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城市景观格局演变的水环境效应研究综述

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摘要: 人类活动导致的城市土地利用覆被变化在景观生态学上表现为城市景观类型的更替和城市景观格局的演变。我国城市景观格局中自然植被景观基质大幅被人工硬化地面所取代, 自然景观斑块破碎化, 城市道路和排水管网等人工廊道大量增加, 造成“源”“汇”景观的比例失衡和格局失调, 从而产生城市景观格局演变的水环境负效应, 如非点源污染、水生生态系统失衡和城市内涝等, 且水环境负效应存在时间尺度差异和空间尺度响应多样性。对城市景观类型及其格局演变产生的城市水环境效应相关研究进行总结, 针对现有研究中存在的城市景观格局演变带来的生态过程变化研究较少、影响城市水环境的景观格局变化阈值不明确、研究结果推广难和重复性较差、人工廊道与城市水环境效应关系关注度较低和水环境负效应综合度研究欠缺等不足之处, 提出未来研究的着力点, 对实现可持续城市具有一定意义。

关键词: 景观格局; 水环境效应; 城市规划

Research review on effects of urban landscape pattern changes on water environment

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Abstract: Urban water environment is an important part of urban ecosystem including natural and man-made water, and the natural elements and urban landscape which are closely related to water at catchment scale. Healthy urban water environment could product positive ecological effects such as water retention and impoundment, environmental decontamination, material transportation, making energy flow smoothly and conserving biodiversity. However, the change of urban land cover induces the deterioration of urban water environment and leads to negative water environment effects, such as non-point pollution, imbalance of aquatic ecosystem and urban flooding. The replacement of urban landscape types and evolution of urban landscape pattern caused by human activities display at following aspects: widespread vegetation matrix is largely replaced by artificial hardened ground while natural landscape patches are fragmentized and manual corridors including urban roads and drainage network increase sharply, resulting in the disproportion of water pollution “source” and “sink” landscape types and landscape pattern. Through statistical analysis and model simulation, researchers at home and abroad find that: the cultivated land and urban construction land are the main sources of non-point pollution while natural vegetation landscape types contribute to the reduction of non-point source pollution. Urban surface hardening reduces the environmental capacity of urban water environment by influencing urban hydrological cycle, for instance, surface runoff, evaporation and infiltration and so on. Together with environmental capacity reduction, the eutrophication of urban water environment makes negative effects on the balance of aquatic ecosystem. Negative water environment effects responding to

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urban landscape pattern will change with spatial and temporal scales. This paper summarizes current researches about the effects of urban landscape types and pattern evolution on water environment and points out the deficiencies of recent researches, such as the lack of specific research coupling landscape pattern change and ecological process, the indeterminacy of the landscape pattern threshold influencing urban water environment, the difficulty in popularizing and repeating research results, neglecting the relationship between urban artificial corridor and water environment effects, and the lack of comprehensive research about negative water environment effects. At last, we put forward five key points of future researches: the lagging response of urban water environment to the change of urban landscape pattern; the differences of water environment effects with different types and distributions; the combined influences from the urban landscape pattern, including matrix, corridor and patch; development of new model which concentrates on urban water environmental effects; a set of related index for urban planning and urban water environmental effects. Our study will contribute to better understanding of urban sustainability.

Key Words: landscape pattern; water environment effects; urban planning

城市水环境以城市自然和人工水体为中心,包括流域尺度内与水体密切相关的自然要素和城市景观,是城市生态系统的重要组成部分^[1]。据统计,1991年七大水系流经城市的支流污染较重,2011年部分城市河段为重度污染,且城市内湖水水质都低于Ⅲ类水质标准,我国城市水环境存在严重污染问题^[2-3]。城市水体质量下降与城市化带来的城市景观格局演变具有一定的关联性^[4]。近年来我国城市发展势头迅猛,城市自然生态系统转为人工生态系统,自然景观斑块趋于破碎化,城市景观格局演变主要表现为城市建成区等大面积不透水面对自然植被景观基质的侵蚀^[5]、城市排水管网和城市道路等人工廊道的大量增长^[6-7]和景观类型的演替^[6]。自然景观与人工景观此消彼长的景观格局对水环境产生城市内涝、非点源污染和水生生态系统失衡等生态负效应^[8-10]。开展城市景观格局演变的水环境效应研究,总结不同城市景观类型及其格局对城市水环境的影响和城市水环境对景观格局演变的响应机制,可以为城市景观格局规划提供参考依据,避免城市水环境对城市规划滞后响应的负面生态效果,从城市生态规划入手保护城市水环境,对城市可持续发展具有重大意义。

1 研究现状

健康的城市水环境在保水蓄水、污染净化、物质输送、能量流动、保持生物多样性等方面可以产生生态正效应^[11-12]。而城市水环境负效应体现在城市水

体形态改变或面积缩减对生态廊道效应的削弱、城市水体污染对居民饮用水安全的威胁、水体富营养化对水生生态系统平衡的破坏和水体环境容量减小对城市内涝发生率的增加等方面^[13-14]。近年来城市水环境负效应严重性和并发性特征显著,国外学者将城市水环境负效应总结为“城市水体综合症 (urban stream syndrome)”并展开相关研究^[15]。

城市水体作为一种景观类型,是城市景观整体的重要组成部分,城市景观格局演变对城市水体有一定影响,从而产生城市水环境负效应。国际上对城市景观格局演变的水环境效应研究集中于非点源污染和水生生物多样性,从城市景观格局、城市水质和水生生物量三者关系入手,通过土地利用转移矩阵^[16]、移动窗口法^[17]和元胞自动机模型^[18]和景观图论^[19]等方法量化城市景观组分及格局变化,采用单一指标评价法、灰色关联评价、BP神经网络评价、模糊数学评价等方法^[20-22]评价水体质量,以表层沉积物组分分析、水体栖息地质量、生物多样性等指标衡量水生生态系统健康程度^[23-24],然后采用因子分析FA、判别分析DA、回归分析RA、聚类分析CA、主成分分析PCA、普通多元线性回归模型OLS和地理加权回归模型GWR (Geographical Weighted Regression)等方法^[25-26],得出各个研究区内水质指标、水生生物指标与景观类型特征及其格局演变的相关关系,并对相关性进行检验,确定对城市水环境具有显著影响的景观类型。相关研究一般流程总结如图1。

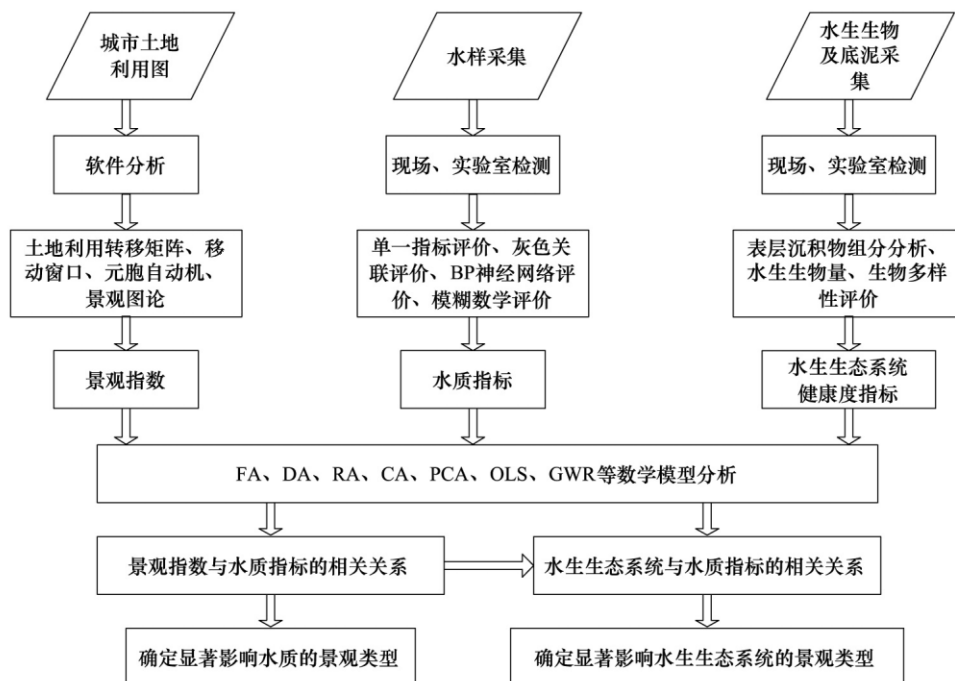


图1 城市景观格局与水环境效应研究一般流程

Fig.1 The general process of urban landscape pattern and water environment effects research

FA: 因子分析 Factor Analysis; DA: 判别分析 Discriminant Analysis; RA: 回归分析 Regression Analysis; CA: 聚类分析 Cluster Analysis; PCA: 主成分分析 Principal Component Analysis; OLS: 普通多元线性回归模型 Ordinary Least Square; GWR: 地理加权回归模型 Geographical Weighted Regression

国外学者开发出多个非点源污染模型^[27],如 HSPF(Hydrologic Simulation Program Fortran)、SWAT (Soil and Water Assessment Tool)、L-THIA(the Long-Term Hydrologic Impact Assessment) 等模型适合模拟长时间序列的非点源污染量,可用于研究城市景观格局时空变化产生的非点源污染效应,而 SWMM (Storm Water Management Model)、MOUSE(Model of Urban Sewers)、P8-UCM(P8-Urban Catchment Model)、GWLF(Generalized Watershed Loading Function) 等模型适合模拟单次暴雨事件,可用于研究城市景观格局与城市内涝的关系。针对外国模型所需数据精度较高和国内外城市水文过程特征差异等问题,我国学者建立出一系列符合单个城市实际的非点源污染模型^[28],但存在模型结构较为简单、模型适用性不高的问题。

2 研究热点

2.1 城市景观格局与“源-汇”理论

陈利顶等在景观格局与生态过程的研究中提出“源-汇”理论^[29],即同个特定的生态过程中,对该生态过程发展有促进作用的景观类型为“源”景观,而

起阻止或延缓作用的景观类型则为“汇”景观。根据“源-汇”理论,国内外学者对非点源污染过程的相关研究在“源-汇”景观类型划分方面共识较多,一般认为城镇建设用、耕地等景观类型为“源”景观,而林地、草地、园地和绿地等透水性好的自然植被或人工植被斑块为“汇”景观^[29-31]。城镇建设用地是城市水环境非点源污染过程中最主要的“源”景观,其景观类型包括居住用地、交通用地、工业用地等生活污染、生产污染较为严重的景观斑块类型。城市建筑屋顶产生的腐蚀剥落物经由屋面径流汇入地表径流^[27];交通尾气和工业排放气体中所含的大量不完全燃烧产物,悬浮于大气中或沉降于城市道路表面,雨水冲刷后成为地表径流污染物的主要来源^[32]。耕地在城市景观格局中所占面积比例不大,但耕地中大量应用化肥、农药,产生的有机物污染经雨水冲刷和灌溉淋溶之后通过地表径流和地下水进入城市水体,造成水体富营养化^[33]。林地和高覆盖度草地透水性好,可以减少降水对土壤的侵蚀冲刷作用,且对地表径流有一定的截流作用,可减少城市径流污染物迁移过程,或通过植物、土壤和微生物等中介在一定程度上吸收地表径流污染物,如氮氮等,在减少

非点源污染物总量、减轻城市水体富营养化方面功不可没^[34-35],甚至有学者认为提高自然植被斑块的生产力比重塑城市景观格局更能净化城市水环境^[36]。而关于裸地的“源-汇”划分,则存在不同看法,有学者认为裸地由于自然植被退化和土壤侵蚀产生大量固体悬浮颗粒物等城市浮尘,为“源”景观^[37];也有相反的观点认为裸地与城市水体水质指标相关性不明显^[38]。

“源”景观类型的斑块面积、数量、聚集度和优势度等格局特征与城市水体质量呈现正相关关系,“汇”景观则相反^[39]。如果“源”“汇”景观斑块形状破碎化,则对城市水环境的影响“源”景观大于“汇”景观,例如城市存在的小面积耕地斑块产生的农业非点源污染对城市水体的污染贡献不可忽视,而城市绿地呈现零散分布,则对减轻非点源污染作用不大^[40]。此外,景观多样性与城市水环境质量一般呈正相关关系^[38]。

2.2 城市景观格局与水生生态系统

国外在城市景观格局对水生生态系统影响方面的研究起步较早,认为城市土地利用强度、城市景观类型及其格局、不透水面比例与城市水生生态系统退化有关^[41]。国内涉及城市景观格局对水生生态系统影响的文献相对较少,主要关注鱼类、底栖无脊椎动物等水生生物对流域景观格局产污量的敏感性^[42]。

城市水生生态系统包括底栖动物、鱼类和浮游藻类等水生生物群落。季节变化和水环境质量变化是影响水生生态系统的两个主要因素,其中季节变化又会影响到非点源污染入水量,间接影响水环境质量^[43]。城市景观格局演变通常存在地表硬化趋势,通过改变地表覆被的蒸散发与下渗等水文过程,间接影响城市水文循环,减少了大气降水和地下水对城市水体的补给^[44],进一步缩减城市水环境容量。城市景观格局演变带来的非点源污染增强和水体环境容量减小促使城市水体自净能力下降,进而恶化水生生物栖息环境。有研究表明,底栖动物生物量与森林景观面积呈现正相关关系,而对城市建设用地和牧场等景观类型面积存在负响应^[42];水生浮游藻类是水生生态系统的基础,是水生生物食物链中的重要一环,藻类对水体营养负荷的敏感性最高,城市景观格局造成的水体富营养化效应引起有毒藻类

生物量的大幅增长,改变藻类群落的多样性和优势种群,促使浮游藻类的群落结构和功能受损,危害水生生态系统和人类健康^[45-46];水体溶解氧下降更导致鱼类等水生生物的死亡,降低水生生物多样性,进而对水生生态系统平衡产生负面影响^[47]。

2.3 水环境效应的时空尺度性

城市景观格局的水环境效应存在时间尺度性,即夏季丰水期、春秋平水期和冬季枯水期的水体污染程度存在差异。丰水期时总氮(TN)、总磷(TP)、化学需氧量(COD)、叶绿素在珠江、太湖和南京28处湿地等水体中浓度最高,水环境污染程度最高^[48-50]。九龙江枯水期城市水体的污染物浓度最高、水质最差,平水期水质最好^[51]。汉水枯水期水质最好^[37]。个别水体的水质状况甚至发生巨大转变,由枯水期最好转变为枯水期最差^[52]。尽管未有一致的结论,但城市水环境变化的季节差异是客观存在的,其原因在于城市水体污染是受点源污染和非点源污染共同作用^[53]。枯水期城市地表径流量最小、水体自净能力最差,受工业污水和生活污水等点源污染影响较多,水体中TN、TP、重金属浓度比丰水期、平水期高^[51]。丰水期时,水体可以最大程度发挥过滤、沉降功能,但地表径流冲刷会使大量的固体悬浮物、氮磷等营养物质和重金属进入水体,水体容纳污染物量超过水体自净能力,造成丰水期水体水质下降^[52];平水期水体水量与地表径流量都较为适中,水环境污染程度居于中下,存在部分水质指标超标可能性^[49, 51]。

城市景观格局的水环境效应还存在空间尺度性,即城市水体对不同空间尺度内的城市景观格局演变的敏感性存在差异。一些研究认为城市水体流域尺度上的城市景观格局决定了非点源污染总量,从源头影响水环境,其景观指数能更好地解释城市水体水质变化^[54]。而另有研究指出水质指标对水体岸边带尺度上景观类型的敏感性更大^[37, 55],若岸边带区域分布大量绿地等“汇”景观,则自然植被和土壤的过滤与吸附作用可以减少非点源污染物进入水体^[56]。众多文献中对水体缓冲区研究尺度的划分也不尽相同,部分水质指标对相同尺度内的景观格局存在截然相反的反应,造成景观格局水环境效应空间尺度的多样性,例如我国汉水流域上游水体水质与100 m河岸带内土地利用类型的相关性比流

域范围内的景观格局更好^[37],纽约州 29 条河流周边 200 m 缓冲区内的城市用地格局对水质有明显负面影响^[55],香港主要饮用水源东江的氨氮($\text{NH}_3\text{-N}$)和硝氮($\text{NO}_3\text{-N}$)与 500 m 汇水单元内的城市景观面积比例呈现正相关,但溶氧(DO)却与之呈现负相关^[57]。

3 研究不足

3.1 城市景观格局与城市内涝

发生城市洪涝现象的主因在于城市排水系统的不健全^[30]、景观类型格局设置不合理^[8]和城市水体容量的减小^[14],城市排水管网可视为人工廊道,目前研究排水管网“雨污分流”设计及设计合理性与城市洪涝关系的研究较多^[58],但针对城市景观格局与城市洪涝的关系研究较少。

在人为规划的城市景观格局中,自然景观斑块逐渐被人工景观斑块取代,各类建设用地斑块形状相对规则,城市道路直线化、网格化^[59],城市表面硬化降低了地表下渗率^[44],自然植被的破碎化、天然水体的面积缩减对城市自有的保水蓄水功能的削弱,这些因素共同改变了城市地表水文过程,为地表径流的流速加快、汇水量增大、汇水时间缩短和瞬时峰值上升提供了可能,地表冲刷量加大^[60],进而造成城市水体水质下降和城市内涝等问题。为增加城市用地面积和满足城市规划美观需求,城市水体的面积和形状常被人改变,例如河流被截弯取直、湖泊湿地被填埋造地等,直接降低了城市水环境容量^[61-63]。城市人工管网为城市中常见的人工廊道,其布局往往根据居住用地、工业用地等产污排废较多的城市用地斑块和城市道路格局而设置^[7]。在城市暴雨事件中地表径流量短时间内大量增大,城市水环境容量有限,而城市人工管网蓄雨能力有限、排水能力不足时,极易产生城市洪涝现象,例如 2012 年北京“7.21”特大城市暴雨事件导致城区内大面积洪涝灾害。而由于有护城河和北海调蓄雨水,历年来故宫周边未发生内涝现象^[64]。我国早在古代就认识到天然水体在调蓄洪水方面的重大作用,但多次严重的城市洪涝灾害表明,我国现代的城市规划对天然水体的水环境正效应的重视程度不够,而现有的城市景观格局演变所产生的水环境负效应也被城市规划者所忽视。

研究表明城市景观基质由自然植被向不透水面的转变对城市地表径流增加存在正相关关系^[8,44]。城市排水管网和城市道路作为城市中常见的人工廊道,在地表径流集中产生时所发挥的汇集、输送、疏浚作用不足,也是城市内涝发生的重要因素之一^[64],但鲜见城市人工廊道格局、生态作用与城市水环境效应的相关性研究,且城市景观基质、人工廊道和水体景观斑块三者变化对城市水环境的综合作用机理尚不明确。

3.2 水环境响应机制

国内外学者在城市景观格局演变方面已经开展了大量的景观指数分析工作,但对城市景观格局演变背后折射出的生态过程变化及其对人类生活的反作用等方面的研究偏少,城市景观格局演变研究急需能够反映一定生态意义的新型生态过程景观指数。

近年来我国城市景观格局对水环境的负效应逐渐成为研究关注的重点,但还处初步研究阶段,关注点集中于单个城市的景观格局的水环境效应,而各个城市在流域环境、水文特点、气象条件等方面存在较大差异,造成城市水环境对景观格局演变的响应机制不同,研究结果推广度不高、重复性不好。国外学者研究发现城市景观格局中不透水面对水环境的水质、水生生态系统产生明显负面影响的面积比例阈值较小,Stuart 认为不透水面比例高于 22%—30% 时赫尔辛基的水环境恶化明显^[65],Lee 等人认为不透水面比例不超过 12% 时水环境不受城市景观格局演变影响^[66],国际上通常认可的阈值为 30%—50%^[67]。而赵军等学者研究发现该阈值对我国城市可能不适用,上海城区不透水面面积比例大于 60% 时,城市水环境质量开始显著下降^[67]。不同城市的景观类型及其格局演变造成的城市水环境负效应的影响区间存在较大差异,目前还尚未有被认可的系统性结论。此外,流域内土地利用类型、城市水环境质量和水生生物群落三者的相关研究中,并未深入分析水生生物群落对景观类型及其格局演变的响应机制,也未提出如何调整城市景观格局以利于维持水生生态系统的生态平衡^[68-69]。

4 研究展望

未来研究可以立足于以下五个方面:一是城市

水环境效应对城市景观格局演变存在的滞后响应研究, 可以尝试将不同的城市景观格局演变类型视为自变量、水环境效应视为因变量, 分别研究城市水体与城市人工景观相间混合分布、相邻分布和包围分布等不同格局特征下的城市景观格局演变过程与城市水环境效应关系, 建立水环境效应对不同类型城市景观演变过程的响应机制; 二是水环境效应的空间差异性研究, 包括景观格局演变对河流、水库、湖泊等不同类型水体产生的水环境效应差异性分析, 以及因水体分布空间差异所产生的水环境效应差异、上下游间的水环境效应累积现象; 三是景观格局变化对水环境效应影响过程的综合作用机理, 深入挖掘城市景观格局中因基质、廊道和斑块的变化所造成的水环境效应差异及综合作用机理, 将城市内涝与城市景观格局演变相联系, 将人工廊道(排水管网和城市道路)格局纳入城市景观格局的水环境效应研究中; 四是开发结构完整的水环境效应模型, 综合考虑城市景观类型及其格局、城市气象气候条件和水文条件, 为城市规划提供模拟预测; 五是“城市水体综合症”的对症之药研究, 即城市景观格局水环境负效应的综合对策, 景观生态学者可以与城市规划人员、城市管理部门进行跨学科合作, 共同提出一个指标体系, 包括不透水面的面积比例阈值、“源”“汇”斑块比例阈值、城市水体水质阈值、城市水体环境容量阈值和水生生态系统健康度等指标, 合理设置“源”“汇”景观斑块布局, 在城市规划阶段就预先考虑城市景观格局演变对水环境造成的生态后果, 为城市生态规划提供科学依据, 进而达到保护城市水环境的目的。

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