

水灾害生态化防治理论模式与关键技术路径

严登华^{1,2}, 王浩¹, 毕吴瑕^{1,2}, 张鑫^{1,2}, 秦天玲^{1,2}, 翁白莎^{1,2}, 李威^{1,2}

(1. 中国水利水电科学研究院流域水循环与水安全全国重点实验室;
2. 水利部防洪抗旱减灾技术创新中心(水旱灾害防御中心))

摘要:基于极端水循环特征,结合富自然-功能协调流域、灰绿基础设施协同等前沿理论,阐释水灾害生态化防治内涵与理论基础;提出灰绿协同的水灾害防治新范式,即集水文畸变三维诊断、径流系数时空重塑、产水与耗用水双控等技术于一体的技术体系;面向当前水旱灾害防御体系转型需求,提出了分区分类实施、智慧化管理、体制机制创新等切实可行的实施路径。研究成果旨在为推进水灾害防治从工程主导的“蓄”“导”模式向生态优先的“适应模式”转型提供理论支撑和技术路径。
关键词:水旱灾害;生态化防治;水文调蓄;灰绿工程;富自然-功能协调流域

Theoretical modes and key technological pathways for ecological prevention and control of water disaster//Yan Denghua^{1,2}, Wang Hao¹, Bi Wuxia^{1,2}, Zhang Xin^{1,2}, Qin Tianling^{1,2}, Weng Baisha^{1,2}, Li Wei^{1,2}(1. State Key Laboratory of Water Cycle and Water Security, China Institute of Water Resources and Hydropower Research; 2. Technology Innovation Center for Flood and Drought Prevention and Disaster Reduction, Ministry of Water Resources)
Abstract: Based on the characteristics of extreme water cycle, the connotation and theoretical basis of ecological prevention and control of water disasters were explained by combining frontier theories, such as Nature Enriched and Attributes Coordinated Watershed and gray-green infrastructure coordination. A new paradigm for water disaster prevention through gray-green infrastructure—a technical system integrating Three-Dimensional Diagnosis of Hydrological Distortion, Spatiotemporal Remapping of Runoff Coefficient, and Dual Control of Water Yield and Consumptive Use were proposed. Addressing the current need for transforming water disaster defense systems, it outlines practical implementation pathways including zoned and categorized implementation, intelligent management, and institutional mechanism innovation. These findings aim to provide the theoretical underpinnings and technical pathways to advance a critical shift in water disaster prevention, involving moving from an engineering-led “storage” and “dredge” mode to an ecology-first “adaptation mode”.
Key words: flood and drought disaster; ecological prevention and control; water regulation; grey-green infrastructures; Nature Enriched and Attributes Coordinated Watershed

全球气候系统正经历以变暖为主要特征的深刻变革,水文循环呈现显著的极端化趋势^[1-2]。我国作为世界上水旱灾害最为严重的国家之一,近年来极端水文事件频发,2021 年郑州特大暴雨最大降水量达 201.9 mm/h,突破我国陆地小时降水量极值^[3-4];2020 年长江流域性洪水多个水文站点流量创 1954 年以来新高^[5]。与此同时,生态系统退化与水文畸变形成恶性循环。据《2022 年中国水土保持公报》报道,我国水土流失面积达 269.27 万 km²,大量湿地湖泊萎缩,这些生态系统的退化显著削弱了流域的自然防御能力^[6]。生态系统退化导致调蓄能力下降,进而加剧灾害风险^[7];而灾害发生又进一

步破坏生态系统,形成正反馈效应^[8-9]。我国在水旱灾害防治方面取得了举世瞩目的成就,建成了较为完善的水旱灾害防御体系,有效保障了经济社会发展和人民生命财产安全。然而,随着极端天气事件的增多增强,新建大型调蓄工程的条件有限,传统以堤防、水库、蓄滞洪区等灰色基础设施为主体的防御体系正面临新的挑战,具体表现为气候变化引发的极端水文事件冲击、生态功能缺失导致的系统性风险、城市化与空间开发的挤压、管理与适配性的滞后、灾害类型的复合型挑战等。
以灰色工程措施为主的防御体系主要存在以下几个方面问题:①生态系统服务功能退化严重。大

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作者简介:严登华(1976—),男,教授级高级工程师,博士,主要从事气候变化与水资源研究。E-mail:yandh@iwhr.com
通信作者:毕吴瑕(1992—),女,高级工程师,博士,主要从事极端水文及生态环境效应研究。E-mail:biwx@iwhr.com

规模的河道硬化、湿地围垦导致自然水文调蓄能力显著下降,流域产汇流过程加快,洪峰流量增大,极端降雨条件下的致灾风险加剧^[10-12]。②防灾体系整体韧性不足。灰色工程措施往往采用蓄和导的控制思路,忽视了自然系统的自我调节能力^[13-14]。③维护成本持续攀升。随着工程设施老化和极端事件频发,单纯依靠工程措施的防灾模式面临着巨大的经济压力^[15]。

当前,美丽中国建设和绿色流域发展理念为我国水旱灾害防治工作指明了新方向。在长江大保护、黄河流域生态保护和高质量发展等国家重大战略推进过程中,如何将生态优先、自然修复的理念融入防灾减灾体系,赋予现有工程更多的绿色化内涵,成为新时期治水实践的重大课题^[16-17]。本文系统阐述水灾害生态化防治的理论内涵,构建灰绿协同的水灾害防治技术框架体系,探索实施路径,旨在为推动我国水灾害防治体系的转型升级提供科学支撑。

1 水灾害生态化防治内涵与理论基础

1.1 变化环境下水灾害治理的总体需求

水文循环的极端化趋势当前主要呈现出强度突破、时空压缩和过程耦合三重特征。强度突破特征表现为降水强度和洪峰流量屡破历史极值,传统按历史序列设计的防洪工程面临超标准运行的严峻考验;同时特大干旱发生频次增加,传统工程调蓄措施不足以支撑旱情调控^[2]。时空压缩特征体现为降雨历时缩短、空间集中度增强,极端降水事件导致流域汇流过程急剧加速,洪峰形成时间大幅缩短,强降水中心高度集中,局地性特征显著^[4,18];同时骤旱等极端干旱事件影响范围变大,给预报预警和应急响应带来巨大挑战。过程耦合特征指多种灾害过程在时空上的叠加效应,暴雨往往与台风、地质灾害、城市内涝等形成灾害链^[19-20],干旱往往与高温、热浪、火灾等形成灾害链,单一工程措施难以应对这种复合型灾害^[21-22],此外旱涝急转、连旱连涝等极端转换过程增多,要求防治体系具备更强的适应性和韧性^[23]。

面对水循环新特征,传统“预测-抵御”模式局限性日益凸显。灰色工程虽能在设计标准内发挥作用,但面对极端事件如超标准洪水等的防御能力急剧衰减^[24];绿色工程虽然通过维护生态系统功能增强应对能力,但一味加大植树造林种草力度会消耗水资源储备,造成新的水资源与水资源安全问题^[25-26]。工程措施是相对静态的,而生态措施是具有自适应的动态过程。现有水网措施虽已削弱静态化措施,

增加动态化措施,但仍需进一步增加生态化措施。此外,水灾害尤其是洪灾,都是暴雨产流和坡面-河道汇流过程,目前在河道层面所做工作多,在坡面所做工作相对较少,而坡面调蓄潜力大,当植被覆盖度低于30%时,林草地的减流效益较低(9%~28%),草地在低覆盖度下甚至可能出现负效益;当植被覆盖度超过60%时,减流效益趋于稳定(50%~69%),同时也可为旱季提供水源^[27-28]。本文聚焦水文调蓄能力提升,提出了水灾害生态化防治理念。

1.2 水灾害生态化防治内涵

水灾害生态化防治是基于对水灾害与生态系统相互作用关系的深刻认识而提出的创新范式,其核心内涵主要体现在理念、过程和功能3个维度。在防治理念上,在遵循自然规律的前提下,采取适度的调控措施^[14];在过程层面上,赋予当前灰色设施更多的绿色和生态内涵,进一步加强绿色措施,以与水文节律动态适应,尤其是在具有巨大调蓄潜力的坡面,通过层层拦截、层层疏导,拦蓄洪水,也为旱季提供水源;在功能层面上,强调灰绿协同,宜绿色则绿色,宜灰色则灰色,赋予水灾害防御体系更深层次的绿色的根、绿色的形、绿色的魂,进而提高其长效性,推进洪枯兼顾、水生态保护等^[29-30]。

1.3 水灾害生态化防治理论基础

从理论基础来看,水灾害生态化防治建立在多个学科理论的交叉融合之上,包括水文学及水资源、生态学、水灾害与水安全、系统工程学等。具体而言,水灾害生态化防治涉及“自然-社会”二元水循环理论^[31]、流域生态完整性理论^[32]、坡面-河道水流运动理论^[33]、复杂科学与系统工程理论^[34]、灰绿基础设施协同^[35]、富自然-功能协调流域等理论^[14]。

水灾害生态化防治首先是基于生态水文学的耦合机制认识,深入理解植被、土壤、地形等生态要素对水文过程的调控作用,特别是在极端条件下的响应机制。研究表明,健康的生态系统能够通过植被截留、土壤入渗、地下水补给等过程,有效削减地表径流峰值(如黄土高原植树造林与水土保持工程可使暴雨径流响应峰值降低24%~86%),延迟产流时间和汇流时间^[28,36-38]。其次是韧性理论的应用,将流域视为一个复杂适应系统,通过增强系统的多样性、冗余性和模块性,提升流域在极端扰动下的适应和恢复能力^[39-40]。生态化防治强调构建多道防线、多重缓冲的防灾格局,避免单一防线失效而产生系统性崩溃^[36,41]。水灾害生态化防治的理论框架主要为:增强生态系统“活性”,强化灾害防御“韧性”,即通过灰绿协同等措施,实现功能协同优化、空间系统配置、时间动态适应等目标,在保障防灾安全的前

提下,最大化生态系统的综合效益,即涵盖防灾、生态、经济、社会等多维度效益(图1)。

2 水灾害生态化防治技术体系

2.1 总体技术框架

水灾害生态化防治总体技术框架以“生态优先、灰绿协同、系统治理、分区施策”为核心原则,构建“源头控制—过程调节—末端保障—智慧调控”的全过程、多层次技术体系,实现水灾害防治与生态保护的协同推进。该框架以“生态化防灾”理念为指导,以提升流域水文调蓄能力为核心目标,充分整合绿色生态措施与灰色工程措施的优势,以“径流

系数管理”为核心抓手,通过系统化的技术整合与优化配置,形成适应不同区域、不同灾害类型的水灾害生态化防治技术方案,主要包括水文畸变诊断、径流系数管理、产-耗水双控等三大关键任务(图2)。水文畸变诊断为径流系数管理和产-耗水双控提供前期背景调研基础,径流系数管理为产-耗水双控的实现提供关键参数支撑。

就水文畸变诊断而言,重点是将传统水文参数赋予生态内涵,建立水文过程与生态过程的量化关联,通过诊断结果精确识别流域功能失调的关键环节,为水灾害生态化防治措施的时空布局提供依据。就径流系数管理而言,重点是将传统静态设计参数

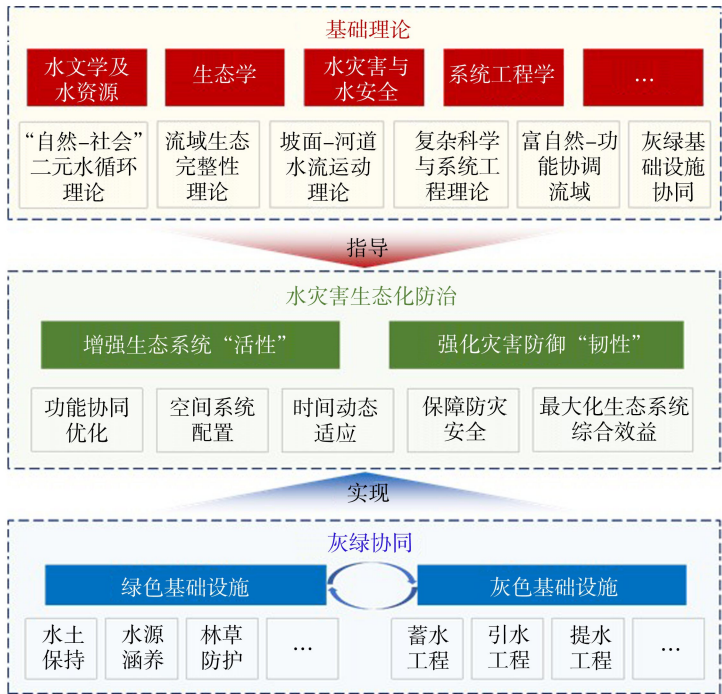


图1 水灾害生态化防治理论框架

Fig.1 Theoretical framework for ecological prevention and control of water disasters

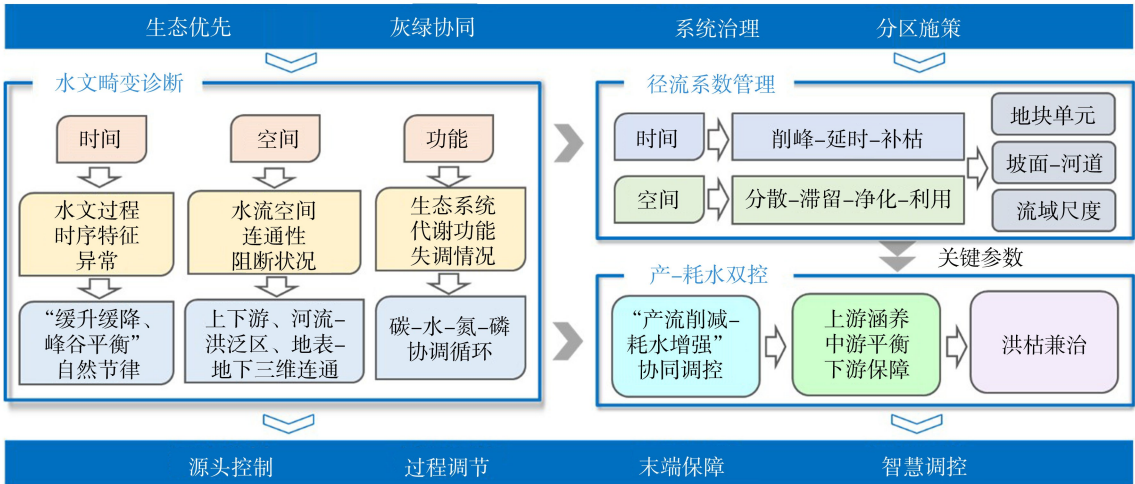


图2 水灾害生态化防治总体技术框架

Fig.2 Technical framework for ecological prevention and control of water disasters

转变为可动态调控的过程变量,通过改变植被覆盖、植被配置、地表糙度等影响因子,适应暴雨产流、干旱等极端过程,实现对径流系数的主动调控,从而改变流域水文响应特征。就产-耗水双控而言,重点是将传统上被忽视的耗水管理纳入防治体系,掌握每个单元的产水、耗水情况,通过产流和耗用水两个维度的协同调控,改变流域水量分配结构,提升水资源利用效率,形成“洪枯兼治”的水灾害防御综合效应。

2.2 关键技术

2.2.1 水文畸变三维诊断技术

为实现水灾害精准诊断和靶向治理,提出水文畸变三维诊断体系,从时间、空间、功能 3 个维度进行评估。

时间上,主要关注水文过程的时序特征异常。健康流域的水文过程应呈现“缓升缓降、峰谷平衡”的自然节律,而畸变状态表现为洪峰响应加速、基流衰退加剧。通过洪峰滞时、洪峰模数比值、基流指数等指标,识别不同场景下流域调蓄功能的退化程度。

空间上,评估水流空间连通性的阻断状况。自然流域应保持纵向(上下游)、横向(河流-洪泛区)、垂向(地表-地下)的三维连通,畸变则表现为河道渠化导致的纵向阻隔、堤防束缚造成的横向隔断、硬化铺装引起的垂向阻滞。通过河流自然度指数、洪泛区连通率、入渗系数等指标,量化不同措施下纵向、横向、垂向水文联系的阻断程度。

功能上,从物质能量循环角度诊断流域健康。健康流域应维持碳-水-氮-磷的协调循环,畸变状态表现为营养物质滞留、能量流动受阻。通过土壤有机质含量、植被净初级生产力、水体营养盐浓度等指标,揭示生态系统代谢功能在极端水文事件中的失调状况。

2.2.2 径流系数时空重塑技术

径流形成受“降雨输入-系统状态-径流输出”三要素控制。降雨输入难以人为改变,径流输出是防治目标,因此调控重点在于改变系统状态。通过调整下垫面条件、优化土地利用、优化植被建设配置等方式,在时间维度上,通过“削峰-延时-补枯”的协同调控,修复水文过程的自然节律;在空间维度上,采用“分散-滞留-净化-利用”的组合策略,通过增强空间异质性重建流域水文多样性。结合水文畸变三维诊断结果,对径流系数进行有效地控制和管理,以适应暴雨产流过程,达到防治水灾害和保护生态环境的目的。

具体而言,系统状态调控可分为地块单元、坡面-河道、流域不同尺度进行精细化调控。地块作为

流域的基本单元,是径流系数调控的起点。地块尺度径流系数调控主要聚焦于增强“截留-入渗-蓄存”功能,实现源头减排。可采用的技术措施包括植被配置优化、土壤结构改良、微地形设计、透水铺砖设计等。坡面-河道连接地块与流域,是径流汇聚的关键通道。地块尺度径流系数调控主要着眼于“延缓-调蓄-传输”功能,实现过程调控。可采用的技术措施包括生态沟渠系统构建、河道生态修复、洪泛湿地恢复、蓄滞空间建设等。流域尺度径流系数调控需统筹上下游、干支流、左右岸关系,实现系统优化。可采用的技术措施包括空间格局优化、时序协调调控、关键节点调控、分区差异化调控等。

2.2.3 产水与耗用水双控技术

产水与耗用水双控技术主要通过量化掌握每个小区单元产水、耗用水情况,开展适度的“产流削减-耗水增强”的协同调控,采用植被恢复、土壤改良、透水铺装等产流控制技术,以及植被蒸腾调控、土壤蒸发管理、水体蒸发利用、雨水资源化与地下水涵养等耗用水控制技术,减少径流量,增加蒸散发和地下水补给,改变水量分配结构;在洪水期通过减少径流和增加系统持水来削峰滞洪,在枯水期补充水源增强的地下水补给来保障生态基流与供水安全,实现洪旱风险的统筹治理。通过产耗水双控的空间优化配置,形成“上游涵养、中游平衡、下游保障”的流域水循环格局,提升流域水文调节能力。上游以增强耗水、涵养水源为主,恢复森林植被,提高蒸腾耗水和蓄水;建设小型蓄水工程,增加入渗补给。中游平衡产流控制与耗水增强,如在农业区推广节水灌溉,减少无效耗水;在城镇区建设雨水利用设施,提高资源利用率。下游以产流控制、快速排泄为主,在保证行洪安全前提下,适度增加绿地、水体,增强局地耗水。

3 水灾害生态化防治实施路径

3.1 分区分类实施

针对不同区域的自然条件、灾害类型和防治需求,制定差异化水灾害生态化防治策略。在山地丘陵区,针对其坡度大、侵蚀强、产流快等特征,以水土保持为核心,实施退耕还林、封山育林、梯田建设、淤地坝等措施,注意匹配不同坡度、坡向等进行植被优化配置^[42-45]。在平原河网区,针对其地势平坦、河网密布、调蓄容量大等特征,重点恢复河湖水系连通,通过生态堤防建设、疏浚河道、退圩还湖、湿地重建、洪泛区恢复等,提升蓄排能力^[46-47]。在农业种植区,针对其地表裸露季节性强、面源污染重等特征,推广保护性耕作、生态沟渠、缓冲带建设等生态

农业技术,降低水灾害引发的水安全问题^[48-49]。在城市建成区,针对其高度硬化、排水压力大、空间受限等特征,大力推进低影响开发,采用绿色屋顶、透水铺装、雨水花园、调蓄池等组合措施,缓解内涝压力^[50-51]。

3.2 智慧化管理

数字革命带来的技术革新可实现智慧化、精细化管理,为水灾害生态化防治提供强大支撑。智慧化水灾害生态化防治管理平台主要包括全息感知网络、智能模拟系统、辅助决策系统等^[52]。全息感知网络整合地面监测站网、气象雷达、卫星遥感、无人机巡查等多源数据,实时获取降雨、水位、流量、土壤墒情、植被状况等信息,在关键节点布置智能传感器监测生态化设施运行状态,构建流域“数字孪生体”,实现物理流域与数字流域的实时映射^[53-56]。智能模拟系统基于实时监测数据、机理实验改进的参数方程,与 AI、机器学习算法深度融合,集成变结构-动参数的水文-水动力-生态耦合模型,提升模拟精确度预测能力^[43,57-59]。辅助决策系统基于情景模拟评估不同防治方案的效果,建立综合考虑洪涝调蓄、生态效益、经济成本等多目标优化方案库,提供最优防治策略与应急调度方案^[60-62]。此外,建立公众参与制度,鼓励群众反馈灾情等信息,通过数据开放共享提高防治工作透明度。通过智慧化管理模式推动水灾害生态化防治从经验决策向科学决策、从静态规划向动态优化的深刻转变。

3.3 体制机制创新

体制机制创新是推动水灾害生态化防治的根本保障。水灾害生态化防治涉及水利、自然资源、生态环境、住建、农业等多个部门,建议建立流域统筹、部门协同机制,在规划法规、技术标准、政策保障等层面实现创新。在规划法规层面,将水灾害生态化防治纳入国土空间规划体系,划定生态防水灾功能区,明确不同区域的主导功能和管控要求,出台相关政策法规;在技术标准方面,借助监测网络和分布式水文-生态模型等工具开展多情景模拟,优化工程级指标配置,实现流域级水灾害防治指标,为灰绿工程系统调控实践提供指导;在政策保障方面,建立健全水灾害生态化防治补偿机制,建立生态防灾基金,对因布设相关措施而受到损失的地区和个人给予合理补偿。

4 结 语

随着水循环极端化趋势加剧,多重水问题交织,需要进一步革新水灾害防治理念与模式。本文系统构建了水灾害生态化防治的理论框架与技术体系。

基于极端水循环特征,融合灰绿基础设施协同、富自然-功能协调流域等理论,从理念、过程和功能 3 个维度阐明水灾害生态化防治的内涵,明确水灾害生态化防治的理论框架主要为了增强生态系统“活性”,强化灾害防御“韧性”。以提升水文调蓄能力为核心,提出以“生态优先、灰绿协同、系统治理、分区施策”为思路的水灾害生态化防治技术框架,包含水文畸变三维诊断、径流系数时空重塑、产水与耗用水双控等关键技术。从分区分类实施、智慧化管理、体制机制创新等方面提供切实可行的实施路径。水灾害生态化防治属多学科交叉研究,未来在基础理论方面,亟须突破气候变化背景下生态-水文耦合机制的理论瓶颈,揭示极端条件下灰绿基础设施的交互机理,基于机理实验改进发展非平稳环境下融合系统的动力演化模型、精准化生态系统防灾功能定量评估模型等平台;在关键技术方面,需要突破生态基础设施的智能化设计、优化配置与功能快速形成的技术约束,研发低成本、高性能、自适应的新型生态工程材料,提升生态措施在极端条件下的自适应性和稳定性,并在不同场景实践中检验完善。探索水灾害生态化防治的实现机制,形成产学研深度融合的创新体系,以系统推进水灾害防治从理念到实践的全方位革新,为构建气候适应型社会、保障国家水安全提供坚实的科技支撑。

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