic model,” “rain garden,” “agricultural production,” “landscape design,” and “sponge city” which are considered the current interests among Chinese scholars’ research on urban waterlogging (Table 6).

4.2 Disciplinary Network and Major Research Interests of Chinese Literature

On the basis of keyword statistics and an overall review of the corresponding Chinese literature, eight subject categories closely related to urban waterlogging in the CNKI database are identified: Urban and Rural Planning, Landscape Architecture, Hydrology, Water Supply and Drainage, Meteorology, Agronomy, Forestry, and Medicine. Detailed research interests are summarized as follows:

1) Urban and Rural Planning has studied the concept and implementation of “sponge city”[31] and “green infrastructure”[32], with practice efforts exploring urbanization construction, municipal road improvement, remote sensing technology, and sustainable development. It also sees research on identifying the causes of urban waterlogging from the perspective of spatial deployment and policies of urban planning.

2）风景园林学主要研究了“低影响开发”理念支撑下的各种雨洪调控措施的应用[33]，尤其对于雨水花园[34]和下凹式绿地[35]关注较多，并且在雨水利用、调蓄、收集、管理等方面进行了较为深入的探索；另外也有学者关注“景观水文”方向，尝试交叉研究水文学与景观设计[36]，但关注点较为微观。

3）水文学对于城市水文的过程[37]与问题有所关注，对于雨水径流的产生、控制与具体参数进行了研究，并运用了MIKE、SCS、SWMM等水文模型[38]对场地尺度的低影响开发措施的选择与布设进行模拟，另外也关注了水资源利用与管理方向，特别是雨洪资源管理。

4）给排水科学与工程更多地关注了水利工程对于洪水的调控，对于城市内涝问题则主要尝试与城乡规划学相互配合来改善城市排水（雨水）防涝系统规划[39]，也提出了诸如大小排水系统、智慧排水管网系统在内的一系列创新性应对方法，并试图借鉴古代雨洪管控智慧[40]。

5）气象学主要关注了气候变化[41]、气象灾害[42]、低压气象、气象灾害预警及信号[43]等方面的内容。

6）农学主要研究了雨涝灾害对农业[44]、渔业、畜禽养殖业的生产和恢复的影响。

7）林学主要研究了林业雨涝灾害及其对林业的影响。

8）医学则关注雨洪灾害所引发的急性血吸虫病、感染性腹泻等流行病的临床表现，对脆弱人群及其疫水接触史也有所探讨[45][46]。

4.3 中文文献反映的研究热点

中文文献主要反映国内学者的研究情况。对高频关键词进行聚类统计后，共得到能反映研究热点的22个聚类（图4），在此基础上结合对这些代表聚类的中文支撑文献的阅读，可进一步提炼出当前国内学者在“城市内涝”问题上的研究热点。主要集中在以下6个方面：

（1）城市内涝调控方法

国内的内涝调控方法主要以“海绵城市”理念为代表[47]，“低影响开发”和“雨水系统”[48]这两个关键词的出现频次也较高，这与2014年中国住房和城乡建设部《海绵城市建设技术指南》的颁布相关。除此之外，也研究了一些国外雨洪管控的代表性理念，如“水敏性城市设计”“最佳管理措施”“可持续排水系统”“低影响城市设计与开

2) Landscape Architecture studies the application of various stormwater management and control measures under the concept of “Low Impact Development”[33], especially rain gardens[34] and sunken green spaces[35], while exploring the issues of rainwater utilization, regulation and storage, collection, management, etc. Scholars also study “landscape hydrology” by combining Hydrology with landscape design[36], at a micro scale though.

3) Hydrology has examined the processes of urban hydrology[37] and related problems, studied the formation, control, and specific parameters of stormwater runoff, and applied hydrological models such as MIKE, SCS, and SWMM[38] for the simulation of Low Impact Development implementation of site-scaled practices. It also sees research on water resource utilization and management, especially rainwater resource management.

4) Water Supply and Drainage pays more attention to flood regulation of water conservancy projects. To urban flooding problems, it combines with Urban and Rural Planning to improve urban planning of drainage (rainwater) and flood control systems[39]. A series of innovative methods, such as drainage systems at varied scales and smart drainage network systems were put forward while drawing on the wisdom of ancient rainwater management[40].

5) Meteorology focuses on climate change[41], meteorological disasters[42], low-pressure meteorology, and meteorological disaster warnings and signals[43].

6) Agronomy concentrates on the impact of storm disasters on the production of agriculture[44], fisheries, livestock, and poultry farming, as well as related restoration.

7) Forestry mainly studies waterlogging and flooding disasters in forests and the impact on forestry.

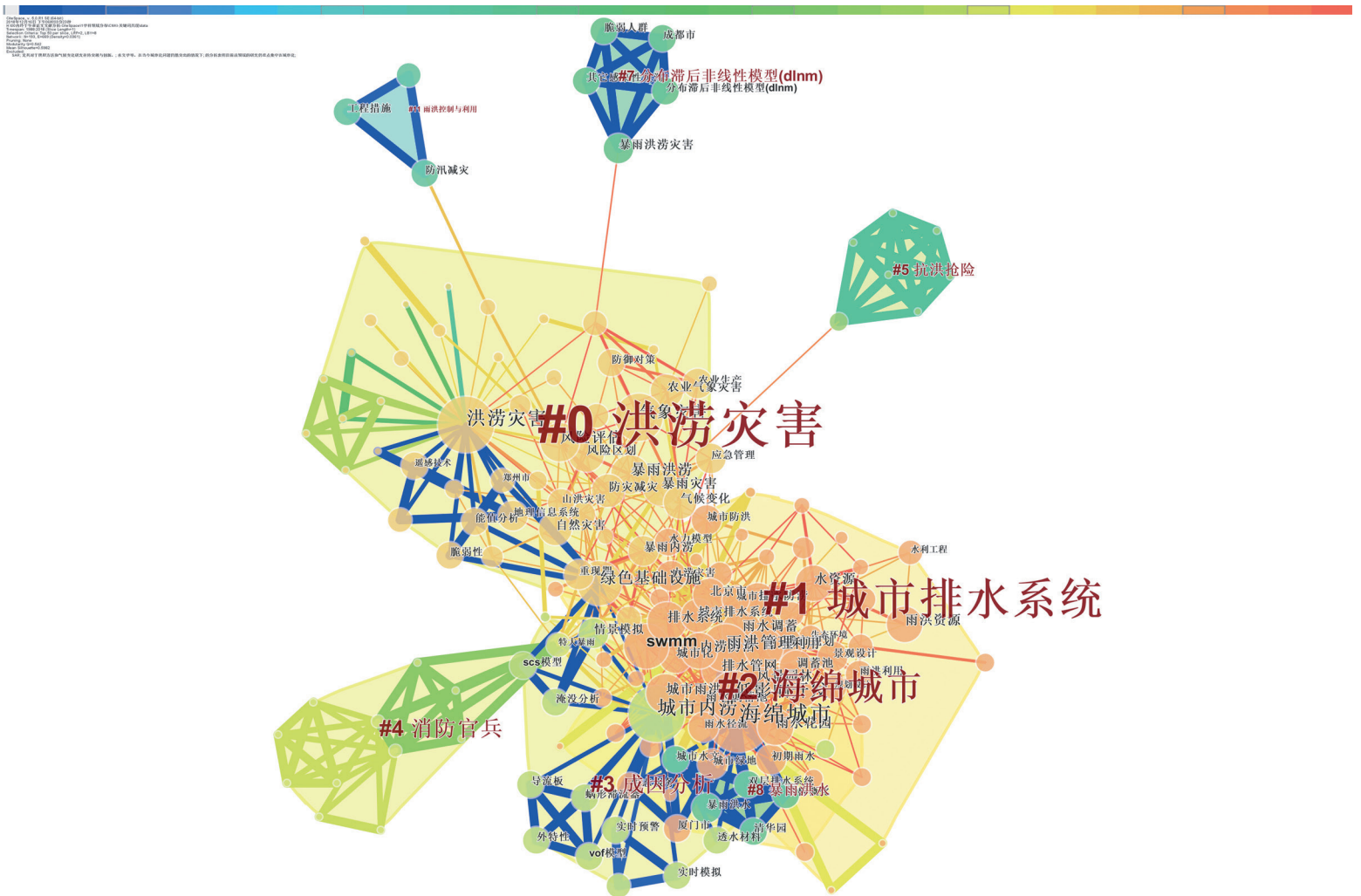
8) Medicine studies the clinical manifestations of epidemics such as acute schistosomiasis and infectious diarrhea caused by waterlogging and flooding events and the history of exposure of vulnerable populations to infected water bodies[45][46].

4.3 Research Hotspots among Chinese Literature

Chinese scholars’ research can be overall learned by reviewing the retrieved Chinese literature. Through clustering statistics of high-occurrence keywords, 22 representative clusters are identified (Fig. 4). Through a thorough review of the Chinese articles in these representative clusters, six major research topics on urban waterlogging are extracted:

(1) Urban Waterlogging Control Methods

Basically, Chinese scholars’ efforts of urban waterlogging control concentrate on exploring the concept of “sponge city”[47], with a high keyword occurrence of “Low Impact Development” and “rainwater system”[48], which is coincided with the



4. 将主要关键词进行聚类分析得到聚类图谱，这些聚类命名是对相似研究主题的关键词进行深入提炼后的术语表达，揭示了中国学者在“城市内涝”问题上的研究热点。

4. Clusters of co-keyword obtained through keywords aggregation analyses. The labels of these clusters are extracted from the keywords in similar research, which reveals the research hotspots on urban waterlogging by Chinese scholars.

发”“ABC水计划”“绿色基础设施”“绿色雨水基础设施”等；另外也提出了一些新的理念，如“绿色海绵系统”[49]和“水生态基础设施”等。设施层面涉及降雨入渗调节系统和日本的雨水贮存渗透方法。另外，在城市规划层面提出了诸如“弹性城市”“韧性城市”[50]“生态安全格局”“雨洪调蓄系统”[51]等宏观策略，其中，“生态安全格局”理念又包括水安全体系的建立和雨洪安全分区的实现方法，并提出预留雨洪蓄滞空间（如城市水系廊道、雨洪廊道、集水区、韧性调蓄空间、潜在蓄水空间、天然河网、滞洪区、集雨型绿地[52]、公园绿地系

introduction of Sponge City Construction Technology Guidelines in 2014. Representative foreign concepts of stormwater control are also studied, including “Water Sensitive Urban Design,” “Best Management Practices,” “Sustainable Drainage Systems,” “Low Impact Urban Design and Development,” “Active Beautiful Clean Water Program,” “Green Infrastructure,” and “Green Stormwater Infrastructure.” New concepts have also been developed, including “Green Sponge System”[49] and “Water Ecological Infrastructure.” Studies on waterlogging control measures focus on rainfall infiltration regulation systems and Japan’s rainwater storage infiltration methods. In addition, macro-scaled urban planning strategies such as “resilient cities”[50], “ecological security patterns,” and “stormwater regulation and storage systems”[51] are proposed. Particularly, the concept of “ecological security pattern” focuses on the establishment of water security systems and stormwater security zoning, and develops strategies like physical reservation measures for rainwater storage (such as urban water corridor,

统、城市排蓄系统、雨水花园、蓄洪公园和雨洪公园）等措施；法定规划层面研究了既有问题与优化途径，如探讨了排水（雨水）防涝规划、城市排水规划、市政道路规划设计、城市绿地系统规划、城市三线规划、市政排水设计的改进方法，也探索了建立蓝绿生态网络、智慧排水管网系统和大小排水系统的方案。

（2）技术与模型

国内学者基于GIS、SWMM、MIKE、SCS[53]、MIKE Urban、SUSTAIN[54]、MUSIC、Info Works、MIKE Flood、FloodArea、DigitalWater等水文水力模型辅助进行了大量淹没分析、雨洪调控效益评估等，另外也提出了可变模糊聚类、TRMM数据、层次分析法、德尔菲法等一系列计算方法，这些模型与方法对雨水调蓄容积、年径流量、绿地雨洪调蓄能力等指标的量化，低影响开发措施的选址[55]和雨水管网的布设，以及灾害风险的评估与区划提供了技术支撑。

（3）内涝成因研究

当前已有较多中文文献专门研究内涝成因，提出了气候变化、城镇化、下垫面变化、城市排水系统落后、地形制约、城市水文过程变化、政策支持不到位等多个层面的影响因素，也从致灾机制、成灾条件等方面系统性地研究了内涝成因。

（4）风险评估与区划

主要指运用了上述软件或模型进行洪水风险、内涝风险[56][57]和暴雨风险[58]的模拟。

（5）损失评估

主要包括洪涝灾情统计、直接经济损失评估、脆弱人群、承灾体脆弱性等方面的研究[59]。

（6）灾害应急对策

雨洪灾害应急对策主要涵盖灾害发生前的实时模拟、实时预警和气象灾害预警，以及灾害发生后的应急管理、抗洪抢险救灾等方面。

rainwater corridor, catchment, resilient stormwater regulation and storage space, potential water storage space, natural river network, flood retention areas, and green space for rain collection[52], park and green space system, urban drainage and storage system, rain garden, flood storage park, and stormwater park). On the planning laws and regulations, scholars study the existing problems and related improvement approaches, including the drainage (rainfall) planning for flood control, urban drainage planning, municipal road planning and design, urban green space system planning, urban three-line planning, and municipal drainage design improvement methods, as well as the establishment of blue-green ecological network, smart drainage pipe network systems, and drainage systems at varied scales.

(2) Technology and Model

Chinese scholars have conducted a great number of modeling simulations of flood inundation and benefit assessment of stormwater management and control based on hydrological or hydraulic models of GIS, SWMM, MIKE, SCS[53], MIKE Urban, SUSTAIN[54], MUSIC, Info Works, MIKE Flood, FloodArea, DigitalWater, etc. In addition, a series of calculating methods such as variable fuzzy clustering, TRMM data, analytic hierarchy process, and Delphi method are also proposed. These models and methods are used for measuring indicators such as rainwater regulation and storage volume, annual runoff, and rainwater regulation and storage capacity of green space, helping site selection to implement Low Impact Development measures[55], the deployment of rainwater pipeline networks, and disaster risk assessment and security zoning.

(3) Research on the Causes of Urban Waterlogging

At present, a large number of Chinese research studies the causes of waterlogging and examines various influencing factors such as climate change, urbanization, underlying surface changes, the backwardness of urban drainage systems, topographical constraints, urban hydrological process changes, and the lack of policy support. Scholars have also systematically studied disaster-causing mechanisms and vulnerabilities.

(4) Risk Assessment and Security Zoning

Risk assessment and security zoning use the above mentioned software or models for simulating and assessing the risk of flooding, waterlogging[56][57], and stormwater[58].

(5) Loss Assessment

Research on loss assessment mainly focuses on flood disaster statistics, assessment of direct economic loss, vulnerable communities, and vulnerability of infected bodies[59].

(6) Disaster Emergency Response

Research on disaster emergency response to stormwater and

表7：英文文献中常见的针对“城市内涝”“雨洪”问题的调控途径术语及对应的常见中文表述
Table 7: Common terms of urban waterlogging and stormwater regulation measures in English literature and the corresponding Chinese terms

分类 Categories	中文名称 Chinese terms	英文表述 English terms
规划理念 Planning concepts	低影响开发	Low Impact Development (LID)
	海绵城市	Sponge City (SPC)
	水敏性城市设计	Water Sensitive Urban Design (WSUD)
	低影响城市设计与开发	Low Impact Urban Design and Development (LIUDD)
	韧性城市	Urban Resilience
基础设施 Infrastructure	绿色基础设施	Green Infrastructure (GI)
	绿色雨水基础设施	Green Stormwater Infrastructure (GSI)
	生态基础设施	Ecological Infrastructure (EI)
	雨水基础设施	Stormwater Infrastructure
	水基础设施	Water Infrastructure
	蓝绿基础设施	Blue-Green Infrastructures (B&GI / BGI)
	灌溉基础设施	Irrigation Infrastructure
	分布式雨水管理基础设施	Distributed Stormwater Management Infrastructure
排水系统 Drainage systems	排水基础设施	Drainage Infrastructure
	可持续排水系统	Sustainable Drainage Systems (SuDS)
	城市雨水排水系统	Urban Stormwater Drainage Systems
	市政独立雨水管道系统	Municipal Separate Storm Sewer System (MS4)
	雨水系统	Stormwater Systems
空间调控 Spatial regulation	土地利用规划	Land Use Planning
	适应性规划	Adaptive Planning
	绿色开放空间网络规划	Green Open Spaces Planning
管理方法 Management methods	最佳管理措施	Best Management Practices (BMPs)
	城市雨水管理	Urban Stormwater Management (USM)
	可持续城市水管理系统	Sustainable Urban Water Management System
	雨水管理计划	Stormwater Management Program Plan (SWMP)
	雨水管理系统	Stormwater Management Systems
	雨水使用管理计划	Stormwater Use Management Plans (SUMPs)
	可持续雨水管理	Sustainable Stormwater Management
	城市雨水资源	Urban Rainwater Resources (URRs)
	雨水收集系统	Rainwater Harvesting System (RWHS)
	水安全计划	Water Safety Plans
微观措施 Micro measures	暴雨控制措施	Stormwater Control Measures (SCMs)
	雨水质量提升设施	Stormwater Quality Improvement Devices (SQIDs)
	气候变化水管理工具	Weather Shift Water Tools
	雨水生物过滤器	Stormwater Biofilters

flood disasters studies real-time simulation, real-time warning and meteorological disaster warning, as well as post-disaster management and relief.

5 Summary of Regulating Approaches Responding to Urban Waterlogging in Chinese and English Literature

Through the analyses in Chapters 3 and 4, the commonly used regulation approaches responding to urban waterlogging among the academia in China and abroad are concluded, ranging from planning concepts, infrastructure, drainage systems, spatial regulation, management methods, and micro measures (Tables 7, 8).

6 Research Review and Perspectives

6.1 Summary of Disciplinary Network

By using CiteSpace, this study reviewed the English and Chinese literature on urban waterlogging in both the WOS Core Collection database from 1974 to 2018 and the CNKI Chinese database from 1988 to 2018 to examine the disciplinary network of the existing literature, which can be summarized as follows:

1) Overall, Chinese and foreign research on urban waterlogging continues to rise over the past decades;

2) The existing literature is contributed from most of subjects, among which the ones with the most published articles include Environmental Sciences, Ecology, Water Resources, Engineering, and Geology. In recent years, the subjects with burst in research include Geography, Urban and Rural Planning, Landscape Architecture, Hydrology, and Water Supply and Drainage;

3) Cross-disciplinary research sees among various subjects, and pivot subjects of a high centrality include Materials Science, Environmental Studies, Ecology, Engineering, and Computer Science;

表8：中文文献中常见的针对“城市内涝”“雨洪”问题的调控途径术语及对应的常见英文表述
Table 8: Common terms of urban waterlogging and stormwater regulation measures in Chinese literature and the corresponding English terms

分类 Categories	中文名称 Chinese terms	英文表述 English terms	分类 Categories	中文名称 Chinese terms	英文表述 English terms
规划理念 Planning concepts	海绵城市	Sponge City (SPC)	空间调控 Spatial regulation	城市绿地（系统）规划	Urban Green Space Planning
	低影响开发	Low Impact Development (LID)		土地利用规划	Land Use Planning
	水敏性城市设计	Water Sensitive Urban Design (WSUD)		城市三线规划	-
	低影响城市设计与开发	Low Impact Urban Design and Development (LIUDD)		水绿生态规划	-
	ABC水计划	Active Beautiful Clean Water Program (ABC Waters)		公园绿地系统	-
	弹性城市	-		绿色海绵系统	-
	韧性城市	-		生态安全格局	Ecological Security Patterns
基础设施 Infrastructure	绿色基础设施	Green Infrastructure (GI)		蓝绿空间	Blue-Green Spaces
	绿色雨水基础设施	Green Stormwater Infrastructure (GSI)		城市水系廊道	-
	雨洪基础设施	-		雨洪廊道	-
	景观基础设施	Landscape Infrastructure		城市雨洪调蓄空间	-
	水生态基础设施	Water Ecological Infrastructure (WEI)		弹性调蓄空间	-
排水系统 Drainage systems	可持续排水系统	Sustainable Drainage Systems (SuDS)		潜在蓄水空间	-
	排水（雨水）防涝规划	-		雨洪调蓄系统	-
	城市排水系统	-		天然河网	-
	城市排蓄系统	-		集水区	-
	市政排水设计	-		滞洪区	-
	智慧排水管网系统	-	管理方法 Management methods	最佳管理措施	Best Management Practices (BMPs)
	大小排水系统	Major and Minor Drainage Systems			
	市政道路规划设计	-	微观措施 Micro measures	降雨入渗调节系统	-
	雨水系统	Stormwater System		雨水贮存渗透技术	-
				集雨型绿地	-
				雨水花园	Rain Garden
				蓄洪公园	-
				雨洪公园	-

注释
当前国内学界的调控途径出现较多中国语境下的术语，它们尚未形成被一致认可的权威英文翻译；另外，如“弹性城市”等术语的英文翻译存在很多版本，易造成歧义，故部分术语没有列出相应的英文表述。
NOTE
Some English terms are absent where the measures are often developed by Chinese professionals and there have been no authoritative corresponding terms in English yet. Besides, Chinese terms such as “弹性城市” refer differently in English, so this research does not include the corresponding English terms.

5 中英文文献中针对内涝问题的调控途径总结

综合第3、4章的分析可以归纳得出目前国内外已有的“城市内涝”常见调控途径，涵盖了规划理念类、基础设施类、排水系统类、空间调控类、管理方法类、微观措施类6个类别（表7，8）。

6 研究述评与展望

6.1 学科分布情况总结

通过运用CiteSpace纵览收录于WOS核心合集数据库1974~2018年间和CNKI中文数据库1988~2018年间“城市内涝”问题研究的英文和中文文献，本研究发现已有研究的学科分布情况具有如下显著特点：

1）国内外针对“城市内涝”问题的研究整体热度持续上升；

2）研究涉及了大部分学科，其中发表文献数量最多的学科有环境科学、生态学、水资源、工程学、地质学等，近年研究突发（关注度猛增）的学科有地理学、城乡规划学、风景园林学、水文学、给排水科学与工程等；

3）各个学科之间存在交叉合作研究现象，起到连接其他领域作用的中心枢纽性学科有材料科学、环境研究、生态学、工程学、计算机科学等；

4）各代表性学科在内涝问题上的主要研究内容各有侧重，而水文学方面的研究多次出现在不同学科的主要关注点中，可见各学科在研究“城市内涝”问题时均对水文循环过程、水文功能等内容有所涉猎。

5）对比来看，英文文献所反映的国外研究已形成较为完善的学科网络体系，通过多学科交叉共同推进雨洪管控。这为国内相关研究提供了宝贵经验，具有很强的理论指导意义。

6.2 研究热点与局限

在研读各代表学科的中英文代表文献，并综合分析其研究重点与研究热点后，发现当前国内外“城市内涝”问题研究的前沿动态与不足主要表现在调控途径、水文学交叉研究、内涝成因、风险管理与评估等方面。

1）当前，国内外出现了很多针对“内涝”“雨洪”问题的调控途径，对于这些调控途径的研究主要从空间布局、绩效评估、效益评估、功能拓展、政策支持、公众参与与认知6个方面展开。后面5项为完成空间布局后进行的理念的推广应用与措施的细化修正。

由于国外在“雨洪管控”方面的研究起步较早且持续时间较长，发展至今，其更偏重于城市雨洪的全面调控，故而涉及学科数量较多，基本涵盖了以上6个方面的研究内容。空间布局研究包括宏观网络的系统与分散布局和微观措施的选址与设计，其中宏观网络布局主要通过土地利用规划来实现，提出划定蓝绿空间和绿色开放空间网络等方法。但是，具体指导合理布局宏观雨洪调蓄空间的文献还较少，方法路径也较为模糊；其他方面的文献很多，主要原因在于国外力图将水质提升、径流削减和多功能拓展三重目标相结合。英文文献还对已建成的雨洪调蓄设施进行了全面的绩效评估与效益评估。其中绩效评

4) The major research interests on waterlogging problems in each representative subject vary. Among them, Hydrology sees a strong connection with other disciplinary fields, evincing that hydrological process and service is the common interest among all the subjects studying the issues of urban waterlogging.

5) In contrast, the existing English literature has established a relatively complete disciplinary network and promoted the stormwater and flooding control through cross-disciplinary research, which provides valuable reference for Chinese scholars' theoretical exploration.

6.2 Research Hotspots and Limitations

After an overall analysis of the research interests and hotspots obtained by studying representative Chinese and English literature among various subjects, it is found that the cutting-edge research and shortcomings on the issues of urban waterlogging in China and abroad involve aspects of regulation approaches, Hydrology-related cross-studies, causes of waterlogging, and risk management and assessment.

1) At present, a number of regulation approaches responding to “waterlogging” and “stormwater” problems have been developed in China and abroad, ranging from spatial deployment, performance assessment, benefit assessment, expanded functions, and policies to public participation and awareness. The latter five aspects mainly focus on the promotion and refinement of conceptual exploration and spatial construction.

Since foreign academia has a longer history of studying the issues of “stormwater management and control,” the existing research has more focused on the overall regulation and control of urban rainwater, covering all the six aspects mentioned above from various disciplinary perspectives. Particularly, spatial deployment research focuses on the systematic and scattered layouts of macro-networks and the site selection and design of micro measures. Macro-network is often established or realized through land use planning while proposing methods such as identification of networks of blue-green space and green open space. However, there are few documents that offer specific guidelines to spatial deployment of macro rain and stormwater storage space, or any clear roadmap. In contrast, the number of literature in the other five aspects is much larger because foreign scholars have attempted to conduct integrated research on water quality improvement, runoff reduction, and multi-functional expansion. English literature has also carried out comprehensive performance and benefit assessments of built-up rainwater storage facilities. Performance assessments often focus on examining the hydrological performance of spatial structures and specific measures that improve the hydrological

估主要探讨了不同理念支撑下的空间结构与具体措施的水文性能，以达到恢复水文连通性这一重要目的[60]；效益评估则尝试将这些理念落地实施后的生态效益量化为经济效益，以指导方案的改进和优化，并且注重对政策、公共参与和认知的探讨。

相较而言，中国目前还主要处于内涝程度控制阶段，提倡最多的“海绵城市”[61]“补短板行动”等理念或口号的直接目的均是减少地表径流[62]，实现路径主要侧重于空间布局层面。中国学者大多偏向于探讨如何从空间规划视角实现内涝缓解和雨洪管控，如通过排水规划和绿地系统规划来落实诸如“海绵城市”等理念[63]。但由于缺乏专门针对内涝调控的具体空间结构系统理论或模型，在规划实践层面依旧存在困难，也因此出现了一些针对新兴理念（如水生态基础设施、雨水基础设施等）的初步探索。

2）学界在水文学层面进行的探讨尝试研究城市水文过程和自然水文过程，以及二者与具体调控设施的关系，提出雨洪调控的最终目的是恢复自然水文循环过程，并强调了绿地、水体等自然空间所发挥的重要雨水疏导功能，试图划分水文敏感区，恢复城市或场地尺度的水文连通性[64]。但是目前的研究多被运用于绿色屋顶等微观设施上，而从城市尺度上全面分析水文过程与雨洪调蓄设施所组成的空间系统之间的关联性的研究还稍显欠缺。

3）当前学界还较为关注内涝成因、雨洪灾害风险评估、风险管理与区划、损失评估、灾害预警与应急措施。特别地，对于“城市内涝”的成因研究，学者们已从政策、规划、排水、景观等层面进行了分析，也从孕灾环境、致灾因子、承灾体等角度分析了致灾机制，虽然强调了城市化对自然水文循环过程的改变与破坏，但缺乏将被破坏的水文过程对应到具体空间类型上的系统性研究，如发挥下渗功能的草地、发挥蓄积功能的湖泊被侵占等，这对实现“恢复水文连通性”

connectivity under different concepts[60]. Benefit assessments are often developed to value ecological benefits of built-up projects to facilitate improvement plans, with a particular focus on policy and public participation and awareness.

In contrast, at present Chinese research still concentrates on controlling the extent of waterlogging events. Most advocated concepts such as “sponge city” [61] and “filling the short-board action” are developed to reduce surface runoff[62], combined with implementation of spatial deployment. Most Chinese scholars tend to explore the issues of waterlogging mitigation and stormwater management through spatial planning, for example, the concept of “sponge city” is applied through drainage planning and green space system planning[63]. However, the lack of systematic theories or models for establishing specific spatial structures leads to the difficulties in planning practices. Scholars have also made preliminary explorations on some emerging concepts such as “Water Ecological Infrastructure” and “Rainwater Infrastructure.”

2) Chinese and foreign research on Hydrology has studied both urban and natural hydrological processes, as well as how they work in specific applications, proposed that stormwater regulation is to restore hydrological cycle processes, emphasized that natural spaces such as green spaces and water bodies play an important role in rainwater drainage, and attempted to restore or improve hydrological connectivity by identifying hydrologically sensitive areas at city or site scales[64]. However, the existing studies have been mostly applied to micro-scaled facilities such as green roofs, while less seeing research that comprehensively examines the city-scaled correlation between hydrological processes and spatial systems composed of rainwater storage facilities.

3) Currently, research hotspots include the causes of waterlogging, risk assessment of stormwater and flood disasters, risk management and zoning, loss assessment, and disaster warning and emergency responses. In particular, the causes of urban waterlogging have been studied from the perspectives of policy, planning, drainage, landscape, etc. while mechanisms are also analyzed in terms of geological conditions, impact factors, and vulnerable bodies — although scholars often emphasize that urbanization has greatly changed or destroyed natural hydrological cycle processes, systematic research of case studies on how the hydrological processes of grasslands or lakes that provide services of infiltration or water storage are destroyed is still absent. It results in the development lagging of “restoring hydrological connectivity,” one of the aims of stormwater management. In addition, research on how to restore, protect, and configure spatial deployment types for a better performance

的雨洪管控核心目标造成了直接阻碍，如何恢复、保护和配置适宜的雨洪调蓄空间类型来修复自然水文循环，进而消减内涝灾害，仍需深入探讨。

6.3 研究趋势展望

相较而言，中国在“城市内涝”问题上的研究起步较晚。在综合评判当前中英文文献所反映出的国内外的研究热点与局限后，笔者认为，中国应当发挥后起优势，在未来研究中重视以下三方面：

1）深化理论研究。理论研究上仍需对国内外出现的各类内涝调控

of improving hydrological cycles and mitigating waterlogging disasters is also expected.

6.3 Research Trends

The history of China's research on urban waterlogging is relatively short. Based on an overall review of the hotspots and limitations of Chinese and English literature, three research shifts are summarized that would shed a light on Chinese scholars' studies in future:

1) Deepening theoretical exploration. It requires scholars to conduct in-depth research on the background, core purposes, and application scenarios of various waterlogging control approaches to help develop roadmaps for establishing

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途径的产生背景、核心目的、应用场景等进行深入研究与辨析，探寻城市中能够发挥雨洪管控功效的理想空间结构的构建方法；

2）扩大研究尺度。学者可以尝试填补宏、中观层面空间规划实现途径的空缺；

3）拓展研究广度。进一步加强不同学科间的交叉配合，特别是从水文学角度阐明内涝产生的直接原因，寻找水文过程与能实现雨洪调控功能的绿地、水体等空间体系之间的关联性，为构建缓解内涝的理想空间结构提供理论依据，进而直接指导“海绵城市”等理念的落实。**LAF**

ideal spatial structures of urban stormwater management and control.

2) Expanding research scales. It expects to fill the gap in the practical approaches of macro- and medium-scaled spatial planning.

3) Enlarging research territory. It encourages transdisciplinary research, especially analyzing the direct causes of waterlogging from the perspective of Hydrology, expounding the correlation between hydrological processes and spatial systems such as green spaces and water bodies that provide service of rainwater regulation, and offering a theoretical basis for building ideal spatial structures responding to waterlogging problems and for the implementation of “sponge city.” **LAF**

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