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黄河水生态承载力的流域整体性和时空连通性

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黄河是中华民族的母亲河, 黄河流域是中华文明的重要发育地. 在中国5000多年的历史长河中, 黄河流域作为全国政治、经济和文化中心占据了3000多年, 孕育了河洛文化、河湟文化、关中文化等, 分布有西安、郑州、洛阳、开封等古都, 诞生了四大发明和《诗经》、《老子》、《史记》等经典著作. 黄河流域是连接青藏高原、黄土高原和华北平原的生态廊道, 是西北和华北地区的重要水源, 以其占全国2.2%的径流量灌溉了占全国15%的耕地, 哺育了流域9省近23.3%的全国人口(2019年), 贡献了21.6%的全国GDP(2018年)[1~5]. 不仅如此, 黄河流域还是中国最重要的煤炭生产地带. 中国排名前14的大型煤炭生产基地中有9个地处黄河流域, 已经探明的煤炭储量累计达7292亿吨(原煤). 特别是, 煤炭工业已经成为黄河流域中、上游晋陕蒙宁甘地区(即山西、陕西、内蒙古、宁夏和甘肃五省区)经济发展的主要经济支柱产业, 煤炭年产量约28亿吨, 占全国总产量的近70%[6]. 因此, 黄河流域生态保护和高质量发展直接关系到中国生态文明建设的成败.

长期以来, 黄河存在水土流失、泥沙淤积和洪水威胁等问题. 特别是近几十年来, 黄河流域气温升高、极端事件及自然灾害频发, 径流减少; 同时, 大规模的能源开发、煤炭开采也需要大量的水资源[3,4]. 气候变化和不合理人类活动使得黄河上游部分生态系统质量退化、水源涵养功能下降; 中游水土流失严重; 下游生态流量偏低, 部分河口湿地萎缩. 目前, 黄河流域水资源短缺、自然生态脆弱、经济社会发展相对滞后, 是中国生态安全保障和经济社会发展的重点和难点地区[7]. 为此, 需要梳理制约黄河流域生态保护与高质量可持续发展存在的问题, 凝炼关键科学问题, 提出当前迫切需要开展的任务.

1 黄河流域的主要生态环境问题

黄河发源于青海省青藏高原巴颜喀拉山北麓的约古宗列盆地, 自西向东流经青海、四川、甘肃、宁夏、内蒙古、陕西、山西、河南以及山东9个省(自治区), 最后注入渤海. 黄河流域跨越3个气候带、8个气候区和15个气候副区(http://www.yrcc.gov.cn/), 流域大部分地区年降水量在200~600 mm, 同时蒸发强烈, 尤其是甘肃、宁夏和内蒙古中西部地区年蒸发量可达2500 mm, 水资源短缺, 人均水量低于600 m^3, 仅为全国平均值的25%[4]. 黄河流域从东到西跨越半湿润区、半干旱区和干旱区, 穿越全球最大、最深厚的黄土区, 分布着约59类植被, 生物多样性丰富[8]; 生态系统类型以草原、农田、荒漠和森林为主(图1), 分别占流域总面积(以流域州市为基本单位计算)的37.9%、24.8%、19.1%和9.0%.



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黄河干流河道总长5464 km, 流域面积约79.5万km^2, 为世界第五大长河, 是中国仅次于长江的第二大河. 以内蒙古托克托县河口镇与河南荥阳市桃花峪为节点将黄河分为上、中、下游三段[8~10](图2), 河口镇以上为黄河上游, 跨越青藏高原和内蒙古高原, 河长约3472 km, 流域面积为42.8万km^2, 占总面积的53.8%, 黄河60%以上的径流量来源于上游; 河口至河南荥阳市桃花峪为黄河中游, 河长约为1224 km, 流域面积为34.4万km^2, 中游地区绝大部分属黄土高原, 是入黄泥沙的主要源区. 桃花峪以东属于下游地区, 河长约为768 km, 流域面积为2.3万km^2, 从山东利津进入黄河三角洲. 由于中上游来的泥沙淤积, 黄河下游大部分河段为“地上悬河”, 易发洪水、河流改道, 对黄淮海平原的生态系统和人民生命财产安全造成严重威胁. 黄河是世界上输沙量最大、含沙量最高的河流, 黄河流域的核心问题是水沙问题, 水少沙多、水沙关系不协调是黄河的主要特征, 也是黄河治理的症结所在[11].

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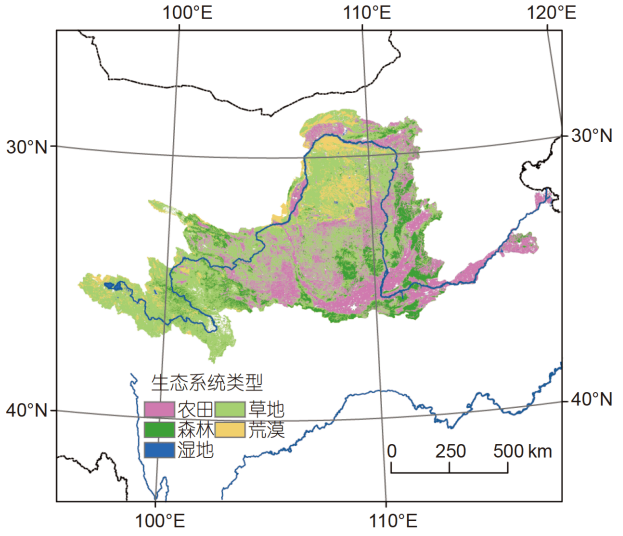


图 1 黄河流域主要生态系统类型分布
Figure 1 Distribution of main types of ecosystems in the Yellow River Basin

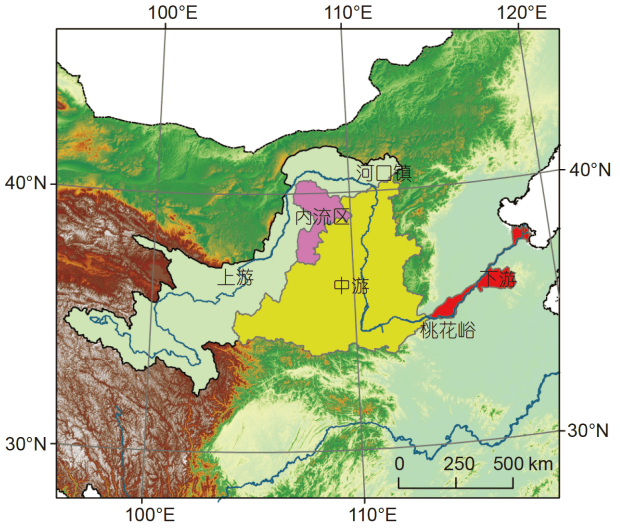


图 2 黄河流域上、中和下游分区
Figure 2 Upper, middle and lower reaches of the Yellow River Basin

1.1 水沙问题

黄河流域的土壤侵蚀产沙方式，主要包括水力侵蚀、风力侵蚀和冻融侵蚀. 水力侵蚀占流域总面积的53%，主要分布在上游的生态脆弱区、退化区和农耕区，尤其在中游黄土高原农耕区由于暴雨多发，水力侵蚀最为严重[5,6,11]. 黄河约80%的泥沙来源于中游河口镇至潼关间的多沙区[10]. 其次是风力侵蚀，主要分布在黄河上游从兰州至河口镇段流域，约占流域总面积的30%. 冻融侵蚀区主要分布在青藏高原和祁连山的季节性冻土区，约占流域总面积的17%，且随全球变暖的影响, 冻融性土壤侵蚀呈日趋严重趋势.

当前，由于区域暖干化和超载放牧、过量采伐开垦等不当人类活动引起部分地区植被退化[12]. 黄河源区70%以上的草原存在不同程度的退化现象，主要表现为植被覆盖度下降、沼泽湿地萎缩、草地沙化和次生裸地面积增加等. 近30年，黄河源区的甘南和川西北湿地萎缩100 km^2，水源涵养能力下降近10%~30%，超过50%的山体植被变成裸土，水土流失严重. 水土流失破坏水土资源，反过来又加剧植被退化，降低农业综合生产能力[5]. 例如，目前治理的近80万公顷的退化黑土滩中，超过60%出现了二次退化. 严重的水土流失不仅导致当地生态环境恶化，加剧荒漠化发展和伴生灾害发生[13,14]，而且造成黄河河道泥沙淤积，在黄河下游河道形成“地上悬河”，加剧下游洪水风险，频繁发生决堤洪灾，引起河流改道，春季初期黄河上游开河后的流冰也容易发生卡冰结坝而导致决堤凌灾，严重威胁华北地区的防洪安全和生态安全，危及该地区人民生活、生产、生态用水安全[5,10].

1.2 煤炭开采加剧水沙问题

黄河流域是中国最重要的煤炭生产地带，大部分地区生态脆弱、抗干扰能力差，加之煤炭开采通常在地表以下数十米、数百米的深处，开采引起的地表裂隙、塌陷地等，对生态系统危害严重. 例如，库布齐沙漠以南、毛乌素沙漠东部边缘地带的煤炭过度开发已经造成地形地貌的严重改变，土地沙漠化进程加速. 黄河流域煤炭开采对生态系统的影响主要表现在破坏水资源和地表生态两个方面[15].

(ⅰ) 煤炭开采加剧黄河流域水资源短缺. 黄河流经区域面积的80%以上属干旱和半干旱气候区, 水资源天然不足. 晋陕蒙宁甘地区已探明的煤炭资源保有储量约占到全国的67%, 但水资源不到全国的4%; 能源金三角(宁东、陕北和蒙西)的煤炭储量约占全国的27%，但水资源仅占全国的0.37%[16]. 过去黄河水资源大部分用于农业, 农业用地的增加对区域水资源的消耗、生态结构和功能影响规模最大[17]. 20世纪90年代以来，随着煤炭工业的高速发展，黄河流域用水结构也必然发生变化. 据统计，每开采1 t煤炭平均要消耗水资源约0.4~2.5 t(包括开采损失的水资源), 整个黄河流域煤矿区按年产量28亿吨计算，消耗的水资源将超过56亿吨. 如果再考虑煤化工企业，每年增加的用水量将超过100亿吨. 同时，煤层开采形成的导水裂缝贯通地表，规模开采将导致矿区地下水位的大范围和大幅度疏降. 据统计，在鄂尔多斯神东煤矿区，大规模煤炭开发前，有144个天然泉眼，现已消失104个，地表水系逐年干涸，大片的天然胡杨林干枯死亡，乔、灌、草等植被出现大面积的衰退，荒漠化进程加速，又进一步加剧地表蒸散发，形成水资源与生态环境之间的恶性循环.

(ⅱ) 煤炭开采对生态环境的影响具有多样性. 黄河流域生态环境差异很大，不同生态环境区煤炭开采导致的生态损毁特征和机理也不相同. 黄河流域上游煤矿区主要位于青海

的高原丘陵区，煤炭露天开采将造成原有地貌破坏和植被消失，表土层破坏和植被损伤. 同时，与采矿相关的地面建(构)筑物及道路建设引起的开挖、移动土方和弃土石渣、排土场占地堆放，将进一步恶化采矿区生态环境. 中游煤矿区位于黄土沟壑区的陕北、晋北、晋中、晋东、黄陇一带和风积沙区的神东和宁东，大规模的煤炭开采引起地表塌陷，加剧水土流失、生态环境恶化，增加流入黄河的泥沙淤积，加重下游防洪负担. 水土流失和水沙不协调是中游煤矿区的主要生态问题. 下游煤矿区主要位于冲积平原区的鲁西和河南，煤炭开采将导致地表沉陷形变和地表积水、产生次生盐碱化导致的土地生产力下降.

2 黄河治理成效和问题

近年来，中国在黄河流域的上游、中游和下游分别开展了三江源生态保护与建设、黄土高原退耕还林还草、黄河三角洲湿地生态修复等系列工程[18~20]. 黄河上游地区的水源涵养量以19.35亿m^3/10 a的趋势稳步提升，三江源自然保护区水源涵养能力已达约200亿m^3；中游地区黄土高原的水土保持能力显著增强，实现了“人进沙退”；下游地区的河口湿地面积有所回升，生物多样性同时增加[6,21]. 特别是1999年以来的退耕还林还草工程的实施，使得黄土高原林草覆被率由20世纪80年代的20%增加到2017年的约65%，62%的区域呈现植被恢复态势[22,23]；植被恢复进入自然演替阶段[24]. 黄河流域植被、土壤、水文等明显改善[25]，局部地区荒漠化和生态系统退化趋势得到初步遏制、区域生态系统服务功能明显提升[13,26]. 但是，黄河流域治理仍未能实现根本性扭转. 例如，气候变暖引起的干旱和多年冻土融化以及不合理的人为活动，导致黄河流域上游高寒草甸植被退化[27,28]，使得水源补给区的水源涵养功能减弱；人工种植植被没有充分考虑不同地区的气候差异，整个流域人工种植林草种类和结构配置单调、生态系统不稳定[5]. 一些地区的人工林营建没有考虑水资源承载力[29]，过度追求高经济效益，出现了土壤干化和植物群落生长衰退现象[3,29,30]. 特别是，黄河流域作为优质苹果的适生区，近年来种植规模不断扩大、种植年限增加，导致果树大小年明显、优果率不高、土壤干燥化等问题[31]. 人工种植林树种单一，又过度密植，导致生态系统生产力与土壤肥力均下降，直接影响人工种植林的可持续经营和生态效益发挥[32]. 同时，国家加大黄河流域水土流失治理力度，开展了一系列黄河上中游水土保持重点防治、治理工程，实施了梯田和淤地坝建设、坡耕地整治和治沟造地等治理措施[13,33]. 在黄河干支流上修建了龙羊峡、刘家峡、三门峡和小浪底等控制性水利工程，在下游修建河道整治工程，有效控制洪水且调水调沙[10,23]，流域水土流失面积治理近50%，入黄泥沙平均每年减少4亿吨以上. 与1919~1959年相比，2000~2012年黄河年均输沙量和径流量分别下降82.7%和45.8%[25]，2000~2018年黄河输沙量锐减85%，中游洪水发生频次降低，下游河道由淤积转为冲刷，明显减少了下游河床的淤积抬升速度，“地上悬河”得到初步遏制[23,34]. 从1999年至今，黄河未出现干流断流，支撑了全国15%的耕地和北方主要城市群用水. 但是，黄土高原水土流失治理面积尚不足50%，且空间治理不均衡，局部地区水土流失依然严重；并且，水沙调节方案对三角洲和海岸系统产生了一定不利影响. 例如，河口悬移质泥沙粒径的增大和悬沙浓度的降低，导致三角洲输沙格局变迁，加剧了三角洲的不平衡，不仅影响河口和海岸生态系统，而且由于黄土地区产沙量因水土保持措施减少使得下游河道的侵蚀也随河床粗化而减少. 入黄泥沙量迅速减少也对下游河道和河口三角洲生态系统结构与功能产生严重影响，导致黄河三角洲盐水入侵加剧，海岸线持续后退，三角洲不断萎缩，河口区域生态安全受到威胁. 水沙调控、修筑生产堤、沿黄河取水量增加等不合理人为活动，导致黄河下游河道湿地不断萎缩、甚至大面积消亡[35].

黄河流域是中国最重要的煤炭生产地带，中国14个大型煤炭生产基地中有9个分布在黄河流域. 近年来，在煤炭开采与水资源、生态保护的关系研究与工程技术方面也取得很大进展，包括煤岩层结构及采动裂隙演化规律[36~40]、煤炭开采与水资源保护[41~43]、煤炭开采对水和生态环境影响[16,44~50]、以及煤炭规模化开采生态修复[51,52]. 特别是，针对黄河流域煤矿区已经建立了生态环境治理和修复示范工程. 在黄河流域中、上游地区，以青海天骏义海公司煤矿、大通煤矿为示范点，兴建了一批治理示范工程，提出了披碱草、冷地早熟禾、中华羊茅、老芒麦和星星草组合的植被快速恢复方法，研发了地表适度平整-覆盖拌有有机肥及保水剂的植生基材-种子播种-耙实铺平并覆盖无纺布-浇水灌溉养护的生态修复工艺[53]；在黄河下游，建立了引黄河泥沙充填复垦采煤沉陷地，挖深垫浅，以及利用当地表土、心土和黄河泥沙组配覆土材料等生态恢复技术[54]，并采用种植花生、大豆等豆科或禾本科植物、增施有机肥等措施来提升复垦土壤的质量[55]. 但是，煤炭开采将严重影响黄河流域的地表生态、加重水资源短缺，黄河流域煤炭开采的水沙调控和生态修复技术仍有待加强. 随气候变化和人类活动影响加剧，黄河流域水沙关系的复杂性和不确定性也在不断提高，仍然是黄河生态保护与高质量发展面临的主要挑战.

3 总结和讨论

黄河流域是中国重要的生态屏障和重要的经济区，黄河流域治理取得了巨大成效，但仍未能实现根本性扭转. 2019年9月18日，习近平总书记在“黄河流域生态保护和高质量发展座谈会”上指出，“黄河一直体弱多病，水患频繁，当前黄河流域仍存在一些突出困难和问题. 究其原因，既有先天不足的客观制约，也有后天失养的人为因素. 可以说，这些问题，表象在黄河，根子在流域”. 因此，黄河治理的关键在于既要考虑上游、中游和下游的流域特点，更要考虑各流域对黄河流

域作为一个整体的影响. 流域是一个由水、土、气、生等自然要素和人口、社会、经济等人文要素相互作用形成的“自然-社会-经济”复合系统, 是一个“山水田林湖草沙人”相互依存的生命共同体[56]. 黄河流域保护与治理要遵循流域复合生态系统的整体性、系统性及内在规律, 综合考虑生命共同体的各要素及其相互作用, 构建具有整体性、系统性、协同性的治理机制, 左右岸、干支流与上下游一体化治理, 兼顾上中下游利益、开发与保护的协调、以及不同行业和不同阶段的协调[57~59], 统筹考虑水的不同用途, 实现气候变暖背景下水资源在生态、工业/采矿、生活、农业与水沙调控等方面的科学分配, 促进人-水-自然和谐.

流域水生态承载力是指流域水资源能够确保流域生态系统健康和社会经济持续发展的能力[60,61], 既涉及流域内水资源利用的各个部分及其在水资源利用的时间、空间和方式(如自然降水、灌溉或人工影响天气等)方面的差异, 更涉及流域作为一个整体对水资源在各个部分以及水资源供给的时间、空间和方式方面的合理安排. 因此, 黄河流域治理既要考虑其整体性, 即上游、中游和下游及其相互作用组成的流域整体, 也要考虑黄河流域及其作为地球系统组成部分受各圈层相互作用在时间和空间上的连续变化, 即时空连通性, 进而实现黄河流域生态保护与高质量发展.

为此, 需要尽快开展以下三方面任务. 一是加快数字黄河信息平台研究. 黄河流域生态保护与高质量可持续发展的关键科学问题在于解决气候变化背景下水资源在生态用水、工业/采矿用水、生活用水、农业用水与水沙调控之间的科学分配. 实现流域水资源的科学分配, 不仅需要弄清流域上、中、下游以及各用水部分的空间分布及其亟需程度(整体性), 还需要弄清空间用水点、用水时间和用水量, 更需要考虑解决水资源供应的方式(如自然降水、灌溉或人工影响天气)(时空连通性). 这就需要以地球系统科学理论为指导, 发展黄河流域数字信息平台的理论和技术, 建立数字黄河信息平台, 及时准确地确定黄河的状况, 为从整体上和时空动态方面综合管理和开发黄河流域提供基础信息. 二是尽快启动黄河全流域水资源监测与空中云水资源开发利用工程建设. 黄河流域的核心问题是水沙问题. 目前, 人工影响天气技术已经较为成熟, 全国县级以上的区域都已经广泛开展人工增雨雪等气象服务. 建议尽快启动黄河全流域水资源监测与空中云水资源开发利用工程建设, 充分利用人工影响天气等先进技术, 合理开发利用空中云水资源, 促进黄河全流域的水资源有效利用. 三是启动生态黄河重大灾害风险识别与预测专项. 现有黄河流域的灾害风险识别与预测大都是零散的, 主要是服务于地方的生态监测与农业生产, 还没有从整个黄河流域生态保护与高质量发展角度考虑灾害风险. 为此, 建议综合已有生态工程与研究成果, 整合天-空-地立体观测、大数据与机器学习、人工智能、5G融合与物联网等技术方法, 研究建立黄河流域重大灾害前兆信息智能感知与识别、灾害情景模拟与风险预测以及灾害风险防控技术体系, 提升黄河生态保护与高质量可持续发展的风险识别与管理能力.

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Summary for “黄河水生态承载力的流域整体性和时空连通性”

Basin integrity and temporal-spatial connectivity of the water ecological carrying capacity of the Yellow River

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The Yellow River Basin is an important ecological barrier and economic zone in China, and both its ecological conservation and sustainable high-quality development are directly related to the success or failure of the ecological civilization construction of China. Currently, the Yellow River Basin, which is short on water resources, has a fragile natural ecology, and lags in economic and social development, is a key and difficult area for the ecological security and economic and social development of China. This paper summarizes the remarkable achievements in comprehensive prevention and control of soil erosion, such as the implementation of a series of major ecological projects, in the Yellow River Basin since the founding of New China, especially in recent years. These major ecological projects were implemented based on the different characteristics of the upstream, midstream, and downstream regions of the Yellow River Basin. However, the ecological function of the Yellow River Basin has not been fundamentally resolved. This is due to three main reasons. The first is the extent and spatial imbalance in the control of water and soil erosion in the Yellow River Basin watershed. Ecosystem quality has degraded and water conservation has declined in the upper reaches of the Yellow River, soil erosion is serious in the middle reaches, and the ecological flow is low and some estuary wetlands have shrunk in the lower reaches. The second reason is the adverse effect of water and sediment regulation on delta and coastal systems. Vegetation coverage has declined at the source of the Yellow River; there is the desertification of grasslands and the area of secondary bare lands has increased. Some degraded black-soil beaches have undergone secondary degradation and associated disasters have also increased. The third reason includes water and sediment problems caused by large-scale coal mining, such as serious changes in topography and landforms. There is the acceleration of land desertification and water shortages, where the original landforms are destroyed and some vegetation disappears in the upper reaches; the ground collapses and serious soil erosion causes increased sediments to flow into the Yellow River in the middle reaches. Surface subsidence deformation, water accumulation, and secondary salinization lead to a decrease in land productivity in the lower reaches. It is proposed that the key to solving the current outstanding problems restricting ecological protection and high-quality sustainable development of the Yellow River Basin lies in the integrity of the water ecology of the basin, spatial-temporal connectivity and ecosystem health to realize the scientific allocation of water resources in ecology, industry/mining, life, agriculture, and water and sediment regulation in the context of climate warming. To realize this scientific objective, three tasks of research are urgently needed. First, the clarification of the theory and technology of the digital Yellow River information platform, and timely and accurate determination of the river’s status are critical to understand and scientifically develop and manage the Yellow River Basin. Second, water resource monitoring and cloud water resource development and utilization across the entire Yellow River Basin must be carried out, which will require full use of advanced technologies, such as artificial weather modification, rational development and utilization of cloud water resources, the construction of water resource monitoring and cloud water resource development and utilization as soon as possible, and promotion of the effective use of water resources. Finally, identification and prediction of major ecological disaster risks are essential, which requires the integration of space-air-ground stereo observation; big data and machine learning; fusion of 5G, artificial intelligence, the Internet of Things, and other technical methods to establish the intelligent perception and identification of precursors for major disasters; disaster scenario simulation and risk prediction; and disaster risk prevention and control technology systems to enhance risk identification and management capabilities in ecological protection and high-quality sustainable development.

Yellow River Basin, water ecological carrying capacity, basin integrity, temporal-spatial connectivity, ecosystem health

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