<table><tr><td rowspan="3">申报</td><td>系列：教师</td></tr><tr><td>专业：城乡规划</td></tr><tr><td>职称：副教授</td></tr></table>

业绩成果材料

（申报人的业绩成果材料包括论文、科研项目、获奖以及其他成果等）

单　位（二级单位）＿＿＿林学与风景园林学院＿＿＿

姓　名＿＿＿**林蔚**＿＿＿

材料核对人：　　　　　　　　　　　　单位盖章：

核对时间：

华南农业大学制

目　录

四、其他业绩

广 东 省 教 育 厅

粤教高函〔2018〕180 号

广东省教育厅关于公布 2018 年广东省高等教育教学改革项目立项名单的通知

各本科高校:

按照《广东省教育厅关于开展 2018 年度省高等教育教学改革项目推荐工作的通知》（粤教高函〔2018〕132 号）安排，省教育厅组织各本科高校开展了 2018 年度省高等教育教学改革项目（以下简称“教改项目”）遴选推荐工作。现将本年度省教改项目立项名单予以公布，并就有关事项通知如下:

一、立项情况

根据文件要求，省教育厅对学校推荐的材料进行了形式审查，确定 2018 年度省高等教育教学改革项目共立项 767 项（详细名单见附件）。

二、项目经费

项目由各校统筹省“创新强校工程”专项资金及自有资金等，根据立项项目研究内容、性质和特点，综合确定资助额度，保障项目顺利开展研究和实践。

省教改项目的立项建设是申报省高等教育教学成果奖的重要基础，项目建设成效同时列入学校“创新强校工程”绩效考核因素，并直接影响下一年度学校教改项目立项限额。

三、项目管理

（一）日常管理

省高等教育教学改革项目要求立足学校教学改革实际，突出问题导向、实践导向和应用导向，项目最终要为推动学校教学改革服务。项目所在高校要加强对项目的日常管理、指导和检查，为项目研究并切实应用于教学实践提供必要条件。

（二）中期检查和结题验收

项目建设周期一般不超过3年，请学校管理部门按期做好项目中期检查和校内结题验收等工作。校内结题时，邀请校外评审专家人数不得少于专家总人数的三分之二。

满足以下条件的项目，经学校正式申请，可以参与省教育厅统一组织的项目验收：

1.项目已完成立项时设定的主要建设目标，且项目建设成果已在教学实践中有效应用；

2.已按照要求完成项目校内结题；

3.符合当年度省统一验收规定的其他条件。

（三）项目变更和调整

为保证项目建设的延续性和成果的一致性，原则上，项目研究过程中不得更换项目负责人；不得大幅变更研究内容或研究方

向；不得拖延项目建设进程。

如遇特殊情况需要进行项目变更或延期的，须由项目负责人在项目结题前至少6个月向学校提出书面申请，学校审核同意后，以正式函件形式（并附相关材料）报省教育厅。

对擅自做出变更决定或临时延长建设期限的项目，将视情予以撤销或终止项目研究，取消相应负责人3年内省教改项目的申报资格，并核减项目所在学校下一轮次教改项目推荐数额。

四、其他事项

（一）2018年度各校向省教育厅推荐并获得立项的项目，学校须将相关项目校内评审推荐及立项材料妥善保存，留底备查。

（二）项目立项后，学校应组织专家对项目进行开题论证，进一步优化项目建设目标和实施计划。

（三）省高等教育教学改革项目优秀成果将以适当方式在省级平台上向广大高校推介。

联系人：刘雨濛、李成军， 联系电话：020-37626882、37629463；传真：020-37627963。

附件：2018年度广东省高等教育教学改革项目立项名单

广东省教育厅

2018年12月5日

公开方式：主动公开

校对人：刘雨濛

2018年度广东省高等教育教学改革项目立项名单

序号	单位名称	项目名称	项目负责人
106	华南农业大学	《商业银行业务与管理》沙盘模拟实训课程的研究	吴易娴
107	华南农业大学	新工科背景下农林高校《化工原理》教学改革与实践	李鑫
108	华南农业大学	学分制改革背景下高校本科生导师制改革与实践研究	刘玲娣
109	华南农业大学	基于慕课的混合教学模式在《农产品加工学》课程教学中的应用	陈佩
110	华南农业大学	林学专业卓越农林人才培养实践体系的构建	何茜
111	华南农业大学	《建筑制图》课程在线教学资源建设与研究	姜焰鸣
112	华南农业大学	大学生革命文学素养教育课程建设与教学改革	傅修海
113	华南农业大学	新时代高校大学语文“课程思政”的探索与实践研究	刘红娟
114	华南农业大学	雨课堂在公共《物理化学》课程教学中的应用研究	刘维
115	华南农业大学	基于雨课堂支持的中文专业语言学课程智慧课堂建设	高列过
116	华南农业大学	基于乡村振兴背景的城乡规划信息技术簇群与实践教学优化研究	林蔚
117	华南农业大学	基于微课的《养猪学》课程混合式教学探究	洪林君

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URBANISM AND ARCHITECTURE
3.2021 №385
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TOD模式下城市土地利用发展策略研究
平流古寨建筑文化特点及其保护形式研究
江西省红色工业遗产的现状调查与特征分析
综合管廊电力舱最佳换气次数的研究
基于使用需求的德国养老机构空间与部品设计探究
开封山陕甘会馆中的砖石雕艺术模式解析
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课程思政视角下的景观设计教学改革实践

林　蔚，刘维东，佘美萱

（华南农业大学林学与风景园林学院，广东广州　510642）

摘要：将生态文明价值观融入专业培养体系中，发挥协同育人效应，是课程思政的重要实践方向。本文依托农林院校城乡规划专业景观设计Ⅱ课程，探讨课程蕴含的生态理念及技术分析内容的切入点，开展融合式教学改革实践，通过构建基于GIS的场地定量分析评价、道路系统设计优化和雨水花园区域设计模式，初步实现了生态文明理念结合专业教育实践的改革目标，对于生态文明教育与专业课程有机融合做出了有益探索。

关键词：课程思政；生态文明；融合途径；规划设计；技术分析

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Practice of Landscape Design Teaching Reform from the Perspective of Curriculum Ideology and Politics

Lin Wei, Liu Weidong, She Meixuan

(College of Forestry and Landscape Architecture, South China Agricultural University, Guangzhou Guangdong 510642, China)

Abstract: Integrating the values of ecological civilization into the professional training system and exerting the effect of collaborative education is an important practical direction of curriculum ideology. Based on the landscape design II course of urban and rural planning major in agricultural and forestry colleges, this paper discusses the ecological concept and the breakthrough point of technical analysis content contained in the course, which carries out the practice of integrated teaching reform. The GIS-based site quantitative analysis and evaluation, road system design optimization, as well as rain garden area design model has been constructed, which initially realizes the reform goal of combining the concept of ecological civilization with professional education practice. It makes a useful exploration for the organic integration of ecological civilization education and professional courses.

Key words: curriculum ideology and politics; ecological civilization; integration way; planning and design; technical analysis

1 背景

教育部印发《高等学校课程思政建设指导纲要》，明确指出全面推进课程思政建设是落实立德树人根本任务的战略。高校要深化教育教学改革，充分挖掘各类课程思想政治资源，发挥好每门课程的育人作用，全面提高人才培养质量。生态文明建设作为新时代中国特色社会主义思想和基本方略的组成部分被提到了新高度。生态文明教育作为生态文明建设的重要环节，在思政课中有独特而重要的使命[1]。如何使专业课程和思想政治教育有机结合起来，形成协同效应，构建全方位育人大格局，是亟须开展实践探索的重要课题。

近两年来，不同专业根据学科特点，在教学内容设计与教学方法改革等方面做出了有益的探索[2, 3]。风景园林学科在新时代生态文明建设、贯彻新发展理念的工作中肩负着极为重大的责任[4]。从生态文明角度出发，在规划设计课程中融入可持续发展观、自然资源保护等多学科知识内容[5]，是风景园林教育事业发展的必然，探索符合生态文明内涵的学科创新是专业延续发展的必经之路[6]。

风景园林学科以协调人与自然之间的关系为宗旨，在学术和教学资源上独具特色，理应在专业课程思政方面有所探索。华南农业大学风景园林学科包括风景园林、园林、城乡规划等专业，城乡规划专业依托风景园林学科开设，逐渐形成了与理工科院校相关专业不同的培养模式；风景园林学科天然的多学科交叉优势，为城乡规划专业建立特色知识体系奠定坚实的基础。本文以城乡规划专业景观设计Ⅱ课程为例，分析生态文明思想和专业课程思政的融合途径和教学方案。

2 风景园林学科下城乡规划专业课程思政改革思路

2.1 城乡规划专业发展现状及景观设计课程思政改革方向

受到学制及学分要求的限制，城乡规划专业课程体系进行了调整，如城乡生态与环境规划仍然处于“缺位”状态，生态环境规划类知识传授和能力培养匮乏的现状与国土空间规划体系下强调生态优先的导向尚不匹配；专业

基金项目：2019年度广东省高等教育教学改革项目“OBE理念下城乡规划专业创新人才培养的进阶式教学模式研究”；广东省高等教育教学研究和改革项目“基于乡村振兴背景的城乡规划信息技术簇群与实践教学优化研究”（粤教高函〔2018〕180号）。

作者简介：林蔚（1986-），男，博士，讲师。研究方向：数字城乡规划。

通讯作者：佘美萱（1979-），女，硕士，副教授。研究方向：城市景观规划与设计。邮箱：xuanxuanshe@126.com。

特色不够突出，未有效结合学校学科在自然生态领域的特色，特色课程（如园林植物学）与核心课程联动效果有限，不能发挥学科资源互补优势。因此，风景园林学科应响应时代号召，将生态文明教育充分融入城乡规划专业教学全过程，形成协同效应，凸显专业特色。

较大尺度场地的景观设计应避免或减少设计对生态环境的不利影响[7]。从成果导向和技术手段层面看，以往景观设计课程偏重于微观尺度的设计实践，由于场地较小（空间异质性单一）和分析技术手段匮乏，学生对场地环境尤其是生态基底了解并不深入，开展相关生态分析与规划更无从谈起。

作为风景园林学理论知识的主要载体，景观设计I和II贯穿城乡规划专业大二学年，在微观设计向中宏观规划转换的关键时期，将生态文明思想和专业课程进行融合，挖掘理论价值和课程培养目标的衔接模式。改革后的教学实践实现了生态优先理念的多尺度渗透，引入场地规划设计的各个层面，重点增加了大尺度场的生态因子认知和生态专题规划分析内容，提高了学生应用生态理念进行规划设计的能力，促进了与相关专业知识的有机融合。

2.2 数字技术为教学实践和课程思政提供契机

定量分析、模拟和表达在规划设计过程中应用广泛。风景园林学界以定量辅助定性来推动学科和人居环境的持续发展[8]。为适应国土空间规划转型期与其他自然资源整合和行业技术流程更新的需要，规划设计专业应借力GIS等技术的优势，创建生态多元的人居环境。

在此背景下，利用信息技术拓展思政元素与专业知识相结合的领域，丰富教育路径和方式，GIS技术工具可成为课程思政隐性渗透的途径。改革后的课程教学采用数字技术支持规划设计过程，在实践教学环节重点讲授生态评价与分析方法，巩固学生对生态相关知识点的理解，提高学生的理论水平和分析能力，为后续专业课程奠定基础。

3 教学改革实践具体内容

3.1 场地概况和课程要求

景观设计II课程以华南农业大学树木园为例，场地面积约为17.5 hm²。树木园创建于1972年，是广东省高校中面积最大、引进植物种类最多的林木种植资源圃。园内亚热带常绿阔叶次生林发育良好，植被群落结构多样，是广州市绿地生态系统的重要组成部分。

针对本次教学改革的目标，在前期调研、小组讨论和方案推演的过程中突出生态优先理念，探讨场地生态系统“山、水、林”等系统要素的相互关系，实施GIS分析技术路线（见图1），开展生态敏感性分析、道路交通系统优化和水文分析专题实践，以支持场地规划设计过程。

3.2 基于GIS技术开展教学改革，践行生态优先理念

3.2.1 场地定量分析与评价

科学定量的场地分析与评价是“因地制宜”的前提，

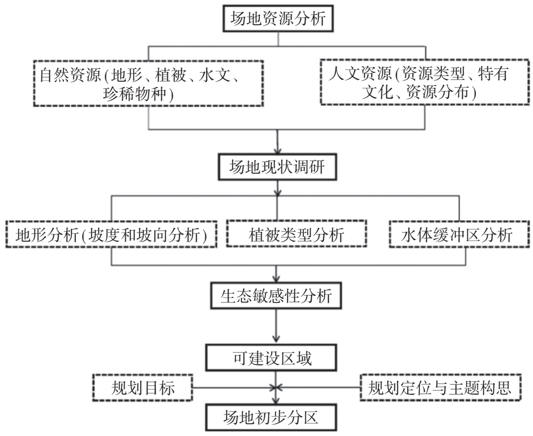

图1 基于GIS的前期分析技术路线（图片来源：作者自绘）

其中生态敏感性、建设适宜性是研究重点，体现了生态优先的原则[9]。生态敏感性和建设适宜性分析的评价指标因子较多。本次设计针对场地地形地貌相对复杂、植被覆盖率高的特征选择评价因子，兼顾数据的可获取性，在生态敏感性分析中选取地形（坡度、坡向）、植物保护性、距水体的距离等开展单因子分析，进而执行多因子综合叠加分析。在生态敏感性分析结果的基础上，筛选出适宜建设区和不可建设区。

学生在场地踏勘的基础上，对场地自然资源展开分析。依托数字高程模型、无人机航拍影像、轨迹调研助手等技术资料，掌握了地形、地貌、植被、水体等单因子分析和多因子综合叠加方法，充分了解了场地环境和生态基底。通过小组讨论，设置影响因子的权重，作为分析阶段的可调整参数，直接代入设计过程。各组均遵循生态优先原则，根据生态敏感性分析和建设适宜性分析结果，结合不同的规划目标定位和主题构思形成场地初步分区。

3.2.2 道路交通系统设计优化

在园路选线的过程中，需要对整个场地景观资源和各项因子进行全面、准确的分析[10]。风景环境道路的选线应与地形地貌相契合，线型灵活多变，避免过大的土方工程，减少对风景环境的人为扰动[11]。

树木园的道路选线过程中，选择坡度因子作为成本—距离矩阵，执行成本—路径分析，串联入口与重要景点，减小对场地环境的干扰。选择坡度成本最低（坡度最缓）、生态敏感性等级较低的区域作为园路系统可选项。根据入口和对应区域景点、主要和次要节点间顺序，分批次独立运算，生成节点与出入口的交通逻辑关系，由此内部路网初具形态。

学生遵照园路系统对场地环境干扰最小化的原则，在场地初步分区基础上讨论景点分布位置，结合道路选线分析结果，比对场地现状路网，逐步推敲路网的线型和节点，景点位置和主次节点均可迭代。经过路径的筛选与优化，生成最终道路形态，用于推敲各功能分区布局（见图2）。相较于传统选线方法对经验和技术的高要求，基于成本—路径分析的计算机选线方法避免了初学者因经验不足、水

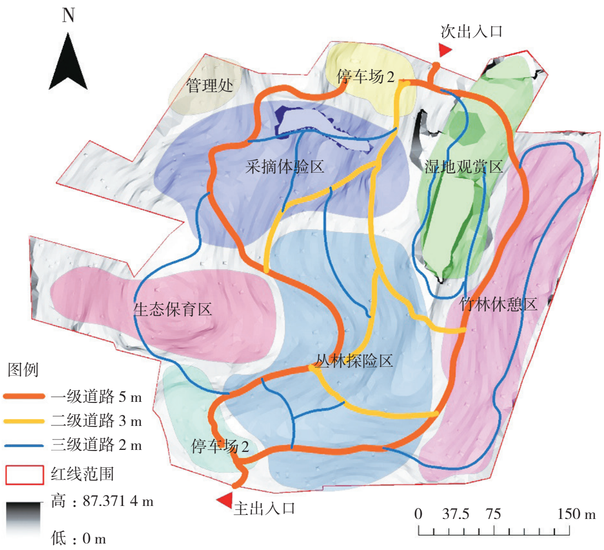

图2 道路选线结果支持场地功能分区（图片来源：作者自绘）

平与手法不同而导致方案的不确定性；能够有效地避开生态敏感区，减少对场地生态环境的影响。

3.2.3 雨水花园区域详细设计

雨水处理措施与景观规划设计相结合已成为城市生态建设的重要举措。场地中的水体与城市河涌段相连接，现状水量水质情况一般，因而是改造关注的焦点。本次改革实践旨在通过水文分析的结果支撑重点片区的设计。

水景营造需考虑利用现有低洼地，分析补给水源及场地汇水规律。方案拟在水体的东北侧修建雨水花园，基于不同暴雨强度情景的场地调研过程，判断现状水体的潜在径流位置。通过数字高程模型水文分析，确定雨水花园的径流补给位置和汇水路径，保证雨水花园在不同季节形成一定的水面景观。基于低影响开发原则，因势利导减少场地工程的土方量，通过生态种植池、透水铺装等措施达到恢复场地自然水文循环的效果。

水景观营造，除了关注传统美学价值，还应挖掘生态价值，该方案有效探索了水资源管理保护与景观营造之间的平衡。通过解读场地地形地貌和水循环特征，依托水文分析结果支持水景观选址。充分尊重场地的自然环境特征，不仅可以满足水景观营造的多目标，而且有助于实现可循环、减量化设计，进一步提升水资源的生态价值。

4 课程改革初步成效与思考

4.1 以技术融合途径为突破点，推动转型期课程思政教学改革

由微观设计向中宏观规划转变过程中，专业教师通过教学内容设计和方法优化，充分挖掘该课程所承载的思政教育功能，以场地分析评价和优化设计为抓手，将思政内容贯穿课程前期，重点引导学生通过GIS等技术手段了解场地概况，思考优势与不足，定量化评价场地各因子及之间的联系，促进学生初步形成生态优先、综合分析的思维模式，以顺利衔接实施中宏观尺度规划类核心课程。

经过两个学年的磨合和尝试，课程反馈中普遍提及能够更好领会本次教学改革的目的。学生重视场地资源的生态价值，以生态敏感性分析结果作为功能分区的依据；在方案的推导过程中，根据定量分析结果，减小对场地生态系统的扰动，因地制宜地采取资源认知、植被改造等相关措施，恢复场地生态系统服务功能。实践人与自然和谐统一，潜移默化地将生态文明理念融入学生的价值观。部分学生能够运用更复杂的GIS分析功能，开展雨水花园区域详细设计。学生因地制宜地开展分析并将结果辅助于方案的推演和设计，在专业能力得到提升的同时，加深了对生态文明建设的理解，初步达到了价值塑造、能力培养、知识传授“三位一体”的功能，取得了一定成效。

4.2 融合式课堂教学模式的探索与不足

任课教师的协作奠定了教学改革的基础，不同专业背景教师加强交流沟通，发挥教学团队各教师专长，推动了教学内容和课程知识结构的优化。在场地调研过程中，由植物分类方向的教师为学生介绍场地内的珍稀树种资源，由生态背景的教师分析场地内外的发展建设情况，追踪社会和学校时事热点，通过课堂讨论激发学生兴趣，引导学生树立正确的生态文明价值观。

教师的角色从传统讲授为主的教学者，朝着引导、咨询、合作等多角色定位转变。本次改革中，基于GIS的数字化技术引入，突破了设计对经验的单纯依赖，在提高设计成果科学性的同时，也易于学生掌握与应用；在教学过程中营造互动式教学环境，帮助学生理解不同专业知识融合的关键点，特别是生态背景知识与信息技术类内容的联动，从实践中促进学生生态文明观的建立；教师根据每个组方案的侧重点提供技术辅导（如雨水花园的水文分析），鼓励学生探索更多GIS技术融合生态要素分析的可能性。将价值引领贯穿到理论和实践环节讲授活动中，形成课程教学“大思政”的新格局[12]。

学生对于融合式的教学模式接受程度较高，通过学习相关技术，针对性地解决场地现存问题，践行生态文明价值观，提高了对课程定位与教学内容的整体认知。受课时和其他条件的限制，本次教改尝试也存在一定的不足：教师首次开展专业课程和思政内容相结合的教学，对于教学内容的设计还有继续整合优化的空间，在教学形式上应加强分析内容和方案推演过程的互馈；个别学生对课程思政内容和专题分析融合的意义理解不深，导致参与度不高，仍须进一步改进。

5 结语

本文初步讨论了生态优先背景下景观设计类课程与技术内容的融合模式，在生态文明建设新时期风景园林学科城乡规划专业课程思政教学改革方面做出了有益探索。在专业培养方案和课程体系改革中，应融入生态观和系统观，牢固树立社会主义生态文明观，推动人与自然和谐发展。今后可进一步发挥技术类课程实践性强的优势，优化

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发展带中麻栗坡发展存在一定滞后，东西、南北向城镇发展主轴发展态势较好，西畴县经济发展较为缓慢；州域北部、东部、南部 3 个发展极核支点稳步发展。

4.2 思考

文山州应加快推进南北向快速路网建设，完善州域内综合交通体系，缩短城市之间经济距离。目前文山州仅有一条穿过北部的东西向高速铁路，应在下一步规划和实施中，重点推进落实南北向交通，构建合理有效的运输网络，串联区域内各个城市，避免较为突出的不平衡发展。尽快落实“沿边铁路”文山—富宁段的建设，弥补南部东西向交通运输的欠缺，同时促进沿边城镇群发展带的构建。

增强州府文山市的服务半径，构建有效的 30 min 内部经济圈，辐射周边城镇群；由于铁路欠缺，文山市 2014—2018 年已然呈现出发展疲软之势，区域核心性正在下降，增强其聚集效应，保障“文砚丘平”的核心性是下一步结构优化的重点；应该合理调控指标，充分发挥高铁沿线丘北、广南、富宁 3 个县的经济潜力。

参考文献

[1] 马璇，张亢，张一凡. 新时期总体规划实施评估的创新实践与方法探索：以杭州为例[J]. 上海城市规划，2020（01）：61-68.

[2] 张尚武，汪劲柏，程大鸣. 新时期城市总体规划实施评估的框架与方法：以武汉市城市总体规划（2010—2020 年）实施评估为例[J]. 城市规划学刊，2018（03）：33-39.

[3] 解瑶，张军民，单建树. 近五年我国城市总体规划实施评估研究综述[J]. 上海城市规划，2015（06）：21-26.

[4] Aday Hernández, Juan Luis Jiménez. Does High-speed Rail Generate Spillovers on Local Budgets?[J]. Transport Policy, 2014, 35(9): 211-219.

[5] SASAKIK, OHSHIT, ANDOA. High-speed Rail Transit Impact on Regional Systems: Does the Shinkansen Contribute to Dispersion?[J]. Annals of Regional Science, 1997, 31(1): 77-98.

[6] 王姣娥，焦敬娟，金凤君. 高速铁路对中国城市空间相互作用强度的影响[J]. 地理学报，2014，69（12）：1833-1846.

[7] 黄洁，钟业喜，李建新，等. 基于高铁网络的中国省会城市经济可达性[J]. 地理研究，2016，35（04）：757-769.

[8] 鲁金萍，杨振武，孙久文. 京津冀城市群经济联系测度研究[J]. 城市发展研究，2015，22（01）：5-10.

[9] 赵云，李雪梅，韦功鼎. 基于可达性的高速铁路站点影响力评价研究[J]. 地域研究与开发，2015，34（03）：12-16.

[10] 姜博，初楠臣，修春亮，等. 中国“四纵四横”高铁网络可达性综合评估与对比[J]. 地理学报，2016，71（04）：591-604.

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思政内容、核心课程与技术连接的实施模式，培养“复合型、跨学科”的专业人才，推动转型期城乡规划专业教学改革继续深化，发挥协同效应，落实立德树人的根本任务。

参考文献

[1] 赵曜. 新冠肺炎疫情背景下对思政课程的思考[J]. 中国高等教育，2020（10）：28-29.

[2] 王艳红，伊力塔，曾燕如.《生态学》教学中“课程思政”教育的探索[J]. 高教学刊，2020（09）：170-172.

[3] 文兰娇，胡伟艳，张安录. 习近平生态文明思想与课程思政的融合和教学设计：以土地资源管理专业课程为例[J]. 黑龙江教师发展学院学报，2020，39（02）：38-40.

[4] 佚名. 风景园林学科承担着生态文明建设的历史使命[J]. 中国园林，2017，33（01）：5-6.

[5] 刘晓惠，罗枫. 生态理念指导下的场地规划课程构建[C]//2012 年风景园林教育大会，2012.

[6] 魏家星，陈宇. 生态文明视域下交互式教学在风景园林专业的探索与实践[J]. 中国农业教育，2017（06）：77-80，95-96.

[7] Stinitz C. Landscape Architecture into the 21st Century-Methods for Digital Techniques[C]// Peer Reviewed Proceedings Digital Landscape Architecture, 2010: 2-26.

[8] 成玉宁. 中国第三届数字景观国际论坛[M]. 南京：东南大学出版社，2017.

[9] 成玉宁，袁旸洋，成实. 基于耦合法的风景园林减量设计策略[J]. 中国园林，2013，29（08）：9-12.

[10] 杜钦，张超. 景观规划 GIS 技术应用教程[M]. 北京：中国林业出版社，2014.

[11] 袁旸洋，成玉宁. 参数化风景环境道路选线研究[J]. 中国园林，2015，31（07）：36-40.

[12] 赵华甫，吴克宁. 土地资源管理类课程思政建设路径探讨：以国家精品资源共享课“土地资源学”为例[J]. 中国农业教育，2020，21（03）：60-67.

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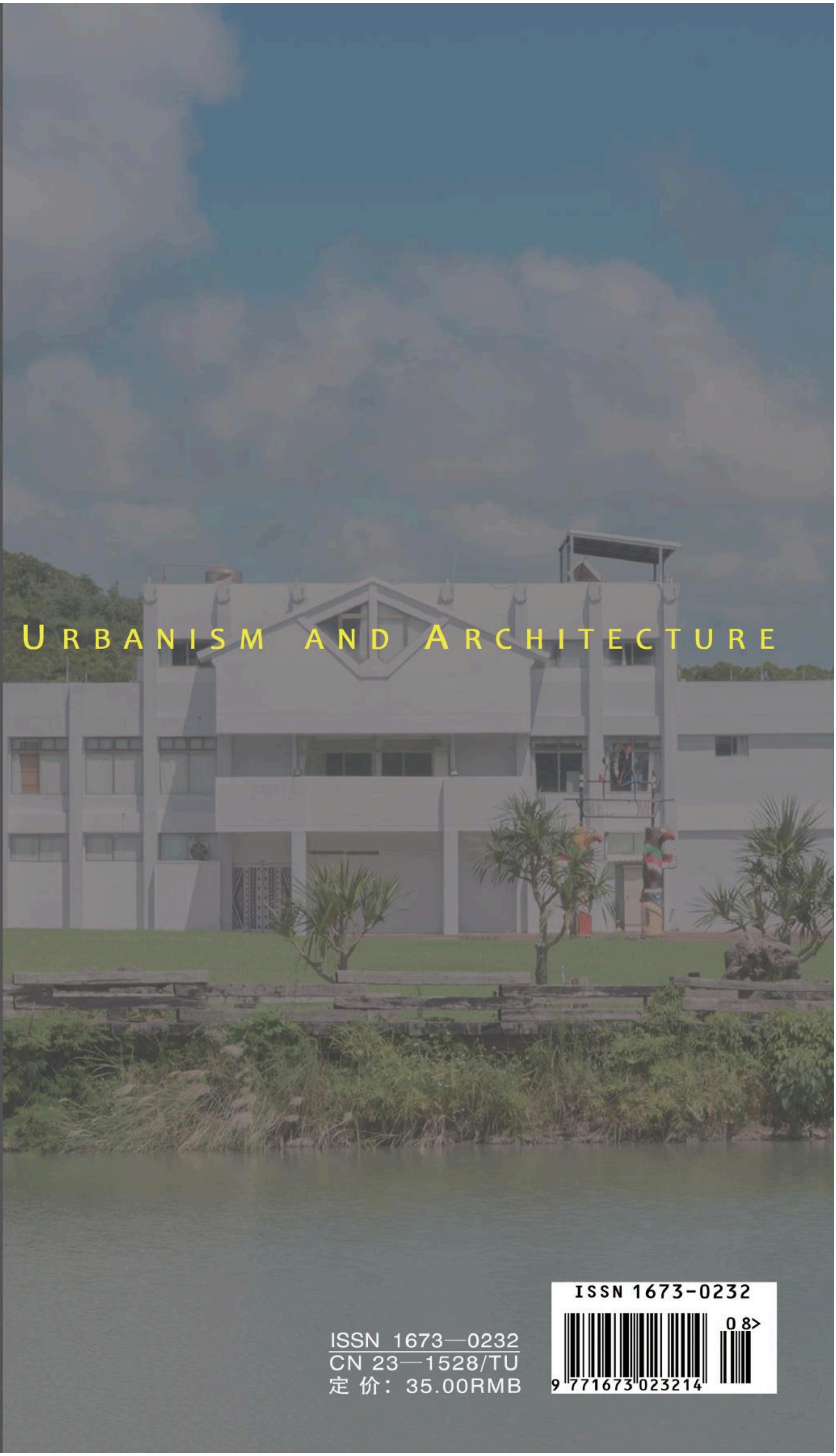

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新工科背景下城乡规划专业信息技术类课程思政探索实践 *

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华南农业大学林学与风景园林学院　广州　510642

摘　要　推进专业课程思政建设是高校教学改革的发展趋势和有力抓手。信息技术类课程作为城乡规划专业教学核心内容，是专业课程思政体系中的重要组成部分。针对课程特点和核心能力培养要求，提出“交叉共融、知行合一”的课程思政建设理念，通过挖掘课程思政元素，探索课程思政教学方案，总结思政教学策略及方法，以期为新工科背景下城乡规划专业的人才培养模式更新和内涵建设提供有益参考。

关键词　新工科；课程思政；城乡规划专业；信息技术；教学改革；城市地理信息系统；GIS

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0　引言

习近平总书记在全国高校思想政治工作会议上强调，要坚持把立德树人作为中心环节，把思想政治工作贯穿教育教学全过程，实现全程育人、全方位育人，努力开创我国高等教育事业发展新局面[1]。《高等学校课程思政课建设指导纲要》明确提出要在所有高校、所有学科专业全面推进课程思政[2]，这既是本科人才培养改革的创新实践，也是社会高质量高水平人才培养的现实响应[3]。课程思政已成为高校开展学生思想教育工作的重要实践活动，将价值观引导寓于知识传授和能力培养之中，坚持育人与育才相统一，全面提高人才培养质量。

近年来，教育部一直积极推进新工科建设，全力探索形成领跑全球工程教育的中国模式、中国经验，助力高等教育强国建设[4]。高校教育作为行业发展的人才培养摇篮，推动新工科建设势在必行。信息技术作为新工科建设的重要组成部分，是城乡规划编制、管理、研究的重要支撑[5]。随着人工智能、智慧城市和大数据时代的来临，信息技术在城乡规划中的应用已经成为规划师核心技能，因此，本文以城乡规划专业信息技术类核心课程城市地理信息系统为例，总结课程思政实践的经验。地理信息系统（Geographic Information System，GIS）作为新型空间信息技术，应用十分广泛。城市地理信息系统课程重点培养学生综合应用分析能力，解决城乡规划设计中遇到的问题。通过网络调研开设城市地理信息系统相关课程高校，课程思政教学实践已成为教学改革的热点趋势，传统测绘土建、地理科学院校以课程实践为载体，挖掘课程中的思政元素，积极探索有效教学引领方式，成效突出。

然而，以上均是基于地理信息科学[6]或测绘工程本科专业[7]开展课程思政教学改革的实践，关于城乡规划专业如何开展信息技术类课程思政探索尚未见报道，尤其是针对城乡规划专业综合性、跨学科的特点[8]，进一步发挥城市地理信息系统课程在城乡规划专业知识体系中的核心作用和思政价值，亟待开展深入讨论。

基于此，突出GIS这一领域改进质量、提高效率的实用技术工具典型优势，结合城乡规划专业综合性、应用性强的特点，探讨课程思政建设目标和内容重点，科学设计课程思政教学体系，探索专业课课程思政的教学改革与实践，为城乡规划专业内涵式发展提供支撑和借鉴，助力新工科建设。

1　课程特点与定位

城市地理信息系统授课对象为城乡规划专业三年级学生，课程性质为选修课。城乡规划作为新兴学科，在人才培养上紧跟新工科发展趋势。新工科背景下大数据、云计算、人工智能和本课程具有天然的结合条件。本课程以信息技术为主线，以技术专题形式开展教学，重点讲授GIS基本方法、主要功能和技术应用。学生已接触大部分专业核心课程，为课程开设创造了良好条件，渴望了解新技术并对如何解决复杂的问题具有较强的求知欲。但是，学生尚未形成软件学习方法，部分学生学习目标不够明确，如何在有限的32学时内完成规定教学内容是巨大的挑战。

本课程教学目标可以从知识传授、能力培养和

* 项目来源：2021年度华南农业大学校级教改重点项目“乡村振兴背景下农林院校城乡规划专业内涵建设研究”；2021年度华南农业大学校级教改一般项目“基于‘工农互促’理念的城乡规划专业乡村振兴高素质人才培养模式改革与创新”。

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价值引领三个方面展开：知识传授方面，培养学生基本掌握 GIS 理论、功能和应用，获得开展研究、创新活动必备的专业能力；能力培养方面，通过案例讲解与操作实践，使学生将所学理论融入规划实践操作中，重点培养学生发现问题、分析问题和解决问题的实践能力；价值引领方面，本课程将紧紧围绕立德树人根本任务，积极响应协同育人理念，引导学生树立正确的理想信念，形成正确的世界观、人生观和价值观，发挥育人作用，培养具有创新意识和专业素养的社会主义建设者，培养具有社会责任感和家国情怀的接班人。

2　课程思政建设理念

基于《高等学校课程思政课建设指导纲要》，城乡规划专业开设城市地理信息系统课程应突出理工兼具、综合性强、应用性强的特点，结合课程教学目标，从家国情怀、专业素养、工匠精神、创新意识等方面确定课程思政元素（表 1），从知识传授、能力培养、价值塑造三个层次细化课程思政目标，充分体现专业教学目标和思政教学目标的有机融合。为落实专业课思政要求，本课程以新工科背景下的“地理信息 +”作为赋能要素，提出“交叉共融、知行合一”理念，以学生为中心，提升其在课程中的参与度和获得感，通过丰富案例和多种教学手段实现专业性与思政性有机融合，让学生在知识、能力和价值三个层次目标上有所收获。本课程围绕“两性一度”进行专项设计，深入挖掘课程育人功能，充分体现专业教育与思政教育的有机融合，实现专业教学和思政育人协同发展。

3　课程思政实施路径

如图 1 所示，根据知识、能力和价值目标，首先对课程内容进行解构，将思政目标具象化为课程思政点，梳理重构课程知识体系，将课程目标由单一的知识传递转变为注重价值引领，在模块化知识单元的基础上融入。以课程思政教学目标为基本方向，在深入分析课程特点和知识体系的基础上，抓住能够渗透思政教育的课程内容作为融入点。本课程基于 GIS 主要功能和常见分析场景，同时体现城乡规划发展前沿动态，在专题教学中充分挖掘思政元素，充分体现“两性一度”的要求。

4　课程思政具体实践

通过充分梳理和深入挖掘课程知识点蕴含的思政元素，把立德树人与专业知识传授相融合，将思政教育贯穿课程教学全过程。以部分教学内容为例，阐述课程思政元素内涵及与教学知识点融合过程。

表 1　课程内容与思政元素对应关系

思政元素	核心要求	课程内容
工匠精神	精益求精	GIS 软件迭代更新；注重图纸成品质量
家国情怀	砥砺前行	国产核心 GIS 与遥感技术；出图环节注重国家主权意识；我国提出的空间参考基准
专业素养	多维统一	能够分析问题，提出解决问题的方法并展开实践；训练科学思维方法和科学伦理；塑造价值观
创新意识	知行合一	开展综合训练；自主选题开展研究

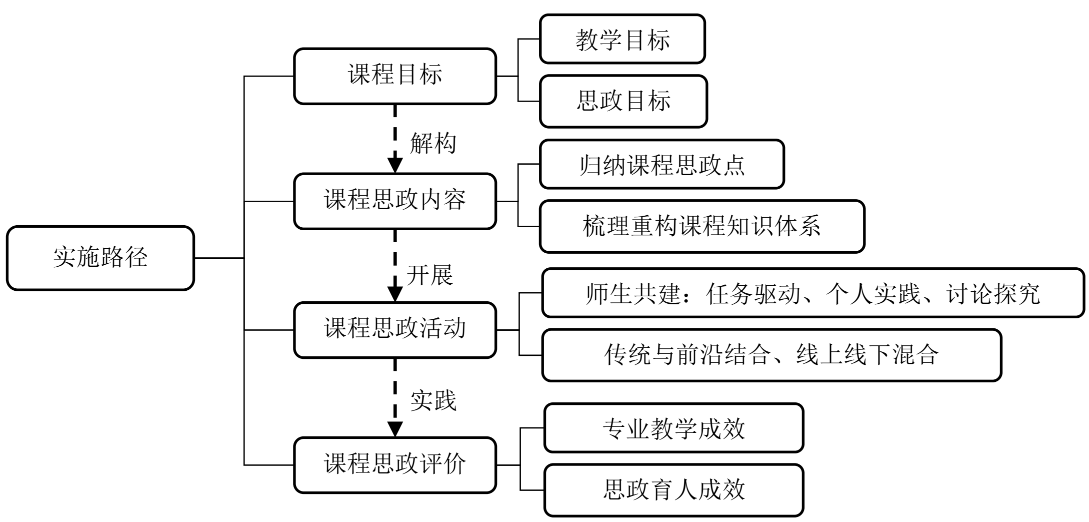

图 1　课程思政实施路径

4.1 GIS应用发展和国产GIS软件：家国情怀、工匠精神

GIS软件是开展教学的工作环境。长期以来，国外的专业软件吸引了大量用户资源，通过介绍国产GIS软件的瞩目成绩和发展历程，增强学生的民族自豪感，坚定文化自信，感受大国工匠精神。国产GIS软件在国土、测绘等多个领域得到广泛应用，国产GIS软件产业的发展壮大离不开从业人员的开拓创新，让学生受到大国工匠事迹的感染，培养精益求精的精神。在“互联网+”时代背景下，国产GIS软件引领技术潮流，与传感器、大数据、人工智能、区块链等技术融合，不断超越自我，具有巨大的发展空间。

信息安全事关国家安全和利益，必须从维护国家安全的战略高度确保国家地理信息安全。地理信息包含详细准确的位置，GIS软件已成为多行业领域的核心支撑软件，管理着大量涉及国家地理安全的敏感信息，充分体现了GIS软件国产化的重要性。

GIS技术在抗击新冠疫情的过程中发挥了重要作用：在疫情跟踪方面，通过对手机信令数据的分析，可以进行动态轨迹追踪，使疫情防控更为准确；针对疫情应对中暴露出的公共医疗资源短缺、结构不合理等城市问题，基于GIS软件分析指出主要优质医疗设施布局不合理，过度集中于中心城区，而基层卫生设施数量严重不足，未来亟须通过规划行动予以解决[9]。GIS服务于国家重大战略需求，服务于社会经济发展，给老百姓生活带来实实在在的价值，这是家国情怀的集中体现。

4.2 制作完整图纸：中国元素、工匠精神

制作完整图纸是GIS软件的核心功能，也是符号化表达的重要环节。完整图纸包括指北针、比例尺、图例、图框、图名等诸多要素，根据要求整饰出图是难点。规划设计图纸对出图环节有着严苛的要求，优秀的科研成果中必然有精美的图示支撑，通过展示科研文献的精美插图，让学生体会制图质量的重要性。学生应通过本节内容的学习，培养精益求精的工匠精神，意识到图纸表达的重要性。

从“问题地图”切入，吸引学生的注意力，让学生意识到图纸完整的重要意义。“问题地图”主要指存在危害国家主权统一、领土完整、安全和利益等严重问题的地图。“问题地图”的常见错误有漏绘钓鱼岛、赤尾屿、南海诸岛等重要岛屿，错误表示台湾省，错绘藏南地区和阿克赛钦地区国界线等。此处应强调地图是国家版图的表达形式，象征国家主权和领土完整，务必做到“一点都不能少，一点都不能错”。根据新版《地图审核管理规定》的要求：地图不得含危害领土主权内容，本节内容以中国版图为底图开展操作示范和应用，可通过教学和练习强调地图要素的完整性，通过案例激发学生的家国情怀。

请学生浏览标准地图服务网站学习相关标准和规定，结合章节学习的要点，检查教师所提供地图案例的正确性。通过布置自选主题制图作业，要求学生寻找合适的数据，确定恰当的符号化方式，完成图纸的制作，调动学生的主观能动性，在提升规范性的同时，进一步培养学生的创新能力，激发学生的专业思维。

4.3 现状容积率统计：专业素养、价值塑造

本节课内容覆盖了常用矢量数据空间分析功能，但能否将这些功能进行综合应用，解决行业实际问题，是高阶性的集中体现。由于本学时内容还涉及制作完整图纸等已学内容，对学生掌握情况是很好的检验；要求学生限时完成分析，也具备一定的挑战度。此外，本节教学内容还与其他专业课程打通，在融合的基础上进一步体现技术创新。

容积率是控制性详细规划中开发强度的重要指标之一，是国有土地使用权出让合同中必须规定的重要内容，也是进行城乡规划行政许可时必须严格控制的关键指标。从“容积率腐败案”说起，让学生意识到专业工作的严肃性，引起学生的重视。一些地方的城乡规划主管部门利用手中的权力擅自修改容积率等重要指标，对调整搞暗箱操作，甚至出现权钱交易谋取私利的违法行为。规划管理的违法违规行为不但给国家造成巨大的经济损失，而且严重损害了政府部门和规划行业在公众中的形象，造成不良社会影响。

通过课堂讲授，要求学生理解容积率的定义、分解步骤和对应工具。容积率统计是矢量数据空间分析的组合拳，重点讲解如何根据技术提要建立分析流程图，如何对分析功能“积木”进行“拼装”开展综合应用，解决行业实际问题，真正理解课程的出发点。通过GIS软件分析，在提升工作效率和精确度的基础上，进一步要求学生严肃认真，恪守职业道德。通过讨论激发学生学习兴趣，号召学生深刻认识维护人民利益、增进人民福祉是规划师重要职业信条。专业素养源自严谨清晰的思路和对细节的把控。

5 课程思政教学策略及方法

5.1 坚持传统与前沿、线上与线下相结合的教学策略

5.1.1 传统教学内容与前沿知识内容相结合

GIS涉及千余种功能操作，难以面面俱到地进

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[6] 虚拟现实技术[DB/OL].https://baike.baidu.com.
[7] 戴晨.基于ARCS动机模式的初中地理优质课教学分析与设计研究[D].广州：广州大学,2022.
[8] 范理婷.ARCS动机模型在高中思想政治课教学中的应用研究：以榆林市×中学为例[D].陕西：延安大学,2022.
[9] 杨从从.ARCS动机模型在高中地理教学中的应用研究[D].山东：聊城大学,2022.
[10] 苏海玲.基于ARCS理论的高中生物学PBL教学模式的实践研究[D].广州：广州大学,2022.

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行介绍。因此，本课程精选核心模块，重点突破极具代表性的功能，以点带面进行学习。同时，作为一门应用性极强的学科，如何利用GIS软件解决城乡规划领域实际问题是教学过程中的焦点，引入行业前沿的分析案例补充传统教学内容，有助于学生进一步领会课程的核心价值。

5.1.2 在教学过程中坚持线上和线下相结合

由于课程教学内容较多，同时涉及大量的软件操作环节，选课学生提问答疑的工作量大，难以全部在线下集中教学环节完成。因此，充分利用线上教学资源，通过提前布置任务、个人分散演练、搜集疑问答疑等形式，有效利用有限的课时，集中力量挑战综合性、高阶性任务。

5.2 形成任务驱动—个人实践—讨论探究的师生共建教学模式

5.2.1 转被动接受为主动探究

以往的软件实操型课程以教师课堂讲授示范为主，以“我教你学”为主要特征，难以保证每位学生都深度参与课堂。因此，通过提前布置课程任务、当堂组织考核等形式，促使学生提前接触当周教学内容并反馈学习情况，激发学生的学习兴趣和热情。

5.2.2 翻转课堂全面提升综合能力

在立足学生软件实操能力的基础上，注重学生口头表达能力、文字凝练能力的培养，提高学生正确认识问题、分析问题和解决问题的能力；通过师生间的交流讨论，可以进一步碰撞出思维的火花，同时增进师生间的互动，让课堂教学更有温度，更有感染力，更有创造力。

6 结束语

培养具有崇高道德水准的高素质人才是高等教育的中心任务[10]。城乡规划专业在实施信息技术类教学过程中融入思政元素，有利于增强教学效果，促进学生全面发展。

当前，课程思政案例日益丰富，但信息技术类专业的课程设计与思政元素的结合还有待进一步提高。通过充分梳理和深入挖掘城市地理信息系统课程所蕴含的思政元素和教育资源，以“地理信息+”作为赋能要素，提出“交叉共融、知行合一”的理念，落实立德树人的育人目标，提出实施路径与方法，将思政元素有机地融入专业知识技能教学，全面提升课程的育人成效，得到学生的普遍肯定，为在新工科背景下专业课教学中如何融入课程思政元素提供了一定的参考和借鉴。

7 参考文献

[1] 习近平在全国高校思想政治工作会议上强调：把思想政治工作贯穿教育教学全过程 开创我国高等教育事业发展新局面[N].人民日报,2016-12-09(1).
[2] 高宁，王喜忠.全面把握《高等学校课程思政建设指导纲要》的理论性、整体性和系统性[J].中国大学教学,2020(9):17-22.
[3] 何云峰，吉列丽，张青青.提升本科人才培养能力：“课程思政”的新时代价值与实践路径[J].教育理论与实践,2019,39(18):37-39.
[4] 陆国栋.“新工科”建设的五个突破与初步探索[J].中国大学教学,2017(5):38-41.
[5] 尹杰，宋斯琦.“数字化转型”背景下城乡规划专业信息技术应用的实践教学研究[J].高教学刊,2019(8):91-93.
[6] 孙伟伟，杨刚，陈碧远.地理信息系统课程思政教学探讨[J].宁波大学学报（教育科学版）,2020,42(5):89-93.
[7] 田劲松.测绘工程专业大地测量学课程思政教学探索与实践[J].大学教育,2022(3):31-33.
[8] 赵建华，蔡健婷，卢丹梅.乡村振兴背景下城乡规划专业人才培养创新与实践[J].中国教育技术装备，2021(18):5-7,11.
[9] 王凯.后疫情时期的规划行动[J].中国建设信息化，2020(21):12-13.
[10] 坚持立德树人 培养优秀人才[N].光明日报,2017-04-10(1).

CONTENTS

获奖成果： 为乡村振兴培养高素质城乡规划专业人才的研究与实践

获 奖 者： 卢丹梅、佘美萱、黄 东、赵建华、陈思颖、彭昌操、郭迪杰、林 蔚、吴宝娜、叶昌东

获奖等级： 一等奖

证书编号： JXCG21017

华南农业大学

二〇二一年六月

荣誉证书

林 蔚 老师：

在华南农业大学首届课程思政教学大赛中荣获“**三等奖**”。

特发此证，以资鼓励！

华南农业大学

2021 年 9 月 18 日

广州市社会科学规划领导小组办公室文件

穗社规办〔2023〕6号

关于广州市哲学社会科学发展“十四五”规划2023年度课题立项的通知

各有关单位科研管理部门：

经专家评审、社会公示，报广州市社会科学规划领导小组审定，广州市哲学社会科学规划2023年度课题立项190项。其中，一般课题90项，羊城青年学人课题74项，广州大典课题22项，博士论文4项。现将有关事项通知如下：

1. 本年度课题立项时间为2023年5月15日，一般课题、羊城青年学人课题及广州大典课题结项时间为2025年5月15日前，博士论文的结项时间为2026年5月15日前。因故不能按期完成结项的，应在结项时间截止前10天提出延期申请。

2. 课题研究应按照《广州市哲学社会科学规划课题申请书》的设计进行。未经市社科规划办同意不得更改研究方向、内容、成果形式及变更管理单位。

3. 本年度广州市社科规划课题资助经费采取一次核定，分期拨款的方式，首期经费为总经费的 50%，课题立项后划拨；后期经费为总经费的 50%，课题结项后划拨。本年度一般课题、广州大典课题资助经费 5 万元/项，羊城青年学人课题、博士论文资助经费 3 万元/项。

4. 请各单位科研管理部门及时将本通知有关事项告知各课题负责人，并组织课题负责人签订《广州市哲学社会科学发展“十四五”规划 2023 年度课题立项协议》一式 3 份（模板下载请联系市社科规划办），于 2023 年 6 月 9 日前送达我办审定盖章。随协议同时报送《广州市哲学社会科学规划课题申请书》纸质版一式 1 份，课题题目以本通知附件的立项名单为准。以上材料签章均需规范齐全。

5. 未及时提交《广州市哲学社会科学发展“十四五”规划 2023 年度课题立项协议》和《广州市哲学社会科学规划课题申请书》的，视为课题负责人自动放弃课题立项。

附件：广州市哲学社会科学发展“十四五”规划 2023 年度课题立项名单

广州市社科规划领导小组办公室

2023 年 5 月 15 日

（联系人：姬老师；联系电话：020－89815149）

附件

广州市哲学社会科学发展“十四五”规划 2023年度课题立项名单

序号	负责人	单位名称	课题名称	课题编号
一般课题90项（每项资助5万元）				
1	李珍	中山大学	数字时代马克思主义理论创新与传播研究——基于利用智能算法提升主流意识形态话语权的视角	2023GZYB01
2	梁增贤	中山大学	广州加快公园城市建设研究	2023GZYB02
3	蔡伟	中山大学	广州提升法律服务全球竞争力路径对策研究	2023GZYB03
4	徐健	中山大学	人才是第一资源的广州实践和对策研究——高校科技人才与企业技术需求对接问题与对策研究	2023GZYB04
5	李海涛	中山大学	新时代增强广州文明传播力影响力研究——广州侨批档案诚信文化价值开发推广研究	2023GZYB05
6	胡诗然	中山大学	中国式现代化建设中坚持改革开放的目标与重点任务研究——数字外交视角下的中美国际传播比较研究	2023GZYB06
7	王晓丽	华南理工大学	在高质量发展中促进共同富裕的制度设计研究——以实现机制为视角	2023GZYB07
8	张国启	华南理工大学	以党的自我革命引领社会革命研究——基于全面建设社会主义现代化国家新征程的实践效应维度	2023GZYB08
9	徐维军	华南理工大学	广州统筹推进碳达峰碳中和与经济社会协同发展研究	2023GZYB09
10	雷玉桃	华南理工大学	广州统筹推进碳达峰碳中和与经济社会协同发展研究：基于制造业碳减排与高质量发展的视角	2023GZYB10

序号	负责人	单位名称	课题名称	课题编号
			主体干预机制研究	
20	许清	暨南大学	广州构建具有全球竞争力的开放创新生态研究——以开放式创新背景下知识产权对技术创新的激励机制为视角	2023GZQN20
21	陈胜蓝	暨南大学	广州民营企业海外权益保护研究：以企业海外知识产权保护为例	2023GZQN21
22	李佳	暨南大学	广州加快岭南文化中心和文化强市建设研究——广州话的传统环境知识语汇整理	2023GZQN22
23	宋婉贞	暨南大学	“一带一路”视域下广州加快建设枢纽型侨都的路径对策研究	2023GZQN23
24	祝哲	暨南大学	新时代广州公共安全应急框架体系研究——政策信息学背景下风险政策叙事的效果评估和体系优化	2023GZQN24
25	周超	华南农业大学	实现第二个百年奋斗目标新的赶考之路上需防范的重大风险研究：开放经济条件下我国农业领域的外汇风险	2023GZQN25
26	刘树鑫	华南农业大学	广州公共文化服务高质量发展路径政策研究	2023GZQN26
27	张奕婧	华南农业大学	广州坚持制造业当家、构建现代化产业体系研究——双碳背景下企业开放性创新机理研究	2023GZQN27
28	朱庆莹	华南农业大学	广州超大城市治理体系和治理能力现代化研究 ——基于城市韧性建设视角	2023GZQN28
29	林蔚	华南农业大学	广州加快森林城市建设研究：供需视角的布局优化与增益路径	2023GZQN29
30	夏宇	华南农业大学	广州加快改善城乡人居环境的政策对策研究——健康老龄化视角下的乡村老年户外支持性环境整治设计研究	2023GZQN30
31	秦楠	华南师范大学	推进大中小学思想政治教育一体化建设研究——基于完整生活的立场	2023GZQN31
32	范云歌	华南师范大学	广州市人口老龄化的伦理问题与应对思路研究：基于家庭养老与社会养老中精神赡养问题的探讨	2023GZQN32
33	谢晓东	华南师范大学	人才是第一资源的广州实践和对策研究——“非升即走”高校青年教师负性情绪等对业	2023GZQN33

课题编号	2023GZQN29

广州市哲学社会科学发展“十四五”规划

2023 年度课题立项协议

甲　方：广州市社会科学规划领导小组办公室/广州市社会科学界联合会

地　址：广州市天河区龙口东路 363 号宝供大厦二楼

联系电话：020 - 89815149

法定代表人：曾伟玉

乙　方：华南农业大学（单位）　林蔚　（课题负责人）

地　址：（单位地址）广州市天河区五山路 483 号

课题负责人（签字）：林蔚

课题负责人手机号码：18144869666

课题负责人邮箱：wlin@scau.edu.cn

二〇二三年五月

广东省哲学社会科学规划专项小组

粤社科规专通〔2024〕38 号

广东省哲学社会科学规划 2024 年度学科共建项目立项通知书

林蔚同志：

经省哲学社会科学工作领导小组审批，您申报的广东省哲学社会科学规划 2024 年度学科共建项目《供需视角下珠三角森林城市群建设空间优化路径研究》获准立项，批准号：GD24XGL044。学科共建项目资助经费为 2 万元，由项目负责人所在单位自筹并分期划拨给项目负责人，第一次拨款 1.4 万元，预留经费 0.6 万元在项目鉴定结项后拨付。请尽快登录

广东省哲学社会科学规划项目管理平台上传签字盖章版申请书 PDF 扫描件并认真填报预算，预算个人填报截止时间为 7 月 26 日 12 点，单位审核截止时间为 7 月 26 日 17 点。逾时未填报立项预算视为放弃立项。

项目负责人填写预算后，本通知即成为具有约束效力的立项协议。项目负责人所在单位须承担保证责任。项目负责人及所在单位须了解和执行以下规定：

1.课题组须学习并遵守《广东省哲学社会科学规划项目管理办法》。对于出现违规行为的，省哲学社会科学规划专项小组依据《广东省哲学社会科学规划项目管理办法》的相关规定进行处理。

2.批准后的项目经费不再追加，课题组可以不接受。而一经接受，将不能以经费不足为由，擅自变更原设计的最终成果形式和内容。

3.项目立项后，课题组须按项目申请书所列计划开展研究。研究过程中，如有变更项目负责人、改变成果内容或形式、变更项目管理单位、变更或增补课题组成员、终止项目或撤消项目、延期等重要事项，项目负责人或所在单位必须及时填写《广东省哲学社会科学规划项目重要事项变更审批表》（可在广东社科规划网“下载专区”下载），报省哲学社会科学

规划专项小组审批。

4.省社科规划项目成果为论文的，在公开发表时必须注明“广东省哲学社会科学规划项目（项目编号）”字样。成果（含阶段成果）为专著、研究报告的，未经规划专项小组组织专家鉴定或经鉴定但未获得通过，出版时不能标明“广东省哲学社会科学规划项目（项目编号）”字样；如成果确实有先出版后鉴定结项的需要，必须先向规划专项小组提出书面申请，经批准后才能出版并标明“广东省哲学社会科学规划项目（项目编号）”字样；如未经鉴定或未向规划专项小组申请，自行出版并标明“广东省哲学社会科学规划项目（项目编号）”字样，规划专项小组不接受项目结项申请，予以撤项处理。

5.项目成果的鉴定结项由省哲学社会科学规划专项小组组织，实行匿名鉴定制度。项目负责人及所在单位须在规定时间内向省哲学社会科学规划专项小组提交项目结项材料，在规定时间内不提交结项材料，将作撤项处理。结项所需材料、装印要求等具体事项，请登录广东社科规划网站“结项信息”栏目查看。

6.成果鉴定等级分为优秀、良好、合格和不合格四个等次。通过结项的，将拨付预留经费。不合格即未能通过结项，其预留经费不予拨付，课题组需修改后半年内重新申请结项鉴

定。仍不能通过的，将作撤项处理。

7.被撤项的项目负责人五年内不得申报国家社科基金项目和省哲学社会科学规划项目。

以上规定，项目负责人及所在单位应严格遵守。如有异议，可不接受资助，立项协议自行废止。

联系人：冯甜恬

地址：广州市天河北路 618 号广东社科中心 B 座 928 室

电话：(020)83825078

邮编：510635

广东省哲学社会科学规划专项小组

广东省哲学社会科学规划领导小组办公室（代章）

2024 年 7 月 11 日

广 东 省 教 育 厅

粤教科函〔2022〕5号

广东省教育厅关于公布2022年度普通高校认定类科研项目立项名单的通知

各有关高校:

为深入实施创新驱动发展战略，落实《广东省教育厅 广东省科学技术厅关于印发科教融合协同推进高校科技创新能力提升工作计划的通知》（粤教科函〔2019〕57号），省教育厅组织开展了2022年度普通高校科研项目认定工作。经学校推荐、省教育厅组织审核，现将批准立项的2022年度普通高校认定类科研项目立项名单（见附件）下达各高校。

请各高校按照国家和省相关科研平台项目管理办法，统筹安排项目资金，加强资金管理，督促项目承担人按照项目申请书开展建设工作，协助解决项目实施过程中遇到的困难和问题，确保研究项目如期完成目标任务。

附件：1.2022年度广东省普通高校特色创新类项目立项名单

1	2022WTSCX001	岭南诗词在环境设计教学中的价值开发和传承创新	郑莉	华南理工大学
2	2022WTSCX002	面向GUI图形用户界面的专利规避设计研究	李淼	华南理工大学
3	2022WTSCX003	纳税信用评级披露对税收遵从的外溢效应研究	杨玉萍	暨南大学
4	2022WTSCX004	基于“三生空间”功能协同的珠三角水网地区传统村落重构策略研究	林蔚	华南农业大学
5	2022WTSCX005	高校音乐教育中岭南传统音乐文化的创造性转化发展研究	石娟娟	华南农业大学
6	2022WTSCX006	新时代廉洁文化建设的VR动画传播与研究	李雷鸣	华南农业大学
7	2022WTSCX007	后疫情时代应急语言服务者胜任力模型及其评价体系的构建研究	李清华	南方医科大学
8	2022WTSCX008	“顶天立地”医疗卫生大格局高质量发展法治保障研究	刘昂	南方医科大学
9	2022WTSCX009	新医科语境下的生命健康叙事与健康管理研究	田峰	南方医科大学
10	2022WTSCX010	基于深度学习和知识图谱的中医古籍知识整理	刘秀峰	广州中医药大学
11	2022WTSCX011	全过程人民民主引领地方治理现代化研究——以广东省为例	董宏鹰	华南师范大学
12	2022WTSCX012	重大突发公共事件中慈善组织社会救助效能研究	彭灵灵	广东外语外贸大学
13	2022WTSCX013	中国“新电视”场域的结构变化、文化生产与边界策略	周娟	广东外语外贸大学
14	2022WTSCX014	商事制度改革与县域企业创新：基于全国实地调研的发现	马晶	广东外语外贸大学
15	2022WTSCX015	“意义”否定表征的实验语言哲学进路	朱晓真	广东外语外贸大学
16	2022WTSCX016	大卫·马梅特戏剧的伦理叙事研究	赖日升	广东外语外贸大学
17	2022WTSCX017	健康语境下负面情绪管理的人际语用学研究	雷容	广东外语外贸大学
18	2022WTSCX018	基于文化空间视角的潮州古城保护和发展实施路径探析	郑红彬	汕头大学
19	2022WTSCX019	粤东地区“文创+IP”产业的转型与创新成长路径研究	贺姿雅	汕头大学
20	2022WTSCX020	文学地图的理论建构和空间可视化创新研究	黄继刚	汕头大学
21	2022WTSCX021	珠江三角洲“自梳女”影像保护研究	孟祥斌	汕头大学
22	2022WTSCX022	清代甘青地区汉族与少数民族法律文化交融研究	李守良	汕头大学

SCAULIB202406212

检索证明

根据委托人提供的论文材料，委托人**华南农业大学林学与风景园林学院 林蔚** 2 篇论文收录情况如下表。

序号	论文名称	发表刊物及发表的年月卷期/页码等	作者排名	论文等级	作者文中单位	收录情况	影响因子	中科院大类分区
1	Integrating Ecosystems and Socioeconomic Systems to Identify Ecological Security Pattern and Restoration Strategy in a Rapidly Urbanizing Landscape	FRONTIERS IN ENVIRONMENTAL SCIENCE 出版年：2022 卷期：10 页码：- 文献号：862310 文献类型：Article	通讯作者	B 类	华南农业大学	SCI	IF2-year=4.6 IF5-year=5.3 （2022）	环境科学与生态学 3 区 Top 期刊：否 （2022）
2	Zoning strategies for ecological restoration in the karst region of Guangdong province, China: a perspective from the "social-ecological system"	FRONTIERS IN ENVIRONMENTAL SCIENCE 出版年：2024 卷期：12 页码：- 文献号：1369635 文献类型：Article	通讯作者	B 类	华南农业大学	SCI	IF2-year=4.6 IF5-year=5.3 （2022）	环境科学与生态学 3 区 Top 期刊：否 （2023）

说明：论文等级和中科院大类分区按《华南农业大学学术论文评价方案（试行）》划分。

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检索员：张进

华南农业大学图书馆

SCAULIB202519262

检索证明

根据委托人提供的论文材料，委托人**华南农业大学林学与风景园林学院 林蔚** 7 篇论文收录情况如下表。

序号	论文名称	发表刊物及发表的年月卷期/页码等	作者排名	论文等级	作者文中单位	收录情况	影响因子	中科院大类分区
1	课程思政视角下的景观设计教学改革实践	城市建筑 出版年：2021 出版日期：2021-03-15 卷期：18 08 页码：166-168+180 文献号： 文献类型：期刊论文	第一作者	普刊类	华南农业大学林学与风景园林学院	CNKI	无	无
2	新工科背景下城乡规划专业信息技术类课程思政探索实践	中国教育技术装备 出版年：2024 出版日期：2024-07-10 卷期： 13 页码：67-69+78 文献号： 文献类型：期刊论文	第一作者	普刊类	华南农业大学林学与风景园林学院	CNKI	无	无
3	面向生态产品价值实现的供需分区优化策略——以喀斯特生态脆弱地区为例	生态经济 出版年：2025 卷期： 页码：- 文献号： 文献类型：	第一作者	C 类	华南农业大学林学与风景园林学院	北大核心	无	无

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东江下游流域城水耦合协调关系评价及其影响因素

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摘要: 针对城镇化进程对水资源系统干扰逐步加强的问题,基于水资源、水环境、水生态子系统构建水资源环境评价体系,基于空间、人口、社会经济子系统构建城镇化质量评价体系,测算东江下游流域 14 个区县单元的城水耦合协调度,并运用灰色关联模型分析城水动态耦合关系的主要影响因素。结果表明,2010—2020 年大湾区东岸城镇化水平不断提高,水资源环境水平波动上升,城水耦合度提升显著,由磨合阶段转变高水平耦合阶段; 耦合协调度在 2010—2015 年显著提升,2016—2020 年微弱下降,其中黄埔、龙华等城市边缘区耦合协调度降幅较为明显,空间分异显著; 高水平城水耦合关系下,人口增长、建设用地扩张是胁迫水资源环境的主要因素,水资源紧缺、用水效率低下以及水生态系统服务功能恶化是限制城镇化发展的主要原因。

关键词: 城镇化; 水资源环境; 耦合协调度; 灰色关联模型; 东江流域下游; 粤港澳大湾区

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Evaluation of urban-water coupling coordination relationship and its influencing factors in lower reaches of the Dongjiang River Basin // LIN Wei[1], CHEN Zilin[2], LI Hui[1] (1. *College of Forestry and Landscape Architecture, South China Agricultural University, Guangzhou* 510642, *China*; 2. *School of Architecture & Urban Planning, Shenzhen University, Shenzhen* 518060, *China*)

Abstract: In view of the increasing interference of urbanization on the water resources system, the evaluation system of water resources and environment was built based on water resources, water environment and water ecology subsystems, and the urbanization quality evaluation system was built based on space, population and socio-economic subsystems. The urban-water coupling coordinated degree of 14 districts and counties in the lower reaches of the Dongjiang River Basin was calculated, and the main influencing factors of the urban-water dynamic coupling relationship were analyzed by using the grey correlation model. The results showed that from 2010 to 2020, the urbanization level of the east bank of the Greater Bay Area continued to improve, and the level of water resources environment was fluctuating upward. The urban-water coupling degree had increased significantly, from running-in stage to high-level coupling stage. The coupling coordination degree increased significantly from 2010 to 2015, and declined slightly from 2016 to 2020. The coupling coordination degree of Huangpu District, Longhua District and other urban fringe areas decreased significantly, with significant spatial differentiation. Under the high-level urban-water coupling relationship, population growth and construction land expansion were the main factors that stress the water resources environment. The shortage of water resources, the low efficiency of water use and the deterioration of water ecosystem services are the main reasons that restrict the development of urbanization.

Key words: urbanization; water resources environment; coupling coordination degree; grey correlation model; lower reaches of the Dongjiang River Basin; Guangdong-Hong Kong-Macao Greater Bay Area

随着人类活动对自然水循环的影响逐渐加深,自然生态系统和经济社会系统逐渐演变失衡,产生了一系列城市水问题,严重制约了社会经济持续健康发展[1-2]。人水互动关系增强,水文系统和人类系统演变为一个耦合系统[3]。粤港澳大湾区人口高密度聚集,水资源与人类社会关系一直都是重要的研究课题,大湾区水问题亟待思考及解决[4-6],已在水资源、水安全、水环境、洪涝灾害等

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方面开展了有益探索[7-10]。通过构建评价指标体系，分析水资源脆弱性和生态敏感性及其演变特征[11-12]。然而，以上成果多从单方面水问题开展研究，或侧重于生态系统方面的指标体系构建和评价分析，对“自然-社会”复合生态系统间复杂的相互作用考虑不足[2]，难以刻画水资源开发利用、经济社会发展及生态环境保护之间复杂、变化的互馈关系[13]。

和谐的城水关系是科学配置城市水资源、改善人居环境、实现人与自然协调发展的前提和基础[2]。随着水问题研究的推进，城镇化与水资源、生态环境的耦合关系分析和耦合协调研究成为热点[14-16]，很多研究通过收集统计数据构建指标体系，以省、市为单元测度耦合协调程度，然而这些研究并未采用生态系统服务表征水循环过程的状态，较少考虑城镇化影响生态系统服务及其时空变化过程，不利于生态文明背景下的城市群发展[17]，对城水耦合关系的支撑有待进一步探讨。

流域是典型的复合生态系统，探析城镇化建设对水资源系统的多维干扰是开展流域治理的重要前提[18]。随着城镇化进程的推进，东江下游城市群面临着水资源短缺、水环境污染和水生态退化的严峻挑战[19]。“十四五”时期，我国城镇化将向高质量发展全面转型，亟待通过城水耦合重塑城市建设与水环境之间良性友好的整体关系[20]。因此，探究流域水资源保护、城市发展与水环境的内在关系，对促进粤港澳大湾区可持续发展具有重要实践价值。本文融合遥感、生态系统服务评估等多种技术方法，构建“水资源-水环境-水生态”的水资源环境系统评价体系，分析其与城镇化质量的耦合协调程度，以期为东江下游城市群提升发展提供参考。

1　研究区概况

东江是粤港澳大湾区东部重要水源地，具有突出的战略地位和生态价值。选取大湾区东部人口集聚、经济发达的下游流域(图1)，行政范围包括广州、深圳、东莞、惠州等4市，涉及10个市辖区、3个县区以及1个地级市(无下辖区县)。下游流域整体地势较为平坦，平均高程低于100 m，多年平均温度约20℃，年均降水量为1 200 ~2 000 mm，水网密布。根据统计年鉴数据，2020年研究区城镇化水平达75%左右[21]。

2　数据来源与研究方法

2.1　数据来源

研究数据包括GlobleLand 30土地覆被数据、

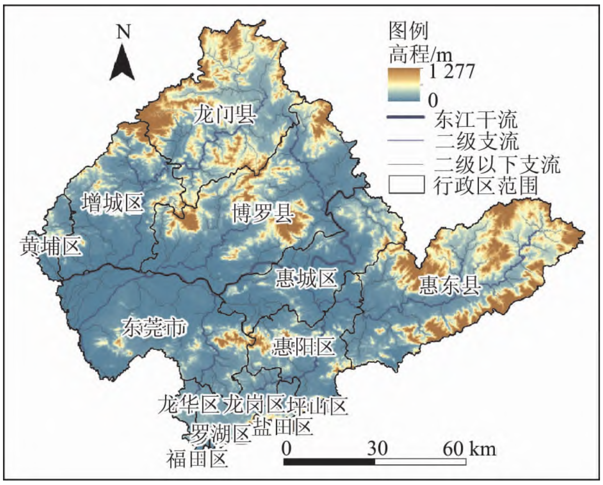

图1　东江下游流域概况

Fig. 1　Overview of lower reaches of the Dongjiang River Basin

MODIS全球蒸散发数据、植被指数数据、精细植被类型数据、气象数据、土壤质地数据、DEM数据以及各地区社会经济、水资源等统计数据，各数据时间序列均选择2010年、2015年及2020年。其中蒸散发数据来源于MOD16A2 8d合成产品(https://www.usgs.gov/)，空间分辨率为500 m，对数据进行拼接合成，提取实际总蒸散波段；植被指数数据来源于MOD13Q1 16合成产品(https://www.usgs.gov/)，空间分辨率为250 m，采用最大值合成法合成研究区逐月NDVI数据；土壤质地数据来源于寒区旱区科学数据中心(http://westdc.westgis.ac.cn/)中国土壤数据集，空间分辨率为1 km；数字高程DEM数据集源自地理空间数据云(http://www.gscloud.cn/)，空间分辨率为30 m；社会经济、水资源及水环境等统计数据源于东江下游流域内广州、深圳、惠州、东莞等地级市统计年鉴、水资源公报等，其中，坪山区(2016年新设)、龙华区(2016年新设)的2010年、2015年部分统计数据分别以龙岗区、宝安区代替。

2.2　指标体系构建

图2为东江下游流域城镇化质量与水资源环境评价指标体系，包括城镇化质量指标体系和水资源环境指标体系两部分(括号中数字为指标权重)。

2.2.1　城镇化质量指标体系

结合研究区城镇化发展情况，借鉴相关研究成果[22-23]，从空间、人口及社会经济发展3个子系统选取6个指标构建城镇化质量指标体系。选取建设用地率反映空间发展情况，人口发展用人口密度和常住人口城镇化率来反映，社会经济发展情况用人

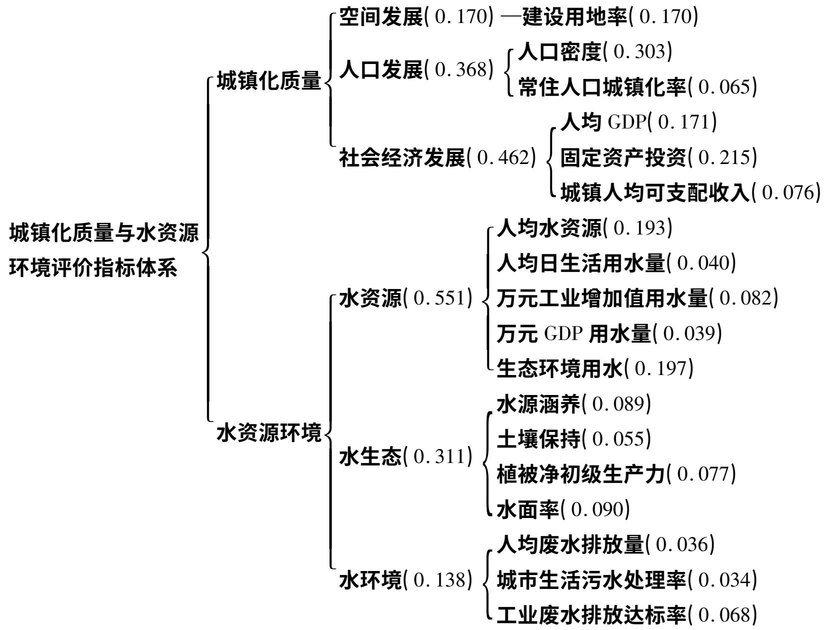

图 2　城镇化质量与水资源环境评价指标体系

Fig. 2　Evaluation index system of urbanization quality and water resources environment

均 GDP、固定资产投资、城镇人均可支配收入来反映。

2.2.2　水资源环境指标体系

流域水资源、水生态与水环境相辅相成，相互制约，水资源对维持城市社会经济发展具有重要意义，完善的水生态功能提供赖以生存的自然环境条件与效用，水环境是与水资源、水生物和污染密切相关的综合体[18-19]。因此，从水资源、水生态和水环境 3 个子系统选取 12 个指标，构建水资源环境评价指标体系。

a. 水资源。研究区 2010 年以来水资源管理制度深化落实，结合已有评价成果，本文从水资源禀赋条件、用水效率及用水需求等方面选取人均水资源量、人均日生活用水量、万元工业增加值用水量以及万元 GDP 用水量、生态环境用水量等 5 个指标进行评价。

b. 水生态。传统的水生态功能评价多采用监测指标或统计数据，本文引入维持水生态系统服务的重要因子：水源涵养、土壤保持、植被净初级生产力以及水面率共同评价水生态功能。其中水源涵养利用 InVEST 模型产水模块中的水量平衡法的变形式进行计算[24]；土壤保持通过修正水土流失方程计算年平均土壤流失量[25]，数值越大，土壤保持能力越差，为负向指标；植被净初级生产力采用 CASA 模型进行计算[26]；水面率为河道面积与区域面积之比[27]。

c. 水环境。良好的水环境质量是流域社会经济绿色协调、可持续发展的重要体现[19]。结合当前研究区水环境治理政策实施情况，选取人均废水排放量、城市生活污水处理率、工业废水排放达标率 3 个指标表征城市水环境状态。

2.2.3　数据标准化处理

由于评价指标存在量纲和属性差异，需引用极差标准化法对正、负向指标数据进行标准化处理[22]，公式分别为

$$Z_{ij} = \frac{X_{ij} - X_{j\min}}{X_{j\min} - X_{j\min}} \tag{1}$$

$$Z_{ij} = \frac{X_{j\max} - X_{ij}}{X_{j\max} - X_{j\min}} \tag{2}$$

式中：Z_{ij}为系统 i 指标 j 标准化后的指标值，其取值范围为 [0,1]；X_{ij}为原始值；$X_{j\max}$、$X_{j\min}$分别为指标 j 的最大值和最小值。

2.2.4　指标权重确定及综合评价指数计算

熵权法通过计算指标信息熵确定权重系数，能有效消除主观因素影响[28-29]，故采用熵权法计算指标权重，图 2 括号中为权重值。依据指标标准化值与权重系数，加权计算城镇化质量与水资源环境综合评价指数，计算公式为

$$f(U) = \sum_{i=1}^{a} m_i U_i \tag{3}$$

$$g(E) = \sum_{i=1}^{b} n_i E_i \tag{4}$$

式中：$f(U)$ 为城镇化质量综合评价指数；$g(E)$ 为水资源环境综合评价指数；m_i与 n_i为评价指标权重；U_i与 E_i分别为城镇化质量和水资源环境标准化指标值；a 和 b 为各系统指标数量。

2.3　耦合协调度模型

耦合度模型能够探究城镇化与水资源环境相互

影响程度，反映城水系统无序和有序状态的转变过程，展现系统内部组成要素间的动态关联关系[30]，耦合度越高，表明系统间关联程度越强[16]。结合相关研究及实际情况，将城镇化质量与水资源环境耦合度 C 划分为4个等级：$C\in(0,0.3]$ 表示处于低水平耦合阶段，$C\in(0.3,0.5]$ 表示拮抗阶段，$C\in(0.5,0.8]$ 表示磨合阶段，$C\in(0.8,1.0]$ 表示高水平耦合阶段。耦合度计算公式[31]为

$$C=\left\{\frac{f(U)g(E)}{[f(U)+g(E)]^2}\right\}^{\frac{1}{2}} \tag{5}$$

耦合度虽反映系统间相互作用程度，但无法表征各功能间是高水平的相互促进还是低水平相互制约[31]，因此进一步引入耦合协调度模型，量化城水系统在发展过程中的均衡状态和协调程度，着重分析系统之间的良性互动关系[30]。结合相关研究及实际情况，将耦合协调度 D 划分为6个等级：$D\in(0,0.2]$ 表示城水关系严重失调，$D\in(0.2,0.4]$ 表示中度失调，$D\in(0.4,0.5]$ 表示濒临失调，$D\in(0.5,0.6]$ 表示勉强协调，$D\in(0.6,0.8]$ 表示中度协调，$D\in(0.8,1.0]$ 表示高度协调。耦合协调度计算公式[31]为

$$D=\sqrt{CT} \tag{6}$$

其中 $$T=\alpha f(U)+\beta g(E)$$

式中：T 为城镇化质量与水资源环境综合发展指数；α 和 β 为系数，本研究认为两者同等重要，因此取 $\alpha=\beta=0.5$。

2.4 灰色关联度模型

城镇化质量与水资源环境交互耦合关系复杂多样，因此引入灰色关联度模型定量分析城镇化质量与水资源环境系统间的动态耦合关系，揭示城水耦合关系的主要影响因素。灰色关联分析是依据各因素序列曲线几何形状的相似程度来判断其联系紧密程度的方法，通过计算要素间的关联系数，根据关联系数对于样本数的平均数计算评价要素间的关联度，对关联度进行排序得到对某一对象影响程度的大小，关联度越大，影响程度就越大。关联度计算公式为

$$\gamma_{ij}=\frac{1}{m}\sum_{t=1}^{m}\xi_{ijt} \quad t=1,2,\cdots,m \tag{7}$$

其中

$$\xi_{ijt}=\frac{\min\limits_i\min\limits_j|Z_{\mathrm{U}it}-Z_{\mathrm{E}jt}|+\rho\max\limits_i\max\limits_j|Z_{\mathrm{U}it}-Z_{\mathrm{E}jt}|}{|Z_{\mathrm{U}it}-Z_{\mathrm{E}jt}|+\rho\max\limits_i\max\limits_j|Z_{\mathrm{U}it}-Z_{\mathrm{E}jt}|}$$

式中：γ_{ij} 为比较序列与参考序列整体关联度；m 为时刻数；ξ_{ijt} 为 t 时刻评价指标与参考序列对应元素的关联系数；$Z_{\mathrm{U}it}$ 和 $Z_{\mathrm{E}jt}$ 分别为各县(区) t 时刻的城镇化质量与水资源环境指标标准化值；ρ 为分辨率系数，一般取值0.5。

通过比较各个指标关联度 γ_{ij} 的大小，可以分析城镇化质量与水资源环境系统内部指标相互关联程度。γ_{ij} 介于0~1区间，值越接近1代表系统间关联性越大。参考相关研究，关联度取值范围及其判断标准划分为4个等级：$\gamma_{ij}\in(0.00,0.35]$ 表示二者为低水平关联状态，$\gamma_{ij}\in(0.35,0.65]$ 表示中等关联，$\gamma_{ij}\in(0.65,0.85]$ 表示高度关联，$\gamma_{ij}\in(0.85,1.00]$ 表示极强关联。

3 结果与分析

3.1 城镇化质量与水资源环境综合评价

3.1.1 城镇化质量时空分异特征

自2010年以来，研究区城镇化质量各项指标均呈现稳步提升，常住人口城镇化率由78%提升至85%，人均GDP上涨1倍，人口密度也大幅提高。2016—2020年，固定资产投资及城镇居民人均可支配收入得到大幅提升。总体而言，2010—2020年城镇化质量综合指数整体呈持续上升趋势，由0.34增加至0.48，其中黄埔、增城、坪山、龙华以及惠城等区提升较为明显。研究区城镇化水平存在显著空间差异，城镇化质量指数高值区主要集中于大湾区腹地的东江下游河段及其左岸支流石马河流域，主要包括福田、罗湖、龙华、盐田、黄埔、东莞等市区。而低值区分布于靠近上游河段的右岸公庄水流域及左岸西枝江流域，包括龙门、惠东、惠阳、博罗等县，整体呈现上游河段至下游河段城镇化水平递增的空间格局特征(表1)。

3.1.2 水资源环境水平时空分异特征

研究区水资源层面整体趋向良性发展，2010—2020年人均日生活用水量已下降35 L/d，水资源利用效率也大幅提升，万元工业增加值用水量及万元GDP用水量逐渐降低，表明研究区用水结构逐步优化。人均水资源2010—2020年由2 161.96 m^3 下降至1 804.65 m^3，低于全省平均水平。水生态层面的水土保持、水源涵养等水生态系统服务功能出现明显恶化趋势，主要原因是粗放的扩张建设导致植被覆盖度减少。数据分析显示，2010—2020年植被净生产力呈现下降趋势，土壤流失量增加16.54%，地表径流量由年均3 933.78 m^3/hm^2 上升至5 288.32 m^3/hm^2，水源涵养量下降7.34%，表明研究区面临较为严峻的水土流失问题。同时，由于河流截弯取直等工程破坏水系结构，水面率也下降6.43%。而水环境治理行动取得明显成效，污水排放处理各项指标均有所提升。

表 1　2010—2020 年各区县城镇化质量综合评价指数

Table 1　Comprehensive evaluation index of urbanization quality of each district and county from 2010 to 2020

年份	龙门县	博罗县	惠城区	惠东县	惠阳区	黄埔区	增城区
2010	0.011	0.068	0.183	0.065	0.142	0.330	0.162
2015	0.018	0.127	0.235	0.082	0.178	0.485	0.211
2020	0.037	0.179	0.286	0.125	0.192	0.538	0.315
年份	东莞市	龙华区	龙岗区	坪山区	福田区	罗湖区	盐田区
2010	0.519	0.493	0.492	0.399	0.783	0.543	0.508
2015	0.554	0.617	0.574	0.444	0.805	0.583	0.571
2020	0.593	0.673	0.646	0.516	0.849	0.629	0.651

水资源环境综合评价指数整体呈现波动变化趋势，2010—2015 年水资源环境水平稳步提升，由 0.38 提升至 0.42，2016—2020 年则下降至 0.40，呈微弱下降趋势。2010—2015 年，提升较为明显的包括龙门县、博罗县、惠城区、增城区及东莞市等干流沿岸地区(表 2)，其主要原因是研究区流域重要河段的水环境治理与修复取得成效；而这些地区在 2015—2020 年水资源环境水平整体有所下降，初步判断为城镇化进程加快导致水资源过度消耗和水生态空间遭受严重挤占。而下游河段发达城区如福田区、龙华区、东莞市、坪山区等水资源环境水平在 2015 年后有所回升，该片区生态环境投入大幅增加，水污染排放有效控制与治理修复促使水资源环境得到明显改善，加之水资源利用效率有所提升，使得水资源环境逐渐恢复。研究区水资源环境水平空间差异较小，下游河段整体水平略优于上游河段，东莞市、石马河流域的盐田区及增江流域的龙门县处于较高水平。

表 2　2010—2020 年各区县水资源环境综合评价指数

Table 2　Comprehensive evaluation index of water resources environment of each district and county from 2010 to 2020

年份	龙门县	博罗县	惠城区	惠东县	惠阳区	黄埔区	增城区
2010	0.443	0.321	0.364	0.344	0.305	0.394	0.432
2015	0.490	0.385	0.392	0.373	0.331	0.394	0.452
2020	0.464	0.358	0.401	0.318	0.317	0.346	0.424
年份	东莞市	龙华区	龙岗区	坪山区	福田区	罗湖区	盐田区
2010	0.471	0.375	0.344	0.361	0.401	0.423	0.526
2015	0.491	0.373	0.335	0.378	0.364	0.420	0.492
2020	0.521	0.377	0.365	0.404	0.402	0.433	0.529

3.2　城镇化质量与水资源环境耦合协调时空分异特征

3.2.1　耦合度时空分异特征

2010—2020 年，研究区城镇化质量与水资源环境耦合度整体呈现逐步上升趋势，自 0.702 提升至 0.813，由磨合阶段转变为高水平耦合阶段，反映了城镇化发展水平与水资源环境高度关联，相互作用程度逐渐提升。表 3 为各区县城镇化质量与水资源环境耦合度情况，可见耦合度持续上升且涨幅较大地区包括坪山、增城、东莞、博罗、惠城等区县。耦合度出现波动变化的主要有黄埔区与龙岗区，在 2010—2015 年呈现下降趋势，水资源环境水平提升速度难以匹配城镇化发展进程。其中，龙岗区由 0.837 降至 0.695，高水平耦合阶段退化为磨合阶段；黄埔区仍大于 0.8，处于高水平耦合阶段，而随着下游河段地区城镇化进程进入高质量发展阶段，龙岗区、黄埔区在 2016—2020 年阶段耦合度回升至高水平耦合阶段，水资源环境与城镇化发展相互适应。东江下游左岸石马河流域包括福田区、盐田区、罗湖区等城区。耦合度变化幅度较小，始终处于高水平耦合阶段，城镇化质量与水资源环境同步发展。2010—2020 年，各区县耦合度差异逐步缩小，但仍然存在明显的空间分异特征，高值区主要分布在东江干流沿岸及其左岸支流石马河流域，包括东莞市、深圳市各区及博罗县等地区，占研究区面积的 78.3%；而低值区主要分布在龙门县、惠东县、惠阳区。

表 3　2010—2020 年各区县城镇化质量与水资源环境耦合度

Table 3　Coupling degree of urbanization quality and water resources environment in each district and county from 2010 to 2020

年份	龙门县	博罗县	惠城区	惠东县	惠阳区	黄埔区	增城区
2010	0.250	0.426	0.546	0.345	0.439	0.923	0.808
2015	0.325	0.689	0.702	0.518	0.593	0.862	0.893
2020	0.404	0.721	0.792	0.540	0.642	0.978	0.954
年份	东莞市	龙华区	龙岗区	坪山区	福田区	罗湖区	盐田区
2010	0.898	0.815	0.837	0.845	0.821	0.802	0.878
2015	0.982	0.837	0.695	0.930	0.909	0.981	0.993
2020	0.998	0.892	0.847	0.984	0.906	0.990	0.991

3.2.2　耦合协调度时空分异特征

表 4 为各区县城镇化质量与水资源环境耦合协调度情况。2010—2020 年，研究区城镇化质量与水资源环境耦合协调度整体呈波动上升趋势，其中 2010—2015 年阶段由 0.557 提升至 0.612，由勉强协调状态转变为中度协调状态，提升较为明显地区主要为东江干流沿岸博罗、惠城、东莞、增城等区县，得益于这期间东江下游开展专项治水行动，以水生态修复为抓手，以水污染治理为重点，提升整体水环境质量，城镇化发展进程也持续推进，城水关系趋向协调共生。2016—2020 年阶段耦合协调度下降至 0.584，呈微弱下降趋势，整体状态仍为中度协调。降幅较大的区县包括黄埔、龙华、增城、惠阳，其中黄埔区由中度协调退化为失调状态，增城区与龙华区由中度协调状态转变为濒临失调状态。近年来，粤港澳大湾区边缘区优化增长和核心区有机更新成为新的发展趋势，如黄埔、龙华、增城等城市边缘区逐

渐成为发展重心。然而，人口快速聚集，人均生活用水和水资源开发压力急剧上升，生活、生产废水排放量持续提升，粗放的建设用地扩张造成水生态系统服务功能逐渐退化，水资源环境质量呈明显下降趋势，难以匹配城镇化快速发展进程，城水关系出现恶化。相较于城市边缘区的粗放扩张，下游河段福田区、罗湖区、盐田区、东莞市等城市核心区近年来进入高质量发展阶段，城镇化与水资源环境基本达到高度协调状态。这些片区随着环保投入的增加、水环境治理能力的强化、水资源利用效率提升、生态滨水空间修复改造等举措逐步落实，水资源环境整体水平得到有效改善，并促进城镇化可持续发展，推动城水关系呈现高水平相互促进，达到协调共生。2010—2020 年，各区县耦合协调度差距有所缩小，但仍然存在显著差异，下游河段整体优于上游河段，其主要原因是区域城镇化发展不平衡以及面临水资源环境压力不一致。上游河段地区包括龙门、博罗、惠东等区县城镇化水平较低，但水资源本底条件较好。2010—2015 年，上游河段地区耦合协调度整体提升显著; 随着城镇化对水资源环境的胁迫增强，2016—2020 年耦合协调度出现下降，部分地区回落至失调状态。而下游河段地区耦合协调度虽有波动变化，但整体仍维持在中度协调状态。

表 4 2010—2020 年各区县城镇化质量与水资源环境耦合协调度

Table 4 Coupling coordination degree of urbanization quality and water resources environment in each district and county from 2010 to 2020

年份	龙门县	博罗县	惠城区	惠东县	惠阳区	黄埔区	增城区
2010	0.281	0.295	0.454	0.358	0.208	0.543	0.590
2015	0.406	0.510	0.506	0.416	0.486	0.669	0.638
2020	0.373	0.478	0.592	0.385	0.373	0.442	0.586
年份	东莞市	龙华区	龙岗区	坪山区	福田区	罗湖区	盐田区
2010	0.837	0.571	0.582	0.602	0.810	0.779	0.894
2015	0.905	0.641	0.489	0.606	0.642	0.766	0.887
2020	0.950	0.593	0.642	0.801	0.833	0.812	0.929

3.3 高水平耦合状态下城水关系影响因素

城镇化质量与水资源环境的耦合关系可从城镇化发展对水资源环境的胁迫和水资源环境对城镇化的制约两个方面进行分析[30]。城镇化发展需要从水资源环境获取大量能量和物质，而该进程可能会对水资源环境产生胁迫作用，导致水资源环境恶化，各种水问题频发; 另一方面，水资源环境是城镇化发展的重要承载条件，将对城镇化发展产生约束作用，当通过有效措施(如控制城镇人口、加大环保投入、提升水资源利用效率) 改善水资源环境时，可促进城镇化发展质量提升(图 3) 。高水平耦合阶段下，城镇化质量与水资源环境系统内部组成要素交互耦合将推动城水系统走向良性或恶性的互动关系。为进一步厘清城水耦合关系的影响因素，以达到高水平耦合状态的 2020 年城镇化质量综合指数与水资源环境综合指数为参考序列，计算系统指标要素间的灰色关联度并排序，进一步揭示城水系统内部各要素交互耦合特征。

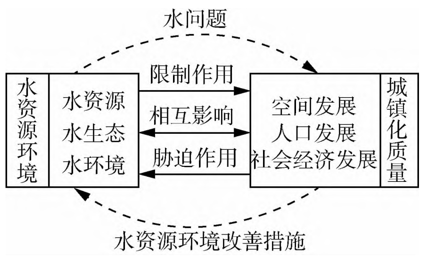

图 3 城水耦合机制

Fig. 3 Urban-water coupling mechanism

3.3.1 城镇化发展对水资源环境的主要胁迫因素

城镇化质量对水资源环境的综合关联度为 0.676，表明城镇化发展对水资源环境胁迫作用显著，主要胁迫因素为: 人口密度(与水资源环境关联度最高，为 0.861) 、建设用地率(关联度为 0.776) 、人口城镇化率(关联度为 0.738) 。人口要素是衡量城镇化水平的基础指标，也是地区水资源环境承载压力剧增的重要原因。2010—2020 年，研究区人口快速增长，人均水资源持续下降，用水需求也急速上升，对水资源环境系统产生胁迫影响最大，这也促使下游河段发达城区不断提升水资源利用效率，并实施城镇人口、产业用水限制等相关政策保护水资源环境。建设用地扩张是城镇化进程的主要体现，但同时也挤占水生态空间并导致巨大的水资源消耗和水污染排放。2010—2020 年，研究区建设用地率增加 6.34%，2010—2015 年建设用地增加集中在研究区下游河段地区，2016—2020 年上游河段建设用地扩张明显，造成区域植被覆盖锐减，水生态系统服务功能逐渐退化，水资源环境面临严峻挑战。人均 GDP(关联度为 0.636) 提升对水资源环境也有一定影响，经济产业快速发展可能导致水环境污染、水资源浪费以及治水成本提升。城镇人均可支配收入(关联度为 0.582) 、固定资产投资(关联度为 0.464) 对水资源环境的胁迫程度较小。

3.3.2 水资源环境对城镇化发展主要制约因素

水资源环境对城镇化质量的综合关联度为 0.642，表明水资源环境系统对城镇化发展具有较大的约束作用。其中，水资源环境系统与城镇化发展的关联度由大到小排序为: 水资源层面(0.713) 、水生态层面(0.621) 、水环境层面(0.614) 。制约城镇

化发展的主要水资源环境因素包括：人均水资源（与城镇化质量关联度最高，为0.858）、水源涵养功能（关联度为0.810）、单位GDP用水量（关联度为0.738）、工业废水排放达标率（关联度为0.672）、万元工业增加值用水量（关联度为0.656）等，表明水资源禀赋条件及用水效率对城镇化发展极为重要。研究区当前用水规模偏大，水资源本底条件及用水效率区域差异明显，制约了城镇化高质量发展。同时，水生态系统服务功能同样影响城镇化质量提升。近年来，龙门、惠东、博罗等山区县由于建设用地扩张、农田开垦导致植被覆盖度降低、土壤侵蚀性增强，河道硬化、截弯取直工程破坏河流自然形态，严重影响河网调蓄功能；水污染日趋严重，水环境治理较为滞后，也成为城镇化质量提升的阻碍之一。生活污水处理率（关联度为0.646）、人均日生活用水量（关联度为0.640）、固碳功能（关联度为0.624）、人均废水排放量（关联度为0.608）、水土保持功能（关联度为0.566）、河网调蓄功能（关联度为0.509）、生态环境用水量（关联度为0.482）等其他水资源环境因素对城镇化发展制约程度较小。

4 结　论

a. 城镇化质量综合评价指数呈现持续上升趋势，但区域间发展极不均衡，下游河段城镇化发展水平远超上游河段；水资源环境综合水平呈现波动变化趋势，2010—2015年稳步提升，2016—2020年出现微弱下降趋势，区域差异较小，下游河段整体水资源环境略优于上游河段。

b. 城镇化质量与水资源环境耦合度逐步上升，由磨合阶段转变至高水平耦合阶段，不同地区耦合度差异逐渐缩小，但仍存在明显的空间分异特征；城镇化质量与水资源环境耦合协调度时序变化出现波动，2010—2015年耦合协调度显著提升，由勉强协调状态转变为中度协调状态，2016—2020年微弱下降，但仍为中度协调状态。耦合协调度空间差异同样显著，下游河段优于上游河段，这与区域城镇化发展不平衡以及面临水资源环境压力不一致有关。

c. 高水平耦合状态下，城镇人口快速增长及建设用地的粗放扩张是城镇化发展胁迫水资源环境的主要因素；水资源紧缺的本底条件、不合理的用水效率以及逐渐恶化的水生态系统服务功能是水资源环境限制城镇化发展的主要原因。

参考文献：

[1] 王浩，贾仰文，杨贵羽，等. 海河流域二元水循环及其伴生过程综合模拟[J]. 科学通报，2013，58(12)：1064-1077.（WANG Hao，JIA Yangwen，YANG Guiyu，et al. Integrated simulation of the dualistic water cycle and its associated processes in the Haihe River Basin[J]. Chinese Science Bulletin，2013，58(12)：1064-1077.（in Chinese））

[2] 王浩，王佳，刘家宏，等. 城市水循环演变及对策分析[J]. 水利学报，2021，52(1)：3-11.（WANG Hao，WANG Jia，LIU Jiahong，et al. Analysis of urban water cycle evolution and countermeasures[J]. Journal of Hydraulic Engineering，2021，52(1)：3-11.（in Chinese））

[3] BLAIR P，BUYTAERT W. Socio-hydrological modelling: a review asking "why，what and how?"[J]. Hydrology and Earth System Sciences，2016，20(1)：443-478.

[4] 李郇，周金苗，黄耀福，等. 从巨型城市区域视角审视粤港澳大湾区空间结构[J]. 地理科学进展，2018，37(12)：1609-1622.（LI Xun，ZHOU Jingmiao，HUANG Yaofu，et al. Understanding the Guangdong-Hong Kong-Macao Greater Bay Area from the perspective of megacity region[J]. Progress in Geography，37(12)：1609-1622.（in Chinese））

[5] 王大洋，王大刚. 粤港澳大湾区背景下广东省9市人水和谐关系时空特性研究[J]. 水资源与水工程学报，2020，31(5)：23-29.（WANG Dayang，WANG Dagang. Spatiotemporal distribution characteristics of the human: water harmony in nine cities of Guangdong Province under the background of the Great Bay Area[J]. Journal of Water Resources & Water Engineering，2020，31(5)：23-29.（in Chinese））

[6] 李骏飞，杨磊三，孟凡松. 粤港澳大湾区面临的水问题探析[J]. 中国给水排水，2019，35(18)：10-14.（LI Junfei，YANG Leisan，MENG Fansong. Discussion on water problems of Guangdong-Hong Kong-Macao Greater Bay Area[J]. China Water & Wastewater，2019，35(18)：10-14.（in Chinese））

[7] 吴盼，赵信文，顾涛，等. 粤港澳大湾区水资源现状及其与社会经济协同演化趋势：与国际湾区对比研究[J]. 中国地质，2021，48(5)：11.（WU Pan，ZHAO Xinwen，GU Tao，et al. Current situation of water resources and its co-evolution trend with social economy in Guangdong-Hong Kong-Macao Greater Bay Area: a comparative study with the international bay area[J]. Geology in China，2021，48(5)：11.（in Chinese））

[8] 高真，黄本胜，邱静，等. 粤港澳大湾区水安全保障存在的问题及对策研究[J]. 中国水利，2020(11)：6-9.（GAO Zhen，HUANG Bensheng，QIU Jing，et al. Research on the water security issues and suggestions in Guangdong-Hong Kong-Macao Greater Bay Area[J]. China Water Resources，2020(11)：6-9.（in Chinese））

[9] 张万顺，张紫倩，彭虹，等. 粤港澳大湾区金山湖流域水质变化规律[J]. 水资源保护，2021，37(5)：1-8.

(ZHANG Wanshun, ZHANG Ziqian, PENG Hong, et al. Water quality variations of Jinshan Lake Basin in Guangdong,Hong Kong and Macao Great Bay Area [J]. Water Resources Protection, 2021, 37(5): 1-8. (in Chinese))

[10] 陈文龙，何颖清. 粤港澳大湾区城市洪涝灾害成因及防御策略[J]. 中国防汛抗旱，2021,31(3): 14-19. (CHEN Wenlong, HE Yingqing. Causes and prevention strategies on urban flood disasters in the Guangdong-Hong Kong-Macao Greater Bay Area [J]. China Flood & Drought Management, 2021, 31(3): 14-19. (in Chinese))

[11] 林钟华，刘丙军，伍颖婷，等. 变化环境下珠三角城市群水资源脆弱性评价[J]. 中山大学学报(自然科学版)，2018, 57(6): 8-16. (LIN Zhonghua, LIU Bingjun, WU Yingting, et al. Assessment of water resource vulnerability of the Pearl River Delta metropolitan under environment change [J]. Acta Scientiarum Naturalium Universitatis Sunyatseni, 2018, 57(6): 8-16. (in Chinese))

[12] 甘琳，陈颖彪，吴志峰，等. 近20年粤港澳大湾区生态敏感性变化[J]. 生态学杂志，2018, 37(8): 228-237. (GAN Lin, CHEN Yingbiao, WU Zhifeng, et al. The variation of ecological sensitivity in Guangdong-Hong Kong-Macao Greater Bay Area in recent 20 years [J]. Chinese Journal of Ecology, 2018, 37(8): 228-237. (in Chinese))

[13] LUO Zengliang, ZUO Qiting. Evaluating the coordinated development of social economy, water, and ecology in a heavily disturbed basin based on the distributed hydrology model and the harmony theory [J]. Journal of Hydrology, 2019, 574: 226-241.

[14] 吕添，吴次芳，李冠，等. 基于耦合模型的赣江水源保护区城市发展与水资源环境关系研究[J]. 水土保持研究，2014, 21(6): 271-277. (LYU Tian, WU Cifang, LI Guan, et al. Study on the relationship between the urban development and the environment of water resources in Ganjiang river based on coupling model [J]. Research of Soil and Water Conservation, 2014, 21(6): 271-277. (in Chinese))

[15] 焦士兴，王安周，李青云，等. 河南省城镇化与水资源耦合协调发展状况[J]. 水资源保护，2020, 36(2): 21-26. (JIAO Shixing, WANG Anzhou, LI Qingyun, et al. Study on coupling and coordinated development of urbanization and water resources in Henan Province [J]. Water Resources Protection, 2020, 36(2): 21-26. (in Chinese))

[16] 童彦，潘玉君，张梅芬，等. 云南省城市化与水资源的耦合协调发展研究[J]. 水土保持通报，2020, 40(6): 243-248. (TONG Yan, PAN Yujun, ZHANG Meifen, et al. Coupling and coordinated development of urbanization and water resources in Yunan Province [J]. Bulletin of Soil and Water Conservation, 2020, 40(6): 243-248. (in Chinese))

[17] 王世豪，黄麟，徐新良，等. 粤港澳大湾区生态系统服务时空演化及其权衡与协同特征[J]. 生态学报，2020, 40(23): 8403-8416. (WANG Shihao, HUANG Lin, XU Xinliang, et al. Spatial and temporal evolution of ecosystem services and its trade-offs and synergies in Guangdong-Hong Kong-Macao Greater Bay Area [J]. Acta Ecologica Sinica, 2020, 40(23): 8403-8416. (in Chinese))

[18] 王浩，王建华，胡鹏. 水资源保护的新内涵"量-质-域-流-生"协同保护和修复[J]. 水资源保护，2021, 37(2): 1-9. (WANG Hao, WANG Jianhua, HU Peng. New connotation of water resources protection: "quantity-quality-domain-connectivity-biology" coordinated protection and restoration [J]. Water Resources Protection, 2021, 37(2): 1-9. (in Chinese))

[19] 何艳虎，郭红江，谭倩，等. 广东省东江流域显著水问题类型识别[J]. 水资源保护，2021,37(5): 16-21. (HE Yanhu, GUO Hongjiang, TAN Qian, et al. Type identification of significant types of water problems in the Dongjiang River Basin,Guangdong Province [J]. Water Resources Protection, 2021, 37(5): 16-21. (in Chinese))

[20] 王世福，张晓阳. 以"城水耦合"实现"城水共生"[N]. 光明日报，2020-10-09.

[21] 吕乐婷，张杰，彭秋志，等. 东江流域景观格局演变分析及变化预测[J]. 生态学报，2019, 39(18): 6850-6859. (LYU Leting, ZHANG Jie, PENG Qiuzhi, et al. Landscape pattern analysis and prediction in the Dongjiang River Basin [J]. Acta Ecologica Sinica, 2019, 39(18): 6850-6859. (in Chinese))

[22] 郑炜. 广东省新型城镇化质量与水资源安全耦合分析[J]. 人民长江，2019,50(1):95-101. (ZHENG Wei. Coupling analysis of new urbanization quality and water resources safety in Guangdong Province [J]. Yangtze River, 2019, 50(1):95-101. (in Chinese))

[23] 王少剑，崔子恬，林靖杰，等. 珠三角地区城镇化与生态韧性的耦合协调研究[J]. 地理学报，2021,76(4): 973-991. (WANG Shaojian, CUI Zitian, LIN Jingjie, et al. Coupling relationship between urbanization and ecological resilience in the Pearl River Delta [J]. Acta Geographica Sinica, 2021, 76(4): 973-991. (in Chinese))

[24] 王秀明，刘谓承，龙颖贤，等. 基于改进的InVEST模型的韶关市生态系统服务功能时空变化特征及影响因素[J]. 水土保持研究，2020,27(5):381-388. (WANG Xiuming, LIU Xucheng, LONG Yingxian, et al. Spatial-temporal changes and influencing factors of ecosystem services in Shaoguan City based on improved InVEST [J].

Research of Soil and Water Conservation,2020,27(5):381-388.(in Chinese))
[25] 苏春生,吴孝情,陈晓宏,等.土地覆盖类型变化对梯度发展流域的土壤侵蚀动态影响[J].中山大学学报(自然科学版),2018,57(2):32-41.(SU Chunsheng, WU Xiaoqing, CHEN Xiaohong, et al. Dynamic impacts of land-cover change on soil erosion in a gradient development basin[J]. Acta Scientiarum Naturalium Universitatis Sunyatseni, 2018, 57(2): 32-41. (in Chinese))
[26] 朱文泉,潘耀忠,张锦水.中国陆地植被净初级生产力遥感估算[J].植物生态学报,2007(3):413-424.(ZHU Wenquan, PAN Yaozhong, ZHANG Jinshui. Estimation of net primary productivity of Chinese terrestrial vegetation based on remote sensing[J]. Chinese Journal of Plant Ecology, 2007(3): 413-424. (in Chinese))
[27] 王跃峰,许有鹏,张倩玉,等.太湖平原区河网结构变化对调蓄能力的影响[J].地理学报,2016,71(3):449-458.(WANG Yuefeng, XU Youpeng, ZHANG Qianyu, et al. Influence of stream structure change on regulation capacity of river networks in Taihu Lake Basin[J]. Acta Geographica Sinica, 2016, 71(3): 449-458. (in Chinese))
[28] 林珍铭,夏斌.熵视角下的广州城市生态系统可持续发展能力分析[J].地理学报,2013,68(1):45-57.(LIN Zhenming, XIA Bin. Analysis of sustainable development ability of the urban ecosystem in Guangzhou City in the perspective of entropy[J]. Acta Geographica Sinica, 2013, 68(1): 45-57. (in Chinese))
[29] 艾亚迪,魏传江,马真臻.基于AHP-熵权法的西安市水资源开发利用程度评价[J].水利水电科技进展,2020,40(2):11-16.(AI Yadi, WEI Chuanjiang, MA Zhenzhen. Evaluation on water resources development and utilization degree based on AHP-entropy weight method[J]. Advances in Science and Technology of Water Resources, 2020, 40(2): 11-16. (in Chinese))
[30] 刘永婷.城市发展对嘉兴市水系连通影响及其与水资源耦合关系研究[D].芜湖:安徽师范大学,2018.
[31] 张凤太,苏维词.贵州省水资源-经济-生态环境-社会系统耦合协调演化特征研究[J].灌溉排水学报,2015,34(6):44-49.(ZHANG Fengtai, SU Weici. The Evolution characteristics of coupling and coordination of water resources-economy-environment-society system in Guizhou[J]. Journal of Irrigation and Drainage, 2015, 34(6): 44-49. (in Chinese))

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[23] 李国栋,张俊华,王乃昂,等.基于重标极差分析和非周期循环分析的气候变化趋势预测:以兰州市为例[J].干旱区研究,2013,30(2):299-307.(LI Guodong, ZHANG Junhua, WANG Naiang, et al. Prediction of climate change trend based on rescaled range analysis and non-periodic cycle analysis: a case study in lanzhou city[J]. Arid Zone Research, 2013, 30(2): 299-307. (in Chinese))
[24] 张鑫,蔡焕杰,尹晓楠.应用重标度极差分析法(R/S)分析无定河流域水沙变化[J].农业工程学报,2010,26(增刊2):212-217.(ZHANG Xin, CAI Huanjie, YIN Xiaonan. Variation trends analysis of runoff and sediment time series based on R/S method in Wuding River Basin[J]. Transactions of the CSAE, 2010, 26(Sup2): 212-217. (in Chinese))
[25] 史贵君,郭力源,林涛,等.深圳市降水变化特征及其未来变化情况预测[J].长江科学院院报,2020,37(5):28-33.(SHI Guijun, GUO Liyuan, LI Tao, et al. Variation characteristics and future changes of precipitation in Shenzhen[J]. Journal of Yangtze River Scientific Research Institute, 2020, 37(5): 28-33. (in Chinese))
[26] 许月卿,李双成,蔡运龙.基于小波分析的河北平原降水变化规律研究[J].中国科学:D辑 地球科学,2004(12):1176-1183.(XU Yueqing, LI Shuangcheng, CAI Yunlong. The research on precipitation change in Hebei Plain based on wavelet analysis[J]. Science in China: Series D Earth Science, 2004, 34(12): 1176-1183. (in Chinese))
[27] 黄奇章.广东降水气候特征及其成因分析[J].热带地理,1990(2):113-124.(HUANG Qizhang. The analysis of the precipitation-climate characteristics and causes of formation in Guangdong Province[J]. Tropical Geography, 1990(2): 113-124. (in Chinese))
[28] 赵嘉阳,王文辉,靳全锋,等.基于EOF的福建省降水量时空变化特征分析[J].重庆理工大学学报(自然科学),2017,31(2):73-79.(ZHAO Jiayang, WANG Wenhui, JIN Quanfeng, et al. Analyzing spatial and temporal distributions of precipitation in Fujian Province using empirical orthogonal function[J]. Journal of Chongqing University of Technology (Natural Science), 2017, 31(2): 73-79. (in Chinese))

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摘 要:为反映生态水文系统的相似性和差异性规律,理解人类活动对生态水文系统的干扰规律,为流域资源开发、灾害预防和生态调控提供科学依据。以汀江上游流域为例,以地形、土壤、植被、水文、水资源与人口统计资料为基础,从生态现状、水文条件、生态背景和人类活动 4 个方面共 14 个指标统计各个子流域指标的特征值。采用主成分分析和聚类分析的方法将汀江上游流域内 35 个子流域划分为五类生态水文分区,并对每个分区的特征指标进行分析并命名,同时基于分区结果提出了相应的生态调控措施。分区结果能够揭示汀江上游流域生态水文特征空间上的差异性和相似性以及人类活动的影响,能够指导具有不同生态水文特征的区域进行因地制宜的发展。

关键词:生态水文分区; 主成分分析; 聚类分析; 生态调控; 汀江上游流域

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Research on Eco-hydrological Regions of Upper Reaches of the Tingjiang River

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Abstract: The similarities and differences of eco-hydrological system and the influences of anthropogenic activities on eco-hydrological system were investigated in order to provide scientific basis for resources development, disaster prevention and ecological regulation of basin. Taking the upper reach of the Tingjiang River (URTR) as the study area, based on the dataset of terrain, soils, vegetation, hydrology, water resources and population statistics, according to ecological status, hydrology condition, ecological background and anthropogenic activities of the URTR, we constructed the indicator system including 10 indexes of region alization. Using principal component analysis and cluster analysis, 35 sub-catchments of the URTR were assigned to 5 eco-hydrological regions (EHR), the characteristics of each EHR were analyzed and corresponding ecological regulation measures were proposed. The similarities and differences as well as the influences of anthropogenic activities on the URTR were revealed by regionalization results, which could provide fundamental basis for sustainable development for different EHR.

Keywords: eco-hydrological regions; principal component analysis; cluster analysis; ecological regulation; upper reach of the Tingjiang River

作为反映自然条件及生态环境在空间上分异特征的空间单元,目前的水文区划[1]、生态分区[2]、水生态分区[3-5]和水生态功能分区[6-7]等方面的研究已经比较成熟,在分区方法和指标体系上业已比较完善。但是针对流域尺度上生态系统和水文系统相互依赖和制约的特点,人类活动逐渐强化生态系统和水文系统的联系,如何协调二者日益成为流域管理的重要议题[8]。而现有的分区体系对于生态水文复合系统分异规律的研究还比较欠缺[9],需要一个合适的空间单元进行流域生态水文进行综合管理。因此,流域生态水文分区应运而生,生态水文分区是指在对流域生态水文系统客观认识的基础上,以流域自然生态水文系统的相似性和差异性规律以及人类活动对流域生态水文系统干扰的规律作为划分生态水文空间单元的

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划分依据[8-9]。进行流(区)域的生态水文综合区划是区域资源开发、灾害预防的重要依据,是对流域生态水文系统进行科学调控的基础。

生态水文分区研究最早应用于河流层面[10],尹民等基于河流生态环境需水量研究的需要将全国河流划分为一级到三级的分区,揭示不同分区单元的生态、水文特征[11],但侧重反映河流的形态结构、水体的水力联系和水利工程对生境的影响[8];杨爱民等根据我国不同流域或区域的生态水文特征,将全国划分为3个生态水文大区和36个生态水文区[9],该研究可以较全面地反映生态和水文系统的空间特征,但用于指定流域内具体的管理目标时尺度偏大[8]。蔡燕等以黄河流域行政县为基本单元划分生态水文分区,并依据分区的生态重要性识别需要优先保护的分区[8];尹晔对长江上游的大渡河流域、云南省分别进行了生态水文区的划分[12];张璐等根据南水北调受水区89个县(市、区)生态水文特征进行了相应区划[13];王韶伟等以福建省泉州市为例进行了生态水文区划研究[14]。综上所述,已有的生态水文分区研究主要侧重于大流域或省市尺度,缺少对我国大量山区范围内的中小河流开展类似分析,尤其缺少生态水文分区结果为山区流域中的城市与区域发展提供生态调控策略的应用。

分区指标是生态水文区划的基础,指标确定的是否合理,对于后续的分区工作有决定性的影响。一方面为准确揭示流域空间特征,指标应尽量全面。分区指标有影响因素和现状特征两种,前者包括影响背景的指标(如气候、地势等)和影响现状的指标(人类活动等),现状特征包括生态现状和水文现状[8]。已有的大型河流流域尺度生态水文分区指标主要包含气候、地形、水文、植被和人类经济活动等方面[9]。另一方面应立足于研究目的,指标需要着重反映研究区域的主要问题[8]。选择指标后,针对仍然存在涉及因素过多,资料收取不易的问题,需要降维的方法来对过多的指标进行简化,遗传算法、多元统计等方法的大量研究为指标筛选提供了良好的基础;主成分分析、系统聚类分析、模糊聚类分析等方法为生态水文区划提供了有效的方法[12]。

长汀县是福建省水土流失历史最久、面积最大、程度最严重的区域,2000年以后开展的新一轮大规模水土流失治理初见成效,但治理任务还相当艰巨,应继续加大自然生态修复的力度[15]。作为生态治理保育的重点,汀江上游流域属于低山轻度水土流失区,但是由于土壤多由风化发育而成,一旦植被遭到破坏,极易造成严重的水土流失。该区以水源涵养林和商品用材林为主,维护着区域森林生态系统的水源涵养和调节功能,对全县水资源供给和水文状况的改善有着重要的意义。本研究以长汀古城区上游的汀江流域为研究区域,通过GIS平台以子流域为划分单元,利用主成分分析及聚类分析方法,对汀江上游流域进行生态水文分区划分。根据生态水文分区结果为流域水生态环境保护、恢复和改善提供指导。

1　研究区概况

汀江上游流域(长汀古城上游)地处东经116°15′—116°33′,北纬25°45′—26°5′,位于福建省长汀县北部,覆盖大同镇、铁长乡、庵杰乡与新桥镇等行政区,东北部为宁化县治平畲族乡,西北部与江西省接壤。研究区面积为472 km^2,高程范围为297～1 350 m,坡降为5‰,主要支流包括七里河、郑坊河和铁长河。汀江上游流域多年平均降雨量超过1 700 mm,其中4—9月是主要的降雨季节,约占全年降雨量的70%。由于气候和地形等因素的影响,研究区极易受到锋面雨和台风雨的影响,最大日降雨量可达200～400 mm,位于研究区下游的国家历史文化名城长汀古城已遭遇若干次流域性特大洪水,给当地的社会经济造成了毁灭性打击,文化遗产和生态建设项目损失巨大。

流域内主要的下垫面类型是林地,占总面积比例近90%,其他的下垫面类型主要是建设用地(3.33%)和耕地(6.66%)。林地类型包括阔叶林、针叶林、毛竹和灌木,具体比例见表1。研究区内的林地虽多为水源涵养林,但受人类活动的影响,现有林分以针叶林和毛竹为主,针叶林主要分布在海拔400～800 m范围内(随海拔高度上升而减少),毛竹则分布于500～1 000 m的海拔区间(随海拔高度上升而增多);幼、中林比重大,天然阔叶林、混交林比重小,水源涵养能力较差。汀江上游流域内主要的土壤类型包括红壤、黄壤和水稻土,其他土壤类型包括潮土、紫色土和石灰土,具体组成比例见表2。

表1　汀江上游流域林地类型组成

林地类型	面积/km^2	比例/%
灌木	18.39	3.9
针叶林	209.08	44.4
阔叶林	28.65	6.09
毛竹	164.06	34.84

2　数据与方法

2.1　基础数据及来源

研究所需的基础数据包括数字高程模型、遥感影

像、土地利用现状图、土壤类型图、植被统计资料以及水文水资源资料和人口统计数据。数字高程模型基于 1∶50 000 数字地形图生成；遥感影像选择 2013 年 Landsat 8 遥感影像，用于研究区植被覆盖度的提取；林地类型分布图利用 2012 年福建省森林资源二类调查数据结合 2015 年福建省林地变更调查结果得到，根据《国家森林资源连续清查技术规定》将林班资料进行归纳整理；研究区土壤类型分布图通过长汀县土壤资源调查图数字化得到。人口数据来自于长汀县第六次人口普查，水文水资源资料均来源于 2013 年《长汀县水资源综合规划》。

表 2　汀江上游流域土壤类型组成

土壤类型	面积/km^2	比例/%
红壤	162.57	34.44
黄壤	199.92	42.36
水稻土	74.3	15.74
潮土	31.87	6.75
石灰土	3.18	0.67
紫色土	0.91	0.19

2.2　生态水文分区区划方法

为更好地认识流域生态水文特征及空间分布规律，为流域可持续发展提供必需的决策，根据汀江上游流域的地形、土壤、植被、水文、水资源与人口资料，采用主成分分析和聚类分析的方法将子流域划分为不同的生态水文分区。具体步骤为：

(1) 将汀江上游流域划分为 35 个子流域，子流域面积 7～23 km^2，平均面积为 13.5 km^2。

(2) 以汀江上游流域内的 35 个子流域作为生态水文分区的划分单元，选取能够反映流域生态系统和水文系统二者相互影响机制以及人类活动干扰规律的指标，统计各个子流域指标的特征值。

(3) 根据各子流域生态水文系统的相似性和差异性规律，利用主成分分析和聚类分析，对所有子流域进行分组，得到生态水文分区结果。

2.3　生态水文分区指标选择

汀江上游流域生态水文分区应遵循以下两个原则：(1) 生态系统和水文系统的整体性原则。二者不仅在地理位置上重叠，而且在结构和功能上不可分割。两种系统具有天然的联系，相互依存、相互制约，人类活动使二者的联系更加突出[8]。(2) 生态水文系统的等级性原则。与生态系统分区的等级性原则不同[2]，该原则主要体现在生态系统重要性大小、水文系统水量丰枯和人类影响的强弱等[8]。

生态水文分区涉及到生态系统和水文系统，在指标选择时还需要考虑到现状指标和影响因素指标。根据汀江上游流域生态区位的重要性，主要的下垫面类型为林地，水资源量比较充沛但容易遭受洪涝灾害影响的特点，在选择指标时要突出重要的生态系统，造成洪涝灾害或水土流失的原因及问题的严重程度等。本研究所选的生态水文分区指标包含生态现状、水文特征、生态背景和人类活动 4 类指标，每类指标特征值获取方法及数据来源见表 3。

(1) 生态现状。选择林地类型组成、植被覆盖度和土壤可侵蚀性三个指标。林地类型组成能够直接说明流域的生态现状，原生阔叶林可有效增加土壤入渗、减少径流量与泥沙量，生态重要性最高，而次生的针叶林和毛竹生态价值和水文效应较差。植被覆盖度表明森林的生长状态，一定程度上能够表征生态功能和涵养水源能力。土壤可侵蚀性(K 值)是一项评价土壤被降雨侵蚀力分离、冲蚀和搬运难易程度的指标[16]。K 值越大，在相同条件下，土壤受侵蚀的潜在危险就越大，反之越小[17]。

(2) 水文条件。水文条件既是影响汀江上游流域生态系统的因素，也是造成洪涝灾害的直接原因。降雨量是直接的径流来源，蒸发是径流形成过程中的主要损失，由于汀江上游流域内只有一个水文站对蒸发量进行长期观测，因此选择年平均降雨量和年平均径流深度反映研究区的水文条件。根据福建省水文图集多年平均径流深等值线图查得长汀县年平均径流深为 900～1 100 mm，年平均降雨量同样来源于福建省多年平均降水量等值线图。

(3) 生态背景。生态系统主要由气候、地形、植被、土壤等因素决定。由于研究区内的气候变化较小，植被和土壤因素在生态现状中已有考虑，因此选择受人类活动影响较少的地形作为影响因素指标。

(4) 人类活动。人类对水资源的开发强度是生态水文系统空间差异的一个重要原因，由于人类过度开发导致生产和生活用水量大幅上升，从而造成生态系统可用水量减少。选择人口密度、人均生产用水和生活用水作为衡量开发强度的指标。同时选择建设用地比例和耕地比例作为反映人为作用影响的指标。

3　结果与分析

3.1　生态水文分区划分

采用主成分分析与 k-means 聚类分析方法，对汀江上游流域进行生态水文分区划分。为剔除原始因子间的相关性，得到不包含重合信息的新变量，将提取出的汀江上游流域的地形、土壤、植被、水文水资源与人口指标经过标准差标准化处理后，在 SPSS 平台上进行主成分分析。抽取出特征值大于 1 的 3 个主成分来解释所有的原始变量，为使主成分便于解释各

原始变量,采用最大方差法实现正交旋转。由主成分分析结果(表4)可见,第一主成分解释了人口密度、人均生产用水、毛竹比例、针叶林比例和建设用地比例五个变量,第二主成分解释了覆盖度、平均坡度、土壤可侵蚀性三个变量,第三主成分解释了径流深度、降雨量、两个变量。在主成分分析结果的基础上,针对35个子流域分别计算抽取出的三个主成分的得分,并根据各子流域各主成分的得分在SPSS平台上进行k-means聚类分析。在聚类分析中以类中心点不再发生变化、或变化小于给定阈值作为收敛条件,由此得到每个子流域的聚类划分结果。经过16次迭代,聚类中心不再发生变化而达到收敛条件,通过上述聚类分析,根据各子流域的主成分得分,将35个子流域划分为五类生态水文分区,将聚类划分结果载入ArcGIS中生成生态水文分区分布图(图1),并统计各生态水文分区的各项指标的均值(表5)。

表3 不同特征值获取方法及数据来源

子流域特征值	获取方法	数据来源
植被状况—林地类型(阔叶林、针叶林、毛竹、灌木)所占比例	GIS叠置分析+统计分析	林地类型分布图
植被状况—覆盖度	波段计算+特征值统计	30 m分辨率Landsat 8遥感影像
土壤可侵蚀性	已有研究[18]	《长汀县土壤志》
年平均降雨量	GIS插值分析	《长汀县水资源综合规划》
年平均径流深度	GIS插值分析	《长汀县水资源综合规划》
地形—平均坡度	GIS地表分析	25 m分辨率数字高程模型
地形—最大高程差	GIS地表分析+统计分析	25 m分辨率数字高程模型
人口密度	GIS统计分析	《长汀县第六次人口普查》
人均生产用水	GIS统计分析	《长汀县水资源综合规划》
人均生活用水	GIS统计分析	《长汀县水资源综合规划》
建设用地比例、耕地比例	GIS统计分析	土地利用现状图

表4 主成分载荷矩阵

项目	主成分1	主成分2	主成分3
覆盖度(X_1)	0.295	0.834	−0.198
平均坡度(X_2)	0.344	0.725	0.028
高程差(X_3)	0.57	0.556	0.156
土壤可侵蚀性(X_4)	0.215	−0.89	0.069
径流深度(X_5)	0.047	−0.181	0.935
降雨量(X_6)	0.039	0.02	0.94
人口密度(X_7)	−0.751	−0.265	0.246
人均生活用水(X_8)	0.386	0.361	0.416
人均生产用水(X_9)	0.747	−0.064	0.254
阔叶林比例(X_{10})	0.482	0.303	0.342
毛竹比例(X_{11})	0.745	0.449	−0.294
针叶林比例(X_{12})	−0.744	−0.475	0.102
耕地比例(X_{13})	−0.342	−0.482	0.544
建设用地比例(X_{14})	−0.862	0.032	−0.094
方差/%	40.145	20.121	11.212
特征根	5.62	2.82	1.57

3.2 生态水文分区特征分析

分区一主要分布在七里河下游和郑坊河下游流域。该分区行政区划主要为大同镇,人口密度为五类分区之首。该分区人均生活用水和生产用水量为最低值。该分区有着最低的毛竹比例(3.3%)和最高的针叶林比例(73.64%),植被覆盖度属于中值。土壤可侵蚀性和最大高程差均为五类分区中的最低值。分区二主要包括铁长河中上游和郑坊河上游,在行政区划上包括铁长乡和庵杰乡西部区域及大同镇部分区域。由于铁长乡和庵杰乡是汀江上游流域主要的毛竹产区,林地结构中毛竹超过45%,该区域以毛竹的加工制造业为主,人口密度最小,人均生产用水量较大。地形方面,该分区的平均坡度和最大高程差均为五类分区中的最大值。分区二有着次高的平均径流深度和最高的降雨量,说明该分区位于汀江上游流域的多雨区。分区三包括大部分七里河流域。该分区的平均径流深和降雨量为五类分区中最低。分区三有着五类分区中最高的毛竹比例,同时植被覆盖度也是最高(约70%),土壤可蚀性在五类分区中较小,说明良好的植被结构能够有效地降低土壤受侵蚀的风险(图1,表5)。

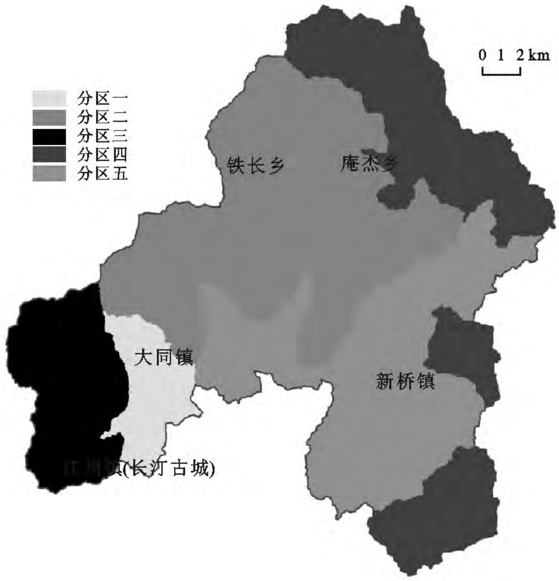

图1 汀江上游流域生态水文分区

表 5　生态水文分区各项指标的平均特征值

指标	生态水文分区				
	一	二	三	四	五
覆盖度(X_1)/%	63.38	68.38	69.97	60.55	53.84
平均坡度(X_2)/(°)	20.61	23.26	21.38	20.39	18.28
高程差(X_3)/m	447.67	767.10	610.00	625.63	518.2
土壤可侵蚀性(X_4)/(t·hm^2·hm^{-2}·MJ^{-1}·mm^{-1})	0.20	0.22	0.21	0.27	0.27
径流深度(X_5)/mm	988.65	1022.31	901.97	979.20	1029.76
降雨量(X_6)/mm	1698.73	1727.13	1608.43	1673.89	1716.43
人口密度(X_7)/(pop km^{-2})	272.35	52.21	58.29	76.10	181.3
人均生活用水(X_8)/m^3	41.01	110.79	41.01	64.31	63.96
人均生产用水(X_9)/m^3	421.25	712.27	421.25	820.85	537.95
阔叶林比例(X_{10})/%	3.46	9.60	2.11	5.83	4.49
毛竹比例(X_{11})/%	3.30	45.79	49.16	45.95	7.36
针叶林比例(X_{12})/%	73.64	31.17	38.86	38.05	66.22
耕地比例(X_{13})/%	4.48	5.41	3.46	4.30	12.75
建设用地比例(X_{14})/%	6.97	1.87	5.38	1.13	3.96

此外，该分区人口密度、人均生产、生活用水均比较低，说明该分区人类开发活动的强度较低。分区四行政区划上主要包括庵杰乡以东和新桥镇的东部、南部。该分区地处汀江干流上游区域。该区域的土壤可侵蚀性为五类分区之首，植被覆盖度较低。该分区的建设用地比例为五类分区中的最低值，毛竹与针叶林比例均比较大，人均生产用水量最高。分区五地处铁长河下游和汀江干流部分区域，行政区划主要包括大同镇东部和新桥镇西部。由于地处汀州镇（长汀古城）的外围，因此人口密度较大。分区五有着最高的平均径流深度和次高的降雨量，说明该分区位于汀江上游流域的多雨区。另一方面，该分区的林地比例是五类分区中最小的(78%)，针叶林比重超过 66%，植被覆盖度也是最低值(54%)，表明分区五的植被结构较差，同时该分区土壤可侵蚀性很大(0.27)。

表 6　汀江上游流域生态水文分区指标特征

分区	地理位置	水文条件	生态现状	开发程度
一	七里河和郑坊河下游	平水	中植被覆盖低土壤侵蚀	低
二	铁长河和郑坊河上游	多水	高植被覆盖低土壤侵蚀	高
三	七里河流域	少水	高植被覆盖低土壤侵蚀	低
四	汀江干流上游	平水	低植被覆盖高土壤侵蚀	高
五	汀江干流下游	多水	低植被覆盖高土壤侵蚀	高

根据各个分区的生态水文特征，采用具体地理位置＋水文条件＋生态现状＋开发程度对生态水文分区进行命名，并提出相应的生态调控策略：分区五为汀江干流下游多水＋低植被覆盖高土壤侵蚀＋高开发强度区；分区四为汀江干流上游平水＋低植被覆盖高土壤侵蚀＋高开发强度区；分区三为七里河少水＋高植被覆盖低土壤侵蚀＋低开发强度区；分区二为铁长河和郑坊河上游多水＋高植被覆盖低土壤侵蚀＋高开发强度区；分区一为七里河和郑坊河下游流域平水＋中植被覆盖低土壤侵蚀＋低开发强度区。

3.3　基于分区结果的生态调控策略

植被破坏是导致水土流失加剧的主要原因，同样也可能造成洪涝灾害风险提高。针对汀江上游流域的下垫面特征和分区结果，保护并进一步发挥森林的生态价值和水文效应是流域层面重要的生态调控措施，有助于流域生态系统的高效与优化。通过流域层面森林类型的逐步改造，发挥森林—土壤结构在一定降雨强度下对洪水的削减作用，不仅可以保持汀江上游流域生态系统的稳定，还可以减小流域内城市与区域遭受洪涝灾害的冲击。

汀江上游流域的林地由于长期受到人为影响，原有的基带性植被已大量破坏，林分质量较差，出现了严重的水土流失问题。近 20 a 来政府高度重视汀江上游流域的生态环境建设，持续进行有规模的造林并取得了一定的成果，但是补种的多为针叶林，分区一、五的针叶林比例分别达到 66%和 73%。由于次生的针叶林群落结构不稳定，水源涵养能力与天然阔叶林相差较大，对应的生态价值和防洪效应均较差[19]。故有必要通过增加阔叶林的比例逐步改善林分结构，改善林地蓄水和保水能力，降低土壤受侵蚀的风险。分区五针叶林比例大，植被覆盖度也是五类分区中最低，作为汀州城区外围的屏障区，由于人口密度较高且开发强度大，在未来应该注意开发建设与生态调控相协调，大力推进林分改造的工作，将针叶林逐步改造为阔叶林或针叶阔叶混交林。

毛竹是研究区主要的经济作物，分区二、三、四的毛竹比例均超过 45%，以毛竹加工制造业为主的经济在带来一定经济效益的同时也提高了生产用水量，甚至可能会给下游地区带来水污染的问题。尤其是分区二和分区四位于汀江干、支流的上游，应该注意避免对毛竹加工制造业的依赖，减小对下游流域的影响。同时需要注意的是，毛竹为单一林分会造成林地多样性急剧下降、生态退化等负面效应[20]。毛竹与阔叶林混交具备生态和经济的双重优势，因此可考虑将原有的毛竹纯林逐步改造为毛竹阔叶混交林，发挥混交林涵养水源的优势，提升汀江上游流域林地的生态价值。分区二虽然同时拥有五类分区中最高的阔叶林比例(9.6%)，但由于较高的毛竹比例，仍建议将大量的毛竹进行改造。

五类分区中，分区五的土壤可蚀性最低，主要受益于相对较好的植被结构和最小的平均坡度。分区三的阔叶林比例在五类分区中最小，但植被覆盖度和

林地比例均是五类分区的最高值，在土壤可蚀性、水文条件和开发强度均较低的背景下，建议通过提高阔叶林的比例增强生态价值和防洪效应。汀江上游流域虽然属于长汀县内水土流失轻度地区，但由于其生态区位重要性，除了林分改造，还需要其他辅助的水土保持措施来降低土壤遭受侵蚀的风险。分区一和四的土壤受侵蚀风险最高，主要受到植被结构的影响，应该在该分区实施生物措施和工程措施综合的生态调控策略[21]，降低土壤受侵蚀的风险。

4　结论

通过分析汀江上游流域生态水文系统的相似性和差异性规律，生态系统和水文系统二者之间相互影响机制以及人类活动干扰规律的指标，从生态现状、水文条件、生态背景和人类活动4个方面统计各个子流域指标的特征值；将以上具有一定相关关系的指标进行主成分分析得到3个相互独立且不含重叠信息的主成分，利用k-means聚类分析方法将汀江上游流域内35个子流域划分为五类生态水文分区，并对其空间分布规律及其生态水文特征进行描述和分析。

分区结果能够揭示流域生态水文特征空间上的差异性和相似性以及人类活动干扰程度，能够指导具有不同生态水文特征的区域进行因地制宜的发展，为汀江上游流域提升生态功能，保证城市与区域的防洪安全提供必需的决策依据。我国东南部大多数山地城市自然生态环境条件优越，林业资源和生物多样性丰富，但自然生态系统十分脆弱，容易发生水土流失和山洪灾害，本研究所用的生态水文分区方法及相应的生态调控措施可为类似区位的山地城市的生态建设与防洪减灾所借鉴。

虽然研究区范围属于较小的流域尺度，但由于分区特征指标和子流域单元的尺度较为匹配，因此生态水文分区结果较为连续。未来可考虑结合流域范围内长时间土地利用变化的情况对生态水文分区的结果进行比较，将能够更为深入探讨人类活动对流域生态水文特征的影响；同时可借鉴“景观安全格局”理论，寻找对于流域水文过程具有重要意义的生态要素，通过城市与区域规划落实为水生态基础设施，可持续地解决流域的生态与水文问题。

参考文献：

[1] 冯平，魏兆珍，李建柱．基于下垫面遥感资料的海河流域水文类型分区划分[J]．自然资源学报，2013，28(8)：1350-1360.
[2] 傅伯杰，刘国华，陈利顶，等．中国生态区划方案[J]．生态学报，2001，21(1)：1-6.
[3] 孟伟，张远，郑丙辉．辽河流域水生态分区研究[J]．环境科学学报，2007，27(6)：911-918.
[4] 刘星才，徐宗学，徐琛．水生态一、二级分区技术框架[J]．生态学报，2010，30(17)：4804-4814.
[5] 孙小银，周启星．中国水生态分区初探[J]．环境科学学报，2010，30(2)：415-423.
[6] 孙然好，汲玉河，尚林源，等．海河流域水生态功能一级二级分区[J]．环境科学，2013，34(2)：509-516.
[7] Gao Y N, Gao J F, Cao J F, et al. Regionalizing aquatic ecosystems based on the river sub-basin taxonomy concept and spatial clustering techniques [J]. International Journal of Environmental Research & Public Health, 2011,8(11):4367-4385.
[8] 蔡燕，鱼京善，王会肖，等．黄河流域生态水文分区及优先保护级别[J]．生态学报，2010，30(15)：4213-4220.
[9] 杨爱民，唐克旺，王浩，等．中国生态水文分区[J]．水利学报，2008，39(3)：332-338.
[10] Snelder T H, Biggs B J, Woods R A. Improved eco-hydrological classification of rivers[J]. River Research & Applications, 2005,21(6):609-628.
[11] 尹民，杨志峰，崔保山．中国河流生态水文分区初探[J]．环境科学学报，2005，25(4)：423-428.
[12] 尹晔．长江上游典型流（区）域生态水文区划分的研究[D]．成都：四川大学，2006.
[13] 张璐，杨爱民，吴赛男，等．南水北调中线一期工程受水区生态水文分区[J]．水利水电技术，2009，40(12)：8-11.
[14] 王韶伟，许新宜，陈海英，等．基于SOFM网络的生态水文区划[J]．生态学杂志，2010，29(11)：2302-2308.
[15] 王维明，陈明华，林敬兰，等．长汀县水土流失动态变化及防治对策研究[J]．水土保持通报，2005，25(4)：73-77.
[16] 梁音，史学正．长江以南东部丘陵山区土壤可蚀性K值研究[J]．水土保持研究，1999，6(2)：47-52.
[17] 邓玉娇，薛重生，林锦祥．基于3S技术实现湖北房县土壤侵蚀定量研究[J]．水土保持研究，2006，13(6)：208-209.
[18] 曾慧娟，潘文斌．基于RS/GIS和RUSLE的福建武步溪流域土壤侵蚀研究[J]．安全与环境学报，2007，7(5)：88-92.
[19] 韩永刚，杨玉盛．森林水文效应的研究进展[J]．亚热带水土保持，2007，19(2)：20-25.
[20] 刘蔚漪，范少辉，漆良华，等．闽北不同类型毛竹水源涵养功能研究[J]．水土保持学报，2011，25(2)：92-96.
[21] 丁文峰，张平仓，任洪玉，等．秦巴山区小流域水土保持综合治理对土壤入渗的影响[J]．水土保持通报，2007，27(1)：11-14.

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Research Topics

Weather and climate extremes in the urban environment: Modeling and observations

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Integrating Ecosystems and Socioeconomic Systems to Identify Ecological Security Pattern and Restoration Strategy in a Rapidly Urbanizing Landscape

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The rapid process of urbanization has been accompanied by a disordered expansion of construction land, which has resulted in the degradation of ecosystem services. The identification of ecological security patterns (ESPs) is an important means to coordinating human-land relationships and carrying out ecological restoration strategies, which are of great significance to protecting ecological sustainability. However, previous studies have ignored the mutual impact of urbanization and ecological protection, which leads to the contradiction between them and useless of ESPs. This paper takes a rapidly urbanizing metropolitan area as an example. Ecological sources were identified based on the integration of ecosystem services and socioeconomic indicators by the Ordered Weighted Averaging (OWA) method, which considers the trade-off between ecosystems and socioeconomic systems. The Linkage Mapper tool was used to extract ecological corridors, and thus ecological barrier points and pinch points were identified to implement ecological restoration. ESPs included 158 ecological sources according to the results. In more detail, the ecological sources and corridors were mainly distributed in the area dominated by ecosystem indicators, whereas the central urban area contributed less ecological sources, which indicates that the trade-off between ecosystems and socioeconomic systems has a significant impact on the construction of ESPs. Specifically, 406 ecological corridors were classified into different resistance levels to extract 433.26 km^2 barrier points and 458.51 km^2 pinch points. The study also proposed primary and secondary ecological restoration strategies for medium-, high- and low-resistance corridors based on the optimization of ESPs, which could not only improve ecosystem quality, but also fulfil the demands of human well-being. The integration of ecosystems and socioeconomic systems improves the existing methods for identifying ecological sources and restoration priority areas, and provides a scientific basis for balancing the development of urbanization and ecological protection in metropolitan regions.

Keywords: ecological security pattern, ecosystem services, socioeconomic system, trade-off, OWA method, Guangzhou

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1 INTRODUCTION

Along with the continuous urbanization of recent decades, disorderly expansion of urban construction land and significant loss of ecological land have restricted the sustainability of urban development (Feist et al., 2017; Peng et al., 2018; Zhai and Huang, 2022). Within a coupled human and natural system, the quantity and quality of the ecosystem services are impacted by anthropogenic disturbances, which affects regional landscape patterns and ecological security (Peng et al., 2017b). As a result, how to ensure the structural stability and functional security of natural ecosystems for sustainable urban development is an urgent issue (Li et al., 2015; Cumming and Allen, 2017; Serra-Llobet and Hermida, 2017). The construction of ecological security patterns (ESPs) was proposed to develop a method for improving ecological security. The ESPs, an interconnected ecological network composed of different ecosystems, is an effective approach to support biological species, maintain natural ecological processes and promote ecosystem services, as well as to achieve regional ecological sustainability (Su et al., 2016; Peng et al., 2018; Fu et al., 2020).The concept of ESPs was derived from landscape ecological planning in the 1990s (Yu, 1996). Many scholars have studied ESPs on different scales from the perspective of landscape ecology and urban planning (Peng et al., 2017b; Peng et al., 2018).

Landscape elements of key significance for ensuring regional ecological processes and ecosystem services, such as ecological sources, ecological corridors and strategic points, are all focused on ESPs (Dong et al., 2021; Gao et al., 2021). Therefore, the basic research paradigm of "identification of ecological sources, construction of resistance surfaces, and extraction of ecological corridors" has been gradually formed (Zhang et al., 2017). The strategy for selecting ecological source areas is fundamental to the construction of an ESPs, which is mainly conducted through assessing the ecological sensitivity, ecological importance or connectivity (Su et al., 2016) (Zhang et al., 2017). The method of identification of ecological sources has changed from the direct selection of nature reserves to the evaluation of ecosystem services that affect regional ecological security (Peng et al., 2017a; Wu et al., 2018). The integration of multiple ecosystem services, such as water yield and biodiversity protection, has been applied to source identification (Peng et al., 2018; Fu et al., 2020).

Integrating various components of coupled human and natural systems is necessary to address complex interconnections and to identify effective solutions to sustainability challenges (Liu et al., 2015). However, ecosystem services and human activities are seldom considered jointly in the assessment of ESPs (Wang et al., 2019); most studies have not adequately considered the ability to fulfill people's demand for ecosystem services when identifying sources of ESPs, which still focus on ecological patches as the supplier of ecosystem services, ignoring the interaction between ecosystems and human socioeconomic systems (Zhang et al., 2017). These ecological patches with the ability to fulfill human demand (e.g., cultural ecosystem services) is essential to consider when evaluating their capacity to form part of the source area.

It is worth noting that previous studies that considered an integrated valuation approach weighting various overlapping types of ecosystem services, may have overlooked the relationships (trade-offs or synergies) between these services. This may have either induced space competition among multiple ecosystem services or undermined the causal interrelationship among multiple ecosystem services (Dai et al., 2017; Zhao et al., 2020; Pan and Li, 2021). There is thus an urgent need to study and balance the trade-offs among multiple ecosystem services in decision-making processes (Zhang et al., 2015). One of the multicriteria evaluation methods, the ordered weighted averaging (OWA) operator, was first developed in the context of fuzzy set theory (Yager, 1988). The use of the OWA method has proven to be an effective approach in decision-making processes, and proposed a set of scientific and flexible planning methods to balance multiple conflicting ecosystem services in ESPs construction processes (Zhao et al., 2020; Pan and Li, 2021). Moreover, increasing economic development has led to urbanization in previous undeveloped areas (Deng et al., 2021), and caused many ecological and environmental problems in the meanwhile. The increasing ecosystem services may lead to the control of the development of urbanization (Li et al., 2022). These are issues needed to be discussed, the mutual impact of urbanization and ecological protection has not been considered and the trade-off between ecosystems and the socioeconomic system is still unclear. To address this gap, socioeconomic indicators should be considered to integrate with ecosystem services in order to construct the ESPs. Therefore, the OWA method was introduced to resolve the contradiction between ecological protection and urbanization decisions in this study. The optimization of ESPs in most of the current studies focused on the improvement of the evaluation process (Peng et al., 2018; Wang et al., 2019). However, there was little research on optimization after the establishment of ESPs (Fu et al., 2020). ESPs can provide a practicable way for ecological restoration to spatially identify key landscape elements; existing studies have identified key restoration areas in ecological corridors, pinch points, break and barrier points (Wang et al., 2018; Fang et al., 2020), and put forward zoning ecological restoration solutions (Ying et al., 2019; Ni et al., 2020). In addition, the ecological restoration of a coupled ecosystem and socioeconomic system based on ESPs is still in its infancy.

In recent years, Guangzhou has grown rapidly and has spread in a disorderly manner (Fan et al., 2018), and the ecological land has been seriously damaged, which seriously affects the welfare of the residents (Zhang et al., 2020). Hence, the Municipality government of Guangzhou proposed a framework of ecological networks and corridors in the metropolitan area and municipal administrative area according to ecological civilization construction planning (2016–2020). There have been similar approaches to constructing an ecological network of Guangzhou and to improving environmental protection under rapid urbanization (Zhao et al., 2017; Yang et al., 2018). However, previous approaches focused solely on ecological elements, such as forest land, natural reserves and the habitats of crucial species, without using an ecosystem service importance evaluation. The

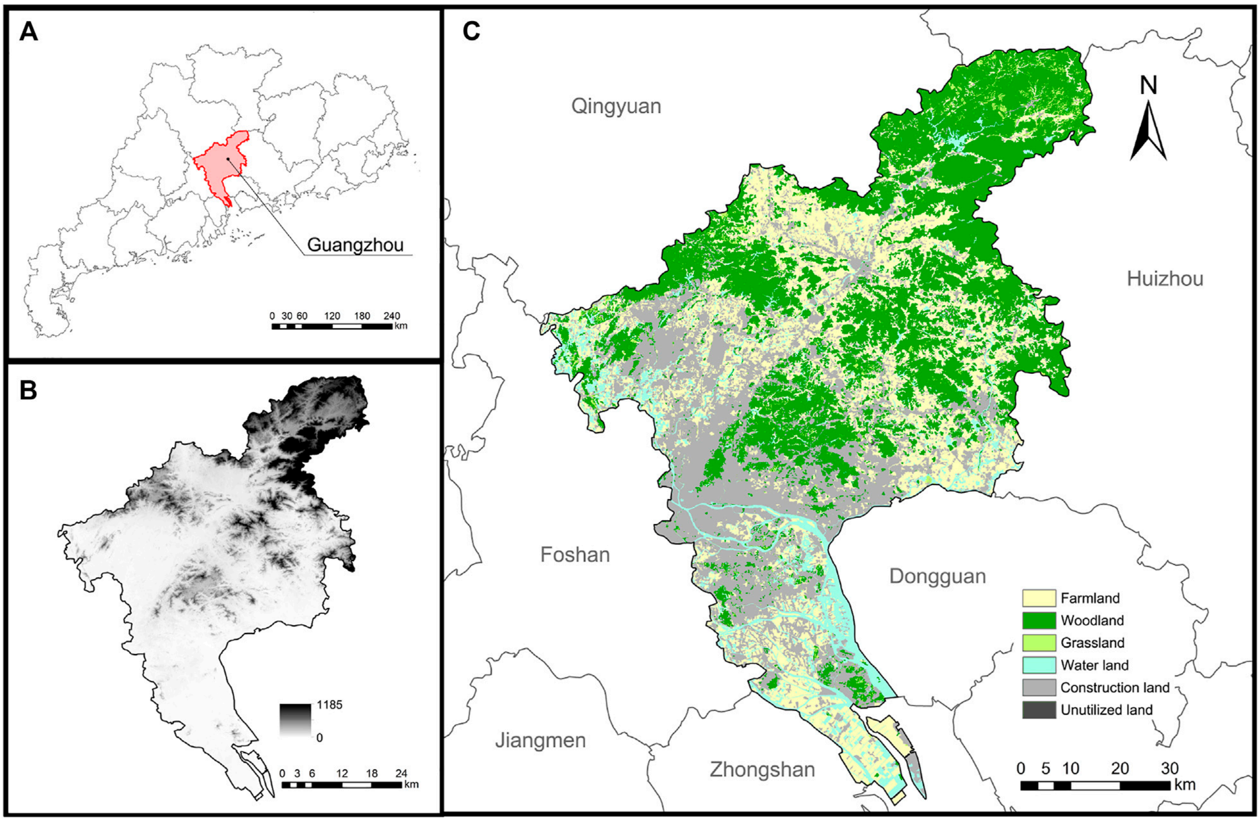

FIGURE 1 | (A)is the site of the study area, **(B)** is the elevation of the study area, **(C)** is land cover types of the study area.

studies mentioned above only assessed the landscape connectivity, failing to consider both the importance of ecosystem services and socioeconomic indicators, as well as restoration strategies. Therefore, it is urgent to move the process of ecological protection and restoration forward in order to identify key restoration regions for Guangzhou based on the optimization of the ESPs.

Based on the above considerations, the research objectives were to identify ecological sources by comprehensively evaluating the integration between ecosystem and socioeconomic indicators, to build ESPs based on the lowest cost path and identify the barrier point and pinch point for the corridors and to propose the optimization of the ecological restoration regions on the basis of ESPs.

2 MATERIALS AND METHODS

2.1 Study Area

Guangzhou is the central city in the Guangdong-Hong Kong-Macao Greater Bay Area, with a total area of 7434.4 km^2. There are eleven municipal districts in Guangzhou (**Figure 1**). Having a topographical structure of densely forested mountains, the northern area is the ecological supporting area of Guangzhou. The central area, with its topography of hilly and basins, is the location of the socioeconomic center. Besides, the southern area is also a potential area for the future development of construction land due to the plain topography. With the rapid socioeconomic development of Guangzhou in the past decade, the construction land has expanded rapidly and the population has grown about 500,000 people per year. Therefore, Guangzhou has become one of the cities where the conflict between urban development and the ecological environment is most prominent in the Greater Bay Area (Li et al., 2021).

2.2 Data

The basic data in this study mainly include: 1) the 2020 Globe Land 30M surface coverage dataset from Globe Land http://www.globallandcover.com/; 2) the 2020 GDEMV2 30M resolution digital elevation data from NASA https://search.earthdata.nasa.gov/search/; 3) Guangdong Province 30M resolution soil erodibility factor dataset from National Science and Technology Infrastructure Platform - National Earth System Science Data Center http://www.geodata.cn; 4) 2020 MODIS MOD13Q1 NDVI 16-days data from NASA https://modis.gsfc.nasa.gov/data/; 5) 2020 monthly values of basic elements of China's international exchange station for meteorological radiation and monthly values of China's ground climate data from the National Meteorological Science Data Center http://data.cma.cn/; 6) 2020 national urban road dataset from Gaode Map https://www.amap.com; 7) 2020 Guangzhou city POI data from Gaode Map https://www.amap.com; 8) NPP/VIIRS annual

TABLE 1 | Assessment methods.

Indicator	Method	Calculation
Carbon Fixation	To study the metabolic capacity of the ecosystem, the net primary productivity is used to characterize the Carbon fixation Yang et al. (2016). Carnegie Ames Stanford (CASA) model	NPP(i,t) = APAR(i,t) × ξ(*i*, *t*); NPP(i,t) is the net primary productivity on-grid i in time period t; APAR(i,t) is the photosynthetically active radiation index on-grid i in time period t, and ξ(*i*, *t*) is the light energy conversion rate on-grid i in time period t
Water Yield	The Water Balance Method Casagrande et al. (2021)	WY = P−ET−D; WY is the annual water yield; P is annual precipitation; ET indicates the annual evapotranspiration; D is the surface runoff, which is the product of surface runoff coefficient and precipitation Wang et al. (2020)
Soil Conservation	RUSLE Erosion Model Ye and Shi (2021)	A = R× K× LS× C× P; A is the erosion amount of soil; PA is the erosion amount of soil; R is the rainfall erosion factor; K is the soil erodibility factor; LS is the slope length slope factor; C is the vegetation cover and management factor, and P is the soil conservation measure factor. Among them, the rainfall erosion factor (R) is set as a constant due to the small difference of precipitation in the study area, and the P and C coefficients will refer to the research results of related literature
Habitat Quality	Habitat Quality module of the InVEST model Liu et al. (2021)	
Cultural Ecosystem Service	Recreation services, accessibility, and historical heritage services Yu et al. (2018); Marina et al. (2020) demonstrate the level of cultural resources in the study area, so the study identifies the potential for sustainable cultural development through this index	CS = 0.9L+0.1CH; L = 0.2LU+0.5P+0.15RD+0.15 PT; CS is the value of cultural services; L is the value of recreation and leisure; CH is the value of spiritual and cultural resources, calculated by estimation of historical and cultural facilities in the study area. LU is the type of land use coverage; P is the service of the parks in the study area, which is quantified with reference to the evaluation of Guangzhou city parks in “Guangzhou City Park Directory” “Guangzhou City Green Space System Plan (2020–2035)”. RD is road density, and PT is public transport station distribution density, which is quantified by kernel density estimation to POI data of public transport stations Yang and Li (2021); Bing et al. (2021)
Landuse Development Degree		The ratio of construction land to the total land area in the study unit. This study quantifies the degree of land use development by the ratio of built-up land to total land area within a 100 m grid Peng et al. (2017a)
Population Density	Worldpop 100 m population density raster dataset	There are significant differences in population density and nighttime lighting index between different areas. Therefore, the study will take the logarithm of the two indicators PD and NL Gong et al. (2019)
Nighttime Lighting	NPP/VIIRS annual nighttime lighting index	

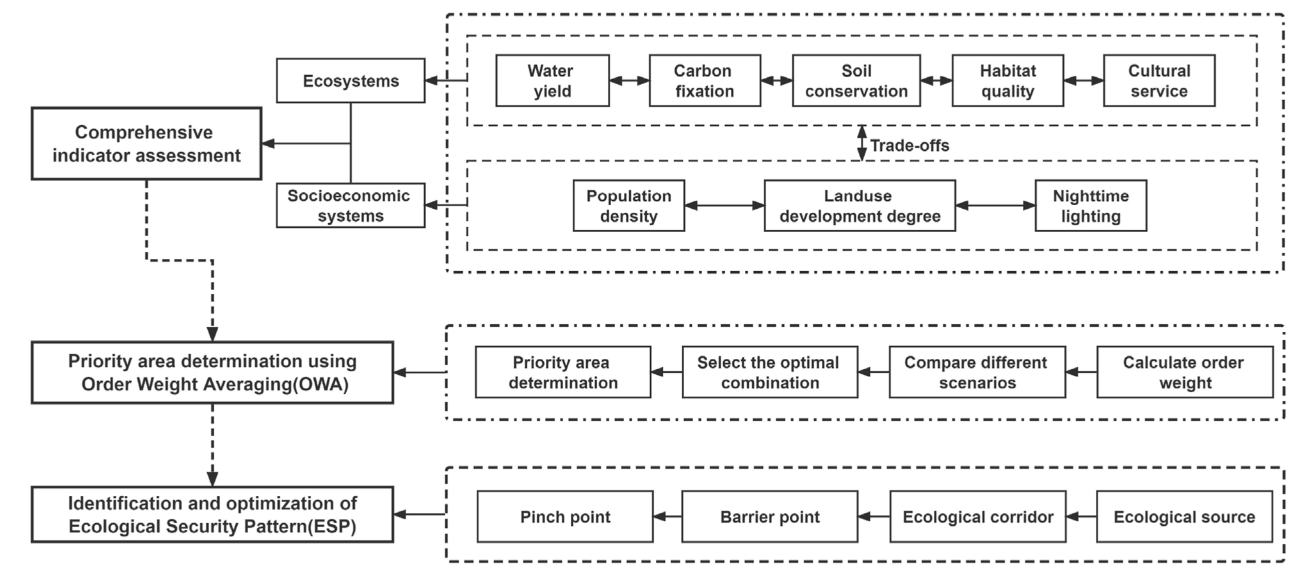

FIGURE 2 | The research framework.

nighttime lighting index sourced from National Oceanic and Atmospheric Administration https://ncc.nesdis.noaa.gov/VIIRS/; 9) 100 m population density raster dataset for 2020 sourced from worldpop https://www.worldpop.org/; (10) Guangzhou City Park Directory http://lyylj.gz.gov.cn/attachment/6/6806/6806818/7295517.pdf

3 METHODOLOGY

3.1 Indicator Assessment

As shown in **Table 1** and **Figure 2**, The assessment of the importance of ecosystem services is the basis for the construction of ESPs. In terms of the topography and land cover types of Guangzhou, the study area is facing some ecological problems of soil erosion, massive destruction of native vegetation, habitat fragmentation and the decline of water yield. Therefore, ecosystem services of Soil Conservation (SC), Habitat Quality (HQ) and Water Yield (WY) were selected as indicators and Carbon Fixation (CF) was also selected because it is a quantitative approach to the delineation of ecological redline for ecological protection in planning. In the meanwhile, due to the incomplete parks and recreation system and increasing demands of cultural ecosystem service in the study area, Cultural Service (CS) was also selected as ecosystem indicators. On the other hand, the degree of Land-use Development (LD), Population Density (PD) and Nighttime Data (NT) were selected to represent the socioeconomic system (Ding et al., 2019).

3.2 Correlation Analysis

According to the previous study, ecosystem and socioeconomic indicator trade-offs and synergies were based on linear data fitting, which can show the direction and intensity of interactions between each of the two indicators (Li et al., 2020). In this study, we first used Pearson correlation analysis to form a correlation matrix by using the GGally package in R, version 4.1.1 The values of eight types of indicators were randomly extracted from a total of 50,000 locations at the scale of the study area. The Pearson correlation coefficients between two indicators were calculated and tested for significance. When the correlation coefficient between two indicators is positive, there was synergy between them. When the correlation coefficient is negative, there were trade-offs between the indicators (Chen et al., 2021). The magnitude of its absolute value reflects the degree of trade-offs or synergy between the indicators. Complex trade-offs may exist among different indicators of the same factor, while specific trade-offs may exist between the ecosystem and socioeconomic system.

3.3 Multicriteria Evaluation

Multicriteria evaluation (MCE) can measure and evaluate regional suitability by weighing multiple relationships (Valente and Vettorazzi, 2008). The OWA method can weigh different decision objectives to determine the optimal decision by performing spatial operations on each evaluation metric. OWA method presents different decision sets by considering the trade-off relationships between different criteria (Chen et al., 2021). OWA method can weigh different decision objectives to determine the optimal decision by controlling each evaluation indicator for spatial operations and balance multiple conflicting indicators in the decision-making process. By considering the trade-offs between different criteria, different decision scenarios were simulated and different decision sets were presented. The formula is as follows (Zhao et al., 2020):

$$OWA\left(x_{ij}\right) = \sum_{i=1}^{n} w_i s_{ij}, \left(w_i \in [0,1], \sum_{i}^{n} w_i = 1, i \text{ and } j = 1,2,3,\ldots,n \right) \quad (1)$$

where x_{ij} is the standardized comprehensive evaluation index value; s_{ij} is the sequence value arranged in descending order by x_{ij} through the size of the attribute value; w_i is the order weight arranged in descending order by x_{ij} through the size of the attribute value; n is the number of indicators.

According to different decision risks, the bit-order weights generated and the trade-offs obtained based on the bit-order weights under various decision risks were calculated as follows:

$$w_i = Q_{RIM}\left(\frac{i}{n}\right) - Q_{RIM}\left(\frac{i-1}{n}\right), i = 1,2,3,\ldots,n \quad (2)$$

$$\mathrm{Q_{RIM}}(r) = r^{\alpha}, \alpha \in (0,\infty) \quad (3)$$

$$\text{trade-off} = 1 - \sqrt{\frac{n\sum_i^n \left(w_i - \frac{1}{n}\right)^2}{n-1}}, 0 \le \text{trade}-\text{off} \le 1 \quad (4)$$

In the formula, Q_{RIM} is the monotonical rule function; w_i is the number of the bit order; n is the number of indicators; α is the decision risk coefficient under different decisions.

In this study, seven decision scenarios (α of 0.001,0.1,0.5,1,2,10,1000)were presented, It shows that under the decision scenario of $\alpha < 1$, ecology space will be restricted protected or even reach the scenario of Complete Protection. On the other hand, changes in decision making from $\alpha = 1$ to $\alpha =$ 1,000 gradually shows the scenario of developing with the risk of ecological destruction (Li et al., 2022). In the process of OWA method, eight evaluation indicators were min-max normalized from 0 to 1 and ranked in descending order by the mean size of the normalized values to obtain the rank order weights of each indicator. The decision risk level was ordered into seven types, and a total of eight decision scenarios were dynamically generated for different decision levels. By multiplying the rank order weights of each indicator with the weighted weight values of the eight assessment indicators and their indicator values, comprehensive ecosystem and socioeconomic evaluation maps can be obtained under different scenarios. The top 20% of each scenario were identified as ecological priority areas based on the comprehensive evaluation map (Chen et al., 2021). By comparing the degree of trade-off in different scenarios, the scenario with the highest degree of trade-off was selected as the optimal scenario. In this scenario, ecological conservation and socioeconomic development will be in dynamic balance, and the city will be in a state of effective conservation while developing (Li et al., 2022).

3.4 Building the Ecological Security Pattern

3.4.1 Ecological Source

In this study, ecological sources were identified by combining ecosystem and socioeconomic system. Ecological priority areas of a certain size are essential for the material and energy connection of the ecological network (Cui et al., 2020). Referring to previous studies and the actual situation of Guangzhou (Long et al., 2018), our study integrated and screened all $\geq 1km^2$ areas from ecological priority areas as ecological sources (Mao et al., 2020).

3.4.2 Ecological Corridor

Urban ecological corridors connect ecological sources in the urban system network (Mao et al., 2020). The resistance surface is the key to influencing material and energy flow between ecological sources. Therefore, the resistance surface value was determined based on the comprehensive evaluation value of the ecosystem and socioeconomic system. In particular, we normalized the integrated assessment value raster to calculate the resistance of the raster with the following equation (Peng et al., 2018).

$$R_i = 1000 \times (1 - A_i) \tag{5}$$

where R_i is the surface value of resistance in grid i; A_i is the comprehensive evaluation value in grid i.

In the next step, the least-cost path was calculated by the Linkage Mapper tool and set the maximum cost-weight distance as 20,000 (Xu et al., 2021a). Linkage Mapper filters the optimal corridors from the source to the neighboring source to map the optimal paths by simulating the minimum cost distance accumulated by ecosystem services (Song and Qin, 2016). This study identifies each ecological corridor's average resistance level by the ratio of the cost-weighted distance of each least-cost path to the Euclidean distance between sources. The corridor ratios were separated by the natural breakpoint method into extremely high resistance, high resistance, medium resistance, low resistance, and extremely low resistance (Su et al., 2021).

3.4.3 Barrier Point Analysis

Barrier points are high-resistance areas that prevent ecological corridors from connecting to the ecological source (Pan and Wang, 2021). In this study, the Barriers Mapper function in the Linkage Mapper tool was used to identify ecological barriers by setting 250, 500, 750 and 1000 m as the search radius. Five intervals were set based on the identification results by the natural breakpoint method, and the highest-value interval was selected as the barrier point (Wang et al., 2022).

3.4.4 Pinch Point Analysis

Ecological pinch point is a high-flow, key node in the ecological process, that should be protected as a priority. Pinch points play an important role in ecological connectivity, being in areas of high resistance and making a large contribution to connecting ecological corridors (Peng et al., 2018). Pinch points can be identified using the Pinch point Mapper function in the Linkage Mapper tool. In this study, the analysis results were divided by the natural breakpoint method. The category with the highest current values (which means the least average resistance distance) is extracted as the ecological pinch point (Zhu et al., 2020).

4 RESULTS

4.1 Indicator Assessment

The normalization result of each indicator value was shown in **Figure 3**. The high values of HQ and SC were located in the northern area and river around the southern area, and therefore would be rich in biodiversity and high soil retention. Besides, the high value of CF was concentrated in the northern area due to the high vegetation cover and woodland there. What's more, there was a relatively low WY capacity due to the effects of high urbanization in the central area. By contrast WY was generally at high value in the northern and southern areas because of abundant precipitation and the impact of rivers in the study area. However, compared with other ecosystem indicators, the high value areas of the CS are situated sporadically in the large forest parks and landscape areas from northern and central area in hilly. In addition, the indicators from the socioeconomic system including LD, PD and NL were highly similar. Their high value was concentrated in the highly urbanized areas in the central area and the southern area under rapid development (Ding et al., 2019).

4.2 Correlation Analysis

The study calculated the correlation coefficients among the comprehensive evaluation indicators (**Figure 4**).The correlation coefficients between ecosystem indicators generally showed a positive correlation. Most indicators' correlation indices were concentrated in the range of 0.1–0.5. The correlation between CF-WY (0.544) and CF-HQ (0.705) showed a significantly positive correlation, indicating synergies between these two relationships, while CS weakly correlated with WY and SC at 0.012 and 0.037, respectively. On the other hand, the data revealed significant positive correlations between the socioeconomic indicators.

Overall, all indicators show negative correlation between ecosystem and socioeconomic system, which indicates that there was an apparent trade-off relationship between them.

4.3 OWA Method for Different Scenarios

As shown from **Table 2**, with the increase in the decision risk coefficient, the rank order weight of high-level comprehensive evaluation indexes decreases continuously. In contrast, the rank order weight of low-level comprehensive evaluation indicators increases continuously.

Under different scenarios, the top 20% of the comprehensive evaluation value was selected as the ecological priority area. Consequently, the map of ecological priority areas under different scenarios was shown (**Figure 5**). From the seven different types of scenarios (**Table 3**), it can be seen that the decision result was optimistic at $\alpha = 0.001, 0.1, 0.5$. The high-value areas were mainly concentrated in the north and south of the study area, and most of the land types in the ecological priority protection areas were woodlands. Obviously, this type of scenario makes it difficult to develop construction land and maybe not easy to meet the growing population needs of megacities. Meanwhile, the criterion weights of all indicators in this study were 0.125 when $\alpha = 1$. The high-value areas were evenly distributed throughout the study area, and the ecological priority areas were mainly forest land at that time. Moreover, farmland, water area and construction area occupy part of the ecological priority area. The comprehensive evaluation weighting value was the

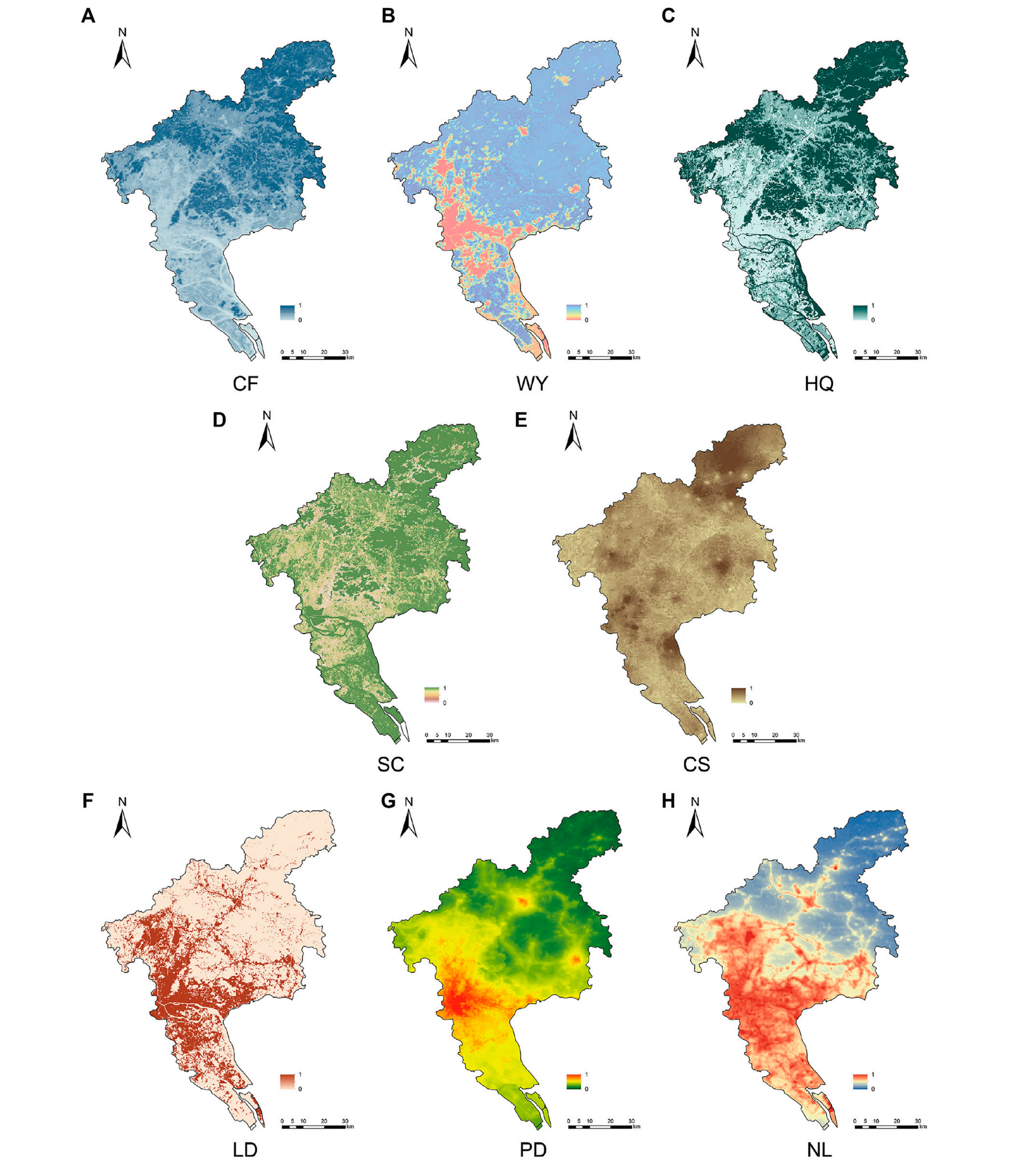

FIGURE 3 | Spatial pattern of ecosystem and socioeconomic system indicators in Guangzhou.

largest when $\alpha = 1$. However, when $\alpha = 2,10,1000$, the decision result was pessimistic. The high-value area was concentrated in the central area, and the ecological priority protection area was mainly dominated by construction land. The indicator of the socioeconomic system currently dominates the comprehensive evaluation indicator, and the area was at a high-risk level. As

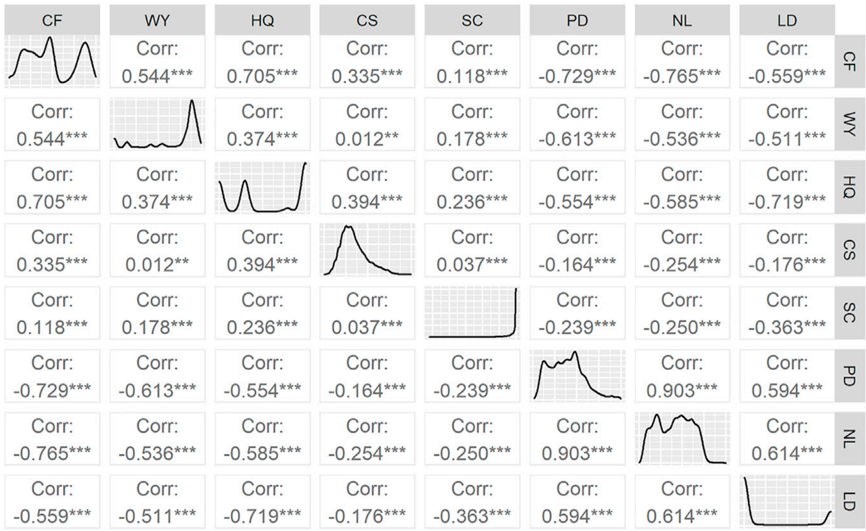

FIGURE 4 | Correlation matrix.

TABLE 2 | Bit order weight operators under different decision risk scenarios.

Scenario	1	2	3	4	5	6	7
α	0.000 1	0.1	0.5	1	2	10	1,000
w_1	0.999 8	0.812 3	0.353 6	0.125 0	0.015 6	0.000 0	0.000 0
w_2	0.000 1	0.058 3	0.146 4	0.125 0	0.046 9	0.000 0	0.000 0
w_3	0.000 0	0.036 0	0.112 4	0.125 0	0.078 1	0.000 1	0.000 0
w_4	0.000 0	0.026 5	0.094 7	0.125 0	0.109 4	0.000 9	0.000 0
w_5	0.000 0	0.021 1	0.083 5	0.125 0	0.140 6	0.008 1	0.000 0
w_6	0.000 0	0.017 6	0.075 5	0.125 0	0.171 9	0.047 2	0.000 0
w_7	0.000 0	0.015 1	0.069 4	0.125 0	0.203 1	0.206 8	0.000 0
w_8	0.000 0	0.013 3	0.064 6	0.125 0	0.234 4	0.736 9	1.000 0
trade-off	0.000 2	0.213 4	0.728 0	1.000 0	0.783 5	0.272 3	0.000 0

the ecological risk gradually increases, the ecological priority area changes from green space, woodland and grassland, to farmland and construction areas.

4.4 The Ecological Security Pattern of Guangzhou

4.4.1 Ecological Source

By simulating the decision risk of each scenario in the OWA method, the result (α = 1), with the highest trade-off was selected as the final scenario. Therefore, the comprehensive evaluation was shown in **Figure 6A** and resistance surface was shown in **Figure 6B** based on the final scenario. In this study, spots of more than 1 km^2 were selected as ecological sources of the study area.

According to **Figure 7**, the number of ecological sources was 158 and the total area of ecological sources was 1,085.34km^2, accounting for 15.03% of the total area of Guangzhou.

From the spatial layout, most ecological sources were distributed in the northern area, accounting for 84.91% of the total area of ecological sources.

The ecological sources in the central area account for 8.88% of the total area of ecological sources. This revealed the fragmentation of green space caused by the expansion of urban construction areas in the central area of Guangzhou, as there were relatively few ecological sources with eligible area and high comprehensive evaluation values.

Moreover, the area of ecological sources in the southern part accounts for 6.21% of the total area of ecological sources. The ecosystem values were much lower than those of the northern part of the study area, where woodland was the main land cover type. The socioeconomic system indicators were lower than those of the central area due to the lack of urbanization activities and population density, which results in a low overall evaluation value. Ecological sources were spatially scattered, and the area of individual sources was small.

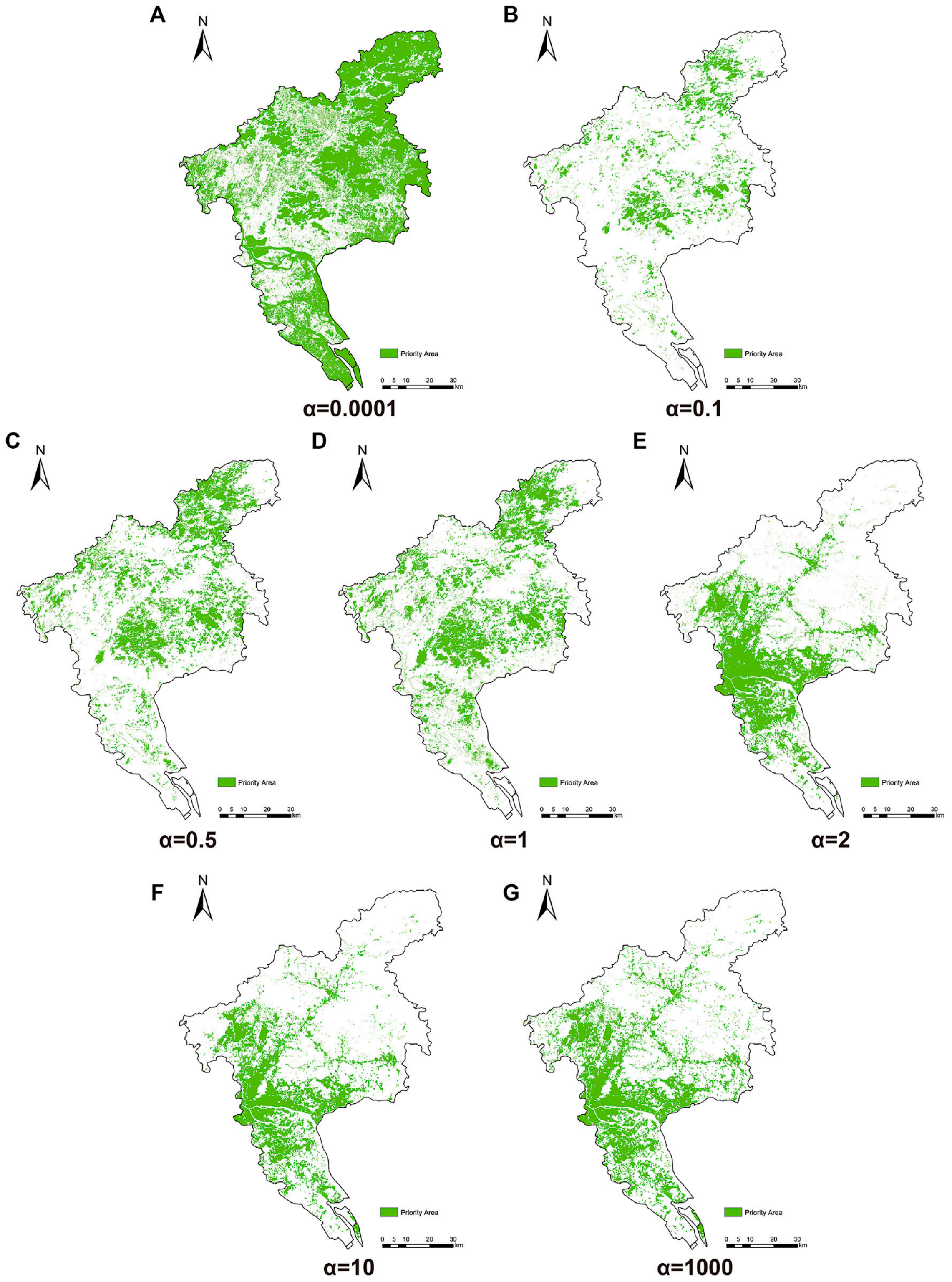

FIGURE 5 | Ecological priority area of different scenarios in Guangzhou.

Most of the ecological sources were woodland, accounting for 85.58% of the total area of ecological sources, with a small proportion of water land and construction land. Due to the trade-offs between ecosystem and socioeconomic system, the sources in the northern and southern area were mostly dominated by ecosystem indicators. Moreover, the

TABLE 3 | Changes in the proportion of land use in ecological priority areas under different scenarios.

α	Farmland (%)	Woodland (%)	Grassland (%)	Waterland (%)	Constructionland (%)
0.000 1	21.73	52.90	3.29	17.24	4.85
0.1	0.00	93.36	0.15	6.49	0.00
0.5	0.05	93.05	0.70	6.20	0.00
1	1.23	85.58	1.16	6.29	5.73
2	2.00	5.76	0.48	1.52	90.25
10	0.33	0.22	0.05	0.10	99.30
1,000	0.77	0.30	0.08	0.13	98.71

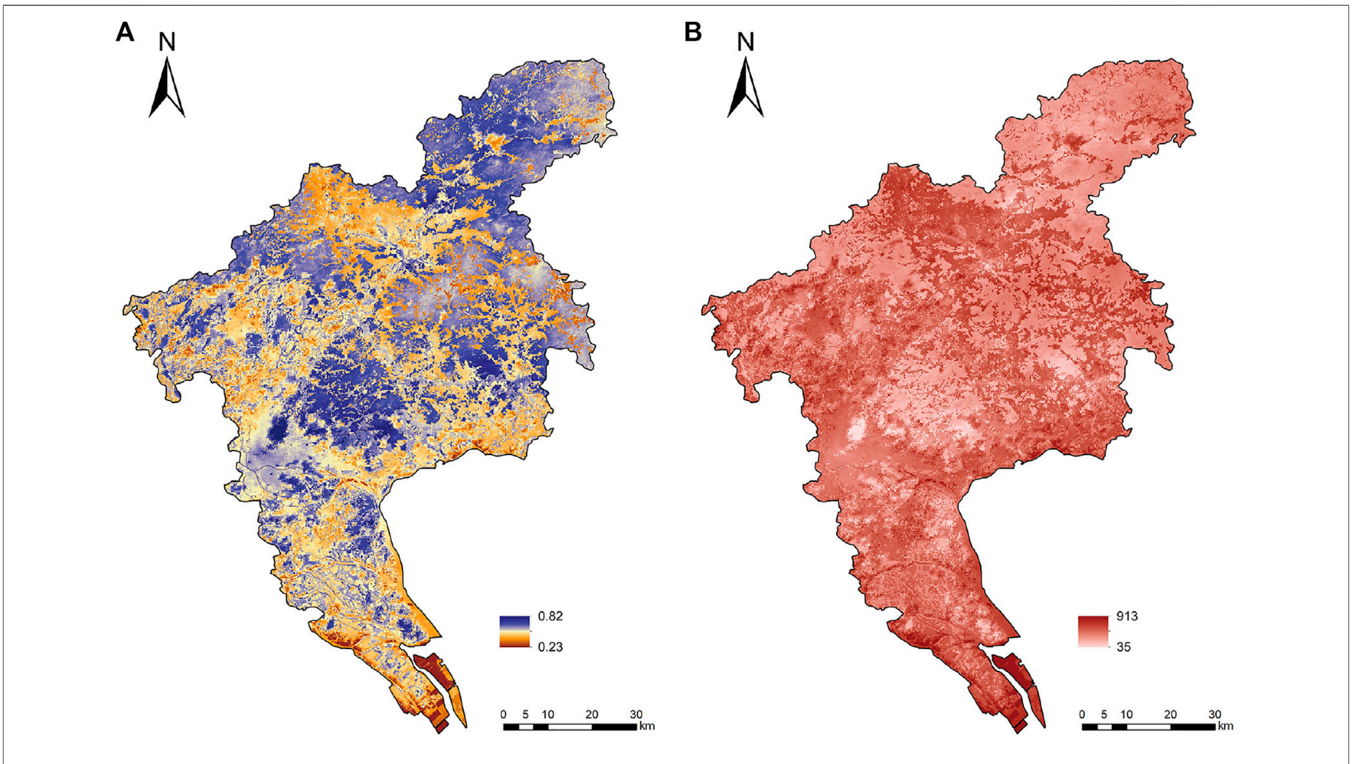

FIGURE 6 | (A) is comprehensive evaluation, **(B)** is resistance surface.

ecological sources in the central urban area were generally dominated by economic indicators.

4.4.2 Ecological Corridor

In total, 406 major ecological corridors with a total length of 1520 km and an average length of 3.3 km were identified in Guangzhou. As shown in **Figure 7**, the ecological corridor in Guangzhou was uniformly distributed, changing from dense in the northern area to sparse in the southern area.

The northern area in Guangzhou has the largest number of ecological corridors, with 334 in total. There was a short average corridor length due to the dense and continuous distribution of ecological sources. Some of the smaller ecological sources connect the northern area through dense, low-cost-distance corridors, occupying most of the area. Therefore, most of the northern corridor could maintain the connectedness of the whole area. There was the lowest number of ecological corridors in the central area, at 30. The spatial layout of corridors in this area was in a circular radial shape. The socioeconomic system index-driven ecological sources link the northern and southern parts, increasing ecological space connectedness in the central zone. However, the average cost distance of corridors in the region was much higher. There were 41 ecological corridors in the southern area. Due to the remote distance between ecological sources, the average distance of corridors was relatively long, and they have a higher cost distance. The southern area was in its initial development stage, and the socioeconomic conditions were far lower than the central area.

Overall, 30 extremely high-, 65 high-, 161 medium-, 147 low- and 2 extremely low-resistance corridors were identified. Extremely high- and high-resistance corridors were normally distributed in the north area, at extremely close distances among the ecological sources. However, the intervening patches of extremely low ecological value significantly reduce

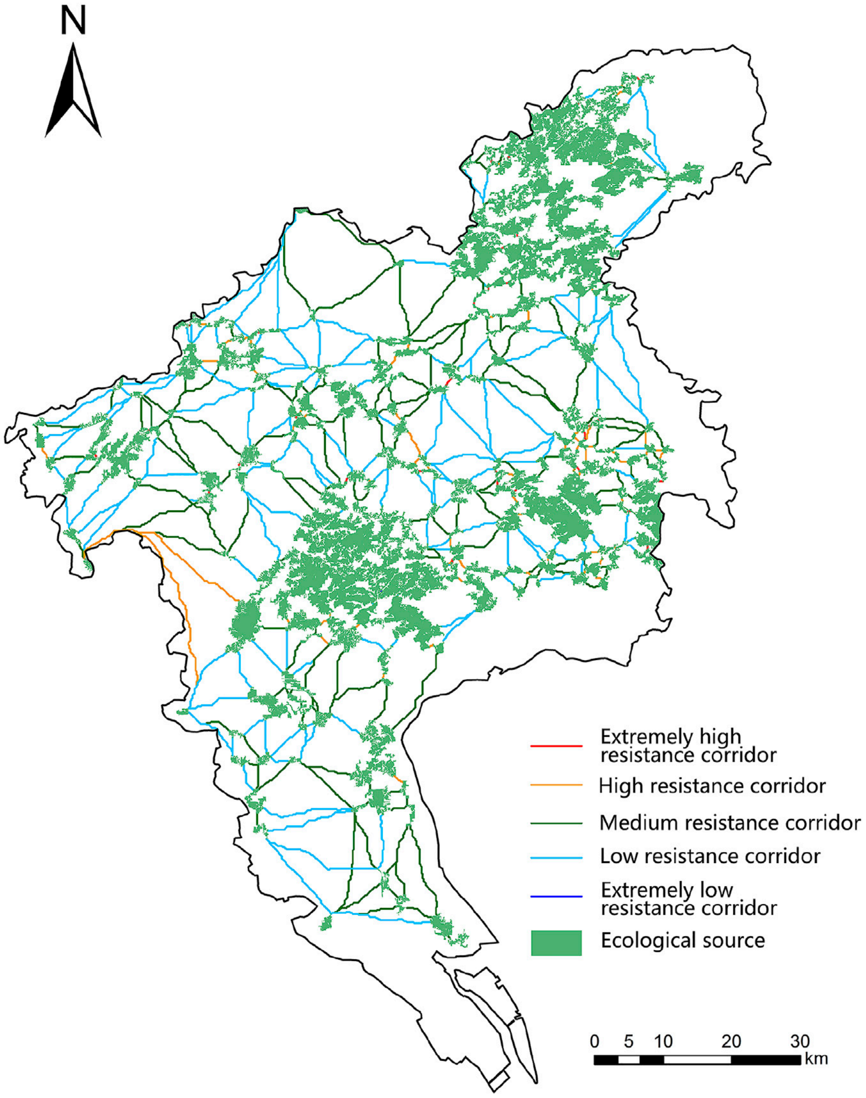

FIGURE 7 | Ecological source and corridor.

the connectedness of the corridor between two sources. Furthermore, medium-resistance corridors were generally located in two ecological sources with longer cost-weighted distances. The complex and various land-use types have an impact on the overall resistance of the corridor.

4.4.3 Barrier Point Analysis

Comparing the results of the different radii, the four different radii have a similar range of barriers. The search results from a smaller radius can accurately search for a higher barrier score in the fine area in the corridor. Therefore, a 250 m radius was selected to identify ecological barrier point and the total area was 433.26 km^2 (**Figure 8A**).

Most of the ecological barrier points were located in the farmland and construction land. When it comes to the spatial layout, there were a large number of scattered barrier points in the northern part of the study area, and it would be very difficult to completely remove them in the future. In the central and southern areas, there were large-scale barrier points. Corridor connectivity can be significantly improved by removing barrier points in this area. Ecological restoration measures should be recommended for optimization.

4.4.4 Pinch Point Analysis

The results (**Figure 8B**) show that the ecological pinch points were mainly located in the northern area. Pinch points were mostly situated in woodland, with a small amount in farmland and construction land. On the other hand, in the southern area, the proportion of pinch points in farmland and construction land was significantly higher.

The narrow pinch point area acts as a catalyst for corridor connectively when the relatively high-resistance patches spread around the area. However, the analysis of ecological corridors with different resistance types shows that although the study

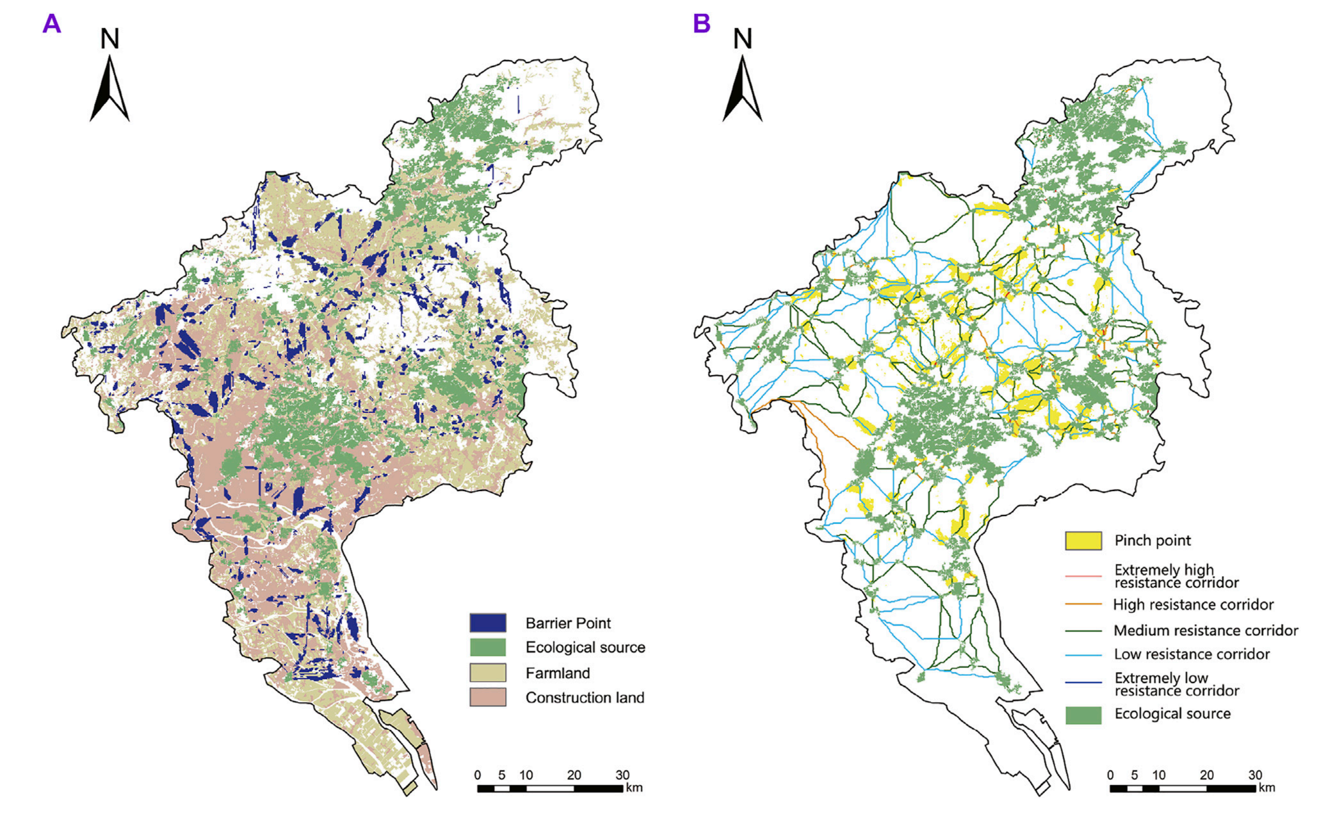

FIGURE 8 | (A) is ecological barrier point, **(B)** is ecological pinch point.

identifies high-value pinch points, they were mostly in low-resistance corridors. Medium- and high-resistance corridors were impeded by the disorderly encroachment of construction land in the northern and southern areas, resulting in the fragmentation of green space and farmland patches. The fragmented areas were highly mixed with various land-use types, and therefore contribute less to connectivity.

5 DISCUSSION

5.1 Significance for Integration of Ecosystem and Socioeconomic System

Previous studies directly select forest patches or habitat areas of wild animals as source areas, but the subjective interference in this selection method was large. Although good accessibility was considered in this selection method, the results only identified ecological patches as the sources of Guangzhou (Yang et al., 2018). Therefore, the high comprehensive value areas in other land-use types tend to be ignored. Furthermore, by changing the selection criteria of sources, the importance of core patches could also be quantitatively evaluated based on the structure of ecosystem and ecological sensitivity (Peng et al., 2017a; Su et al., 2022). The ecosystem services-based ESPs were regarded as an effective method for strengthening the integrity of ecosystems and socioeconomic systems (Fan et al., 2021). It is reasonable to rank patches based on their multifunction of providing key ecosystem services, however, the interaction between the ecosystem and human socioeconomic system cannot be neglected due to the role of ESPs in figuring out the contradiction between ecological land protection and urban development.

We proposed a comprehensive selection method containing five crucial ecosystem services in Guangzhou; aside from regulation and provision ecosystem services, cultural services were also included to quantify the importance of ecological areas. To understand the relationship between ecosystem and socioeconomic system, several scenarios based on the OWA method were compared to identify the ecological sources. Our approach identified the demand for human well-being and the ability to provide effective services (Peng et al., 2017a). Green space and parks in the central part of Guangzhou were also extracted, although the patches were fragmented due to the expansion of construction land. Specifically, a small proportion of construction land also extracted due to the trade-offs between ecosystem and socioeconomic system, which can be identified as the strategic points in the ESPs. Our selection method, therefore, is more conducive to the identification of ecological sources.

In the context of global climate change and anthropogenic disturbances, socioeconomic development will lead to more prominent eco-environmental problems (Liu, 2016). Aiming to solve problems of ecological security,the Guangzhou government has carried out a series of projects and plans such as ecological protection redline, however, these “bottom-line” policies mainly concerned ecological space while neglected the human-land contradiction in metropolitan area (Xu et al., 2021b), or neglect the potential crucial patches outside the ecological protection redline (Ye et al., 2018). To address this gap, this study considered both the ecosystem and socioeconomic system to construct the ESPs. It is worth noting that the most ecological sources were distributed in the hilly area with woodland, which tend to be threatened by unforeseeable human activities. It should be of great concern to integrate ecosystem and socioeconomic system to deal with future climate changes and sustainable development.

5.2 Limitations and Challenges

Previous studies mostly used the artificial discrimination method to eliminate results directly, but it was not easy to determine the ecological sources (Fu et al., 2020). In this study, the ecological sources were selected under the specified threshold, and as a result, ecological sources in the southern and central areas of Guangzhou were much less abundant than in the northern area. Several important "green core" areas such as Dafu Mountain, Seagull Island, and Huang Shan lu forest park were identified. Some important patches such as Nansha wetland in the southern area were eliminated due to their small area, though they may have potential value in other ecosystem services. Future study is still needed to determine the rationality of the threshold, and the assessment indexes need to be enhanced to make sure that the ecological sources are in their best state.

Referring to related studies, the selection of ecosystem indicators is mainly based on support, cultural and regulating services. However, the farmland is usually contributed to the provision of ecosystem services and may be underestimated when the study does not select food production as an indicator (Xu et al., 2014). As a result, high-quality farmland in the southern area may not be highly valued, leading to a reduction in ecological sources in the south. Therefore, the range of evaluation indicators could be expanded in future studies, which could add into the integration of ecosystem and socioeconomic system relationships in comparison with the results of current studies.

The connectivity of heterogeneous landscapes can be effectively identified by the least-cost path. However, the identification of corridor importance merits further discussion (Song and Qin, 2016). Circuit theory can provide multiple potential corridors and contribute to identifying corridors of priority importance (Liu et al., 2021; Pan and Wang, 2021), but it is not possible to intuitively investigate corridor movement pathways and connectivity because of random-walk (LaPoint et al., 2013). Therefore, we use the intuitive least-cost path to describe the priority of each corridor and ratio of cost-weighted distance to length to determine the relative resistance. This could be more flexible in researching corridor connectivity. However, compared with circuit theory it is still insufficient in identifying the importance of multiple pathways (McRae et al., 2008).

Different ecological corridor widths have an impact on the identification of ecological barrier points and pinch points. Consequently, they can provide the scientific basis for the definition of ecological restoration and protection areas in ecological corridors (Hou et al., 2021). An agreement regarding the widths of different ecological corridors has not yet been reached (Peng et al., 2017c). Therefore, determining the widths of corridors is an essential point in the implementation of ESPs (Zhai and Huang, 2022). However, this has not been discussed due to the constraints of the study, but should be considered in future research.

5.3 Optimization and Restoration

Different strategies should be proposed depending on the land-use types of different areas. For the northern areas dominated by the ecosystems, it is necessary to consider this area as the role of the ecological supporting area and focus on ecological conservation strategy. Ecological protection areas such as forest parks should be strictly protected, while appropriate recreational services should be provided as rationally direct ecological resources. For the central area, which is dominated by socioeconomic systems, small green spaces should be constructed and distributed throughout the area. Moreover, green spaces should be designed to deliver recreational and cultural characteristics, balancing ecosystem values with socioeconomic system values. In addition, in the southern area, which is a potential area for urban construction in Guangzhou according to Territorial Spatial Planning, the expansion of construction land should be rationally restricted to prevent the shrinkage of ecological space. Strategies such as exposure to green space and ecological greenways (Zhang et al., 2021), which can deliver different kinds of ecosystem services and enhance the multifunctionality of corridors, are recommended to integrate complementary ecosystem connectivity (Carlier and Moran, 2019).

Corridors play an important role in the maintenance of ecological processes (Peng et al., 2018). Furthermore, in order to implement ecological restoration in ecological corridors, the areas of barriers points and pinch points should be given more priority (Peng et al., 2018). Medium-to-high-resistance ecological corridors should be set as priority areas for future ecological restoration. Ecological restoration should start by prioritizing the removal of ecological barriers. In urban spaces, corridors should be connected by road green belts and greenways. It is possible to improve the corridor barrier points by enriching the green space with various types, vegetation species and vertical structures. Furthermore, the barrier point can be also improved by combining green and blue spaces to form an ecological network and green infrastructure (Yu et al., 2020), which simultaneously contribute to human well-being and sustainable climate adaption planning (Ignatieva et al., 2011; Monteiro et al., 2020; Yang et al., 2020; Yu et al., 2021). When it comes to the connectedness of farmland, high-standard farmland should be interpenetrated by building connecting channels within the space which could interfere with the corridor's connectivity.

Ecological pinch points should be a conservation priority, including strategies to maintain and recover the areas (Castilho et al., 2015). It is necessary to integrate the fragmented patches through land consolidation, which can integrate different spaces with various land-use types in a unified way and carry out spatial reconfiguration. Low-resistance ecological corridors should be flexibly maintained. These scattered barrier points can be set as secondary areas for ecological restoration and can be gradually improved by nature-based solutions (Bush and Doyon, 2019). In the future, the area needs to avoid being divided into fragmented spaces. Throughout the stages of development, these areas should be centrally classified by a unified authority, which will also facilitate maintenance at a later stage.

6 CONCLUSION

Although previous studies have identified ecological security patterns based on multiple ecosystem services, traditional methods only identified what were considered “ecological patches” as the suppliers, and lacked integration between ecosystems and the socioeconomic systems. This study selected comprehensive evaluation indicators including ecosystems and socioeconomic systems to identify ecological sources, introducing the OWA method from the perspective of trade-off. The highest trade-off scenario was selected and, finally, the ecological sources and resistance surfaces were identified.

There were 158 ecological sources with an area of 1,085.34 km^2 and 406 ecological corridors with a total length of 1506 km in Guangzhou. The pattern of ecological sources and corridors from various areas were influenced by the dominant ecosystem or socioeconomic system, which indicates that the trade-off between ecosystem and socioeconomic system has a significant impact on the construction of ESPs. Moreover, ecological barrier points and pinch points with total areas of 433.26 and 458.51 km^2, respectively, were recognized to implement ecological restoration. This study also proposed primary ecological restoration strategies for medium- and high-resistance corridors. A large number of scattered barrier points were located in the northern area and large-scale barrier points were generally situated in the central and southern areas. Therefore, restoration strategies including enriching vegetation types and vertical structures and building green belts and greenways should be proposed to restore large-scale barriers points. When it comes to pinch points, land consolidation strategies such as construction land reclamation and farmland preservation should be implemented in medium- and high-resistance corridors, while buffer zones should be constructed to enhance the resilience of low-resistance corridors. This could achieve the win-win scenario of preserving ecological space while furthering urban development.

The integration of ecosystems and the socioeconomic systems was used as a fundamental basis to improve the existing methods of constructing ecological security patterns. The proposed ecological restoration solutions based on this method contribute to the overall improvement of the connectivity of the ESPs, offering a reference for balancing the development of urbanization and ecological protection in other metropolitan areas.

DATA AVAILABILITY STATEMENT

Information about the existing publicly accessible datasets is contained within the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, WL JT, and HL; methodology, WL and JT; data analysis, JT; validation, WL and JT; investigation, WL; resources, WL; writing—original draft preparation, JT and WL; writing—review and editing, WL and HL; visualization, JT; supervision, WL and HL; project administration, HL; funding acquisition, HL All authors have read and agreed to the published version of the manuscript.

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REFERENCES

Bing, Z., Qiu, Y., Huang, H., Chen, T., Zhong, W., and Jiang, H. (2021). Spatial Distribution of Cultural Ecosystem Services Demand and Supply in Urban and Suburban Areas: A Case Study from Shanghai, china. *Ecol. Indic.* 127, 107720. doi:10.1016/j.ecolind.2021.107720

Bush, J., and Doyon, A. (2019). Building Urban Resilience with Nature-Based Solutions: How Can Urban Planning Contribute? *Cities* 95, 102483. doi:10.1016/j.cities.2019.102483

Carlier, J., and Moran, J. (2019). Landscape Typology and Ecological Connectivity Assessment to Inform Greenway Design. *Sci. Total Environ.* 651, 3241–3252. doi:10.1016/j.scitotenv.2018.10.077

Casagrande, E., Recanati, F., Rulli, M. C., Bevacqua, D., and Melià, P. (2021). Water Balance Partitioning for Ecosystem Service Assessment. A Case Study in the Amazon. *Ecol. Indic.* 121, 107155. doi:10.1016/j.ecolind.2020.107155

Castilho, C. S., Hackbart, V. C. S., Pivello, V. R., and dos Santos, R. F. (2015). Evaluating Landscape Connectivity for Puma Concolor and panthera Onca Among atlantic forest Protected Areas. *Environ. Manage.* 55, 1377–1389. doi:10.1007/s00267-015-0463-7

Chen, T., Li, P., and Wang, Q. (2021). Identification of Ecological Security Patterns in Chengdu-Chongqing Urban Agglomeration Based on Multi-Scenario Decision Making and Ecosystem Service Trade-Offs. *Chin. Environ. Sci.*, 1–23. doi:10.19674/j.cnki.issn1000-6923.20210324.001

Cui, L., Wang, J., Sun, L., and Lv, C. (2020). Construction and Optimization of green Space Ecological Networks in Urban Fringe Areas: A Case Study with the

Urban Fringe Area of Tongzhou District in Beijing. *J. Clean. Prod.* 276, 124266. doi:10.1016/j.jclepro.2020.124266
Cumming, G. S., and Allen, C. R. (2017). Protected Areas as Social-Ecological Systems: Perspectives from Resilience and Social-Ecological Systems Theory. *Ecol. Appl.* 27, 1709–1717. doi:10.1002/eap.1584
Dai, E.-f., Wang, X.-l., Zhu, J.-j., and Xi, W.-m. (2017). Quantifying Ecosystem Service Trade-Offs for Plantation forest Management to Benefit Provisioning and Regulating Services. *Ecol. Evol.* 7, 7807–7821. doi:10.1002/ece3.3286
Deng, C., Liu, J., Nie, X., Li, Z., Liu, Y., Xiao, H., et al. (2021). How Trade-Offs between Ecological Construction and Urbanization Expansion Affect Ecosystem Services. *Ecol. Indic.* 122, 107253. doi:10.1016/j.ecolind.2020.107253
Ding, Y., Zhang, L., and Zeng, X. (2019). The Construction of an Ecological Function Network and its Application in the Greater bay Area, china. *J. Ecol. Rural Environ.* 35, 573–581. doi:10.19741/j.issn.1673-4831.2018.0244
Dong, J., Jiang, H., Gu, T., Liu, Y., and Peng, J. (2021). Sustainable Landscape Pattern: a Landscape Approach to Serving Spatial Planning. *Landscape Ecol.* 37, 31–42 .doi:10.1007/s10980-021-01329-0
Fan, S., Chen, X., Ren, H., Shen, W., Rongbo, X., Zhang, Q., et al. (2018). Landscape Structure and Network Characteristics of the Greenway System in Guangzhou City, south china. *Landscape Ecol. Eng.* 15, 25–35. doi:10.1007/s11355-018-0358-x
Fan, F., Liu, Y., Chen, J., and Dong, J. (2021). Scenario-based Ecological Security Patterns to Indicate Landscape Sustainability: a Case Study on the Qinghai-Tibet Plateau. *Landscape Ecol.* 36, 2175–2188. doi:10.1007/s10980-020-01044-2
Fang, Y., Wang, J., Huang, L.-y., and Zhai, T.-l. (2020). Determining and Identifying Key Areas of Ecosystempreservation and Restoration for Territorial Spatial Planning Based on Ecological Security Patterns: A Case Study of Yantai City. *J. Nat. Res.* 35, 190. doi:10.31497/zrzyxb.20200116
Feist, B. E., Buhle, E. R., Baldwin, D. H., Spromberg, J. A., Damm, S. E., Davis, J. W., et al. (2017). Roads to Ruin: Conservation Threats to a sentinel Species across an Urban Gradient. *Ecol. Appl.* 27, 2382–2396. doi:10.1002/eap.1615
Fu, Y., Shi, X., He, J., Yuan, Y., and Qu, L. (2020). Identification and Optimization Strategy of County Ecological Security Pattern: A Case Study in the Loess Plateau, china. *Ecol. Indic.* 112, 106030. doi:10.1016/j.ecolind.2019.106030
Gao, J., Du, F., Zuo, L., and Jiang, Y. (2021). Integrating Ecosystem Services and Rocky Desertification into Identification of Karst Ecological Security Pattern. *Landscape Ecol.* 36, 2113–2133. doi:10.1007/s10980-020-01100-x
Gong, J., Liu, D., Zhang, J., Xie, Y., Cao, E., and Li, H. (2019). Tradeoffs/synergies of Multiple Ecosystem Services Based on Land Use Simulation in a Mountain-basin Area, Western china. *Ecol. Indic.* 99, 283–293. doi:10.1016/j.ecolind.2018.12.027
Hou, Q., Du, Y., Dong, W., Zeng, Z., Zhang, L., Duan, Y., et al. (2021). Smart City Oriented Ecological Corridor Layout of Sanshui River basin in Arid Area of Loess Plateau. *Sustainable Energ. Tech. Assess.* 44, 100993. doi:10.1016/j.seta.2021.100993
Ignatieva, M., Stewart, G. H., and Meurk, C. (2011). Planning and Design of Ecological Networks in Urban Areas. *Landscape Ecol. Eng.* 7, 17–25. doi:10.1007/s11355-010-0143-y
LaPoint, S., Gallery, P., Wikelski, M., and Kays, R. (2013). Animal Behavior, Cost-Based Corridor Models, and Real Corridors. *Landscape Ecol.* 28, 1615–1630. doi:10.1007/s10980-013-9910-0
Li, C., Zheng, H., Li, S., Chen, X., Li, J., Zeng, W., et al. (2015). Impacts of Conservation and Human Development Policy across Stakeholders and Scales. *Proc. Natl. Acad. Sci.* 112, 7396–7401. doi:10.1073/pnas.1406486112
Li, Z., Deng, X., Jin, G., Mohmmed, A., and Arowolo, A. O. (2020). Tradeoffs between Agricultural Production and Ecosystem Services: A Case Study in Zhangye, Northwest china. *Sci. Total Environ.* 707, 136032. doi:10.1016/j.scitotenv.2019.136032
Li, X., Xiao, J., Wang, J., Wu, J., and Long, N. (2021). Research on the Evaluation and Application of Natural Resources Assets for Ecological Restoration: A Case Study of Guangzhou City. *Acta Ecol. Sin.* 42, 1192–1202.
Li, H., Yao, Y., Yang, X., Dong, X., Yang, J., Ma, Z., et al. (2022). Simulating Ecologucal Security Pattern in the Xiong'an New Area Based on the Multicriteria Evaluation of AHP-OWA. *Acta Ecol. Sin.* 42 (1), 1–11. doi:10.5846/stxb202010162642
Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., et al. (2015). Systems Integration for Global Sustainability. *Science* 347, 1258832. doi:10.1126/science.1258832
Liu, Z., Huang, Q., and Yang, H. (2021). Supply-demand Spatial Patterns of Park Cultural Services in Megalopolis Area of Shenzhen, china. *Ecol. Indicators* 121, 107066. doi:10.1016/j.ecolind.2020.107066
Liu, G. (2016). Formation and Evolution Mechanism of Ecological Security Pattern in Southwest china. *Acta Ecol. Sin.* 36, 7088–7091. doi:10.5846/stxb201611212364
Long, N., Huang, H., Li, X., Wu, J., and Lei, D. (2018). A Research on Urban Ecological Corridors Network Planning of Megacities: A Case Study of Guangzhou. *Urban. Architect.* 3, 53–57. doi:10.19892/j.cnki.csjz.2018.03.010
Mao, C., Dai, L., Qi, L., Wang, Y., Zhou, W., Zhou, L., et al. (2020). Constructing Ecological Security Pattern Based on Ecosystem Services: A Case Study in Liaohe River basin, Liaoning Province, china. *Acta Ecol. Sin.* 40, 6486–6494. doi:10.5846/stxb201909191954
Marina, L. S., Antonio, T. C., and Mercedes, L. G. d. P. (2020). The Potential Role of Cultural Ecosystem Services in Heritage Research through a Set of Indicators. *Ecol. Indic.* 117, 106670. doi:10.1016/j.ecolind.2020.106670
McRae, B. H., Dickson, B. G., Keitt, T. H., and Shah, V. B. (2008). Using Circuit Theory to Model Connectivity in Ecology, Evolution, and Conservation. *Ecology* 89, 2712–2724. doi:10.1890/07-1861.1
Monteiro, R., Ferreira, J. C., and Antunes, P. (2020). Green Infrastructure Planning Principles: An Integrated Literature Review. *Land* 9, 525. doi:10.3390/land9120525
Ni, Q., Hou, H., Ding, Z., Li, Y., and Li, J. (2020). Ecological Remediation Zoning of Territory Based on the Ecological Security Pattern Recognition: Taking Jiawang District of Xuzhou City as an Example. *J. Nat. Res.* 35, 204. doi:10.31497/zrzyxb.20200117
Pan, J., and Li, L. (2021). Optimization of Ecological Security Pattern in Gansu Section of the Yellow River basin Using OWA and Circuit Model. *Trans. Chin. Soc. Agric. Eng.* 37, 259–268. doi:10.11975/j.issn.1002-6819.2021.03.031
Pan, J., and Wang, Y. (2021). Ecological Security Evaluation and Ecological Pattern Optimization in Taolai River basin Based on CVOR and Circuit Theory. *Acta Ecol. Sin.* 41, 2582–2595. doi:10.5846/stxb202005111183
Peng, J., Yang, Y., Xie, P., and Liu, Y. (2017a). Zoning for the Construction of green Space Ecological Networks in Guangdong Province Based on the Supply and Demand of Ecosystem Services. *Acta Ecol. Sin.* 37, 4562–4572. doi:10.1016/j.chnaes.2016.12.002
Peng, J., Zhao, H., Liu, B., and Wu, J. (2017b). Research Progress and prospect on Regional Ecological Security Pattern Construction. *Geogr. Res.* 36, 407. doi:10.11821/dlyj201703001
Peng, J., Zhao, H., and Liu, Y. (2017c). Urban Ecological Corridors Construction: A Review. *Acta Ecol. Sin.* 37, 23–30. doi:10.1016/j.chnaes.2016.12.002
Peng, J., Yang, Y., Liu, Y., Hu, Y., Du, Y., Meersmans, J., et al. (2018). Linking Ecosystem Services and Circuit Theory to Identify Ecological Security Patterns. *Sci. Total Environ.* 644, 781–790. doi:10.1016/j.scitotenv.2018.06.292
Serra-Llobet, A., and Hermida, M. A. (2017). Opportunities for green Infrastructure under ecuador's New Legal Framework. *Landscape Urban Plann.* 159, 1–4. doi:10.1016/j.landurbplan.2016.02.004
Song, L., and Qin, M. (2016). Identification of Ecological Corridors and its Importance by Integrating Circuit Theory. *Chin. J. Appl. Ecol.* 27, 3344–3352. doi:10.13287/j.1001-9332.201610.035
Su, Y., Chen, X., Liao, J., Zhang, H., Wang, C., Ye, Y., et al. (2016). Modeling the Optimal Ecological Security Pattern for Guiding the Urban Constructed Land Expansions. *Urban For. Urban Green.* 19, 35–46. doi:10.1016/j.ufug.2016.06.013
Su, J., Yin, H., and Kong, F. (2021). Ecological Networks in Response to Climate Change and the Human Footprint in the Yangtze River delta Urban Agglomeration, china. *Landscape Ecol.* 36, 2095–2112. doi:10.1007/s10980-020-01129-y
Su, X., Shen, Y., Xiao, Y., Liu, Y., Cheng, H., Wan, L., et al. (2022). Identifying Ecological Security Patterns Based on Ecosystem Services Is a Significative Practice for Sustainable Development in Southwest china. *Front. Ecol. Evol.* 9, 810204. doi:10.3389/fevo.2021.810204
Valente, R. d. O. A., and Vettorazzi, C. A. (2008). Definition of Priority Areas for forest Conservation through the Ordered Weighted Averaging Method. *For. Ecol. Manage.* 256, 1408–1417. doi:10.1016/j.foreco.2008.07.006
Wang, M., Hou, X., and Wang, J. (2018). Resilience Mechanism and Practical Insights from Water-Related Physical Form in Jiangnan Based on Traditional

Ecological Wisdom. *Landcape Archit. J.* 25, 52–57. doi:10.14085/j.fjyl.2018.06.0052.06

Wang, D., Chen, J., Zhang, L., Sun, Z., Wang, X., Zhang, X., et al. (2019). Establishing an Ecological Security Pattern for Urban Agglomeration, Taking Ecosystem Services and Human Interference Factors into Consideration. *PeerJ* 7, e7306. doi:10.7717/peerj.7306

Wang, L., Feng, X., Chang, Q., Liu, H., and Wang, J. (2020). Pattern Construction of Habitat Network for Urban green Space Based on the Compound Model of InVEST and MCR. *Chin. Landscape Archit.* 36, 113–118. doi:10.19775/j.cla.2020.06.0113

Wang, X., Zhao, P., Zhao, Y., Song, W., and Liu, X. (2022). Identification of key areas of land space ecological protection and restoration based on the pattern of ecological security in Guangdong, Hong Kong and Macau. *Acta Ecol. Sin.* 1–12, 450–461. doi:10.5846/stxb202011072848

Wu, J., Ma, H., and Peng, J. (2018). Improving Urban Ecological Security Pattern Based on Functional Nodes-Key Corridors: A Case Study of Shenzhen City. *Prog. Geogr.* 37, 1663–1671. doi:10.18306/dlkxjz.2018.12.008

Xu, L., Yin, H., Li, Z., and Li, S. (2014). Land Ecological Security Evaluation of Guangzhou, china. *Int. J. Environ. Res. Public Health* 11, 10537–10558. doi:10.3390/ijerph111010537

Xu, C., Cheng, L., Su, J., Yin, H., and Guo, Y. (2021a). Developing Regional Ecological Networks along the Grand Canal Based on an Integrated Analysis Framework. *J. Resour. Ecol.* 12, 801–813. doi:10.5814/j.issn.1674-764x.2021.06.008

Xu, C., Meng, N., Zhang, Y., Xie, S., Han, B., Su, Z., et al. (2021b). Urban Ecological Conservation Redlines Delineation and Management: A Case Study of macao Special Administrative Region. *Acta Ecol. Sin.* 41, 9103–9117. doi:10.5846/stxb202105071200

Yager, R. (1988). On Ordered Weighted Averaging Aggregation Operators in Multicriteria Decisionmaking. *IEEE Trans. Syst. Man, Cyber.* 18, 183–190. doi:10.1109/21.87068

Yang, Y., and Li, Q. (2021). Distribution Pattern and its Formation Mechanism of Public Recreational Space Based on POI Data: A Case Study of the Main Urban Area of Changsha City. *Mod. Urban Res.* 3, 91–97. doi:10.3969/j.issn.1009-6000.2021.03.013

Yang, X., Zhou, Z., Li, J., Fu, X., Mu, X., and Li, T. (2016). Trade-offs between Carbon Sequestration, Soil Retention and Water Yield in the Guanzhong-Tianshui Economic Region of china. *J. Geogr. Sci.* 26, 1449–1462. doi:10.1007/s11442-016-1337-5

Yang, Z., Jiang, Z., Guo, C., Yang, X., Xu, X., Li, X., et al. (2018). Construction of Ecological Network Using Morphological Spatial Pattern Analysis and Minimal Cumulative Resistance Models in Guangzhou City, china. *Chin. J. Appl. Ecol.* 29, 3367–3376. doi:10.13287/j.1001-9332.201810.019

Yang, G., Yu, Z., Jørgensen, G., and Vejre, H. (2020). How Can Urban Blue-green Space Be Planned for Climate Adaption in High-Latitude Cities? a Seasonal Perspective. *Sustain. Cities Soc.* 53, 101932. doi:10.1016/j.scs.2019.101932

Ye, L., and Shi, Z. (2021). Analysis of RUSLE Model Parameter Acquisition Methods Based on Domestic Literature. *Yunnan Geogr. Environ. Res.* 33, 45–51. doi:10.3969/j.issn.1001-7852.2021.02.006

Ye, X., Zou, C., Liu, G., Lin, N., and Xu, M. (2018). Main Research Contents and Advances in the Ecological Security Pattern. *Acta Ecol. Sin.* 38, 53–57. doi:10.5846/stxb201701110083

Ying, L., Wang, J., and Zhou, Y. (2019). Ecological-environmental Problems and Solutions in the Minjiang River basin, Fujian Province, china. *Acta Ecol. Sin.* 39, 8857–8866. doi:10.5846/stxb201905291106

Yu, L., Liu, J., Li, T., and Zhu, H. (2018). Research Progress of Urban Public Recreational Space in china. *Acta Geogr. Sin.* 73, 1923–1941. doi:10.11821/dlxb201810008

Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M., and Vejre, H. (2020). Critical Review on the Cooling Effect of Urban Blue-Green Space: A Threshold-Size Perspective. *Urban For. Urban Green.* 49, 126630. doi:10.1016/j.ufug.2020.126630

Yu, Z., Zhang, J., and Yang, G. (2021). How to Build a Heat Network to Alleviate Surface Heat Island Effect? *Sustain. Cities Soc.* 74, 103135. doi:10.1016/j.scs.2021.103135

Yu, K. (1996). Security Patterns and Surface Model in Landscape Ecological Planning. *Landscape Urban Plann.* 36, 1–17. doi:10.1016/S0169-2046(96)00331-3

Zhai, T., and Huang, L. (2022). Linking MSPA and Circuit Theory to Identify the Spatial Range of Ecological Networks and its Priority Areas for Conservation and Restoration in Urban Agglomeration. *Front. Ecol. Evol.* 10. doi:10.3389/fevo.2022.828979

Zhang, L., Fu, B., Lü, Y., and Zeng, Y. (2015). Balancing Multiple Ecosystem Services in Conservation Priority Setting. *Landscape Ecol.* 30, 535–546. doi:10.1007/s10980-014-0106-z

Zhang, L., Peng, J., Liu, Y., and Wu, J. (2017). Coupling Ecosystem Services Supply and Human Ecological Demand to Identify Landscape Ecological Security Pattern: A Case Study in Beijing–Tianjin–Hebei Region, china. *Urban Ecosyst.* 20, 1–14. doi:10.1007/s11252-016-0629-y

Zhang, Y., Hu, Y., and Zhuang, D. (2020). A Highly Integrated, Expansible, and Comprehensive Analytical Framework for Urban Ecological Land: A Case Study in Guangzhou, china. *J. Clean. Prod.* 268, 122360. doi:10.1016/j.jclepro.2020.122360

Zhang, J., Yu, Z., Cheng, Y., Sha, X., and Zhang, H. (2021). A Novel Hierarchical Framework to Evaluate Residential Exposure to green Spaces. *Landscape Ecol.* Available at: https://link.springer.com/article/10.1007/s10980-021-01378-5. doi:10.1007/s10980-021-01378-5

Zhao, K., Li, X., and Yuan, N. (2017). From American "greenway" to European Greenway: The Construction of Ecological Network in Urban and Rural Space—a Case Study of Zengcheng District of Guangzhou. *Chin. Landscape Archit.* 33, 82–87.

Zhao, W., Han, Z., Yan, X., and Zhong, J. (2020). Ecological Security pattern construction based on multi-scenario trade-off of ecosystem services: A Case Study of wafangdian, Dalian. *J. Nat. Res.* 35, 546. doi:10.31497/zrzyxb.20200304

Zhu, J., Su, J., Haiwei, Y., and Fanhua, K. (2020). Construction of xuzhou Ecological network based on comprehensive sources identification and multi-scale nesting. *J. Nat. Res.* 35, 1986–2001. doi:10.31497/zrzyxb.20200817

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Spatial and Temporal Evolution of Ecosystem Service Values and Topography-Driven Effects Based on Land Use Change: A Case Study of the Guangdong–Hong Kong–Macao Greater Bay Area

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Abstract: The Guangdong–Hong Kong–Macao Greater Bay Area (GBA) is rich in natural and marine resources, and it is scientifically valuable to study the evolution patterns and driving mechanisms of the ecosystem service values (ESVs) of the GBA for the governance and conservation of its ecosystems. Based on the land use changes in the GBA from 2000 to 2020, the ESVs in the GBA were measured at the grid scale, and the Markov model was used to predict the ESVs in 2030; the calculated results were used to analyze the spatial and temporal variation characteristics of the ESVs during the 30-year period, while the driving role of the topographic factors on the ESVs is revealed through the construction of the geographically weighted regression model (GWR). The results show the following: (1) During the 20-year period, the area of arable land and water in the GBA fluctuated greatly, with the area decreasing year by year and shifting mainly into construction land; in terms of shifting the center of gravity of the land, and the center of gravity of the grassland and unused land shifted the greatest distance due to the expansion of construction land, with the center of gravity shifting westward as a whole. (2) The ecosystem services (ESs) in the GBA show obvious aggregation in the spatial distribution, with the total ESVs decreasing year by year. Among them, the areas with an increasing total value are mainly located in the cities of Zhaoqing and Huizhou in the GBA, accounting for 27%, and the areas with a decreasing total value year by year are mainly located in the dense urban areas in the central part of the GBA, accounting for 35%, and the area is increasing, indicating that the habitat quality is deteriorating, and the model prediction shows that the value of ecosystem services in 2030 have a decreasing trend under the development of the natural state. (3) Topographic factors have a significant influence on the ESVs, and in terms of spatial distribution, the areas with the strongest effect are distributed in the northwestern and northeastern parts of the GBA, and the main uses for the land are wood land, arable land, water and the area of the water–land intersection near the sea.

Keywords: The Guangdong–Hong Kong–Macao Greater Bay Area; ecosystem service value; temporal and spatial evolution; topographic factors; geographically weighted regression model

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1. Introduction

As a strategic national development region, the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) has a key geographical location and a wealth of natural resources. The sustainable development of the GBA plays a crucial role in the enhancement of regional ESVs as well as the construction and optimization of ecological patterns [1]. For the coastal areas with complex and fragile environments, impaired habitat quality will lead to a decline in the ESVs and negatively affect environmental security and socioeconomic development [2]. Therefore, strengthening the accounting of the ESVs and analyzing the influencing factors that affect the evolution of the ESVs will help with the governance and protection of ecosystems in the GBA [3].

The concept of ecosystems was first proposed by Tasley in the 1930s, marking the gradual refinement of the study of ecosystems; on this basis, SCEP first proposed the concept of ESs in the 1970s [4], and listed a number of ESs provided by the natural environment. Subsequently, Costanza deepened his research on ESVs and classified them into 17 categories, including gas regulation, climate regulation, water regulation, soil formation, nutrient cycling and recreation, based on four dimensions including production, basic functions, environmental benefits and recreation, which became the basis for the classification of subsequent scholars and greatly enriched the research results in this field. At the beginning of the 21st century, the UN Millennium Ecosystem Assessment redefined the concept of ESs and classified them as provisioning, regulating, cultural and supporting services in relation to human benefits, leading to a boom in research on the value of ecosystem services. In China, the study of ESs began in the 1990s when Liu Xiaodi introduced the concept of ESs to the country based on the research results of Daily [5]; subsequently, Ouyang Zhiyun conducted in-depth research on this concept, continuously enriching the theoretical findings on ecosystem services [6]. In the same era, Xie Gaoqi defined ES functions as products and services obtained directly or indirectly through ecosystem functions and classified them into three major categories, namely, production functions, ecological functions and recreational and leisure functions [7]; since then, domestic research on ES functions has been gradually enriched and diversified [8,9].

Early research on ESs at home and abroad focused on the valuation of ecosystem services. There are two main approaches to accounting; the first is the physical quality assessment method, which, in turn, includes the functional volume assessment method and the energy value assessment method. The material quality refers to the value of the final products or services obtained by humans directly or indirectly from the ecosystem [10]. Its principle is to obtain the total value of an ecosystem service from its functional volume and the unit price of that volume [11,12]; the functional volume of the relevant indicator is usually calculated using models such as InVEST and ARIES, which are commonly used. The advantages of the physical quality assessment method are that the results can objectively reflect the structural functions and ecological processes of the ecosystem, but the limitations are that there are uncertainties in the data acquisition and the calculation process is cumbersome, and there are differences in the units of measurement for the individual functional indicators, which makes it difficult to measure the value of ecosystem services with multiple functions. The second approach is the value–volume approach, which includes the monetary and value-equivalent approaches. The principle of this approach is to quantify ecosystem services using economic algorithms, including the direct market approach, the substitution market approach and the simulated market approach [13]. The analysis of the different ecosystem service valuation methods shows that each method has its own advantages and limitations, so the appropriate method can be weighed according to the purpose and focus of the study [1]. Based on changes in the social environment and the different methods of accounting for value, scholars measured the ESVs at different environmental scales and gradually built up a systematic research method for quantifying ESs [14–17], of which a highly representative research result was the principle and method of valuing ESs proposed by Costanza et al. in 1997 [18]; Costanza first accounted the ESVs at the global scale using this method. Subsequently, Chinese scholars such as Xie Gaodi combined the actual situation of ESs in China and, after a series of revisions, developed a table of value equivalent factors applicable to terrestrial ecosystems in China [19]. Later research directions integrate spatial techniques in value assessment to explore the coupling between the land use types and the ESVs. The number and rate of land type changes can directly reflect the intensity of the land type conversion [20–22], thus exploring the temporal and spatial evolution and variation of ESVs in the region from multiple dimensions.

At present, research on the factors influencing the evolution of ESVs has made great progress, mainly focusing on the relevance of physical geographic factors to ESVs [23–26], while regional topography, as one of the determinants of landscape patterns, has an important influence on the evolution of ESVs [27,28]. There are two main methods for coupling ESVs with topographic factors. The first is the direct coupling method, which is mainly calculated through the topographic position index; this index is a composite analysis of the elevation and slope, and is often used to quantify the spatial effects of land use on topographic gradients. The second is the model coupling method, which is mainly carried out through a spatial autocorrelation analysis, such as the Moran index and the geographically weighted models, among which the GWR is more advantageous in the analysis of coupling relationships, because it can express the data characteristics of spatial data at different locations and can reflect the weight size of local areas in the data [29,30]. Therefore, it is important to use spatial autocorrelation analysis to study the driving effect of ESVs in order to optimize the regional ESVs and build an ecological security pattern [31,32].

From the current research results, it can be seen that studies on ESVs in the GBA mostly focus on the relationship between urbanization and ESVs, but the depth of the studies are still insufficient [33–35], mainly in two aspects. Firstly, current studies on the spatial and temporal variation of regional ESVs seldom involve future-year scenarios, and at the same time, when analyzing the spatial and temporal variation of ESVs in regions with rapid urbanization, the coupling study of ESVs and land use changes is seldom involved; secondly, studies of the driving effects of ESVs within the GBA are less likely to involve topographic factors. Therefore, based on the remote sensing image interpretation maps of the GBA from 2000 to 2020, this study measures and predicts ESVs in the GBA in 2030 at the grid scale, analyzes its spatial and temporal variation characteristics, and introduces a model called GWR to reveal the driving effect of topographic factors on ESVs. The aim is to explore the following issues: (1) the spatial and temporal evolutionary characteristics of ESVs in the GBA; (2) the impact of land use on changes in the ESVs; and (3) the relationship between topographic factors and ESVs. These issues are explored to deepen the content of the study and to provide theoretical guidance for the GBA ecosystem to achieve regional ecological governance and integrated urban development.

2. Materials and Methods

2.1. Study Area Overview

The GBA belongs to one of the four major bay areas in the world, with a total surface area of about 56,000 square kilometers. In terms of administrative area, it mainly consists of the nine cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing in the Guangdong Province and the special administrative regions of Hong Kong and Macau (Figure 1). The study area has a mild and humid climate, with a dense network of rivers and water, and is distributed in the mountainous forests of Mafeng Mountain–Baiyun Mountain, Gudou Mountain–Wuguishan Mountain–Phoenix Mountain, Daling Mountain–Yangtai Mountain–Tanglang Mountain, etc., which form an inter-urban ecological transition zone. The study area also has a wide distribution of forests and agricultural land, with arable land scattered throughout the bay area; wetland resources are abundant, with water entering the rivers located in the four cities of Foshan, Zhuhai, Shenzhen and Zhongshan [36,37].

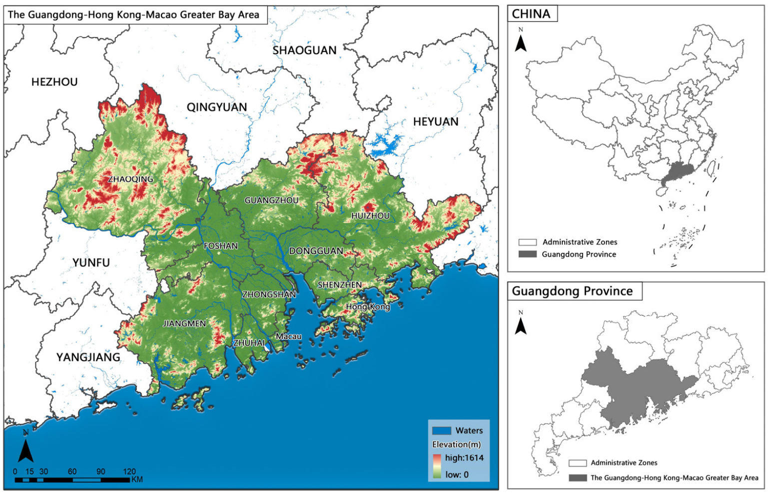


Figure 1. Map of the Guangdong–Hong Kong–Macao Greater Bay Area, China.

2.2. Data Sources and Initial Data Processing

The remote sensing image source data selected for this study were obtained from the Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 1 July 2021), with three periods including 2000, 2010 and 2020, and the spatial resolution of the data is 30 m. The topographic data were obtained from the geospatial data cloud database (http://www.gscloud.cn/, accessed on 1 July 2021), with the type ASTER GDEM. The relevant statistical data were mainly obtained from the Guangdong Statistical Yearbook, the Hong Kong Statistical Yearbook and the Macao Statistical Yearbook during the study period. The collected remote sensing data were corrected and classified using ArcGIS software, and according to the previous research results, the land types were classified into six categories, such as construction land, arable land, grassland, woodland, water and unused land [38]; the relevant yearbook data were collated, summarized and analyzed, and processed using SPSS software.

2.3. Research Methods

The research idea and process are shown in Figure 2.

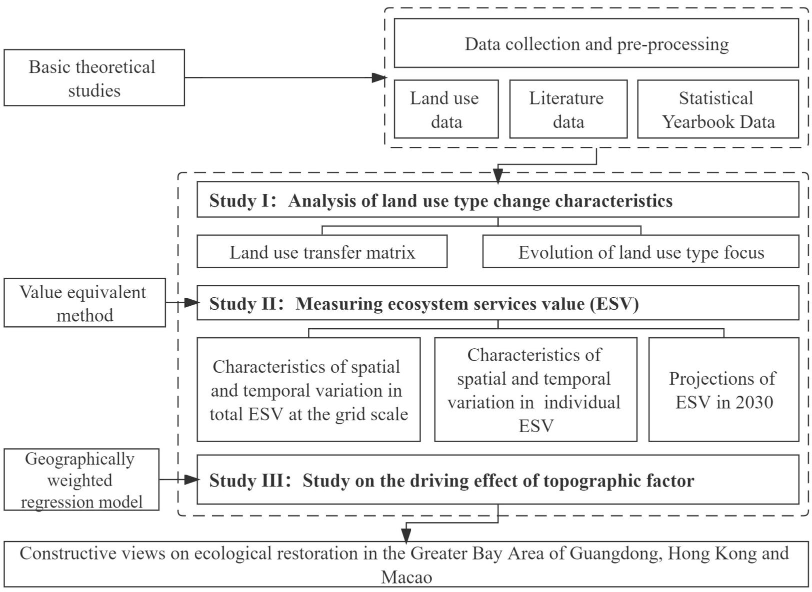


Figure 2. Article flow chart.

2.3.1. Analysis of Land Use Change

The land use transfer matrix can concretely reflect the characteristics of the land use structure. It reflects the transition relationship between a certain land type within a certain time interval, and calculates the transition process of land state from moment t to moment $t + 1$ using Equation (1) [39,40]; the direction and distance of the land center of gravity shift can reflect the natural economic conditions as well as the quality of land in the region [41,42], and the coordinate change of the land use type center of gravity can be calculated using Equation (2) as follows:

$$S_{\mathrm{ab}} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1\mathrm{n}} \\ S_{21} & S_{22} & \cdots & S_{2\mathrm{n}} \\ \vdots & \vdots & \vdots & \vdots \\ S_{\mathrm{n}1} & S_{\mathrm{n}2} & \cdots & S_{\mathrm{nn}} \end{bmatrix} \tag{1}$$

In the equation, S_{ab} represents the land use status at the beginning and end of the study, and n represents the number of land use types.

$$X_{\mathrm{a}} = \frac{\sum_{i=1}^{n}(C_{\mathrm{a}i} \times X_i)}{\sum_{i=1}^{n} C_{\mathrm{a}i}} Y_{\mathrm{a}} = \frac{\sum_{i=1}^{n}(C_{\mathrm{a}i} \times Y_i)}{\sum_{i=1}^{n} C_{\mathrm{a}i}} \tag{2}$$

In the equation, X_a and Y_a represent the latitude and longitude coordinates of the center of gravity of a land type in year a, C_{ai} represents the area of the i patch in a land type in year a, and X_i and Y_i represent the latitude and longitude coordinates of the center of gravity of the i patch in a land type.

2.3.2. Ecosystem Service Value at the Grid Scale

The grid scale can quantify the spatial heterogeneity of the land use types in the study area and express their information adequately, which is an effective evaluation unit for quantifying the spatial and temporal evolution of the land use [43]. In this study, 1 km × 1 km, 3 km × 3 km, 5 km × 5 km, 10 km × 10 km, 15 km × 15 km and 20 km × 20 km grids were constructed as pre-selected evaluation units based on previous research results. Considering the scale and shape characteristics of the study area, in order to make the grid cells not only have certain regional characteristics, but also contain sufficient research information, and at the same time, be able to reflect the spatial variation of ESVs in the study area more freshly, we referred to a large amount of the literature relevant to our study and compared the spatial variation effect of different grid calculation results, and finally chose 3 km × 3 km as the base measurement cell (Figure 3). The calculation of ESVs referred to the equivalence factor table modified by Xie Gaodi according to the actual situation in China; in addition, considering the differences in grain prices in different regions, the average grain price of farmland in the Guangdong Province was chosen as the average grain price in this study, while the ESV coefficients for construction land referred to the coefficients proposed in the table for the value of each ecosystem service per unit area of the different types of terrestrial ecosystems in China to make corrections [44,45]. In terms of the value per unit area, ESVs at the grid scale were corrected using the coefficient proposed by Xie Gaodi (1.40 for Guangdong Province) and using the vegetation cover [46], resulting in ESVs per unit area in the GBA (Table 1), with the following revised equation:

$$\begin{gathered} FV = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \\ F_{\mathrm{a}} = \mathrm{f}_{\mathrm{ai}}/\mathrm{f} \\ E = E_{\mathrm{a}} \times F_{\mathrm{a}} \end{gathered} \tag{3}$$

In the equation, FV is the vegetation index, $NDVI$ is the standard value of vegetation cover, f_a denotes the sum of the FV values of the ath grid cell, f is the mean value of FV,

E_a and E refer to ESVs before and after the revision and F_a denotes the vegetation cover revision factor of the ath grid cell.

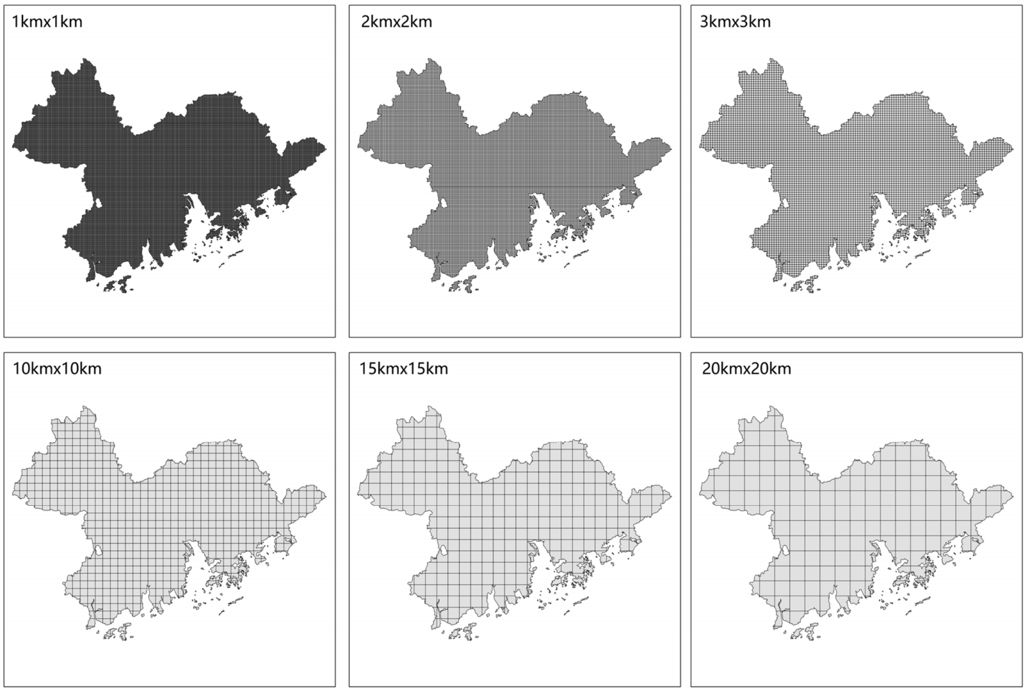


Figure 3. Schematic diagram of grid scale in the research area.

Table 1. Ecosystem service values (1×10^8 CNY) per unit area in the Guangdong–Hong Kong–Macao Greater Bay Area.

Ecosystem Services	Arable Land	Woodland	Grassland	Water	Unused Land	Construction Land
Food production	1833.63	605.10	788.46	971.82	36.67	-
Raw material production	715.12	5464.22	660.11	641.77	73.35	-
Atmospheric regulation	1320.21	7921.28	2750.44	935.15	110.02	-
Climate regulation	1778.62	7462.87	2860.46	3777.28	238.37	-
Hydrological regulation	1411.90	7499.55	2805.45	34,417.24	128.35	−6678.00
Waste disposal	2548.75	3153.84	2420.39	27,229.41	476.74	−2174.10
Soil maintenance	2695.44	7371.19	4107.33	751.79	311.72	3480.00
Biodiversity maintenance	1870.30	8269.67	3428.89	6289.35	733.45	-
Recreation	311.72	3813.95	1595.26	8141.32	440.07	-
Total	14,485.68	51,561.68	21,416.80	83,155.12	2548.75	−5372.10

2.3.3. Markov Model

Markov chain represents the sequential state of the development process of things, which is discrete in time and state, and the development process of things is only linked to adjacent things. Markov model can be used on this basis to predict the future state of things in the same time interval according to the development process and state of things [47–49]. In this study, the Markov model is used to predict and analyze the change in land use types in the GBA in 2030 and estimate the ESVs in the study area based on the prediction results. The relevant calculation equation is as follows:

$$S(a+1) = P_{ij} \times S(a) \tag{4}$$

In the equation, $S(a)$, $S(a + 1)$ represent the states of the ground class at moments a, $a + 1$; P_{ij} represents the state transfer matrix.

2.3.4. Geographically Weighted Regression Model

Geographically weighted regression model (GWR) is a local regression model that assists the original spatial data in determining the coordinate location parameters [50], which is based on the principle of independent linear regression calculations at all point locations, thereby allowing for the expression of data characteristics of spatial data at different locations, perfectly compensating for the shortcomings of the global regression model, while reflecting the magnitude of the weights of local areas in the data [51,52]. In this study, the relationship between topography and slope data and ESVs is analyzed comprehensively by constructing a GWR model, in which topography and slope data are used as independent variables, and the ESVs are used as dependent variables, from which the corresponding explanatory variable coefficients (predicted) and local R^2 data can be calculated. The Y value represents the predicted estimate of the dependent variable, and the closer the Y value is to the ESVs, the better the fit between the two; the local R^2 means the fit of the local regression model to the Y value, with larger values indicating a higher model accuracy [53]. The relevant calculation equation is as follows:

$$\mathrm{Y_i} = \beta_0(\mu_\mathrm{a}, \nu_\mathrm{a}) + \sum_{\mathrm{a}=1}^{\mathrm{k}} \beta_\mathrm{k}(\mu_\mathrm{a}, \nu_\mathrm{a}) X_\mathrm{ak} + \varepsilon_\mathrm{a} \quad (5)$$

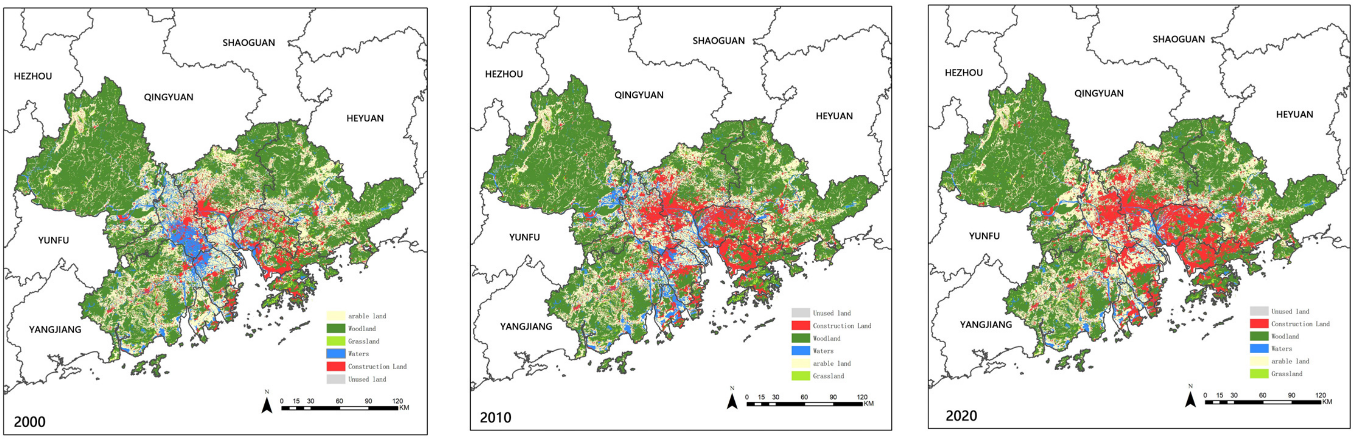
In the equation, (u_a, v_a) represents the spatial coordinate point a; Ya and K_{ak} are the dependent variable Y and the set of sub variables X_k of the measured values of the spatial position; k is the number of independent variables; β_0 (u_a, v_a) is the spatial position of the constant term (u_a, v_a); β_k (u_a, v_a) is the value of the continuous function β_k (u_a, v_a) at point a and ε_a represents the random error term.

3. Results

3.1. Analysis of Spatial and Temporal Land Use Change Characteristics

3.1.1. Land Use Transfer Matrix

From the land use transfer matrix of the study area (Table 2), the urban boundaries within the GBA expanded continuously from 2000 to 2010, encroaching on the surrounding arable land, woodland and water. The areas of arable land, water and woodland transferred out of the GBA during the 10-year period were 2636 km^2, 1098 km^2 and 992 km^2, respectively, while the largest amount of construction land was transferred in, accounting for 43% of the original area, which is mainly due to the fact that the urban master plan expanded the use of reserve land resources such as mudflats and coastal zones, while the construction of infrastructure also accelerated the change in the construction land. From 2010 to 2020, arable land, waters and woodland remained the largest land types transferred out, with areas of 3459 km^2, 2141 km^2 and 1937 km^2, respectively, while construction land was transferred in at 4205 km^2. In general, the area of arable land in the GBA fluctuated due to the national policy of returning farmland to forests and the continuous reduction in the primary industry over the past 20 years; the area of woodland changed less, while the area of land transferred for construction reached 51% of the original area over the past 20 years, which shows that the rapid development of the GBA has put the ecological land under pressure (Figure 4).



(**a**) (**b**) (**c**)

Figure 4. Schematic diagram of grid scale in the research area.

Table 2. Land Use Transfer Matrix for the Greater Bay Area of Guangdong, Hong Kong and Macau (km^2).

2000	2010					
	Arable Land	**Woodland**	**Grassland**	**Water**	**Construction Land**	**Unused Land**
Arable land	11,794.79	200.47	6.57	640.16	1788.17	0.14
Woodland	146.54	29,617.05	23.74	65.25	755.93	0.39
Grassland	10.14	76.23	1063.23	11.52	64.40	0.03
Water	542.56	39.28	4.26	3152.38	511.80	0.03
Construction land	130.03	92.71	3.79	71.54	4135.00	0.05
Unused land	2.10	0.91	0.02	3.23	6.61	10.63
2010	**2020**					
	Arable Land	**Woodland**	**Grassland**	**Water**	**Construction Land**	**Unused Land**
Arable land	10,971.15	760.73	36.61	244.38	2407.70	9.73
Woodland	617.77	28,671.65	221.40	115.43	973.95	8.69
Grassland	42.13	270.49	820.73	11.59	79.91	0.71
Water	1169.43	144.25	11.69	2108.89	736.71	79.34
Construction land	232.96	122.17	5.63	34.43	4026.30	11.63
Unused land	3.44	1.85	0.14	0.18	6.74	11.17

3.1.2. Shift in Land Use Focus

From 2000 to 2020, the center of gravity of the grassland, unused land and water areas in the GBA shifted significantly. The main reason for this is the expansion of the urban land area and the excessive artificial reclamation, which led to the occupation of ecological land such as ponds, dike-ponds and lakes; the center of gravity of the grassland moved 22,897 m to the northwest, and the center of gravity of the urban construction land moved 3602 m to the north and then 936 m to the southeast. The results of the analysis show the impact of the reorientation of urban development in different periods on various types of land, and that the shift in the center of gravity of the land use indicates a change in the structure of the land use in the region, as the environmental carrying capacity and self-regulating ability of the GBA are affected, resulting in a change in the ESVs (Table 3).

Table 3. Land use focus shift in the Guangdong, Hong Kong and Macao Greater Bay Area (m).

Type of Land Use	2000–2010		2010–2020	
	Transfer Distance	Transfer Direction	Transfer Distance	Transfer Direction
Arable land	3733	Northwest	3625	West
Woodland	1171	Northwest	591	Southeast
Grassland	2935	Northwest	19,962	Northwest
Water	3448	South	4276	Southeast
Construction land	3602	North	936	Southeast
Unused land	11,086	East	24,404	Southwest

3.2. Analysis of the Spatial and Temporal Evolution of Ecosystem Service Values

3.2.1. Time Series Changes in Ecosystem Service Values

In terms of the changes in the total ESVs, there is an overall decreasing trend from 2000 to 2020; in terms of the magnitude of change, there is a greater change in the waters, woodlands and croplands, thus indicating a continuous decline in the environmental quality of the region (Table 4).

In terms of the change in the ESVs of the different land types, hydrological regulation, biodiversity and soil conservation have the highest contribution ratings, with all three contributing more than 44.8%, while the least contribution is made by recreation and food production, which account for less than 10%. Specifically, soil conservation, food production and biodiversity maintenance are the main service functions of arable land; the main service function of woodland is biodiversity; the main service function of grassland is soil conservation, but the overall contribution of grassland is low due to its small footprint and the main service function of the watershed area is hydrological regulation and waste disposal. It is worth mentioning that the ESVs of the watershed area declined significantly by 139.37 × 10^8 CNY from 2010 to 2020, which is mainly due to the destruction of watershed habitats as a result of the dike-pond reclamation project and urban expansion, with the watershed area decreasing year by year. Overall, the ESVs in the study area show a decreasing trend due to the expansion of urban construction sites and the increasing negative impacts of human disturbances such as industrial waste emissions, domestic waste and vehicle exhaust (Figure 5).

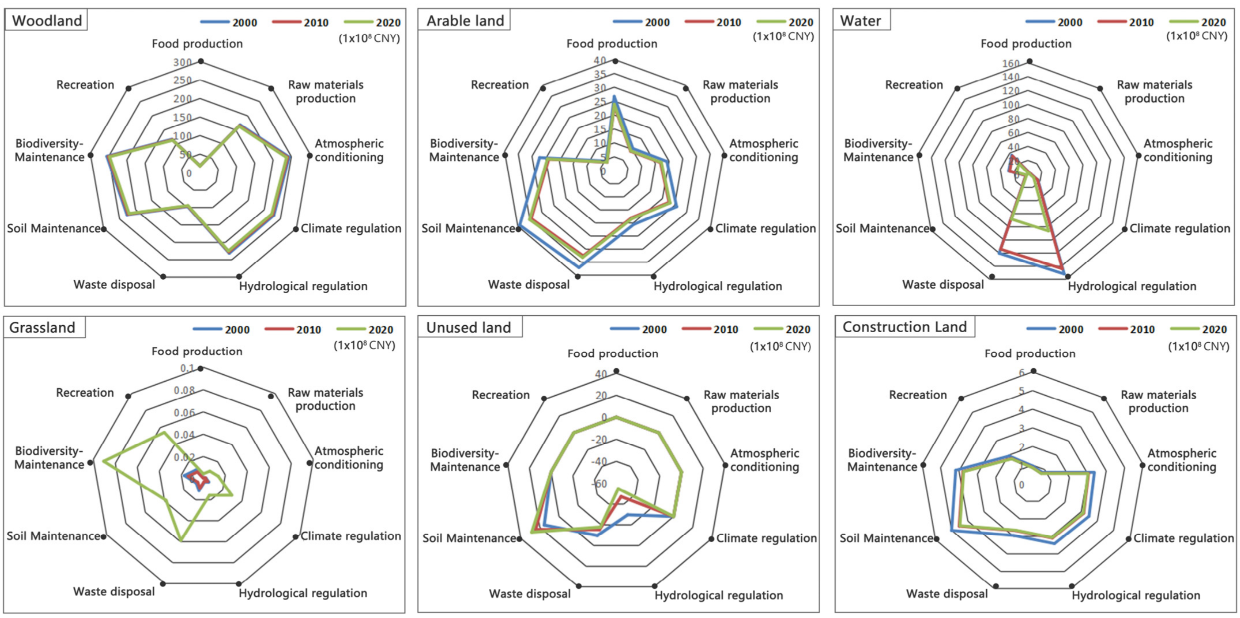


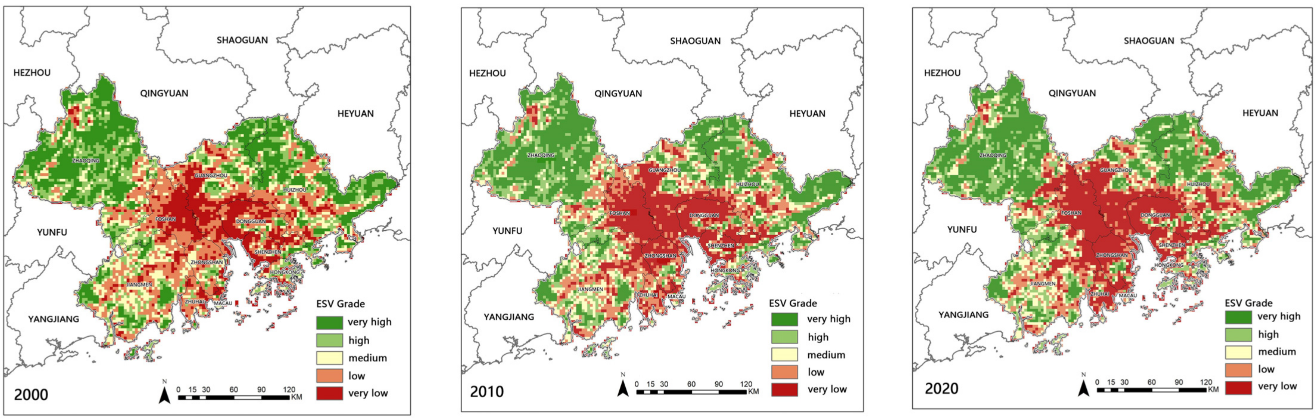
Figure 5. Land use interpretation map of Guangdong, Hong Kong and Macao Greater Bay Area in 2000 (**a**), 2010 (**b**) and 2020 (**c**).

Table 4. Changes of ecosystem service values (1 × 10^8 CNY) in the Guangdong–Hong Kong–Macao Greater Bay Area.

Ecosystem Service Functions		**2000**			**2010**			**2020**		
		ESV	**Contribution Rate (%)**	**Class**	**ESV**	**Contribution Rate (%)**	**Class**	**ESV**	**Contribution Rate (%)**	**Class**
Supply Services	Food production	50.55	2.33	9	46.69	2.25	9	45.29	2.36	9
	Raw material production	182.23	8.41	7	177.95	8.56	7	175.06	9.12	7
Reconciliation Services	Atmospheric regulation	270.50	12.48	5	263.59	12.68	5	259.44	13.52	4
	Climate regulation	275.75	12.72	4	267.60	12.87	4	258.97	13.50	5
	Hydrological regulation	377.05	17.40	1	344.90	16.59	1	277.16	14.44	3
Support Services	Waste disposal	247.68	11.43	6	229.28	11.03	6	180.65	9.41	6
	Soil maintenance	289.92	13.38	3	289.89	13.94	3	290.58	15.14	2
	Biodiversity maintenance	313.71	14.48	2	304.34	14.64	2	291.28	15.18	1
Cultural Services	Recreation	159.83	7.37	8	155.27	7.47	8	140.34	7.31	8
Total		2167.22	100	-	2079.50	100	-	1918.76	100	-

3.2.2. Spatial Changes in Ecosystem Service Values

The results of ESVs in the GBA are classified into the following five standard classes: very low(ESV < 15 × 10^6 CNY/hm^2), low (ESV of 15 × 10^6–30 × 10^6 CNY/hm^2), medium (ESV of 30 × 10^6–45 × 10^6 CNY/hm^2), high (ESV of 40 × 10^6–60 × 10^6 CNY/hm^2) and very high (ESV > 60 × 10^6 CNY/hm^2). In terms of the spatial distribution of the regional ESV class (Figure 6), the areas with a very high ESV class in the GBA are mainly located in the northeastern part of Zhaoqing, the northeastern part of Huizhou and the western and southern part of Jiangmen, which is mainly due to the rich woodland resources and good ecological substrate in the area. The very low ESV classes are found in the central part of the region, which is mainly due to the concentration of urban agglomerations in the region and the high level of disturbance from human activities, which accelerated changes in vegetation, climate and other related factors and led to a continuous decrease in the quality of water areas and water resources, with a large number of ponds and other water areas being encroached upon, as well as the negative impact of urban sewage on rivers and marine ecosystems, ultimately leading to a continuous decrease in the quality of habitats in the central urban agglomerations. Specifically, from 2000 to 2010, the area of low ESVs in the GBA expanded significantly. By 2020, low ESV areas became the dominant class type, accounting for 27.24% of the area, and still show an increasing trend, indicating that the ESVs in the GBA have been decreasing over the past 20 years. From the grid cells, the ESV cells in the GBA are mainly medium and low grade, and the high ESV area shows a small increase between 2000 and 2020, from 1534 cells to 1740 cells, which is mainly due to the related cities in the northwest of the GBA to increase the protection and restoration of forest land, slowing down the trend of reducing the forest land area. Among them, the proportion of high-grade cells in the Hong Kong and Macao special administrative regions is 3%, and it shows a small increase over 20 years, which is mainly due to the fact that the forest area in the Hong Kong and Macao special administrative region has increased by about 85 km^2 in 20 years, which contributed to the rebound of ESVs to a certain extent (Table 5).



(**a**) (**b**) (**c**)

Figure 6. Individual ecosystem service values in the Guangdong–Hong Kong–Macao Greater Bay Area.

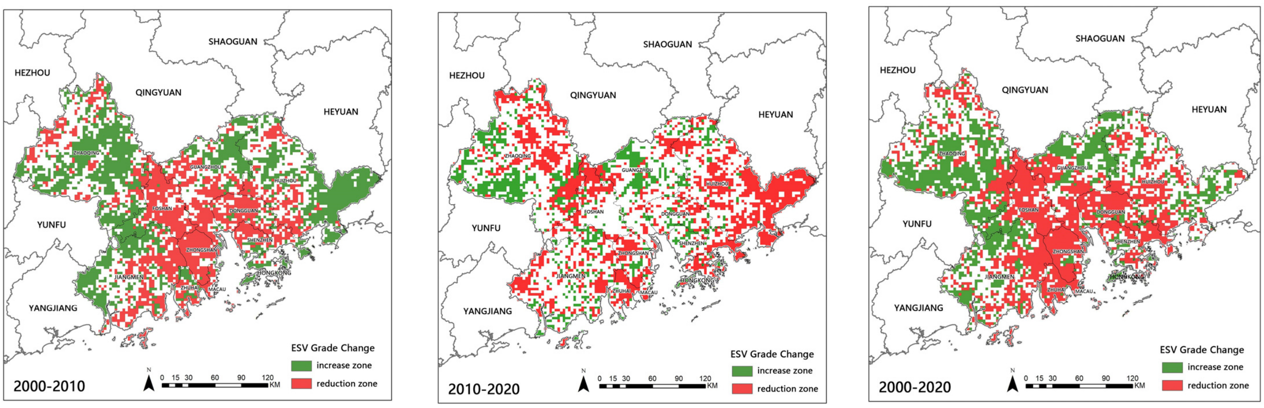
Table 5. Area statistics for different classes of ecosystem service values (number of cells).

Year	Very Low	Low	Medium	High	Very High
2000	1092	1577	1091	1157	1534
2010	1543	1159	933	1055	1761
2020	1757	992	916	1046	1740

In terms of the spatial changes in the ESV class, the overall ESV rank in the GBA remained stable from 2000 to 2010, with 34% of the regional ranks increasing, and 29% of them decreasing, mainly because the economic growth in the GBA was still slow at the beginning of the 21st century, with less disturbance to the ecological environment and land. Among them, the nine cities in the Pearl River Delta have a high proportion of areas with no significant changes and small increases in the ES levels, while the Hong Kong and Macao special administrative regions have an increasing trend in the ES function levels, mainly because the ecological restoration of Mai Po Nature Reserve in Hong Kong was effective, and the restored mangrove and mudflat ecosystems can provide a better ecological benefit. During 2010–2020, the overall ES level of the GBA declined significantly, among which the ES level of nine cities in the Pearl River Delta declined significantly, which is mainly due to the continuous adjustment in urban construction and industrial structure, and the accelerated growth rate of economic development in Zhaoqing, Huizhou, Zhongshan and other cities. A total of 33% of the regional ESV levels in the Hong Kong and Macau special administrative regions showed a declining trend, among which the level in the coastal areas declined significantly, which is mainly due to the prosperity of land reclamation projects in coastal areas, the decline of the retention rate of the natural shoreline, and the large changes in the regional ecological environment quality and ecological pattern (Table 6). Overall, 38% of the regional ESV class in the GBA did not change significantly over the 20-year period, the proportion of decreasing regional cells was 35%, the proportion of increasing regional cells was 27% and the number of decreasing regional cells continuously increased, indicating that the regional habitat quality is deteriorating (Figure 7).

Table 6. Area statistics on changes in ecosystem service value class (number of cells).

Year	ESV Reduction Zone (<−2.4 × 10^6 CNY/hm^2)	ESV No Significant Change Zone (−2.4–2.4 × 10^6 CNY/hm^2)	ESV Increase Zone (>2.4 × 10^6 CNY/hm^2)
2000–2010	1875	2387	2189
Proportion	29	37	34
2010–2020	2098	3373	980
Proportion	33	52	15
2000–2020	2286	2436	1729
Proportion	35	38	27

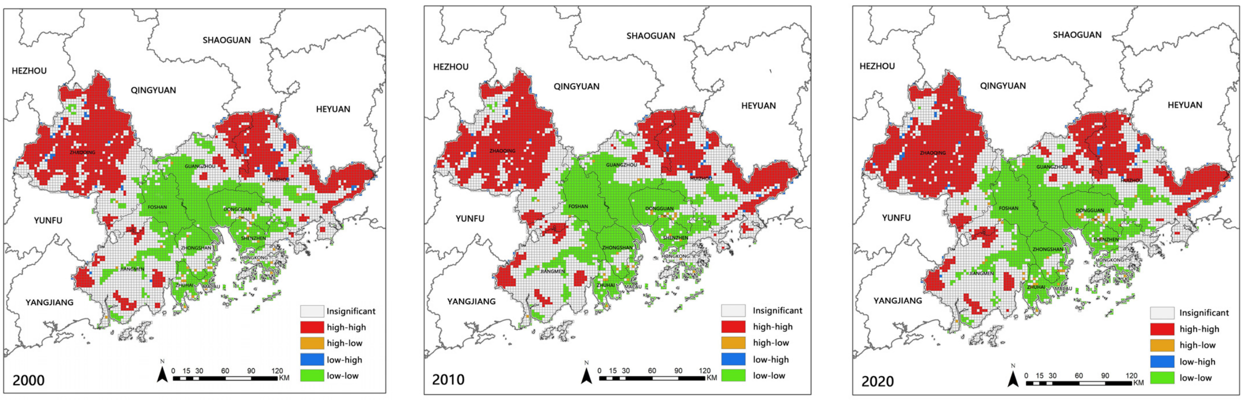


(**a**) (**b**) (**c**)

Figure 7. Ecosystem service values class for the Guangdong–Hong Kong–Macao Greater Bay Area in 2000 (**a**), 2010 (**b**) and 2020 (**c**).

In terms of the regional spatial correlation, the ESVs in the GBA show significant spatial aggregation, with "high-high" and "low-low" indicating the proximity of high-value and low-value areas of ESVs. The global Moran index of the study area shows an increasing trend from 2000 to 2020, indicating the increasing aggregation of ESVs in the GBA. Specifically, from 2000 to 2010, the "high-high" area continued to expand southward, which is mainly due to the obvious transfer of woodland to the south of the

GBA, the high vegetation cover of wetlands and river corridors, the better maintained landscape pattern and the more stable ecological land function structure. The "low-low" region is shifting from scattered distribution to patchy development, such as in Foshan, Zhongshan, Jiangmen and other cities, mainly because the concentrated development of construction land increased the intensity of land use and increased pressure on the ecological environment within the city. The Hong Kong and Macao special administrative regions also belong to the "low-low" region, mainly because of the limited space for urban development in the region, so a large number of land reclamation projects were carried out, encroaching on natural ecological land such as coastal shorelines and water areas, and the increase in the proportion of human-made land surface reduced the ESVs. From 2010 to 2020, the "high-high" zone continued to develop to the south, and the "low-low" zone is dominated by areas of concentrated urban agglomerations, which generate low ESVs due to a low intra-urban landscape diversity (Figure 8).



(**a**) (**b**) (**c**)

Figure 8. Areas of change in ecosystem service values class in 2000 (**a**), 2010 (**b**) and 2020 (**c**).

3.2.3. Forecasting the Ecosystem Service Values

By running the Markov model under the natural development scenario, the predicted ESV in 2030 reaches 1853.921 $\times$ 10^8 CNY, a decrease of 64.839 $\times$ 10^8 CNY compared to 2020, which is mainly due to the decreasing areas of watershed, woodland and grassland from 2000 to 2020, while the area of arable land shows stability in the context of policy protection. According to this pattern of development, the areas of watershed, woodland and grassland will keep decreasing in the future, resulting in a decreasing ESV in the forecast year 2030. At the same time, it can be observed that the future decline of water resources will remain a serious problem, and therefore, scientific and rational planning are needed to reduce damage to water resources and the near-coastal environment (Table 7).

Table 7. Projections of ecosystem service values (1 $\times$ 10^8 CNY) in the Guangdong–Hong Kong–Macao Greater Bay Area in 2030.

Ecosystem Service Types	Ecosystem Services	Arable Land	Woodland	Grassland	Water	Unused Land	Construction Land	Total
Supply Services	Food production	23.930	18.121	0.861	1.697	0.006	0.000	44.616
	Raw material production	9.333	163.641	0.721	1.121	0.012	0.000	174.828
Reconciliation Services	Atmospheric regulation	17.230	237.224	3.005	1.633	0.018	0.000	259.110
	Climate regulation	23.212	223.496	3.125	6.598	0.039	0.000	256.470
	Hydrological regulation	18.426	224.594	3.065	60.115	0.021	−60.090	246.131
Support Services	Waste disposal	33.263	94.450	2.644	47.560	0.078	−19.563	158.433
	Soil maintenance	35.177	220.750	4.487	1.313	0.051	31.314	293.093
	Biodiversity maintenance	24.409	247.658	3.746	10.985	0.121	0.000	286.918
Cultural Services	Recreation	4.068	114.219	1.743	14.220	0.072	0.000	134.322
Total		189.048	1544.154	23.395	145.244	0.419	−48.339	1853.921

3.3. Analysis of the Topographic Factor-Driven Effects of Ecosystem Service Value

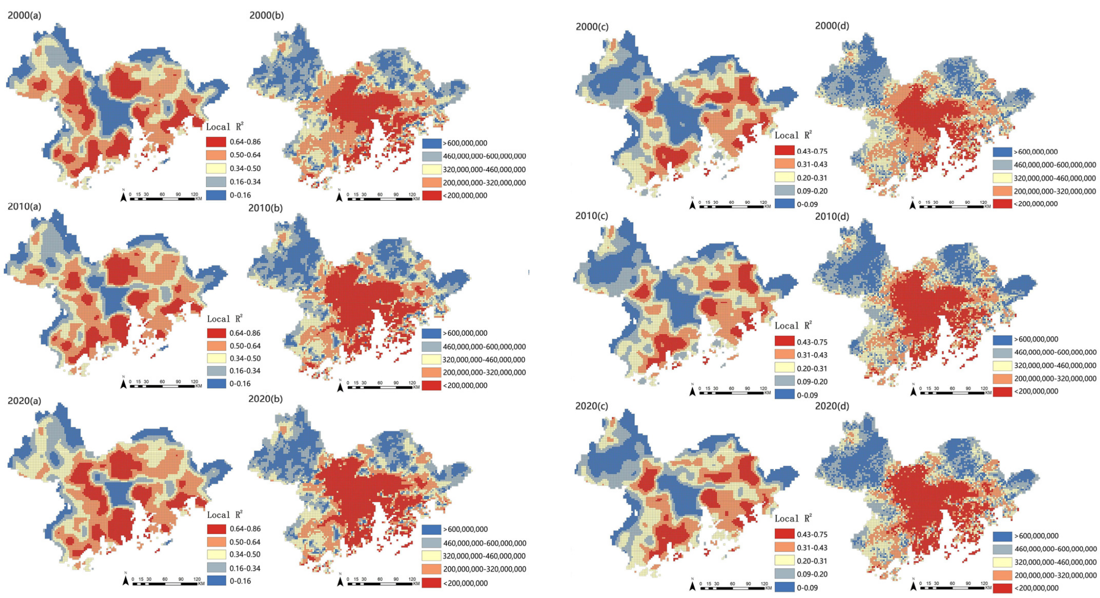
The elevation and slope were selected as the topographic characterization factors of the study area with reference to the relevant literature. The results of the geographically weighted regression model (GWR) show that $R^2 > 0.8$ and local $R^2 > 0.8$, indicating that the model operation results meet the accuracy requirements. The results show that the local R^2 of the data from 2000 to 2020 changed significantly, showing a decreasing trend and then an increasing trend, indicating that the influence of topographic factors on ESVs generally show an increasing trend. The regression parameters of the topographic factors (Table 8) show that the local R^2 values are above 0.85 in all years, indicating a significant correlation between the topographic factors and the ESVs.

Table 8. Topographic Factor Regression Parameter Table for Guangdong, Hong Kong and Macau Greater Bay Area.

Year	2000	2010	2020
Local R^2	0–0.8541	0–0.8532	0–0.8584
R^2	0.8022	0.8267	0.8317
Adjusted R^2	0.7883	0.8146	0.8200
AICC	256,353.8	256,973.8	256,797.1

In terms of spatial distribution, the strongest influence of topography on ESV is found in the northwestern and northeastern parts of the GBA, where the correlation with the land use data shows that woodland, arable land and water are the main land types, while the influence of the land–water interface in the south is also evident. Elevation and slope have a direct influence on plant growth, which determines the vegetation cover of the area and, thus, has a further influence on the ESVs provided (Figure 9).

From the perspective of construction land, apart from parks and green belts within the city, most areas have poor green infrastructure, and grey infrastructure, human housing and other construction land directly change the ecological landscape pattern of the land, which shows that human factors have a very strong influence on the ESVs. From 2000 to 2020, the trend of the overall pattern of the GBA clusters into patches, which shows that the influence of topographic factors on ESVs is gradually increasing.



(**a**) (**b**)

Figure 9. Local spatial autocorrelation of ecosystem service values in the Guangdong–Hong Kong–Macao Greater Bay Area in 2000 (**a**), 2010 (**b**) and 2020 (**c**).

4. Discussion and Conclusions

4.1. Discussion

4.1.1. Land Use Change Significantly Affects Ecosystem Service Values

Land is fundamental; the state and structure of the ecosystem are dependent on the land use approach, and the excessive repurposing of ecological land areas will cause the center of gravity of the land to continuously migrate, changing the landscape pattern of the region to a large extent, while affecting the supply of ESs. To achieve the sustainable development of the regional ecosystem, we must first pay attention to the adjustment of the land use structure; the regulation capacity and carrying capacity of the natural environment need reasonable planning of land use [54]. For example, in the areas around construction sites, the construction of nature reserves, the ecological restoration of rivers and lakes and the management of land reclamation projects can be strengthened to safeguard biodiversity, soil conservation and other ecological functions so as to safeguard the carrying capacity and self-regulating ability of the natural environment as a whole and enhance ESVs [55,56].

4.1.2. Spatial and Temporal Variation in Ecosystem Service Values and Strategies for Optimization

The spatial and temporal variations in ESVs in the GBA were significant from 2000 to 2020. Overall, in terms of the spatial distribution, the high-value areas are concentrated in the northwest, northeast and southwest regions where ecological land is widely distributed, while the low-value areas are mainly concentrated in the urban contiguous development areas and some coastal areas in the central part of the GBA, and the area of the low-value areas is still increasing. Specifically, in order to slow down the rate of diminishing ESVs, we should take the initiative to find entry points and explore optimization strategies in terms of human social life [57–59]. In terms of water resources, while the deep treatment and re-circulation of domestic fecal water and industrial wastewater should be carried out to achieve less or no discharge and improve the utilization rate of water resources, the rational use of water resources should be strengthened, water supply and drainage systems should be improved, land use planning should be carried out scientifically and reasonably and damage to water resources and the near-shore environment should be reduced [60,61]. In terms of energy use, the characteristics of each city in the GBA should be addressed, the upgrading of equipment for renewable and clean energy and the development of new energy sources should be enhanced to provide a reasonable and effective supplement [62]. In terms of solid waste treatment, while improving the harmless treatment of waste, the whole process of management and control should be implemented from all aspects of waste generation, collection, transportation, reuse and treatment to avoid causing adverse effects on the ecological environment and achieve control of waste generation.

4.1.3. Topographic Factors and Ecosystem Service Values

Topography has a direct impact on the growth state and diversity of plants, while the type, growth and distribution of plants have a critical impact on key regional ESs, such as soil and water conservation and water harvesting functions. The above analysis shows that there is a significant correlation between topographic factors and ESVs in the GBA, with an increase from 2000 to 2020. In the northwestern and northeastern parts of the region, the influence of topography on ES is particularly significant in areas such as woodland, arable land and the land–water interface, so that the protection and optimization of these areas is conducive to the sustainable development of the region, to the optimization of ESVs and to the construction of ecological security patterns across the region [63].

4.1.4. Sustainability in the Guangdong–Hong Kong–Macao Greater Bay Area

The results of the valuation of ESs in the GBA show that the region is currently facing significant ecological degradation and intensified resource and environmental constraints. At the same time, due to the GBA being located in the subtropical monsoon climate zone, its special geographical location and climatic conditions expose it to ecological risks such as flooding, storm surges and sea level rise, which pose challenges to regional ecological restoration and the construction of ecological security patterns. In the face of the continuous decline of ecological and environmental quality in the GBA, it is necessary to gradually promote the formation of green and low-carbon production and lifestyle and urban construction and operation mode to realize the sustainable development of the GBA. Therefore, the future development planning of the GBA should pay attention to the delineation of ecological protection zones and the control of urban expansion boundaries, and resist ecological risks such as storm surges and sea level rise by building a resilient multi-objective, cross-habitat and land–sea integrated regional ecological security pattern, while promoting the ecological restoration of coastal wetlands and coastal zone maintenance to construct a coastal security barrier in the GBA to achieve sustainable development [41].

4.2. Conclusions

Based on the land use changes in the GBA from 2000 to 2020, this study measures the ESVs in the GBA at the grid scale, predicts the ESVs in 2030 and analyzes its spatial and temporal evolution characteristics and the influence of topographic factors in ESVs. This will provide scientific guidance for optimizing ESVs.

(1) Over the past 20 years, in terms of the shift in the land area, the most obvious fluctuations are in the areas of water, arable land and construction land; the northwestern and northeastern areas with high vegetation cover gradually decreased, while the impervious area of the urban agglomerations in the central area is increasing, and the ecological land around the urban agglomerations, such as arable land and wetlands, is decreasing. In terms of the shift in the center of gravity of the land, the center of gravity of all types of land has shifted to different degrees, with the center of gravity of construction land shifting northward, while the center of gravity of grassland and unused land shifted westward, and the center of gravity of forest land has shifted northwestward, with significant contradictions between the survival of ecological land and the expansion of urban construction land.

(2) From an overall perspective, the ESVs in the GBA from highest to lowest are the following: regulating services > supporting services > provisioning services > cultural services. Hydrological regulation, biodiversity and soil conservation are the three items that contribute the most to the values of individual ESs. In terms of temporal changes, the ESs in the GBA showed a decreasing trend in the overall and individual values over the 20-year period. In terms of the spatial changes in rank, the area with the lowest ESV rank is located in the dense urban area in the central part of the GBA, accounting for 35% of the total area and increasing in size, indicating the deteriorating quality of the habitat; the area with a relatively high ESV rank is located in the city of Zhaoqing, northeastern Huizhou and Jiangmen in the GBA, accounting for 27% of the total area. The Markov model predicts that the ecosystem service value in 2030 shows a decreasing trend under the development of a natural state.

(3) The spatial distribution of ESVs in the GBA is aggregated, and there is a regional adjacency between the high-value and low-value areas of ESVs. From 2010 to 2020, the "high" area continues to develop to the south, and the scope of the low-value aggregation area is also expanding. The construction land in the low-value area is increasing, and the population and traffic pressure are becoming bigger and bigger, which has a great impact on the urban green space system and reduces the anti-disturbance ability of the inner-city green space ecosystem.

(4) There is a significant correlation between topographic factors and ESV, where topographic factors have a strong influence on ESVs mainly in the northwestern and northeastern parts of the GBA, and the coupling analysis with the land use data show that the main land types in this area are forest land, arable land and water. At the same time, the influence of the water–land intersection zone in the south is also obvious; the weaker influence is mainly located in the central part of the study area and the border area, and the main land types are construction land, dike-ponds and forest land.

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References

1. Liu, Y.; Yan, Y.; Li, X. An Empirical Analysis of an Integrated Accounting Method to Assess the Non-Monetary and Monetary Value of Ecosystem Services. *Sustainability* **2020**, *12*, 8296. [CrossRef]
2. Li, X.; Zhou, J.; Huang, Y.; Huang, M. Understanding the Guangdong-Hong Kong-Macao Greater Bay Area from the perspective of megacity region. *Prog. Geogr.* **2018**, *37*, 1609–1622.
3. Feng, S.; Fan, F. Spatiotemporal changes of landscape pattern using impervious surface in Guangdong-Hong Kong-Macao Greater Bay Area, China Hong Kong-Macao Greater Bay Area, China. *J. Appl. Ecol.* **2018**, *29*, 2907–2914.
4. SCEP. *Man's Impact on the Global Environment: Study of Critical Environmental Problems*; MIT Press: Cambridge, MA, USA, 1970.
5. Liu, X. Ecosystem Services. *Environ. Her.* **1998**, *1*, 44.
6. Ouyang, Z.; Zheng, H. Ecological mechanisms of ecosystem services. *Acta Ecol. Sin.* **2009**, *29*, 6183–6188.
7. Xie, G.; Xiao, Y.; Zhen, L.; Lu, C. Study on ecosystem services value of food production in China. *Chin. J. Eco-Agric.* **2005**, *13*, 10–13.
8. Yan, S.; Wang, X. Advances of Research on Ecosystem Service. *Chin. J. Ecol.* **2002**, *21*, 61–68.
9. Aodeng, G.; Liang, Y.; Han, G. Overview of grassland ecosystem service functions and their eco-economic value. *Inn. Mong. Prataculture* **2004**, *16*, 46–47.
10. Li, L.; Wang, X.; Luo, L.; Yi, X.; Zhao, Y.; Zhao, Y.; Bachagha, N. A systematic review on the methods of ecosystem services value assessment. *Chin. J. Ecol.* **2018**, *37*, 1233–1245. [CrossRef]
11. Kareiva, P.; Marvier, M. Conserving biodiversity coldspots-Recent calls to direct conservation funding to the world's biodiversity hotspots may be bad investment advice. *Am. Sci.* **2003**, *4*, 220–224.
12. Robertson, G.P.; Swinton, S.M. Reconciling agricultural productivity and environmental integrity: A grand challenge for agriculture. *Front. Ecol. Environ.* **2005**, *1*, 38–46. [CrossRef]
13. Li, L.; Lin, W.; Ren, C.; Xv, D. Comparative Study on Two Assessment Methods of Ecosystem Service Value—A Case Study of Hangzhou Bay Area. *Res. Soil Water Conserv.* **2022**, *29*, 228–234.
14. Zhou, Y.; Yi, L.; Kuang, H.; He, Y.; Yang, D.; Zhou, L. Study on the Changes and Ecological System Service Values in Guangdong-Hong Kong-Macao Greater Bay Area. *Environ. Prot.* **2019**, *47*, 56–60.
15. Wang, S.; Huang, L.; Xv, X.; Xv, S. Spatial and temporal evolution of ecosystem services and its trade-offs and synergies in Guangdong-Hong KongMacao Greater Bay Area. *Acta Ecol. Sin.* **2020**, *40*, 8403–8416.
16. Lin, M.; Zhou, R.; Zhong, L. Research on the changes of ecosystem services in Guangdong-Hong Kong-Macao Greater Bay Area based on the change of landscape pattern. *J. Guangzhou Univ. (Nat. Sci. Ed.)* **2019**, *18*, 87–95.
17. Li, J.; Wang, J. Identification, classification, and mapping of coastal ecosystem services of the Guangdong, Hong Kong, and Macao Great Bay Area. *Acta Ecol. Sin.* **2019**, *39*, 6393–6403.
18. Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'neill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
19. Xie, G.; Zhang, C.; Zhang, L.; Chen, W.; Li, S. Improvement of the Evaluation Method for Ecosystem Service Value Based on Per Unit Area. *J. Nat. Resour.* **2015**, *30*, 1243–1254.
20. Wang, W.; Guo, H.; Chuai, X.; Dai, C.; Lai, L.; Zhang, M. The impact of land use change on the temporospatial variations of ecosystems servicesvalue in China and an optimized land use solution. *Environ. Sci. Policy* **2014**, *44*, 62–72. [CrossRef]
21. Xie, W.; Fu, W.; Yang, D.; Liu, J. Spatio-temporal Evolution and Simulation Forecast of Ecosystem Service Value in Jiangsu Province Based on Land Use Changes. *Areal Res. Dev.* **2022**, *41*, 126–158.
22. Ma, S.; Shi, M.; Yang, G.; Xv, X.; Yin, J. Analysis on spatiotemporal Change of Land Use Based on GIS Technology—Taking Xingjiang Tarim Basin as an Example. *Res. Soil Water Conserv.* **2013**, *20*, 177–181.
23. Hu, X.; Hong, W.; Wu, C.; Qi, X. Spatiotemporal differentiation ofland eco-system service in Fuzhou City. *China Environ. Sci.* **2013**, *33*, 881–888.
24. Wang, X.; Yan, F.; Su, F. Impacts of Urbanization on the Ecosystem Services in the Guangdong-Hong Kong-Macao Greater Bay Area, China. *Remote Sens.* **2020**, *12*, 3269. [CrossRef]

25. Wu, L.; Sun, C.; Fan, F. Estimating the Characteristic Spatiotemporal Variation in Habitat Quality Using the InVEST Model—A Case Study from Guangdong-Hong Kong-Macao Greater Bay Area. *Remote Sens.* **2021**, *13*, 1008. [CrossRef]
26. Liu, Y.; Hou, X.; Li, X.; Song, B.; Wang, C. Assessing and predicting changes in ecosystem service values based on land use/cover change in the Bohai Rim coastal zone. *Ecol. Indic.* **2020**, *111*, 106004. [CrossRef]
27. Jiang, T. Thesis for Master Degree of Science Change of Farmland Ecosystem Services Values and Its Driving Forces in Northwestern Arid Area—A Case Study on Minqin County Tongchang JIANG. Master's Thesis, Lanzhou University, Lanzhou, China, 2010.
28. Yao, C.; Zhu, H.; Lv, X.; Liu, Y. Study on theImpact of Socio-economic Driving Factors of Land Use Change on the Ecosystem Service Values in Fujian Province. *J. Nat. Resour.* **2009**, *24*, 225–233.
29. Chen, Y.; Li, J.; Xv, J. The influence of socio-economic factors on the value of ecological services in Hubei Province based on GWR. *China Land Sci.* **2015**, *29*, 89–96.
30. Li, Q.; Li, T.; Yang, M.; Ying, W. Spatiotemporal variation of ecosystem services value based on gradient analysis in Wuhan. *Acta Ecol. Sin.* **2017**, *37*, 2118–2125.
31. Yao, X.; Zhou, D.; Huang, W.; Liu, X. Spatial and temporal effects of ecosystem service values on topographic gradients in northwest Qianxi. *Agric. Technol.* **2022**, *42*, 93–100.
32. Zhang, T.; Qu, Y.; Liu, Y.; Yan, G.; Foliente, G. Spatiotemporal Response of Ecosystem Service Values to Land Use Change in Xiamen, China. *Sustainability* **2022**, *14*, 12532. [CrossRef]
33. Liu, Z.; Wang, S.; Fang, C. Spatiotemporal evolution and influencing mechanism of ecosystem service value in the Guangdong-Hong Kong-Macao Greater Bay Area. *Acta Geogr. Sin.* **2021**, *76*, 2797–2813.
34. Wu, J.; Jiang, W.; Huang, Y. Spatial-Temporal Changes of Ecosystem Service Value in the Guangdong-Hong Kong-Macao Greater Bay Area. *South Archit.* **2022**, *6*, 52–61.
35. Hou, J.; Qin, T.; Liu, S.; Wang, J.; Dong, B.; Yan, S.; Nie, H. Analysis and Prediction of Ecosystem Service Values Based on Land Use/Cover Change in the Yiluo River Basin. *Sustainability* **2021**, *13*, 6432. [CrossRef]
36. Chunshan, Z.; Luo, L.; Shi, C.; Wang, J. Spatio-temporal Evolutionary Characteristics of the Economic Development in the Guangdong-Hong Kong-Macao Greater Bay Area and Its Influencing Factors. *Trop. Geogr.* **2017**, *37*, 802–813.
37. Gu, S.; Cao, D.; Yang, M. The Strategic Thinking of Building Innovation Ecosystem in Guangdong-Hong Kong-Macao Greater Bay Area. *Chin. Soft Sci.* **2018**, *4*, 1–9.
38. Zhu, M.; Fu, X. Spatial-temporal Evolution of Urban Land Use Efficiency in the Guangdong-Hong Kong-Macao Greater Bay Area. *Trop. Geogr.* **2017**, *37*, 814–823.
39. Wang, F.; Gao, J.; Shao, H.; Zhang, T.; Zhang, Y.; Xv, X.; Zhao, C.; Wang, H. Response of ecosystem service values to land use change based on GIS and ecological compensation in Loess Plateau. *Sci. Soil Water Conserv.* **2013**, *11*, 25–31.
40. Niu, X. Research on Distributed Assessment and Quantitative Compensation of Forest Ecological Benefit—Case Studies with Guangdong and Liaoning Provinces. Master's Thesis, Beijing Forestry University, Beijing, China, 2012.
41. Zhang, J.; Li, Q.; Wu, X.; Zhang, C.; Wang, J.; Wu, G. Evolution of the ecosystem services value and carrying capacity in the Guangdong-Hong KongMacao Greater Bay Area based on land use changes. *Acta Ecol. Sin.* **2021**, *41*, 8375–8386.
42. Chang, X.; Li, X.; Diao, H. Analysis of spatial and temporal changes in land use and shift of focus in mining areas. *J. Inn. Mong. Agric. Univ. (Nat. Sci. Ed.)* **2021**, *42*, 41–48.
43. Yang, G.; Lv, K.; Li, F. Spatial and Temporal Correlation Analysis of Land Use Change and Ecosystem Service Value in Nanchang City Based on Grid Scale. *China Land Sci.* **2022**, *36*, 121–130.
44. Shi, Y.; Wang, R.; Huang, J.; Yang, W. Analysis of spatial and temporal variation in terrestrial ecosystem service functions in China. *Sci. Bull.* **2012**, *57*, 720–731. [CrossRef]
45. Zhang, L.; Yu, X.; Jiang, M.; Xue, Z.; Lu, X.; Zou, Y. A consistent ecosystem services valuation method based on Total Economic Value and Equivalent Value Factors: A case study in the Sanjiang Plain, Northeast China. *Ecol. Complex.* **2017**, *29*, 40–48. [CrossRef]
46. Xie, G.; Lu, C.; Cheng, S. Advances in global ecosystem service valuation research. *Resour. Sci.* **2001**, *6*, 5–9.
47. Xv, Y.; Zhou, Y.; He, Y.; Kuang, H.; Yang, D. Study on the prediction of ecological system service values based on the changes of land use in Guangdong-Hongkong-Macau Greater Bay Area. *Ecol. Sci.* **2020**, *39*, 207–212.
48. Luo, D.; Zhang, W. A comparison of Markov model-based methods for predicting the ecosystem service value of land use in Wuhan, central China. *Ecosyst. Serv.* **2014**, *7*, 57–65. [CrossRef]
49. Gao, X.; Wang, J.; Li, C.; Shen, W.; Song, Z.; Nie, C.; Zhang, X. Land use change simulation and spatial analysis of ecosystem service value in Shijiazhuang under multi-scenarios. *Environ. Sci. Pollut. Res.* **2021**, *28*, 31043–31058. [CrossRef] [PubMed]
50. Brunsdon, C.; Fotheringham, A.S.; Charlton, M.E. Geographically weighted regression: A method for exploring spatial nonstationarity. *Geogr. Anal.* **1996**, *28*, 281–298. [CrossRef]
51. Noresah, M.S.; Ruslan, R. Modelling urban spatil structure using Geographically weighed Ression. In Proceedings of the 18th World IMACS Congress and MODMS09 International Congress on Modelling and Simulation, Cairns, Australia, 13–17 July 2009; Australian National University: Canberra, Australia, 2009; Volume 9, pp. 13–17.
52. Platt, R.V. Global and local analysis of fragmentation in a mountain region of Colorado. *Agric. Ecosyt. Environ.* **2004**, *2*, 207–218. [CrossRef]
53. Chen, X. Comparison and analysis of spatial prediction and variability of soil pH in Anhui Province based on three kinds of geographically weighted regression. *Sci. Geogr. Sin.* **2023**, *5*, 5–6.

54. Hasan, S.S.; Zhen, L.; Miah, M.G.; Ahamed, T.; Samie, A. Impact of land use change on ecosystem services: A review. *Environ. Dev.* **2020**, *34*, 100527. [CrossRef]
55. Fu, B.; Zhang, L. Land-use change and ecosystem services: Concepts, methods and progress. *Prog. Geogr.* **2014**, *33*, 441–446.
56. Talukdar, S.; Singha, P.; Shahfahad; Mahato, S.; Praveen, B.; Rahman, A. Dynamics of ecosystem services (ESs) in response to land use land cover (LU/LC) changes in the lower Gangetic plain of India. *Ecol. Indic.* **2020**, *112*, 106121. [CrossRef]
57. Wang, Y.; Shen, J.; Xiang, W. Ecosystem service of green infrastructure for adaptation to urban growth: Function and configuration. *Ecosyst. Health Sustain.* **2018**, *4*, 132–143. [CrossRef]
58. Zheng, W.; Ke, X.; Xiao, B.; Zhou, T. Optimising land use allocation to balance ecosystem services and economic benefits-A case study in Wuhan, China. *J. Environ. Manag.* **2019**, *248*, 109306. [CrossRef]
59. Jin, G.; Deng, X.; Chu, X.; Li, Z.; Wang, Y. Optimization of land-use management for ecosystem service improvement: A review. *Phys. Chem. Earth Parts A/B/C* **2017**, *101*, 70–77. [CrossRef]
60. Jin, G.; Wang, P.; Zhao, T.; Bai, Y.; Zhao, C.; Chen, D. Reviews on land use change induced effects on regional hydrological ecosystem services for integrated water resources management. *Phys. Chem. Earth Parts A/B/C* **2015**, *89–90*, 33–39. [CrossRef]
61. Liu, J.; Li, J.; Gao, Z.; Yang, M.; Qin, K.; Yang, X. Ecosystem Services Insights into Water Resources Management in China: A Case of Xi'an City. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1169. [CrossRef] [PubMed]
62. Picchi, P.; van Lierop, M.; Geneletti, D.; Stremke, S. Advancing the relationship between renewable energy and ecosystem services for landscape planning and design: A literature review. *Ecosyst. Serv.* **2019**, *35*, 241–259. [CrossRef]
63. Xie, B.; Meng, S.; Zhang, M. Evolution of Habitat Quality and Its Response to Topographic Gradient Effect in a Karst Plateau: A Case Study of the Key Biodiversity Conservation Project Area of Wuling Mountains. *Int. J. Environ. Res. Public Health* **2023**, *20*, 331. [CrossRef]

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Zoning strategies for ecological restoration in the karst region of Guangdong province, China: a perspective from the "social-ecological system"

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Ecological restoration holds great significance in addressing environmental degradation and rock desertification in karst areas. Zoning strategy is a fundamental task in understanding the interrelationship between human-environment to foster sustainable development. We explore "social-ecological" system and conduct a case study on the karst region in Guangdong Province, China. An evaluation framework consists of "development pressure", "sensitivity status", and "resilience potential" was established. The results show that: regions with high pressure of development are predominantly located in high-density urban areas. The generally distribution of the comprehensive status index exhibits significant spatial heterogeneity. Regions with low sensitivity are found on the eastern and western sides of the study area. The comprehensive resilience values are largely influenced by *per capita* energy-saving and environmental protection expenditures. The restoration zones mainly concentrated in the contiguous regions of the northwestern and southern parts, covering more than half of the total area. The conservation zones are more numerous and primarily situated in the northern and eastern parts. By integrating socio-economic and ecological factors, this study proposes ecological restoration strategies for specific zones. It helps for improve development issues arising from complex interactions between human-environment, facilitating the implementation of restoration practices.

KEYWORDS

social-ecological system, ecological restoration zoning, development pressure, sensitivity status, resilience potential, restoration strategies, karst region of Guangdong province, China

1 Introduction

Increasingly severe degradation and damage to ecosystems are among the current global hot topics (Van der Biest et al., 2020). With the acceleration of China's industrialization and urbanization, high-intensity development and irrational human activities have led to continuous deterioration of the ecological environment, to some extent affecting the economy and the sustainable use of natural resources (Tang et al., 2022; Hu et al., 2023). To address the escalating environmental issues and gradually achieve the goal of sustainable development, it is crucial to correctly understand and manage the relationship between human activities and ecosystems (Li et al., 2023a). In recent years, the significance of ecological restoration for sustainable development has become increasingly prominent. Actively identifying priority areas for ecological protection and restoration through natural or human interventions to restore degraded ecosystems is a critical strategic task for ecological security and human wellbeing (Peng et al., 2020; Zhao et al., 2023). Scientifically delineating zones enhances the precision and targeting of ecological restoration, serving as an important prerequisite for spatial control of ecological restoration projects and differentiated spatial governance (Yue et al., 2022). Currently, ecological restoration primarily focuses on administrative units or natural watersheds, and zoning methods include research frameworks based on regional dominant functions (Tian et al., 2017; Cai et al., 2020), ecological security pattern construction (Ni et al., 2020; Jiang et al., 2022; Zhang et al., 2023), supply-demand of ecosystem services (Xie et al., 2020; Yue et al., 2022; Hu et al., 2023; Li et al., 2023c), comprehensive indicator systems. Regional context, landscape heterogeneity, human activities, socio-economic are interplay with ecosystem, which needs to be integrated during ecological restoration zoning, the comprehensive indicators not only offer an intuitive depiction of the ecological characteristics and interplay of human activities and economic growth but can also be aligned with the critical objectives of enhancing the level of ecosystem services. The multi-dimensional and multi-functional evaluation underscores the holistic and systematic nature of ecological restoration, demonstrating its effectiveness (Cao et al., 2019; Dan et al., 2020; Li et al., 2023b).

In previous studies, human activities and economic indicators were generally considered as stressors on regional ecological environments, reflecting the conflict within the "social-ecological" system (Wang and Zhong, 2019). However, there is a growing demand for promoting a harmonious coexistence of humans and nature and for reconciling the relationship between ecosystems and socio-economic development (Bai et al., 2019). In recent years, the focus has shifted towards the "social-ecological" system perspective in human-environment research (Vos et al., 2019). Qualitative and quantitative research, which includes aspects such as vulnerability and resilience, marks the beginning of "social-ecological" system research (Liu et al., 2023). While frameworks like DSPIR, PSR, and VSD provide evaluation methods for ecological vulnerability and ecosystem health, they have not offered partitioning schemes for mitigating ecosystem degradation and restoring ecosystem functions and services (Song et al., 2019; Liu et al., 2020). Therefore, to comprehensively address the systemic and holistic issues in both ecosystem protection and social system governance (Ahammad et al., 2023; Wang H. et al., 2023), integrating ecological conservation and restoration into socio-economic development can effectively promote the coordination of human-environment relationships and the sustainable development of the "social-ecological" system (Tedesco et al., 2023). Ecological restoration zoning needs to consider simultaneously the pressure of human activities on the ecosystem, the state of the ecosystem itself, and the resilience potential created by socio-economic development. Based on the results of ecological restoration zoning, appropriate governance approaches and relevant policy recommendations can be proposed.

Karst areas account for about a fifth of the global land area, of which the South China Karst (SCK), is an ecologically fragile area of the largest distribution (Xiong et al., 2023). The SCK is characterized by acute human-environment conflicts, resulting in issues such as frequent soil erosion, the degradation of vegetation cover, and increased poverty. The combined effects of a fragile natural environment and irrational human activities severely hampers socio-economic development, making it imperative to implement ecological protection and restoration (He et al., 2019). The primary task is to delineate comprehensive zoning. Previous land spatial zoning studies in karst areas have not comprehensively considered the spatial variations of desertification and human disturbances (Zhang et al., 2020). Some researchers have established ecological restoration zoning at the basin and grid scales, they have elucidated the inherent characteristics and relationships between various levels of zoning, but precise boundary delineation for implementation was not addressed (Wang and Zhao, 2022; Wang Y. et al., 2023). The key ecological protection and restoration areas from a "social-ecological" system perspective and policy implementation still need to be explored. Therefore, ecological restoration zoning in karst areas should not only consider factors like the degree of ecosystem degradation but should also integrate human activities and the resilience potential of social systems into the framework. Only then can it better contribute to regional sustainable development and improvement of human-environment relationships.

Guangdong's karst region is mainly concentrated in the northern and northwestern parts of the province. It is situated in the upstream of the Pearl River Delta, serving as a critical ecological barrier and freshwater source for the Guangdong-Hong Kong-Macau Greater Bay Area. Compared to the existing research on karst regions in the SCK, the desertification control in Guangdong's karst region is currently limited to statistical analysis and comprehensive zoning strategies are still unclear. There is an urgent need for zoning studies to guide the steady progress of ecological restoration efforts. This paper approaches the issue from the perspective of the "social-ecological system" and proposes the "development pressure-sensitivity state-resilience potential" framework. By constructing comprehensive evaluation indicators for quantitative assessment, the goal is to delineate ecological restoration zones that harmonize ecological conditions with the socio-economic systems. This is expected to provide a reference for differentiated management and restoration strategies of desertification issues in karst areas.

2 Materials and methods

2.1 Study area overview

The selected study area focuses on the concentrated and contiguous regions with prominent desertification issues, which account for over 90% of the total desertification area in Guangdong province. This area includes the following counties and cities: Qingxin District, Yingde City, Yangshan County, Liannan Yao Autonomous County, and Lian-zhou City in Qingyuan City; Lechang City, Ruyuan Yao Autonomous County, Wujiang District, and Wengyuan County in Shaoguan City; and Lianping County in Heyuan City (Figure 1). The study area is

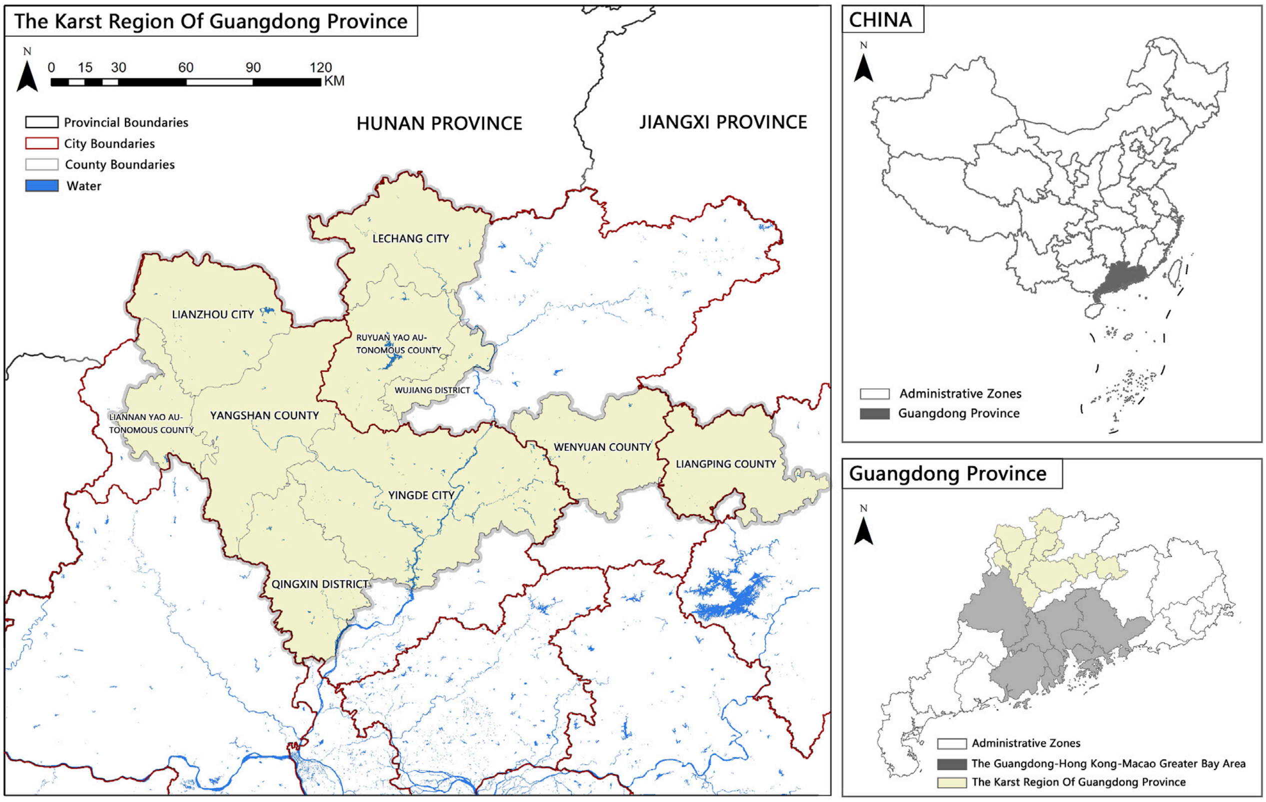

FIGURE 1
Location of the karst region of Guangdong province, China.

located between 112°2′to 114° 56′east longitude and 23°32′to 25°34′north latitude, covering a total area of approximately 25,077.23 square kilometers. The topography of the study area is complex and includes various landforms. It falls within a subtropical monsoon climate zone with abundant rainfall, averaging between 1,200 and 2000 mm annually. According to data from various city statistical year-books, the study area had a permanent population of approximately 3,993,200 people in the year 2020. The population distribution is uneven, with sparsely populated areas in the mountainous regions and dense populations in hilly areas. The overall Gross Domestic Product (GDP) of the region is relatively low, with Wujiang District and Qingxin District ranking first and second, respectively.

2.2 Data sources and initial data processing

The research data mainly include the following: 1. Land use remote sensing monitoring data with a spatial resolution of 1 km for the years 2013 and 2020.2. Normalized Difference Vegetation Index (NDVI) data with a spatial resolution of 1 km for the year 2020.3. Digital Elevation Model (DEM) data with a spatial resolution of 1 km. All three types of data are sourced from the Chinese Academy of Sciences Resource and Environmental Science Data Center. 4. Normalized Difference Rock Index (NDRI) data, calculated using the PIE Engine Studio remote sensing computing cloud service platform, with a spatial resolution of 1 km for the year 2020.5. Meteorological data, obtained from the National Earth System Science Data Center, with a spatial resolution of 1 km, providing monthly rainfall data for the year 2020.6. Soil erodibility data for Guangdong Province, sourced from the High-Performance Computing Platform for Geographic Data and Application Analysis at the Faculty of Geographic Science, Beijing Normal University. The data has been resampled to a spatial resolution of 1 km for the year 2021.7. Socio-economic and population data collected from the official websites of Qingyuan, Shaoguan, and Heyuan governments, statistical yearbooks, and the "Compilation of National Agricultural Product Cost and Income Data." The data is for the year 2020.

All raster data types have been reprojected to a common coordinate system, specifically the National Geodetic Coordinate System, and have been extracted based on the study area's boundaries.

2.3 Research methods

The issue of karst desertification in karst regions arises from the intricate interplay between social and natural factors. It is consequence of the detrimental effects of human activities on the ecosystems, with unreasonable human interventions being the predominant contributing factor. This expansion of urban

TABLE 1 Evaluation indicators.

Dimension	Indicators	Attribute of indicators
Development pressure	Spatial Conflict Comprehensive Index between PLES	-
	Population density	-
	Proportion of built-up land area	-
Sensitivity status	Vegetation coverage	+
	Rock exposure rate	-
	Soil Erosion Modulus	-
Resilience potential	Ecosystem Service Value	+
	Per Capita Energy Conservation and Environmental Protection Expenditure	+
	Proportion of Land Converted to Woodland and Grassland	+

development and the rapid population growth, exerting substantial pressure on the local ecosystems.

The level of sensitivity reflects the degree to which karst regions react to the disruptions caused by socio-economic development and human activities. It signifies how easily and likely karst desertification might occur in response to disturbances. This level can be described using a set of indicators or characteristics, including vegetation cover, soil erosion, and exposed bedrock, which highlight the critical features of karst desertification.

Resilience potential describes the ability of karst regions to self-regulate their ecosystems in response to disturbances and pressures. It also encompasses the capacity of socio-economic factors to facilitate the restoration of ecosystems to their original structure and functional levels. Typically, the government capital investment and human-initiated restoration activities are employed to measure resilience potential. The crucial principle in ecological restoration practices is "giving priority to natural restoration", nature-based solutions can be assessed using ecosystem service values (Fan et al., 2022; Gong et al., 2020).

To scientifically delineate ecological restoration zones for karst desertification, it is crucial to select representative and systematic indicators. In this study, based on the interaction between socio-economic factors and ecosystems, we have established an evaluation framework of "development pressure-sensitivity status-resilience potential" and selected appropriate indicators to create an evaluation system (Table 1).

2.3.1 Development pressure

We selected indicators such as the proportion of built-up land area and population density for characterization. Specifically, a higher proportion of built-up land indicates a greater likelihood of encroachment on arable land and woodland. Population density serves as a reflection of the pressure on the ecosystem, where higher population density implies greater stress on the ecosystem. With the promotion of rapid economic and social development, land use has undergone profound processes of transition, leaving the production–living–ecological spaces (PLES) and landscape pattern reconfigured, thus further affecting regional eco-environmental quality and landscape ecological risk (Chen et al., 2022). Therefore, we also incorporated the Spatial Conflict Comprehensive Index between PLES to reflect the irrational land use in karst areas.

2.3.1.1 Spatial conflict comprehensive index between PLES

Based on the multifunctionality of land, and considering the dominant and secondary functions in space, land use is divided into following categories (Liao et al., 2017; Zhao et al., 2019).

- Living-Production Space (urban land, rural residential areas, and other construction land)
- Production-Ecological Space (paddy fields and dryland)
- Ecological -Production Space (woodland and reservoirs/ponds)
- Ecological Space (grassland, rivers, lakes, tidal flats, wastelands, and bare land)

The conflict in land use spatially can be represented as a comprehensive analysis of system complexity, vulnerability, and stability. This conflict index aims to capture the spatial dynamics and potential tensions resulting from land use activities in karst regions.

$$\boldsymbol{SCCI} = \boldsymbol{CI} + \boldsymbol{FI} - \boldsymbol{SI} \tag{1}$$

In the Eq. 1, SCCI, representing the Spatial Conflict Comprehensive Index between PLES, is accompanied by CI (Spatial Complexity Index), FI (Spatial Fragility Index), and SI (Spatial Stability Index). The detailed methods for computing each of these indices can be found in the cited reference (Liao et al., 2017).

Taking into consideration factors like the study area's extent, zoning units, and spatial resolution, these indices were computed using a 10 km × 10 km window size, resulting in the Spatial Conflict Comprehensive Index (SCCI) with values falling within the [0,1] range. Drawing inspiration from the curve distribution model of Spatial Conflict Index, the index values are classified into the following categories (Feng, 2021): Stable and Controllable [0, 0.4), Essentially Controllable [0.4, 0.6), Essentially Uncontrollable [0.6, 0.8), and Significantly Conflictive [0.8, 1].

2.3.1.2 Population density and proportion of construction land area

Population density (people/km^2) is computed based on 2020 population data for each county. The proportion of construction land area is determined as the ratio of the combined area occupied by urban, industrial, mining, and residential land to the total administrative area of each county, utilizing land use remote sensing monitoring data from the year 2020.

2.3.1.3 Comprehensive pressure index

The comprehensive pressure index is derived to delineate the spatial distribution characteristics and data variations among the three indicators. Given the substantial numerical differences in population density and the proportion of construction land area among individual counties, we employ a natural logarithm method from statistics to mitigate the sharp fluctuations between assessment units (Dan et al., 2020). All three indicators in the pressure layer share the same directionality, which means that a larger value of the comprehensive pressure index signifies heightened development pressure on the county. The specific formula for calculation is as follows:

$$P_i = SCCI_i \times lg(POP_i) \times CLP_i \tag{2}$$

In the Eq. 2, P_i denotes the comprehensive pressure index for the ith county evaluation unit, while $SCCI_i$ corresponds to the Spatial Conflict Comprehensive Index between PLES. POP_i represents the population density, and CLP_i signifies the proportion of construction land area.

2.3.2 Sensitivity status

Sensitivity status provides insights into the responsiveness of ecosystem to human-induced pressures. Among the key characterization factors, vegetation coverage and rock exposure rate are pivotal for accurately assessing the distribution of karst desertification (Wang et al., 2019). Higher vegetation coverage suggests a lower likelihood of karst desertification in the region. Conversely, a higher rate of rock exposure signifies a more severe karst desertification issue. Notably, karst desertification is often accompanied by secondary disasters like soil erosion, which further exacerbate its severity. Soil erosion modulus, a commonly used indicator for assessing soil erosion risk, is inversely related to sensitivity status, meaning lower soil erosion intensity corresponds to lower sensitivity.

2.3.2.1 Vegetation cover

Based on pixel-based binary models, the normalized difference vegetation index (NDVI) is selected to extract vegetation cover. Specific calculation methods can be found in the referenced literature (Wu et al., 2020). The average vegetation cover for each county is calculated using zoning statistics tools.

2.3.2.2 Rock exposure rate

The rock exposure rate (D) is extracted by combining the calculation of the normalized rock index (NDRI) with pixel-based binary models. Specific calculation formulas can be found in the referenced literature (Sun et al., 2022). The average rock exposure rate for each county is calculated using the PIE Engine Studio remote sensing computing cloud service platform and zoning statistics tools.

2.3.2.3 Soil erosion modulus

The Revised universal Soil Loss Equation (RUSLE) model is used to assess soil erosion. The model expression is as follows:

$$A = R \times K \times L \times S \times C \times P \tag{3}$$

In the Eq. 3.

- A represents the soil erosion modulus, measured in "t/(hm^2·a)".
- R is the rainfall erosion factor, measured in " [(MJmm)/(hm^2·a)]".
- K is the soil erodibility factor, measured in " [(thm^2·h)/(MJhm^2·mm)]".
- L and S are terrain factors, with L being the slope length factor and S being the slope steepness factor.
- C is the land cover management factor.
- P is the soil conservation measure factor.

All factors (L, S, C, P) are dimensionless. The rainfall erosion factor R is calculated based on monthly rainfall data following the guidelines in "SL 773–2018 - Guidelines for Estimating Soil Loss from Production and Construction Projects." The soil erodibility factor K is obtained directly from the 2018 Chinese soil erodibility factor dataset, specifically the data for Guangdong Province, and is extracted based on the study area.

The slope length factor (LS) is calculated using the slope length model as proposed by (Liu et al., 2010). The land cover management and soil conservation factors (C, P) are assigned values based on regional similarity and reference from existing research (Zhong et al., 2022).

The study employs the Albers projection as the spatial reference, and the spatial resolution is set at 1 km × 1 km. The calculations for individual factors and erosion modulus are performed using raster calculators.

2.3.2.4 Comprehensive state index

The comprehensive state index is calculated by combining vegetation cover, rock exposure rate, and soil erosion. A natural logarithm method is used to mitigate local fluctuations in the soil erosion index. To account for the differing trends of vegetation cover, rock exposure, and soil erosion on ecosystem status, a negative standardization is applied during calculation. A higher value of the comprehensive state index indicates a higher level of sensitivity. The specific calculation formula is as follows:

$$S_i = F_i \times D_i \times \lg(A_i) \tag{4}$$

In the Eq. 4, Si denotes the comprehensive state index for the ith county evaluation unit, Fi corresponds to the negatively processed vegetation cover data, Di represents the rock exposure rate, and Ai indicates the soil erosion modulus.

2.3.3 Resilience potential

While socio-economic development exerts pressure on ecosystem, it also presents opportunities for ecological restoration. A primary goal of ecological restoration is to preserve and enhance regional ecosystem services (Kong et al., 2019). Ecosystem services value can visually demonstrate the contribution of ecosystems to supporting socio-economic development (He et al., 2019; Bai et al., 2019), reflecting the self-restoration capacity within the "socio-ecological" system and providing a foundation for ecological restoration zoning. Regional economic development, coupled with increased environmental

TABLE 2 Ecosystem Services value of per unit area (CNY).

Ecosystem services	Arable land	Woodland	Grassland	Water	Unused land
Food production	1.105	0.253	0.233	0.655	0.005
Raw material production	0.245	0.580	0.343	0.365	0.015
Water resource production	−1.305	0.300	0.190	5.440	0.010
Atmospheric regulation	0.890	1.908	1.207	1.335	0.065
Climate regulation	0.465	5.708	3.190	2.945	0.050
Waste disposal	0.135	1.673	1.053	4.575	0.205
Hydrological regulation	1.495	3.735	2.337	43.235	0.120
Soil maintenance	0.520	2.323	1.470	1.620	0.075
Nutrient cycling maintenance	0.155	0.178	0.113	0.125	0.005
Biodiversity maintenance	0.170	2.115	1.337	5.210	0.070
Recreation	0.075	0.928	0.590	3.310	0.030

protection efforts, gradually introduces resilience potential for ecosystem recovery and management strategies (Ye et al., 2019). *Per capita* energy-saving and environmental protection expenditure reflects the government's financial commitment to ecological restoration, and the conversion of cropland to forests and grassland is a widely acknowledged ecological engineering measure in the context of desertification control, with the proportion of the area used as an indicator of existing ecological restoration achievements.

2.3.3.1 Ecosystem services value (ESV)

We utilized the Chinese ecosystem service value equivalent table to estimate the ecosystem service values of the primary ecosystem types in the study area. Compared to woodland, arable land and wetland, *etc.*, the ESV of construction land is almost negligible. Therefore, according to the previous studies (Xie et al., 2015; Zhu et al., 2020; Feng et al., 2022), urban, industrial, mining, and residential land were omitted from the computation. The unit standard equivalent was based on major food crops and adjusted to align with the economic development status of the study area. Specific parameters can be found in Table 2.

2.3.3.2 Per capita energy conservation and environmental protection expenditure

We retrieved data on energy conservation and environmental protection expenditures from the statistical yearbooks of each county in the study area. To calculate *per capita* energy conservation and environmental protection expenditure (in thousands of RMB per square kilometer), we divided the total expenditure by the administrative area of each county.

2.3.3.3 Proportion of land converted to woodland and grassland

This metric assesses the extent of land transformation from arable land in 2013 to woodland and grassland areas in 2020.

2.3.3.4 Comprehensive potential index

The comprehensive potential index is derived from the data of the three aforementioned indicators. A higher value of this index indicates a greater level of socio-economic investment in ecological restoration and a higher resilience potential. The specific formula is as follows:

$$\boldsymbol{R_i} = \mathbf{lg}(\boldsymbol{ESV_i}) \times \mathbf{lg}(\boldsymbol{Z_i}) \times \boldsymbol{T_i} \tag{5}$$

In this Eq. 5, R_i signifies the comprehensive potential index of the ith county-level evaluation unit, ESV_i represents the corresponding ecosystem service value, Z_i denotes the per-square-kilometer energy-saving and environmental protection expenditure, and T_i reflects the proportion of converted cropland to woodland and grassland.

2.3.4 Ecological restoration zoning

Considering that the delineation of ecological restoration zones should cater to regional coordinated development and specific governance needs, it is prudent to establish these zones at the county level to ensure a high degree of territorial integrity. To strike a balance between the influence of development pressure, sensitivity status, and resilience potential on the restoration zones, making restoration strategies more precise and well-founded, we employ z-score standardization based on three key indicators: comprehensive pressure, sensitivity status, and resilience potential. By comparing the relative magnitudes of these indicators, we categorize the ecological restoration zones into different types. Z-score standardization facilitates the comparison of multiple datasets on a consistent scale. The specific formula for calculation is as follows:

$$\boldsymbol{y_i} = \frac{\boldsymbol{x_i - \mu}}{\boldsymbol{\sigma}} \tag{6}$$

In the Eq. 6, y_i represents the z-score standardized value of the ith indicator for a county, x_i is the original value, "μ" denotes the mean of all county-level indicator data for the ith indicator, and "σ" is the standard deviation of all county-level indicator data for the ith indicator.

The comprehensive sensitivity, being more representative of each county's ecosystem status, serves as the primary determinant

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TABLE 3 Criteria for karst desertification ecological restoration zones.

Type	Zone name	Criteria for division	Basis for division
Restoration (Sensitive status >0, poor ecosystem status)	Priority Restoration Zone	Pressure >0, Resilience <0	Human activities lead to increased development pressure and reduced levels of societal investment in ecological restoration
	Autonomous Restoration Zone	Pressure <0, Resilience >0	Human activities lead to lower development pressure and higher ecological restoration potential
	Coordinated Restoration Zone	Pressure <0, Resilience <0	Human activities lead to lower development pressure and reduced societal investment in ecological restoration
Protection (Sensitive status <0, good ecosystem status)	Autonomous Conservation Zone	Pressure >0, Resilience >0	Human activities impose significant development pressure, and they are complemented by a substantial commitment to ecological restoration
	Priority Conservation Zone	Pressure >0, Resilience <0	Intensive human activities create significant development pressure, accompanied by a relatively limited commitment to ecological restoration efforts within society
	Coordinated Conservation Zone	Pressure <0, Resilience <0	Human activities lead to less development pressure, and there is a comparatively lower level of societal investment in ecological restoration

Note: Sensitive status refers to the sensitivity of the ecosystem to human activities. Pressure represents the impact of human activities on development, while resilience represents the potential for ecological restoration.

for zone classification. Because of a negative standardization is applied during sensitivity calculation, the standardized comprehensive status index higher than 0 means relatively poorer ecological status and high sensitivity, classifying them as restoration zones. Conversely, those with values smaller than 0 are categorized as conservation zones. Further distinction in the urgency of restoration or conservation is made by considering the development pressure and resilience potential indicators. Those with standardized result of comprehensive resilience potential higher than 0 means more resilient, which are designated as autonomous zones, signifying a greater level of socio-economic investment for restoration or conservation. In contrast, areas where with resilience potential values smaller than 0 and development pressure values higher than 0 means less resilient and ongoing expansion of human activities and more socioeconomic pressure on ecosystem, which are identified as priority zones. Both the standardized comprehensive pressure and resilience potential results are small than 0 means the lower level of socioeconomic growth and ecological restoration investment, which is classified as coordination zones (Table 3).

3 Results

3.1 Development pressure index

There are significant spatial variations in both population density and urban development extent in the study area. Regions characterized by low population density, with approximately 100 people per square kilometer, are primarily found in minority autonomous counties. In contrast, areas with high population density and substantial urban development are predominantly situated in Wujiang District and Qingxin District, corresponding to the urban centers of Shaoguan and Qingyuan. In Wujiang District, the population density reaches 554.83 people per square kilometer, with a construction land pro-portion of 6.86%, significantly higher than in most other counties, which remains largely below 3%. This highlights the intense nature of urban development in these areas. The Spatial Conflict Comprehensive Index, applied across all counties, consistently falls within the range from "stable and controllable" to "basically controllable." Yingde City, Lechang City, Wujiang District, and Wengyuan County exhibit relatively higher values. This is primarily due to the dense and fragmented distribution of production and living spaces within these regions, signifying a heightened degree of land development and utilization. In contrast, counties characterized by lower conflict levels are primarily concentrated within minority autonomous regions, where ecological spaces exhibit a broader and more dispersed pattern. The comprehensive evaluation of development pressure (Table 4) across the study area is notably influenced by population density. Regions facing increased pressure from human activities are mainly concentrated within urban areas, showing a discernible southeast-to-northwest gradient. Wujiang District, situated within the high-value zone, serves as a prominent example. Meanwhile, medium-value areas encompass Qingxin District, Yingde City, and Wengyuan County, primarily distributed in the eastern sector. Conversely, substantial low-value areas are identified in the western part of the study area, including counties such as Lianzhou, Liannan Yao Autonomous County, Yangshan County, Ruyuan Yao Autonomous County, and Lechang City (Figure 2).

3.2 Sensitivity status index

Significant variations are observed among the sensitivity status indicators within the study area. Notably, the implementation of the national land greening project has had a substantial impact on vegetation cover. Lianping County and Liannan Yao Autonomous County stand out with vegetation cover exceeding 85%. Conversely, Wujiang District, Qingxin District, and Yingde City exhibit relatively lower vegetation cover, all falling below the 80% mark. The distribution of exposed bedrock rates follows a contrasting pattern, with higher values predominantly found in Wujiang District and Yingde City, both ex-ceeding 43%. In contrast, Yangshan

TABLE 4 Development pressure index evaluation.

County/ District	Spatial conflict comprehensive index between PLES	Population density (people/km^2)	Proportion of construction land area (%)	Comprehensive development pressure index
Wujiang District	0.43	554.82	6.86	0.081
Wengyuan County	0.43	148.05	3.24	0.030
Ruyuan Yao Autonomous County	0.34	81.69	1.31	0.009
Lechang City	0.43	158.12	1.94	0.018
Lianping County	0.38	125.37	1.69	0.013
Qingxin District	0.40	262.40	3.13	0.030
Yangshan County	0.38	110.38	0.62	0.005
Liannan Yao Autonomous County	0.30	110.62	0.61	0.004
Yingde City	0.48	167.05	3.11	0.033
Lianzhou City	0.39	140.96	1.42	0.012

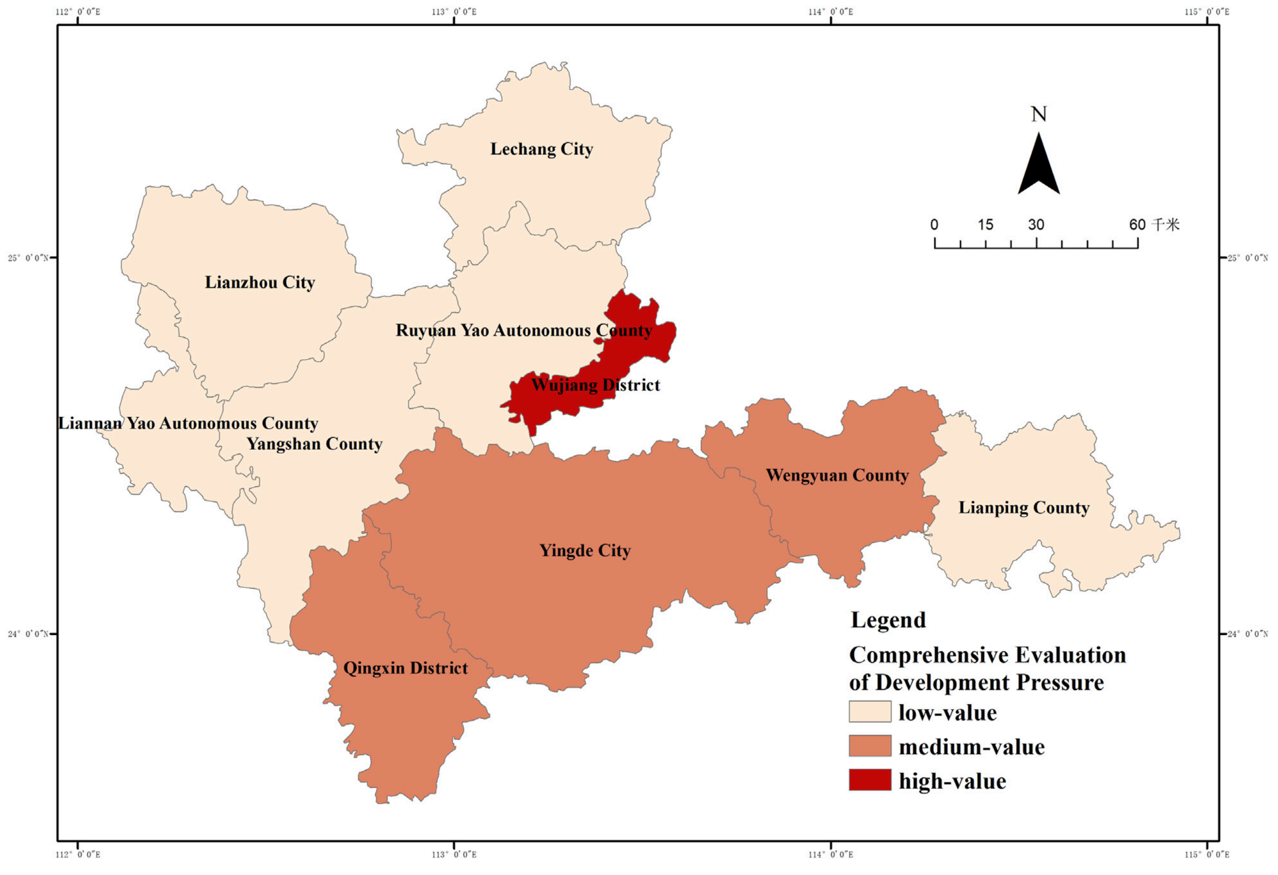

FIGURE 2
Comprehensive evaluation of development pressure.

TABLE 5 Sensitivity status index evaluation.

County/District	Vegetation cover (%)	Rock exposure rate (%)	Soil erosion modulus (%)	Comprehensive sensitivity status index
Wujiang District	78.61	43.69	116.65	0.193
Wengyuan County	82.73	41.21	525.02	0.194
Ruyuan Yao Autonomous County	83.16	40.66	480.21	0.184
Lechang City	82.55	40.85	456.36	0.190
Lianping County	87.57	39.29	573.05	0.135
Qingxin District	78.45	41.43	526.45	0.243
Yangshan County	81.32	39.71	1,035.51	0.224
Liannan Yao Autonomous County	85.51	37.95	347.43	0.140
Yingde City	79.56	43.83	1,452.87	0.283
Lianzhou City	80.61	40.52	594.57	0.218

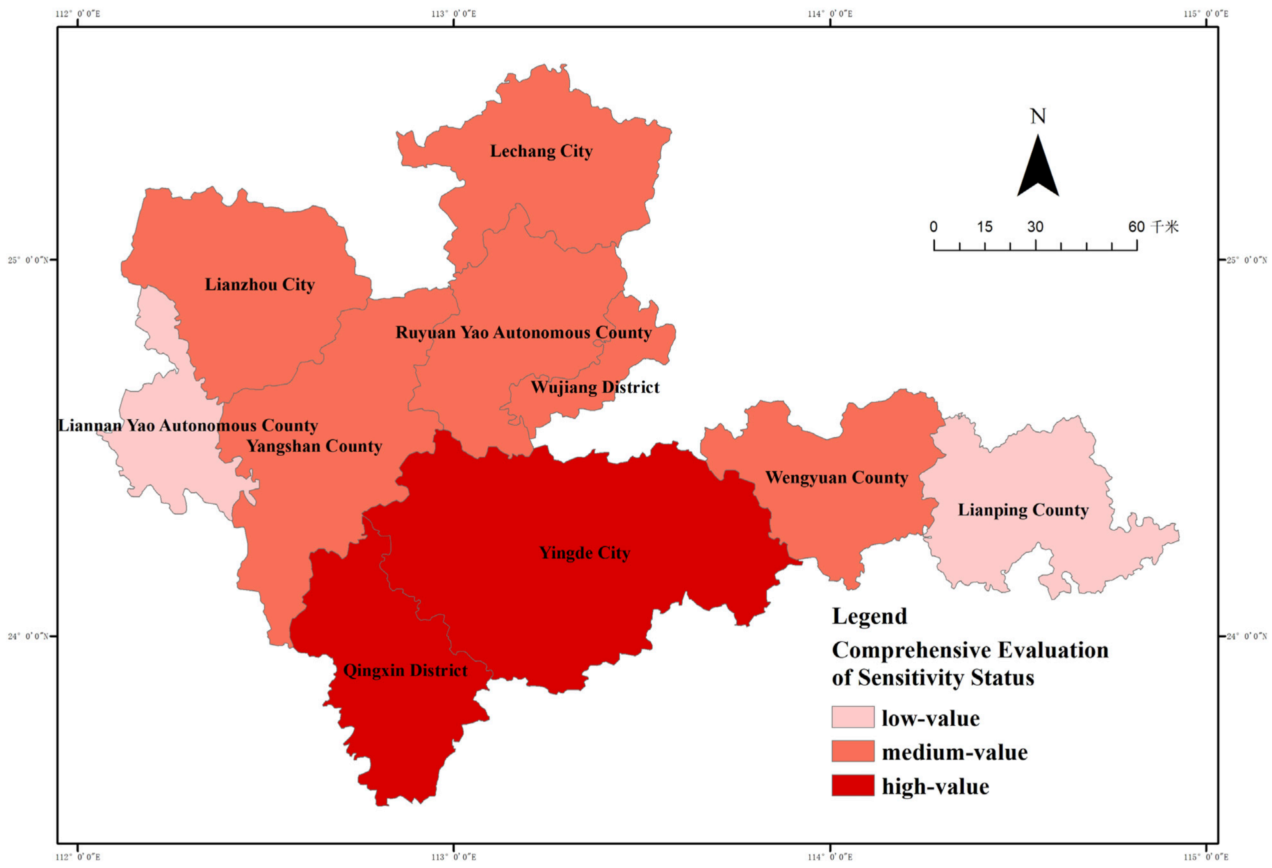

FIGURE 3
Comprehensive evaluation of sensitivity status.

County, Lianping County, and Liannan Yao Autonomous County show relatively lower rates of exposed bedrock. Soil erosion levels are notably high in Yangshan County and Yingde City, attributed to the typical impact of karst desertification. On the other hand, areas with lower erosion levels primarily include Liannan Yao Autonomous County and Wujiang District. This is influenced by effective vegetation cover management and soil conservation practices. The comprehensive state index (Table 5)

TABLE 6 Resilience potential index evaluation.

County/District	ESV(CNY)	Per capita energy conservation and environmental protection expenditure (thousands of RMB per square kilometer)	Proportion of land converted to woodland and Grassland (%)	Comprehensive resilience potential index
Wujiang District	$1.73*10^{13}$	2.12	6.35	0.274
Wengyuan County	$5.60*10^{13}$	12.41	6.89	1.037
Ruyuan Yao Autonomous County	$6.73*10^{13}$	4.23	4.01	0.347
Lechang City	$6.13*10^{13}$	13.25	7.30	1.129
Lianping County	$6.00*10^{13}$	4.05	5.17	0.433
Qingxin District	$6.31*10^{13}$	2.63	6.21	0.360
Yangshan County	$8.82*10^{13}$	1.23	7.05	0.088
Liannan Yao Autonomous County	$3.55*10^{13}$	3.26	4.50	0.313
Yingde City	$1.43*10^{14}$	3.17	7.72	0.547
Lianzhou City	$6.69*10^{13}$	0.82	7.85	−0.095

reflects significant spatial disparities throughout the study area, with higher values concentrated in the central region and lower values along the eastern and western sides. Counties with lower index values are less numerous and encompass Lianping County and Liannan Yao Autonomous County. Conversely, Qingxin District and Yingde City stand out with higher index values, with Qingxin District having the least vegetation cover compared to other counties. Yingde City exhibits the highest levels of exposed bedrock and soil erosion in the study area, resulting in the highest overall sensitivity (Figure 3).

3.3 Resilience potential index

Owing to substantial variations in county sizes, the distribution pattern of ESV across the study area exhibits a higher value in the central regions and lower values along the periphery. The highest ESV is observed in Yingde City, which is also the largest area county-level administrative in Guangdong Province. Counties with relatively lower ESV include Wujiang District and Liannan Yao Autonomous County. As a whole, the study area demonstrates relatively lower per-unit area expenditures in energy conservation and environmental protection. The majority of counties have per-unit expenditures below 4,000 yuan per square kilometer. The highest expenditures are found in Lechang City and Wengyuan County, while the lowest can be seen in Lianzhou City at just 0.82 yuan per square kilometer. From 2013 to 2020, the study area achieved a total afforestation area of 1,663 square kilometers. Areas with a relatively high afforestation rate include Lechang City, Lianzhou City, and Yingde City, while counties with smaller afforestation areas con-sist of Liannan Yao Autonomous County, Ruyuan Yao Autonomous County, and Lianping County. The overall comprehensive resilience potential (Table 6) in the study area is significantly influenced by per-unit area expenditures in energy conservation and environmental protection. There are notable disparities in the overall levels: Lechang City and Wengyuan County fall into the high-value category, with per-unit expenditures in energy conservation and environmental protection significantly surpassing those in Lianzhou City and Yangshan County, which belong to the low-value category. The remaining counties are generally classified as mid-value (Figure 4).

3.4 Zoning results and ecological restoration strategies

Based on the z-score standardized results, the study area is classified into Restoration Zones and Conservation Zones (Figure 5). Notably, the Restoration Zones cover more than half of the total area and are primarily situated in the northwestern and southern parts of the study area, with these regions bordering each other. The Conservation Zones consist of six counties in total, primarily located in the northern, western, and eastern parts of the study area. All three zone—Autonomous Restoration, Coordinated Restoration, and Coordinated Conservation—encompass more than 20% of the total area (Table 7).

3.4.1 Priority restoration zone

Qingxin District, situated within Qingyuan City, is under substantial development pressure due to human activities. Pressure is influenced by low vegetation cover, high rock exposure rates, and soil erosion, resulting in a less favorable ecological system status. Furthermore, *per capita* energy expenditure and reforestation areas show limited resilience potential. To reverse the adverse ecological conditions, this region should increase in-vestments in ecological restoration,

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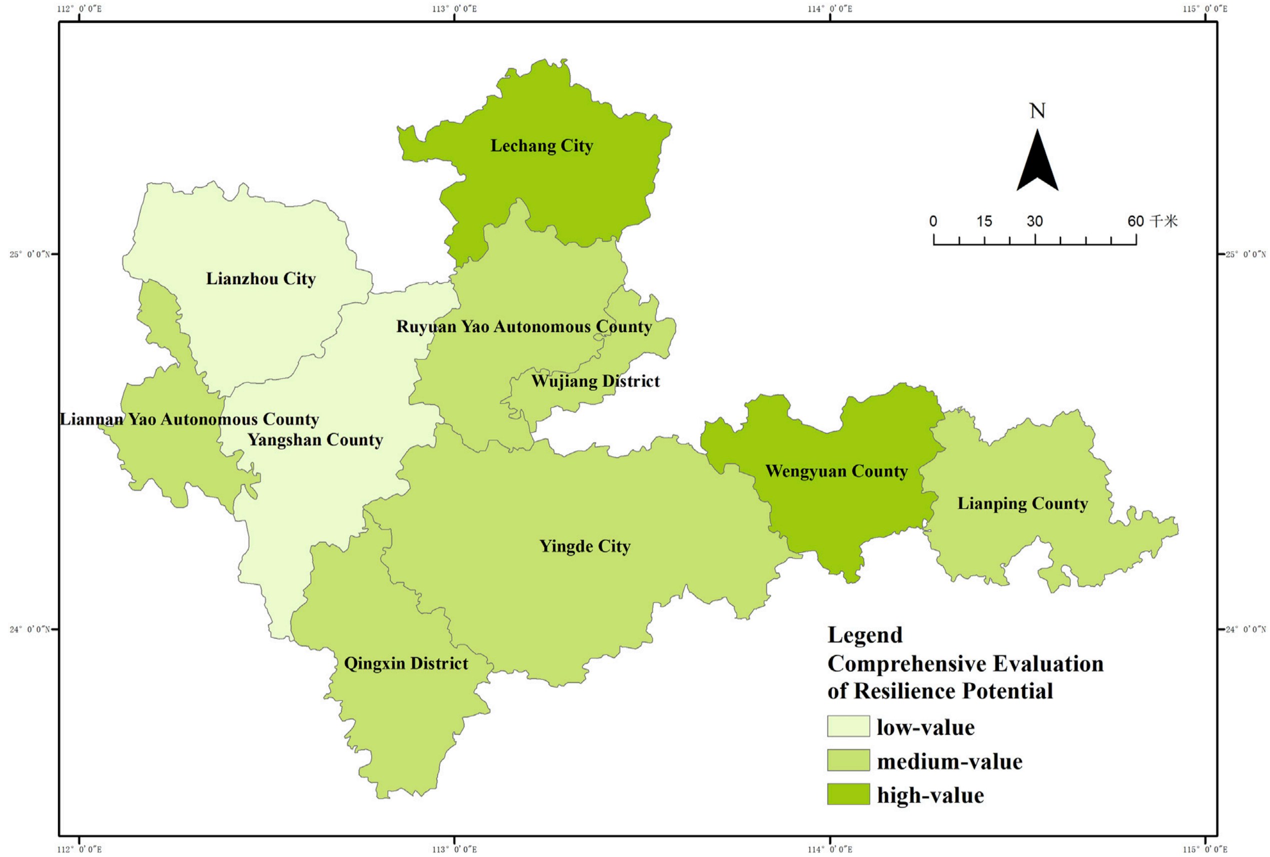

FIGURE 4
Comprehensive evaluation of resilience potential.

implement ecological protection and restoration policies, and prioritize actions aimed at preventing ecosystem degradation from inappropriate human activities. The goal is to transform the excessive pressure exerted on the ecosystem by human development into resilience potential. Continuously advance the greening of territorial space, develop distinctive forestry products, and focus on the development model of undergrowth economy, including “medicine, fungi, tea, livestock, and forest tourism."

3.4.2 Autonomous restoration zone

Corresponding to Yingde City, this area experiences low pressure and exhibits high resilience potential. The primary focus here is on alleviating conflicts within the PLES, strengthening the advantages of ecosystem service values, and enhancing the self-restorative capacity of the ecosystem. Due to the relatively high rock exposure rates and severe soil erosion, additional efforts should be made to enhance water source conservation forests, ecological public welfare forest construction. With the engineering measures and reforestation, promote comprehensive mining reclamation. This will help prevent soil erosion caused by inappropriate human activities. Additionally, implementing ecological compensation policies and creating a “those who undertake the restoration stand to gain the benefits " market mechanism can encourage the involvement of social capital in the entire ecological restoration process.

3.4.3 Coordinated restoration zone

This zone includes Lianzhou City and Yangshan County, characterized by low human activity pressure and limited resilience potential. The main focus is to increase environmental governance investments, thereby facilitating effective ecological restoration. Due to the low investment in energy conservation and environmental protection funds, it is crucial to make effective use of financial support from higher-level governments and rein-force lateral collaborative governance in the region. In order to the effective restoration of damaged ecosystems, this zone can also collaborate with the Guangdong Nanling National Park construction, integrating ecological elements such as mountains, water, and forests in the restoration of natural resources, by preventing and managing soil erosion, it aims to maintain the ecological barrier integrity of the surrounding mountains. This is achieved through a combination of afforestation, greening initiatives, and forest regeneration, thereby promoting the continuous advancement of desertification control efforts.

3.4.4 Autonomous conservation zone

This category comprises Lechang City and Wengyuan County, regions with a well-established ecological foundation, a high development pressure, and strong resilience potential. The primary objective is to consolidate the existing ecological

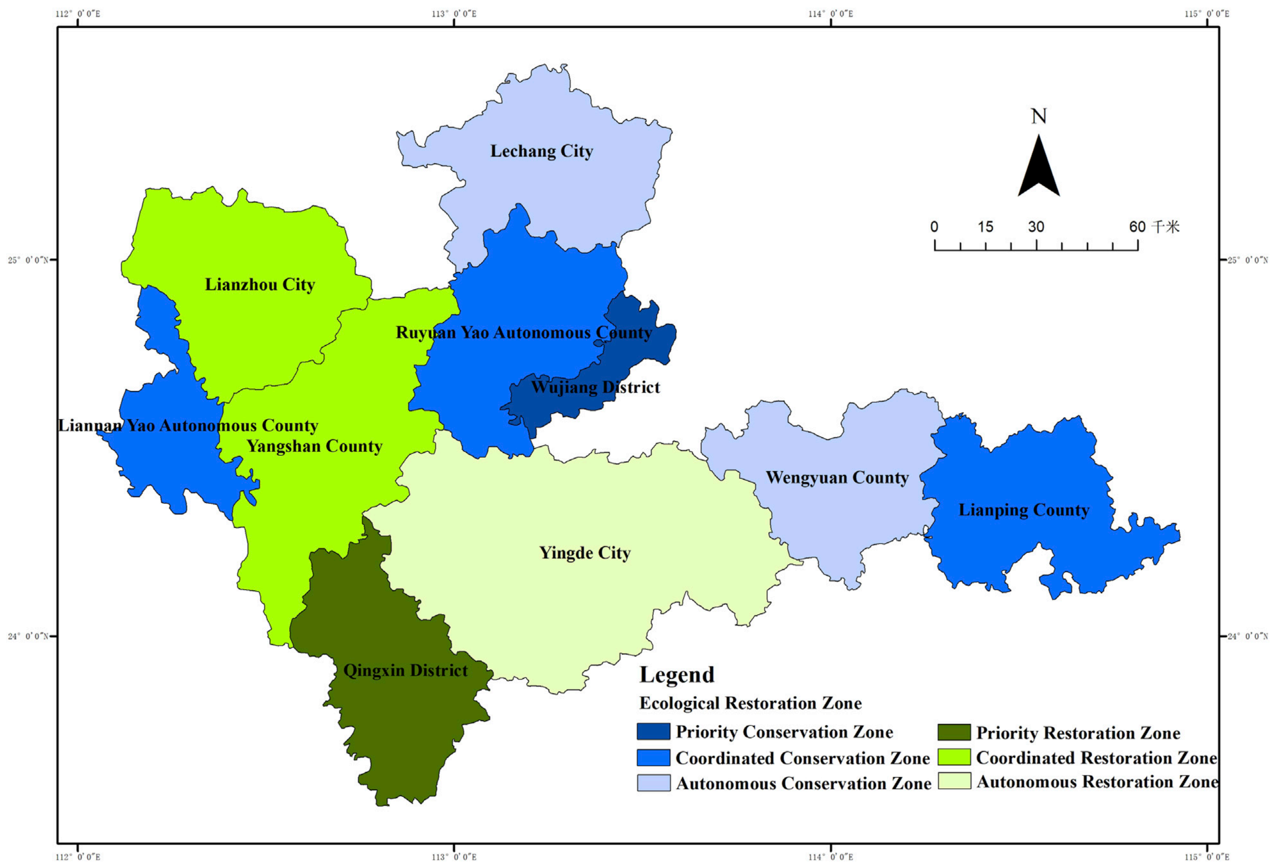

FIGURE 5
Ecological restoration zone.

TABLE 7 Karst desertification ecological restoration zone results.

Zone name	County/District	Area (km^2)	Proportion (%)
Priority Restoration Zone	Qingxin District	2 351.75	9.38
Autonomous Restoration Zone	Yingde City	5 634.95	22.47
Coordinated Restoration Zone	Lianzhou City, Yangshan County	6 006.05	23.95
Autonomous Conservation Zone	Wengyuan County, Lechang City	4 598.44	18.34
Coordinated Conservation Zone	Ruyuan Yao Autonomous County, Lianping County, Liannan Yao Autonomous County	5 810.33	23.17
Priority Conservation Zone	Wujiang District	675.71	2.69

foundation, implement water source conservation forests, and precisely enhance forest quality. Innovative measures for desertification control should be introduced, with continued investment in energy conservation and environmental protection, ensuring the protection of the eco-system's services. Simultaneously, single human intervention measures should be avoid-ed, with further regulation of human development activities and the optimization layout of the PLES, resulting in an improved pattern of production and living. Implementing ecological restoration measures on historically abandoned industrial sites to enhance the ecological quality of the land, while also creating opportunities for local green economic growth.

3.4.5 Coordinated conservation zone

This zone encompasses Ruyuan Yao Autonomous County, Lianping County, and Liannan Yao Autonomous County, with low development pressure and resilience potential. This area has high vegetation cover and should implement afforestation and greening initiatives. By promoting regional economic development while enhancing ecological protection efforts, it aims to advance the construction of the Wanshanchaowang National Desert Park and the Xijing Ancient Road National Desert Park. Leveraging its excellent ecological foundation, the zone should develop leisure tourism industries and actively promote the development of high-value specialty industries. This approach explores the efficient transformation path for the value realization of ecological product, promoting ecological restoration through ecological industrialization.

3.4.6 Priority conservation zone

The corresponding administrative region is Wujiang District, which is the most densely populated built-up area in the study. It experiences significant development pressure and possesses limited resilience potential. The primary objective is to prevent excessive damage to the ecological foundation, balancing ecological and economic benefits. This area should engage in strategic urban planning within the limits of its resource and environmental carrying capacity, thereby avoiding new issues related to desertification and human-induced soil erosion. Additionally, it should increase investments in environmental protection to improve small watershed soil and water erosion control efforts. Gradually expanding forest coverage and enhancing forest quality, and creating a new pattern for ecological construction.

4 Discussion

4.1 Framework for zoning, restoration goals, and stakeholders based on the "social-ecological" system

The study area, situated in a karst region characterized by prominent human-environment conflicts and ecological sensitivity, underscores the intricate interplay between social-ecological system. Unreasonable human activities have led to the degradation of ecosystem functions, impeding local socio-economic development (Ye et al., 2019). If this feedback loop remains unchecked, it may cause the "social-ecological" system to deteriorate further (Wang Z. et al., 2023), leading to a vicious cycle of "vegetation destruction" and "land reclamation equals poverty." Therefore, there is an urgent need for governance strategies based on a "social-ecological" system analysis framework. Desertification is "negative" feedback resulting from human interference with the ecosystem, leading to the unsustainability of the "social-ecological" system. Therefore, the ultimate goal of ecological restoration zoning is to start from sustainability, coupling multiple objectives within the "social-ecological" system, integrating social, economic, and ecological elements (Polyakov et al., 2023) and processes to formulate ecological restoration zoning decision-making and implementation strategies.

In the context of promote harmonious coexistence between human and environment, ecological restoration should primarily prioritize maintaining regional ecological security, promoting continuous improvement in ecosystem diversity and stability, and achieving synergy between conservation and development. By delineating the interactive processes of the "social-ecological" system, conducting a comprehensive analysis of existing ecological issues, and assessing the relationship between socio-economic system and ecosystem, this study proposes restoration strategies and recommendation measures for each zone. Based on the zoning results, the contiguous regions of the northwestern and southern parts of the study area require more comprehensive engineering and greening measures, the benefits from rocky desertification treatment and reforestation/afforestation will promote the synergistic effect of "social-ecological" system. The conservation zones are primarily situated in the northern and eastern parts of the study area, ecological and economic benefits can be brought from giving priority to natural restoration, ecological industry and reasonable PLES layout also contribute to the "social-ecological" system.

Domestic and international trends in ecological restoration zoning research and practical cases reveals an evolving focus (Smith et al., 2022; Zhou et al., 2022; Reader et al., 2023). Ecological restoration in Karst region entails a comprehensive approach, acknowledging the intricate inter-connections and interdependencies among forest, mountain, and water elements. This holistic perspective reflects the core concept of "integral protection, systematic restoration, and comprehensive management" (Suding et al., 2015). Furthermore, it is crucial to recognize that government bodies, corporate investors, and the stakeholder are central participants in the ecological restoration process (Toma and Buisson, 2022). Their varying perspectives and requirements will directly impact the effectiveness of restoration planning and project implementation. The application of multi-agent modeling to support decision analysis encourages the collective involvement of multiple stakeholders. This approach acknowledges that the success of ecological restoration in karst regions necessitates the active collaboration of various stakeholders and underscores the importance of harmonizing their differing interests and needs for the collective benefit of the human and environment.

4.2 Research advantages and limitations

In the context of a transition towards more harmonious human-environment relationships within the realm of ecological restoration, this study takes a "social-ecological" system approach. It constructs an evaluation index that comprises "development pressure," "sensitivity status," and "resilience potential." The study performs quantitative assessments and integrated zoning, using the karst-concentrated areas of Guangdong Province as an illustrative example. This research addresses previous inadequacies by providing a more comprehensive perspective. It considers ecological issues and human disturbances while integrating the restorative capacity created by the ecosystem's resilience potential and socio-economic development. The integrated index allows for the portrayal of societal pressures on ecological systems, the sensitive characteristics of the ecosystem, and the "social-ecological" system's resilience potential. This enhances our overall understanding of how to resolve human-environment conflicts in ecologically vulnerable areas. This study departs from the practice of assigning weights to indicator factors, which can be subjective. Instead, it employs a standardization method to compare the results of different indicator combinations. This approach is more objective and uses a concise set of critical indicators to reflect regional disparities, making it more operationally feasible. The ultimate goal of the zoning method is to facilitate the implementation of zoning results and ecological restoration. The research framework of this study is clear, easily quantifiable, and holds promise for practical applications.

Compared to studies based on grid or watershed units, this research primarily focuses on reflecting the "social-ecological" system characteristics of various administrative units within a region. This approach provides differentiated governance measures for regional coordinated development. Subsequent steps may involve further refining data granularity and analyzing the spatial heterogeneity characteristics within the units to identify key ecological restoration areas and provide precise strategies (Sun et al., 2022). It is important to note that the sample selection for evaluation units in this study did not include several counties with dispersed distribution of desertification. Future research could encompass a comprehensive analysis of desertification restoration in Guangdong Province and even the karst regions of southern China. Due to data availability and computational constraints, this study did not account for the temporal changes in the "social-ecological" system characteristics. Therefore, it is crucial to explore the relationship between "social-ecological" systems in ecologically fragile karst areas, considering their multi-scale and cross-temporal dimensions in the future.

5 Conclusion

Ecological restoration zoning involves various socio-economic and ecological factors, making it challenging to accurately identify the ecological restoration zones and propose targeted strategies. In the context of shifting towards coordinated human-environment relationships, this study constructs a comprehensive evaluation framework based on the perspective of "socio-ecological" system. This approach represents a preliminary exploration of the complex interplay between socio-economic and ecological factors, offering a more integrated understanding of the multi-target and multi-stakeholder trends in ecological restoration. Moreover, it provides valuable insights for guiding the treatment of karst desertification and ecological restoration.

The spatial distribution of these indicators shows significant characteristics. Development pressure is strongly influenced by population density, with areas experiencing higher human activity pressure primarily concentrated in urban areas, with the most prominent in Wujiang District. Sensitivity status is predominantly determined by soil erosion levels and vegetation coverage. Qinxin District County and Yingde City exhibit the most severe environmental issues. The overall level of resilience potential varies significantly and is mainly influenced by *per capita* energy conservation and environmental protection expenditures.

Based on the characteristics of development pressure, sensitivity status, and resilience potential, the study area is recognized to two main categories of restoration units, corresponding "socio-ecological" system restoration strategies were proposed. Restoration-type units should utilize the ecological resilience and focus on reversing poor ecosystem status preventing further ecosystem degradation due to inappropriate human activities. Participation of inter-regional, multi-stakeholder of restoration mechanisms are yet to be established. Conservation -type units should aim to regulate human activities further and promote the rational layout of PLES. These zones should actively explore paths for realizing ecological product value while intensifying ecological protection.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YL: Conceptualization, Project administration, Validation, Writing–original draft. JH: Formal Analysis, Methodology, Software, Visualization, Writing–original draft. WL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

Author YL is employed by Guangdong Duoyuan Geographic Information Service Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ahammad, R., Kamal Hossain, M., Sobhan, I., Hasan, R., Biswas, S. R., and Mukul, S. A. (2023). Social-ecological and institutional factors affecting forest and landscape restoration in the chittagong hill tracts of Bangladesh. *Land Use Policy* 125 (February), 106478. doi:10.1016/j.landusepol.2022.106478

Bai, Z., Zhou, W., Wang, J., Zhao, Z., Cao, Y., and Zhou, Y. (2019). Overall protection, systematic restoration and comprehensive management of land space. *China Land Sci.* 33 (2), 1–11. doi:10.11994/zgtdkx.20190218.090442

Cai, H., Chen, Yi, Zha, D., Zeng, Y., Shao, H., and Hong, T. (2020). Principle and method for ecological restoration zoning of territorial space based on the dominant function. *China Land Sci.* 36 (15), 261–270+325. doi:10.11975/j.issn.1002-6819.2020.15.032

Cao, Yu, Wang, J., and Li, G. (2019). Ecological restoration for territorial space: basic concepts and foundations. *China Land Sci.* 33 (7), 1–10. doi:10.11994/zgtdkx.20190625.083700

Chen, Z., Liu, Y., and Tu, S. (2022). Comprehensive eco-environmental effects caused by land use transition from the perspective of production–living–ecological spaces in a typical region: a case study of the guangxi Zhuang autonomous region, China. *Land* 11 (12), 2160. doi:10.3390/land11122160

Dan, Y., Peng, J., Zhang, Z., Xu, Z., Qi, M., and Dong, J. (2020). Territorially ecological restoration zoning based on the framework of degradation pressures, upply state and restoration potential: a case study in the Pearl River Delta region. *Acta Ecol. Sin.* 40 (23), 8451–8460. doi:10.5846/stxb202004240982

Feng, Q., Zhou, Z., Quan, C., and Zhu, C. (2022). Spatial-temporal evolution research of ecosystem service value in ecologically vulnerable karst regions under the perspective of poverty alleviation relocation. *Acta Ecol. Sin.* 42 (7). doi:10.5846/stxb202103260798

Fan, Y., Zhou, Y., and Han, Bo (2022). Ecological restoration zoning of agricultural land of the sunan district from the perspective of national land and space governance. *Trans. Chin. Soc. Agric. Eng.* 38 (1), 287–296. doi:10.11975/j.issn.1002-6819.2022.01.032

Feng, Y. (2021). *Construction land optimization of mountain-basin system based on suitability and ecological-production-living spaces conflict——a case study of huishui county in guizhou province*. Master Dissertation. Guiyang, China: Guizhou Normal University. doi:10.27048/d.cnki.ggzsu.2021.000674

Gong, Q., Zhang, H., Ye, Y., and Yuan, S. (2020). Planning strategy of land and space ecological restoration under the framework of man-land system coupling: take the Guangdong-Hong Kong-Macao greater Bay area as an example. *Geogr. Res.* 39 (9), 2176–2188. doi:10.11821/dlyj020200413

He, X., Wang, L., Ke, B., Yue, Y., Wang, K., Cao, J., et al. (2019). Progress on ecological conservation and restoration for China Karst. *Acta Ecol. Sin.* 39 (18). doi:10.5846/stxb201812292842

Hu, M., Zhang, H., Tang, J., and Yan, S. (2023). Zoning and optimization strategies of land spatial ecological restoration in liangjiang new area of chongqing based on the supply–demand relationship of ecosystem services. *Land* 12 (6), 1255. doi:10.3390/land12061255

Jiang, H., Peng, J., Zhao, Y., Xu, D., and Dong, J. (2022). Zoning for ecosystem restoration based on ecological network in mountainous region. *Ecol. Indic.* 142 (September), 109138. doi:10.1016/j.ecolind.2022.109138

Kong, L., Zheng, H., and Ouyang, Z. (2019). Ecological protection and restoration of forest, wetland, grassland and cropland based on the perspective of ecosystem services: a case study in Dongting Lake Watershed. *Acta Ecol. Sin.* 39 (23). doi:10.5846/stxb201905301137

Li, X. H., Zhang, X., Yao, L., Li, Y., and Yue, L. (2023a). Spatial-temporal evolution characteristics of social - ecological system resilience in hexi region. *J. Arid Land Resour. Environ.* 37 (7), 38–47. doi:10.13448/j.cnki.jalre.2023.159

Li, Z., Jiang, C., Cheng, Li, and Gu, S. (2023b). Ecological restoration and protection of national land space in coal resource-based cities from the perspective of ecological security pattern: a case study in huaibei city, China. *Land* 12 (2), 442. doi:10.3390/land12020442

Li, Z., Ma, L., Chen, X., Wang, X., and Bai, J. (2023c). Zoning and management of ecological restoration from the perspective of ecosystem service supply and demand: a case study of yuzhong county in longzhong loess hilly region, China. *Land* 12 (5), 992. doi:10.3390/land12050992

Liao, L., Dai, W., Chen, J., Huang, W., Jiang, F., and Hu, Q. (2017). Spatial conflict between ecological-production-living spaces on pingtan island during rapid urbanization. *Resour. Sci.* 39 (10), 1823–1833. doi:10.18402/resci.2017.10.03

Liu, F., Dai, E., and Yin, J. (2023). A review of social–ecological system research and geographical applications. *Sustainability* 15 (8), 6930. doi:10.3390/su15086930

Liu, Y., Fu, B., Wang, S., Zhao, W., and Li, Y. (2020). Research progress of human-earth system dynamics based on spatial resilience theory. *ACTA Geogr. SIN.* 75 (5), 891–903. doi:10.11821/dlxb202005001

Ni, Q.-lin, Hou, H.-ping, Zhong-yi, D., Yi-bo, Li, and Jin-rong, Li (2020). Ecological remediation zoning of territory based on the ecological security pattern recognition: taking Jiawang district of Xuzhou city as an example. *J. Nat. Resour.* 35 (1), 204. doi:10.31497/zrzyxb.20200117

Peng, J., Li, B., Dong, J., Liu, Y., Lv, D., Du, Y., et al. (2020). Basic logic of territorial ecological restoration. *China Land Sci.* 34 (5), 18–26. doi:10.11994/zgtdkx.20200427.124442

Polyakov, M., Dempster, F., Park, G., and Pannell, D. J. (2023). Joining the dots versus growing the blobs: evaluating spatial targeting strategies for ecological restoration. *Ecol. Econ.* 204 (February), 107671. doi:10.1016/j.ecolecon.2022.107671

Reader, M. O., Eppinga, M. B., Jan de Boer, H., Damm, A., Petchey, O. L., and Santos, M. J. (2023). Biodiversity mediates relationships between anthropogenic drivers and ecosystem services across global mountain, island and Delta systems. *Glob. Environ. Change* 78 (January), 102612. doi:10.1016/j.gloenvcha.2022.102612

Smith, L. M., Erin, M., Reschke, J. J. B., Harvey, J. E., and Kevin Summers, J. (2022). A conceptual approach to characterizing ecological suitability: informing socio-ecological measures for restoration effectiveness. *Ecol. Indic.* 143 (October), 109385. doi:10.1016/j.ecolind.2022.109385

Song, S., Wang, S., Fu, B., Chen, H., Liu, Y., and Zhao, W. (2019). Study on adaptive governance of social-ecological system: progress and prospect. *ACTA Geogr. SIN.* 74 (11), 2401–2410. doi:10.11821/dlxb201911015

Suding, K., Higgs, E., Palmer, M., Baird Callicott, J., Anderson, C. B., Baker, M., et al. (2015). Committing to ecological restoration. *Science* 348 (6235), 638–640. doi:10.1126/science.aaa4216

Sun, R., Jin, X., Han, Bo, Liang, X., Zhang, X., and Zhou, Y. (2022). Does scale matter? Analysis and measurement of ecosystem service supply and demand status based on ecological unit. *Environ. Impact Assess. Rev.* 95 (July), 106785. doi:10.1016/j.eiar.2022.106785

Sun, Y., Zhou, Z., Zhao, Y., Fang, M., and Wu, Y. (2022). Evolution and distribution pattern of land use and rocky desertificaiton in karst mountainous area. *Res. Soil Water Conservation* 29 (1), 311–318. doi:10.13869/j.cnki.rswc.2022.01.034

Tang, F., Wang, Li, Guo, Y., Fu, M., Huang, Ni, Duan, W., et al. (2022). Spatio-temporal variation and coupling coordination relationship between urbanisation and habitat quality in the grand canal, China. *Land Use Policy* 117 (June), 106119. doi:10.1016/j.landusepol.2022.106119

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.-V., et al. (2023). Beyond ecology: ecosystem restoration as a process for social-ecological transformation. *Trends Ecol. Evol.* 38 (7), 643–653. doi:10.1016/j.tree.2023.02.007

Tian, M., Gao, J., Song, G., Zou, C., and Zheng, H. (2017). Zoning for ecological remediation by dominant ecological function and ecological degradation degree. *J. Ecol. Rural Environ.* 33 (1), 7–14. doi:10.11934/j.issn.1673-4831.2017.01.002

Toma, T. S. P., and Buisson, E. (2022). Taking cultural landscapes into account: implications for scaling up ecological restoration. *Land Use Policy* 120 (September), 106233. doi:10.1016/j.landusepol.2022.106233

Van der Biest, K., Meire, P., Schellekens, T., D'hondt, B., Bonte, D., Vanagt, T., et al. (2020). Aligning biodiversity conservation and ecosystem services in spatial planning: focus on ecosystem processes. *Sci. Total Environ.* 712 (April), 136350. doi:10.1016/j.scitotenv.2019.136350

Vos, A. de, Biggs, R., and Preiser, R. (2019). Methods for understanding social-ecological systems: a review of place-based studies. *Ecol. Soc.* 24 (4), art16. doi:10.5751/ES-11236-240416

Wang, H., Zhang, D., Ting, H., Zhao, Y., Wang, Z., and Wu, J. (2023). Social-ecological systems: research trends, theme evolution, and regional practices. *Acta Ecol. Sin.* 43 (15), 6499–6513. doi:10.5846/stxb202208212395

Wang, J., and Zhong, L. (2019). Application of ecosystem service theory for ecological protection and restoration of mountain-river-forest-field-lake-grassland. *Acta Ecol. Sin.* 39 (23). doi:10.5846/stxb201905291110

Wang, M., Wang, S., Bai, X., Li, S., Li, H., Cao, Y., et al. (2019). Evolution characteristics of karst rocky desertification in typical small watershed and the key characterization factor and driving factor. *ACTA Ecol. SIN.* 39 (16), 6083–6097. doi:10.5846/stxb201902170278

Wang, P., and Zhao, W. (2022). Ecological restoration zoning of territorial space in typical karst region: a case study of Maotiao River Basin in Guizhou. *J. Nat. Resour.* 37 (9), 2403. doi:10.31497/zrzyxb.20220914

Wang, Y., Hu, Y., Gao, M., and Niu, S. (2023). Land-space ecological restoration zoning of karst rocky desertification areas in guangxi from multi-dimensional perspectives. *Trans. Chin. Soc. Agric. Eng.* 39 (1), 223–231. doi:10.11975/j.issn.1002-6819.202210065

Wang, Z., Fu, B., Wu, X., Li, Y., Wang, S., and Lu, N. (2023). Escaping social–ecological traps through ecological restoration and socioeconomic development in China's loess plateau. *People Nat.* 5 (4), 1364–1379. doi:10.1002/pan3.10513

Wu, Y., Zhou, Z., Zhao, X., Dan, Y., and Huang, D. (2020). Spatiotemporal variation of vegetation coverage in plateau mountainous areas based on remote sensing cloud computing platform: a case study of guizhou province. *CARSOLOGICA Sin.* 39 (2), 196–205. doi:10.11932/karst2020y16

Xie, G., Zhang, C., Zhang, L., Chen, W., and Li, S. (2015). Improvement of the evaluation method for ecosystem service value based on per unit area. *J. Nat. Resour.* 30 (8), 1243–1254. doi:10.11849/zrzyxb.2015.08.001

Xie, Y.-chu, Zhang, S.-xin, Lin, B., Zhao, Y.-jun, and Bao-qing, Hu (2020). Spatial zoning for land ecological consolidation in Guangxi based on the ecosystem services supply and demand. *J. Nat. Resour.* 35 (1), 217. doi:10.31497/zrzyxb.20200118

Xiong, K., Cheng, He, Mingsheng, Z., and Junbing, Pu (2023). A new advance on the improvement of forest ecosystem functions in the karst desertification control. *Forests* 14 (10), 2115. doi:10.3390/f14102115

Ye, Y., Lin, Y., Liu, S., and Luo, M. (2019). Social-ecological system (SES) analysis framework for application in ecological restoration engineering of mountains-rivers-forests-farmlands-lakes-grasslands: utilizing the source area of Qiantang River in Zhejiang Province as an example. *Acta Ecol. Sin.* 39 (23). doi:10.5846/stxb201905301139

Yue, W., Hou, Li, Xia, H., Wei, J., and Lu, Y. (2022). Territorially ecological restoration zoning and optimization strategy in guyuan city of ningxia, China: based on the balance of ecosystem service supply and demand. *Chin. J. Appl. Ecol.* 33 (1), 149–158. doi:10.13287/j.1001-9332.202112.024

Zhang, X., Qi, X., Yue, Y., Wang, K., Zhang, X., and Liu, D. (2020). Natural regionalization for rocky desertification treatment in karst peak-cluster depression regions. *Acta Ecol. Sin.* 40 (16), 5490–5501. doi:10.5846/stxb201910092093

Zhang, X., Wang, Z., Liu, Y., Shi, J., and Du, H. (2023). Ecological security assessment and territory spatial restoration and management of inland river basin—based on the perspective of production–living–ecological space. *Land* 12 (8), 1612. doi:10.3390/land12081612

Zhao, Xu, Tang, F., Zhang, P., Hu, B., and Xu, L. (2019). Dynamic simulation and characteristic analysis of county production-living-ecological spatial conflicts based on CLUE-S model. *Acta Ecol. Sin.* 39 (16). doi:10.5846/stxb201901070059

Zhao, Y., Luo, J., Li, T., Chen, J., Yi, Mi, and Wang, K. (2023). A framework to identify priority areas for restoration: integrating human demand and ecosystem services in dongting lake eco-economic zone, China. *Land* 12 (5), 965. doi:10.3390/land12050965

Zhong, X., Zhang, Su, Wu, R., Jing, Y., Men, L., and Zhou, T. (2022). Analysis of dynamic changes and driving forces of soil erosion in tuojiang river basin. *Res. Soil Water Conservation* 29 (2), 43–49+56. doi:10.13869/j.cnki.rswc.2022.02.003

Zhou, L., Zhang, H., Bi, G., Su, K., Wang, Li, Chen, H., et al. (2022). Multiscale perspective research on the evolution characteristics of the ecosystem services supply-demand relationship in the chongqing section of the three gorges reservoir area. *Ecol. Indic.* 142 (September), 109227. doi:10.1016/j.ecolind.2022.109227

Zhu, C., Zhou, Z., Wu, Y., Tan, W., Ma, G., and An, D. (2020). Spatial coupling between ecosystem services and economy based on grid in rocky desertification area. *Bull. Soil Water Conservation* 40 (3), 189–194+325. doi:10.13961/j.cnki.stbctb.2020.03.027

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南方报业传媒集团
广东省志愿者联合会

团粤联发〔2018〕12号

关于“美丽乡村·幸福蓝图”——“碧桂园杯”南粤村庄（整治）规划设计大赛获奖作品的通报

为认真贯彻落实省委、省政府关于打赢脱贫攻坚战、推进新

农村建设的战略部署，2017年7月，省委农办、省住房城乡建设厅、团省委、省教育厅、省文明办、省扶贫办、南方报业传媒集团、省志愿者联合会等单位共同实施了“我为美丽乡村绘蓝图”——2017年南粤村庄（整治）规划志愿行动，广泛动员城乡规划设计及相关专业人员，以志愿服务的形式推进省定贫困村村庄（整治）规划编制，集中社会力量助力农村人居生态环境综合整治。

按照《关于开展“我为美丽乡村绘蓝图”——2017年南粤村庄（整治）规划志愿行动的通知》（团粤联发〔2017〕44号）工作安排，主办方配套举办了“美丽乡村·幸福蓝图”——“碧桂园杯”南粤村庄（整治）规划设计大赛。根据设计大赛有关规定，经评审，共有181个村庄（整治）规划作品符合参评条件，其中惠来县隆江镇孔美村、连州市大路边镇顺泉村和英德市浛光镇鱼咀村3个村庄（整治）规划作品荣获特等奖（每个奖励团队10万元），连州市连州镇巾峰村等6个村庄（整治）规划作品荣获一等奖（每个奖励团队5万元），连州市龙坪镇龙坪村等19个村庄（整治）规划作品荣获二等奖（每个奖励团队4万元），徐闻县南山镇芒海村等26个村庄（整治）规划作品荣获三等奖（每个奖励团队3万元），阳山县杜步镇旱坑村等127个村庄（整治）规划作品荣获优秀奖（每个奖励团队2万元），以上奖金由支持单位提供。

希望获奖单位和志愿服务团队珍惜荣誉，再接再厉，示范带

动城乡规划设计及相关行业专业力量，积极投身我省精准脱贫攻坚和社会主义新农村建设，为助力广东决胜全面建成小康社会贡献青春和力量。

附件：“美丽乡村·幸福蓝图”——“碧桂园杯”南粤村庄（整治）规划设计大赛获奖名单

中共广东省委农村工作办公室　　广东省住房和城乡建设厅

共青团广东省委员会　　广东省教育厅

广东省精神文明建设委员会办公室　　广东省扶贫开发办公室

南方报业传媒集团　　　　广东省志愿者联合会

2018年3月22日

附件

“美丽乡村·幸福蓝图”——“碧桂园杯”南粤村庄（整治）规划设计大赛获奖名单

特等奖（3个）

序号	单位（志愿服务团队）	村庄名称
1	华南理工大学	惠来县隆江镇孔美村
2	广东省城乡规划设计研究院	连州市大路边镇顺泉村
3	广东博意建筑设计院有限公司	英德市浛光镇鱼咀村

一等奖（6个）

序号	单位（志愿服务团队）	村庄名称
1	华南农业大学	连州市连州镇巾峰村
2	深圳市城市规划设计研究院有限公司	连州市瑶安瑶族乡田心村
3	华南农业大学	连州市保安镇保安村
4	华南理工大学	惠来县隆江镇凤红村
5	广东省城乡规划设计研究院·广州大学	东源县义合镇下屯村
6	广东海洋大学	雷州市英利镇青桐村

二等奖（19个）

序号	单位（志愿服务团队）	村庄名称
1	广东省建筑设计研究院	连州市龙坪镇龙坪村

序号	单位（志愿服务团队）	村庄名称
2	深圳市蕾奥规划设计咨询股份有限公司	陆丰市河东镇浮洲村
3	广东博意建筑设计院有限公司	连州市大路边镇东大村
4	华南农业大学	连州市大路边镇黄太村
5	韶关学院	始兴县隘子镇风度村
6	华南农业大学	连州市星子镇马水村
7	广东省城乡规划设计研究院	连州市星子镇周联村
8	华南农业大学	连州市星子镇沈家村
9	深圳市新城市规划建筑设计股份有限公司	惠来县华湖镇溪洋村
10	暨南大学	清远市清新区浸潭镇塘坑村
11	华南农业大学	连州市保安镇湾村村
12	广州大学	东源县船塘镇黄沙村
13	肇庆学院	云浮市云城区前锋镇矮岭村
14	深圳市城市规划设计研究院有限公司	连州市瑶安瑶族乡大营村
15	华南农业大学	连州市星子镇姜联村
16	广州大学	东源县上莞镇新民村
17	华南理工大学	惠来县隆江镇凤光村
18	肇庆学院	云浮市云城区河口街道红阳村
19	中山大学	连州市西岸镇东江村

三等奖（26 个）

序号	单位（志愿服务团队）	村庄名称
1	湛江市海建城乡规划设计院有限公司	徐闻县南山镇芒海村
2	广东顺建规划设计研究院有限公司	连州市保安镇新塘村
3	广州大学	紫金县苏区镇永坑村

序号	单位（志愿服务团队）	村庄名称
4	仲恺农业工程学院	阳山县杨梅镇杨梅村
5	华南农业大学	韶关市浈江区犁市镇大村村
6	广东财经大学	和平县优胜镇新联村
7	顺德职业技术学院	雷州市纪家镇上郎村
8	佛山科学技术学院	连州市西江镇大田村
9	华南师范大学	东源县柳城镇柳城村
10	广东省建筑设计研究院	惠来县仙庵镇华园村
11	深圳市新城市规划建筑设计股份有限公司	陆丰市河东镇大屯村
12	广东博意建筑设计院有限公司	阳山县杜步镇杜步村
13	中山大学	连州市保安镇黄村村
14	中山大学	连州市丰阳镇柯木湾村
15	广东工业大学	陆丰市南塘镇南湖村
16	雅克设计有限公司深圳分公司	惠来县葵潭镇门口葛村
17	华南农业大学	连州市连州镇龙咀村
18	韶关学院	始兴县太平镇乌石村
19	顺德职业技术学院	连州市保安镇万家村
20	广东省城乡规划设计研究院	连州市大路边镇大坳村
21	华南师范大学	东源县灯塔镇柯木村
22	广东省建科建筑设计院有限公司	揭西县钱坑镇钱北村
23	雅克设计有限公司深圳分公司	惠来县葵潭镇石田村
24	广东省建筑设计研究院	阳山县秤架瑶族乡秤架村
25	肇庆学院	云浮市云城区思劳镇云贡村
26	韶关学院	韶关市浈江区犁市镇下陂村

优秀奖（127 个）

序号	单位（志愿服务团队）	村庄名称
1	广东博意建筑设计院有限公司	阳山县杜步镇旱坑村
2	广东中誉设计院有限公司	阳山县青莲镇青莲村
3	广东博意建筑设计院有限公司	连州市龙坪镇袁屋村
4	广东财经大学	和平县古寨镇三联村
5	广东海洋大学	雷州市调风镇企树村
6	广东睿博建筑设计研究有限公司	连州市大路边镇油田村
7	广东中誉设计院有限公司	阳山县青莲镇南塘村
8	广州大学华软软件学院	始兴县沈所镇兴仁村
9	华南理工大学	惠来县隆江镇西塘村
10	华南理工大学	惠来县隆江镇海埕村
11	华南师范大学	揭阳市蓝城区白塔镇红坡村
12	肇庆学院	云浮市云城区高峰街道赤黎村
13	肇庆学院	云浮市云城区安塘街道安塘村
14	中山大学	连州市连州镇沙子岗村
15	中山大学	连州市丰阳镇湖江村
16	河源市岭南城乡规划设计院	龙川县黄石镇长洲村
17	华南师范大学	东源县骆湖镇江坑村
18	华南师范大学	乐昌市坪石镇陈家坪村
19	广州大学	东源县仙塘镇龙利村
20	广州大学华软软件学院	始兴县澄江镇暖田村
21	广州大学华软软件学院	始兴县罗坝镇角田村
22	华南农业大学	连州市星子镇上庄村
23	江门市规划勘察设计研究院	连州市大路边镇汛塘村

序号	单位（志愿服务团队）	村庄名称
24	清远市城乡规划设计院	阳山县七拱镇新圩村
25	中山大学	连州市三水瑶族乡云雾村
26	佛山科学技术学院	连州市星子镇东红村
27	佛山科学技术学院	连州市瑶安瑶族乡新九村
28	广东工业大学	陆丰市金厢镇下埔村
29	广东省建筑设计研究院	连州市星子镇四方村
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31	广州大学	东源县仙塘镇东方红村
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33	肇庆学院	云浮市云城区腰古镇腰古村
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35	广东博意建筑设计院有限公司	连州市星子镇水源村
36	广东工业大学	陆丰市南塘镇乌石村
37	广东工业大学	陆丰市南塘镇溪南村
38	广东海洋大学寸金学院	湛江市南三岛滨海旅游示范区南三镇巴东村
39	广东省建科建筑设计院有限公司	惠来县靖海镇资深村
40	韶关学院	南雄市湖口镇三角村
41	肇庆学院	云浮市云城区前锋镇前锋村
42	仲恺农业工程学院	连州市大路边镇东联村
43	广东工业大学	陆丰市南塘镇潭头村
44	江门市规划勘察设计研究院	连州市连州镇龙口村
45	清远市城乡规划设计院	阳山县黎埠镇水井村
46	肇庆学院	云浮市云城区南盛镇枧岭村
47	东莞理工学院城市学院	紫金县好义镇小古村
48	广东工业大学	陆丰市湖东镇竹林村

序号	单位（志愿服务团队）	村庄名称
49	广东省城乡规划设计研究院	连州市大路边镇荒塘村
50	河源市岭南城乡规划设计院	龙川县丰稔镇高坑村
51	华南师范大学	东源县灯塔镇灯塔村
52	暨南大学	南雄市水口镇篛过村
53	珠海市建筑设计院	惠来县葵潭镇土角寮村
54	福建农林大学	惠来县华湖镇池畔村
55	广东博意建筑设计院有限公司	阳山县七拱镇塘坪村
56	广东省城乡规划设计研究院	连州市星子镇昌黎村
57	广东财经大学	和平县上陵镇三乐村
58	广东工业大学	陆丰市湖东镇竹湖村
59	广东工业大学	陆丰市上英镇玄溪村
60	广州大学	东源县义合镇曲滩村
61	广东海洋大学	吴川市黄坡镇平城村
62	广东财经大学	和平县贝墩镇武联村
63	广东顺建规划设计研究院有限公司	连州市保安镇本公洞村
64	华南师范大学	乐昌市廊田镇廊田村
65	惠州学院	东源县黄村镇三洞村
66	中山大学	连州市丰阳镇夏湟村
67	广东白云学院	阳山县小江镇沙寮村
68	广东博意建筑设计院有限公司	阳山县七拱镇隔坑村
69	广东科贸职业学院	韶关市武江区重阳镇万侯村
70	华南师范大学	普宁市大南山街道什石洋村
71	暨南大学	清远市清新区浸潭镇丁坑村
72	韶关学院	乐昌市廊田镇葫芦坪村
73	珠海市建筑设计院	惠来县隆江镇竹湖村

序号	单位（志愿服务团队）	村庄名称
74	广东海洋大学寸金学院	湛江市南三岛滨海旅游示范区南三镇五里村
75	广东省城乡规划设计研究院	连州市星子镇赤塘村
76	华南师范大学	乐昌市廊田镇马屋村
77	韶关学院	始兴县隘子镇满堂村
78	广东博意建筑设计院有限公司	英德市黎溪镇恒昌村
79	广东工业大学	陆丰市金厢镇十二岗村
80	广州大学	东源县新港镇青溪村
81	华南师范大学	乐昌市廊田镇白平村
82	广东工业大学	陆丰市城东街道高美村
83	广东中誉设计院有限公司	阳山县青莲镇江佐村
84	暨南大学	清远市清新区浸潭镇根竹村
85	韶关学院	始兴县太平镇水南村
86	佛山科学技术学院	连州市保安镇麻北村
87	广东博意建筑设计院有限公司	始兴县沈所镇黄所村
88	广东省建科建筑设计院有限公司	阳江市阳东区大八镇走马坪村
89	广东文艺职业学院	连州市龙坪镇石桥村
90	广州大学华软软件学院	始兴县罗坝镇东二村
91	中山大学	连州市西岸镇冲口村
92	珠海市建筑设计院	惠来县隆江镇井美村
93	东莞理工学院城市学院	连州市西江镇斜磅村
94	福建农林大学	惠来县神泉镇前湖村
95	广东工业大学	陆丰市湖东镇樟田村
96	广东海洋大学	湛江市南三岛滨海旅游示范区南三镇光明村
97	广东省建筑设计研究院	阳山县岭背镇蒲芦洲村

序号	单位（志愿服务团队）	村庄名称
98	暨南大学	阳山县岭背镇水建村
99	韶关学院	始兴县沈所镇花山村
100	深圳市市政设计研究院	惠来县靖海镇驿后村
101	肇庆学院	云浮市云城区南盛镇横岗村
102	广东工业大学	陆丰市湖东镇长溪村
103	广东南华工商职业学院	惠来县靖海镇西锋村
104	中山大学	连州市东陂镇东塘村
105	广东工业大学	陆丰市湖东镇深田湖村
106	暨南大学	阳山县秤架瑶族乡大陂村
107	肇庆学院	云浮市云城区南盛镇料洞村
108	中山大学	连州市西岸镇东村
109	广东财经大学	和平县合水镇中和村
110	韶关学院	始兴县沈所镇沈南村
111	广东博意建筑设计院有限公司	阳山县江英镇英阳村
112	广东工业大学	陆丰市金厢镇望尧村
113	广州城建职业学院	阳山县七拱镇西路村
114	华南理工大学	惠来县隆江镇见龙村
115	华南师范大学	揭阳市蓝城区龙尾镇新丰村
116	广东财经大学	和平县阳明镇梅径村
117	华南师范大学	惠来县靖海镇葛山村
118	广东博意建筑设计院有限公司	阳山县江英镇马坪村
119	广东南华工商职业学院	惠来县隆江镇北洋村
120	广东睿博建筑设计研究有限公司	连州市龙坪镇青石村
121	东莞理工学院城市学院	连州市西江镇铁坑村
122	东莞理工学院城市学院	连州市西江镇西江村

序号	单位（志愿服务团队）	村庄名称
123	广东科贸职业学院	始兴县马市镇联俄村
124	江门市规划勘察设计研究院	连州市大路边镇新水罗村
125	广州大学华软软件学院	始兴县澄江镇澄江村
126	中山大学	连州市西岸镇三水村
127	广东工程职业技术学院	雷州市乌石镇那毛村

共青团广东省委办公室	2018年3月22日印发

（共印320份）

证 明

2017 年 7 月，团省委、省委农办、省住房城乡建设厅、省教育厅、省文明办、省扶贫办、南方报业传媒集团、省志愿者联合会共同开展了“我为美丽乡村绘蓝图”——南粤村庄（整治）规划志愿行动，并配套举办了“美丽乡村·幸福蓝图”——“碧桂园杯”南粤村庄（整治）规划设计大赛。我校十支队伍在活动中取得优异成绩，具体获奖名单见附件及活动主办方颁发的荣誉证书。

特此证明。

共青团华南农业大学委员会

2018 年 6 月 1 日

附件：

"美丽乡村·幸福蓝图"——"碧桂园杯"南粤村庄（整治）规划设计大赛获奖情况公布表

奖项	作品名称	项目负责	学院	参与人员	工号/学号
一等奖	连州市连州镇巾峰村整治创建规划	赵建华（30002328）、卢丹梅（30003921）	林学与风景园林学院	韦通洋	201430540313
				梁嘉瑶	201430540310
				徐文发	201430540315
				黄泳姿	201518210112
				包秋香	201518210101
				严文俊	201518210126
一等奖	连州市连州镇保安村整治创建规划	卢丹梅（30003921）、赵建华（30002328）	林学与风景园林学院	陈丹	201430540301
				郭楚怡	201430860163
				刘淑瑜	201430540213
				李易燃	201518210114
				王如珂	201518210122
				黄嘉仪	201518210111
二等奖	连州市大路边镇黄太村整治创建规划	佘美萱（30002605）、陈思颖（30004143）	林学与风景园林学院	林蔚（教师）	30004407
				赵晓铭（教师）	30003313
				练东鑫	201518210115
				莫莉	201518210118
				邓可欣	201518210204
				赖嘉娱	2016307113
				张晓敏	201430540154
				谭杰琪	201518210221
二等奖	连州市星子镇沈家村整治创建规划	陈思颖（30004143）、佘美萱（30002605）	林学与风景园林学院	赵晓铭（教师）	30003313
				林蔚（教师）	30004407
				刘维东	201430540311
				张冰	201430540319
				韦瑶	201430540314
				张金娜	201518210228
				叶梦婷	201518210226
				陈秋菲	201518210106
二等奖	连州市连州镇湾村村整治创建规划	卢丹梅（30003921）、赵建华（30002328）	林学与风景园林学院	卓友庆	20173071041
				谢楠	20173071033
				季莹莹	201430540306
				马燕虹	201430540216
				郭大为	201518210110
				许心怡	201518210125
二等奖	连州市星子镇姜联	王凌	林学与风景	王婷(教师)	30002930

	村社会主义新农村示范村整治创建规划	（30001130）	园林学院	李家裕	201430540307
				杨燕娟	201430540316
				唐敏婷	201518210222
				陈伟旋	201518210203
				林腾	201430540211
				刘剑翔	201430540212
二等奖	连州市星子镇马水村社会主义新农村示范村整治创建规划	王婷（30002930）	林学与风景园林学院	王凌（教师）	30001130
				陈小芮	201430540202
				谭超群	201430540218
				黄宇轩	201430540206
				陈雨忱	201430540316
				王蘅	201430540219
三等奖	韶关市浈江区犁市镇大村村社会主义新农村示范村村整治规划	杨文越（30004211）	林学与风景园林学院	赵晓铭（教师）	30003313
				叶昌东（教师）	30003674
				刘冬妮	2016307120
				梁惠兰	20173071015
				甄新瑜	201430540322
				莫樱梅	201518210219
三等奖	连州市连州镇龙咀村社会主义新农村示范村整治创建规划	赵建华（30002328）、卢丹梅（30003921）	林学与风景园林学院	林蔚（教师）	30004407
				冼颖婷	201518210124
				陈小洁	201518210107
				蔡雅颖	201518210103
				蔡晓丽	201518210102
				张童浩	201430540320
优秀奖	连州市星子镇上庄村整治创建规划	陈思颖（30004143）、佘美萱（30002605）	林学与风景园林学院	吴宝娜（教师）	30002931
				黄建林	201518210208
				温炜彤	201518210223
				杨善惠	201518210224
				黎诗韵	201518210212
				张晓晴	201518210229
				王鑫	201430540148

荣誉证书

林　蔚：

被评为2018-2020年度华南农业大学优秀班主任。

特发此证，以资鼓励。

华南农业大学

二O二一年七月

荣誉证书

《连州市保安镇保安村社会主义新农村示范村整治创建规划
——立足乡村特质的贫困村脱贫致富规划探索》

获 2019 年度广东省优秀城市规划设计奖

三等奖

获奖单位：华南农业大学　　　广州维深城市规划设计有限公司

获奖人员：卢丹梅　赵建华　陈思颖　王潇文　李易燃　林　蔚　卓友庆　谢　楠　李小琦
黄嘉仪　王如珂　黄泳姿　阳文韬　李　俊　蔡健婷

广东省国土空间规划协会

二〇二〇年七月

证书编号：2019-3-119