

DOI: 10.14042/j.cnki.32.1309.2020.05.015

水电工程水生态环境效应评价方法与调控措施

陈求稳^{1,2}, 张建云^{1,2}, 莫康乐³, 陈宇琛³, 关铁生¹, 王国庆¹, 林育青^{2,3}

(1. 南京水利科学研究院水文水资源与水利工程科学国家重点实验室, 江苏 南京 210029;

2. 长江保护与绿色发展研究院, 江苏 南京 210098;

3. 南京水利科学研究院生态环境研究所, 江苏 南京 210029)

摘要: 围绕水电工程的水生态环境问题, 重点梳理了水库运行下关键生源要素生物地球化学循环的变化及其水生态效应、底栖动物生境和鱼类生境以及鱼类洄游通道的影响、水生态环境保护工程与非工程措施等方面的研究进展, 剖析了当前科学研究和工程应用中存在的难题, 从理论、方法与技术角度阐明了出现这些难题的原因。提出了水电开发水生态环境保护未来需要重点开展的研究: 长期系统性观测, 揭示库内生源要素的滞留-转化-输送过程与机制及水生态环境累积效应; 水库调控导致的鱼类性腺发育有效积温 and 产卵临界水温节律变化以及两者对鱼类种群繁衍的联合作用。最后特别指出当前针对鱼类保护的部分强制性措施存在的问题, 并提出了高坝多环境因子调控的生态调度和支流生境替代等鱼类保护技术以及保护效果量化评价新方法。

关键词: 水电开发; 水生态环境效应; 模拟评价; 对策措施

中图分类号: TV61; X171.1 **文献标志码:** A **文章编号:** 1001-6791(2020)05-0793-18

水电开发是保障能源安全、优化能源结构甚至支持欠发达地区社会发展的重要措施。但是, 水库运行改变了河流的水文过程, 从而影响河流中生源要素的生物地球化学行为及相应的物质场、能量场、化学场和生物场, 最终改变河流生态系统的物种构成、栖息地分布以及相应的生态功能。因此, 水电工程生态环境效应已成为水电可持续开发利用的瓶颈, 也是国际水科学长期的研究热点。

Harman 和 Stewardson^[1]、Chen 和 Olden^[2]研究了水电站运行对河流自然水文过程的改变, 发展了生态水文学; Schmitt 等^[3]研究了建坝对河流泥沙与河貌形态的影响, 发展了生态河貌学。针对水体的理化特性, 研究了水库运行对关键生源要素生物地球化学行为的作用, 揭示了碳、氮、磷、硅的滞留^[4-5]和库内营养盐结构变化、藻类水华及温室气体释放的机制^[6-8]。Orr 等^[9]和 Moran 等^[10]研究了水电运行对河流生物群落的影响, 发现浮游生物显著性增加, 无脊椎动物的分布和密度显著减少^[11]。在水电开发对鱼类影响方面, 重点研究了洄游性鱼类、珍稀鱼类和重要经济鱼类的保护^[12-15], 研制了鱼类电子传感器与跟踪装备、基于个体的鱼类行为模型、气体过饱和控制、生态鱼道设计等, 建立了生态水力学。Grumbine 和 Xu^[16]揭示了水库蓄水对滞落区的影响及库区土壤盐碱化和沼泽化过程, Ngor^[17]研究了水电开发对流域生态系统的影响, 指出水电开发可能导致下游洪泛区湿地减少、生物多样性降低、生态服务功能退化、鱼类生物量显著下降。在水电开发水生态环境保护方面, 重点研究了鱼类洄游通道^[12], 建立了生态鱼道、升鱼机、集鱼放流等技术; 研究了一序列的生态流量确定方法^[14,18-19], 提出了最小生态流量、适宜生态流量、生态流量过程等^[2,20-21], 建立了面向水温需求的分层取水技术^[22]、面向下游生态流量保障^[23-24]的生态调度技术; 针对部分鱼类, 研

收稿日期: 2020-04-15; 网络出版日期: 2020-06-12

网络出版地址: <https://kns.cnki.net/kcms/detail/32.1309.P.20200611.1728.012.html>

基金项目: 国家重点研发计划资助项目(2016YFC0502205); 国家自然科学基金资助项目(91547206)

作者简介: 陈求稳(1974—), 男, 湖北黄梅人, 研究员, 主要从事生态水力学和水环境信息学方面研究。

E-mail: qwchen@nhri.cn

通信作者: 张建云, 中国工程院院士。E-mail: jyzhang@nhri.cn

究了增殖放流、替代生境构造等生态补偿措施^[10,13]。国内结合三峡、小浪底、二滩、小湾、糯扎渡等特大型水利水电工程,研究了径流情势变化及其水生态效应^[25],中华鲟、裂腹鱼、圆口铜鱼等珍稀鱼类的增殖放流技术^[26];针对长江“四大家鱼”和中华鲟保护,开展了生态调度研究并进行了工程应用^[26-27],研究了库区消落带生源要素转化以及生态修复与开发利用技术^[28],库湾富营养化与水动力的关系等^[29]。在重大水电工程建设的推动下,中国提出并发展了生态水工学^[30],深化了生态水力学^[31-32]。虽然围绕水电开发生态环境效应与保护问题已经开展了大量且深入的研究,但是随着水电开发进一步向河流上游尤其是生态脆弱区发展,新的挑战不断出现;已建水电工程随着运行时间的增长,生态环境累积效应和前期未知生态环境问题逐步凸显;众多生态环境调控措施经过工程实践的检验,未能达到预期效果而急需重新研究评价。同时,由于观测技术的提升和相关学科理论方法的发展与交叉,一些新的现象被逐步发现,新的机制被逐步揭示。

本文针对水电工程的水生态环境问题,重点阐述水库运行对碳、氮、磷形态转化与输送通量、鱼类物理生境关键因子、鱼类洄游通道等影响的定量评价方法的研究进展,分析生态环境保护的工程与非工程措施存在的难题及其内在原因,从而提出未来需要重点突破的研究难点。

1 水电工程对关键生源要素循环影响

水电开发对关键生源要素碳、氮、磷、硅的影响最为直接显著。其中对碳、氮的关注重点是水库温室气体的排放,对磷、硅的关注重点是水库的拦截,重点对象包括库内水体、沉积物和消落带,如图1。

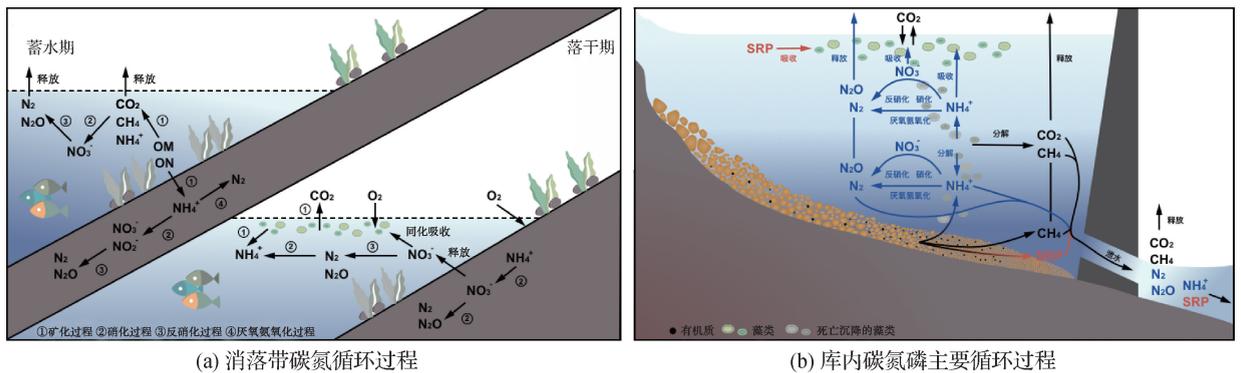


图1 水库运行影响下消落带和库内关键生源要素生物地球化学循环过程

Fig. 1 Biogeochemical cycle of key biogenic elements in water fluctuation zones and reservoirs under reservoir operations

水库建设改变了河流自然水文情势,水力停留时间增大,库内初级生产力上升,有机质在库内沉积,造成 CH₄ 和 N₂O 的释放,主要包括扩散和气泡两种排放方式,由于 CH₄ 和 N₂O 具有更强的温室效应,因此一种观点认为水库显著增加了温室效应潜力,从而引发对于水电清洁性的争议^[33]。水库温室气体的监测方法主要包括薄边界层法、静态箱法等,赵炎等^[34]系统阐述了静态箱法、梯度法、倒置漏斗法、涡度相关法等监测方法,比较了各自的优缺点及适用范围。由于中国水库在蓄水之前普遍采取严格的清库措施,水库温室气体群体的排放通量普遍低于世界平均水平^[7]。Shi 等^[8,35]在澜沧江梯级水库的研究发现,澜沧江梯级水库温室气体排放通量远远低于世界平均水平,并随着库龄的增长呈现快速降低的趋势。水库建设形成大量新的洲滩和水库消落带,受发电影响,库水位频繁波动,导致洲滩和消落带周期性淹没-落干,增强了水体与洲滩和消落带之间的水热及物质交换^[36]。Yu 等^[28]研究发现在水位反季节调控的三峡水库,消落带在落干向淹没转变过程中,发生 N₂O 从汇向源的转换,而且存在较高的初期释放峰值。Shi 等^[8]在澜沧江洲滩的研究发现,发电导致库水位频繁波动强化了水库反硝化脱氮。目前,针对水库温室气体及水电清洁性的综合评价可采取水库全生命周期碳足迹的方法^[37],但是,该方法的评价结果存在较大的不确定性。

水库对溶解性硅酸盐的拦截主要是由于水力停留时间延长,促进库内藻类繁殖,硅藻由于密度相对较大,容易下沉而滞留在库内,从而阻止硅酸盐向下游的输送。崔彦萍等^[38]分析发现三峡水库蓄水后对长江河口 SiO_3^{2-} -Si 浓度产生影响,导致 SiO_3^{2-} -Si/DIN、 SiO_3^{2-} -Si/ PO_4^{3-} -P 比值降低。Wang 等^[39]进一步分析了 SiO_3^{2-} -Si 浓度以及营养盐结构变化对长江口浮游植物群落的影响,发现虽然硅藻依然是河口的优势种类,但是其占比显著下降。Chen 等^[6]在澜沧江梯级水库的研究中也发现类似的现象,上游梯级,尤其高坝大库,导致下游硅酸盐显著降低,受温度梯度和营养盐结构的共同影响,上游水库以硅藻为优势种,逐步过渡到下游水库以绿藻和蓝绿藻为优势种。但是,该研究指出由于沿程的补给,硅酸盐浓度呈现逐步回升的趋势。

水电大坝对磷的影响一直是水电工程生态环境效应关注的焦点,通常的方法主要包括:基于磷的物料平衡模型进行估算^[4,7],基于水库对泥沙及其携带的颗粒态磷的拦截进行估算。Maavara 等^[4]认为,水库大量拦截了总磷和溶解态磷,且拦截比例随着水库水力停留时间呈指数增长,最高达到 80% 以上,从而对全球磷的循环产生影响。Stone^[40]和 Schmitt 等^[3]针对湄公河水电开发的研究认为,由于水库对泥沙的拦截,可能导致 40% 的磷被拦截在库内^[40]。但是,Chen 等^[6]认为这些研究首先缺乏足够的长序列观测数据的支撑,其次聚焦于水库对泥沙中结合态磷的拦截,忽略了水库内发生的磷生物地球化学转化过程以及与之相应的生物有效磷的释放与输送;他们通过对澜沧江梯级水库的研究结果发现,澜沧江梯级水电可能并不会导致下游河道生物可利用磷降低,提出了高坝深库对磷生物地球化学转化及输送的影响机制概念模型。研究结果冲击了长期以来有关建坝对河流生源要素影响的传统认知,并指明水电开发生态环境影响长期系统性监测的重要性。

水库建设后,由于水文水动力条件的变化以及水力停留时间的显著增加,在库湾水域容易发生水华现象,尤其是在出现水温分层的高坝大库局部水域。Liu 等^[29]探索了三峡水库分层异重流形成机制,分析了不同分层异重流情势下库湾微流场特征,构建了入库支流河口区域临界层、光补偿层和混合层 3 层结构与藻类水华的关系模型,发现库湾底层倒灌异重流和中层倒灌异重流导致的水温特殊分层及营养盐输移补给是香溪河库湾浮游植物群落演替和水华暴发的关键诱因。该研究表明库内微流场精细观测和分析对于揭示水库物质循环及其水生态环境效应的重要性。

2 水电工程对河流水温情势影响

伴随着水电工程建设带来的水文情势改变,河流水体温度在空间分布和时间节律上均受到不同程度的影响。水温是水体重要的物理特征指标之一,其变化直接影响河水物理、化学、生物等一系列过程,包括物质溶解、初级生产力、鱼类栖息地等^[41-42]。水库建设改变了河流水面宽度、水深、水力停留时间等,对水温最直观的影响表现在库区水温分层和坝下沿程河道水温节律变化^[43]。高频次的水温原位观测研究可以揭示水库水温分层变化的全过程,Liu 等^[44]发现水库水温分层循环可以分为 3 个阶段:形成期、稳定期、减弱期。研究发现水温分层现象呈现出水深越大,分层现象越显著^[43]。由于水库水温的分层,水库表层和底层水体的下泄直接影响下游河道的水温节律。一般情况下,河流表层水体和与之接触的空气层的热交换决定了水体温度,其受到气温、辐射、风速等环境因子影响较大,然而大坝泄水改变了这一情况,水库底层水的下泄显著影响了下游河流水温^[45],下泄水温成为了控制下游河道水温的主要因素^[46],通常表现为下游河道水温夏季比自然情况偏低,冬季比自然情况偏高,如图 2(a)。

河流水温自然节律的改变,直接影响了整个河流水生态系统,大部分生物对环境温度具有感知适应性,水温节律的变化对群落结构和组成造成影响^[47-48]。Lugg 和 Copeland^[49]综述了水温在整个鱼类生活史中的影响,表明温度改变会引发鱼类的心率、呼吸率、代谢率、产卵率、孵化率等产生不同程度的响应。鱼类在长期适应气候条件后,其繁殖遵循季节交替规律,当水温变化节律被扰乱时,鱼类产卵将受到外在环境压力的影响^[50]。例如,卵母发育过程的延迟^[51]、卵子产量的降低^[47]、有效繁殖率和生存率降低^[22,52]等各种不利于鱼类繁衍的情景,在水温节律改变的情况下均会发生。物种繁殖有具体的热量需求^[53],描述鱼类发育、

产卵和生长受温度变化的影响^[52,54-55]主要通过触发产卵的临界温度和性腺发育过程的积温阈值作为主要指标。开始产卵的临界水温与产卵季节、鱼类种类、栖息地、地理因素有关^[56]。例如,长江中华鲟开始产卵的临界水温值在 18 °C 以下^[22], Clanwilliam 大坝下游黄鱼产卵的临界水温值在 19 °C 以上^[57], 比斯开湾的凤尾鱼产卵临界水温值在 14 °C 以上^[58-59]。然而, 仅依赖触发产卵的临界水温不足以完整描述水温对鱼类繁殖的影响, 因为产卵前期性腺发育成熟是一个较长的时间过程, 而以性腺发育积温阈值表征的是长期度量指标^[60], 可以更好地描述水温对鱼类繁殖的影响。例如在发育起点温度为 15 °C 和 18 °C 时, 欧洲鳗鱼发育至性成熟的积温阈值为 900 °C · d 和 1 300 °C · d^[61]。此外, 由于鱼类对外界环境压力的适应性和可塑性^[62-63], 鱼类繁殖积温和产卵临界水温具有一定的耐受范围^[55]。性腺发育积温阈值和产卵临界水温阈值到达的时间共同决定了鱼类的繁殖效率, 如图 2(b)、图 2(c)。

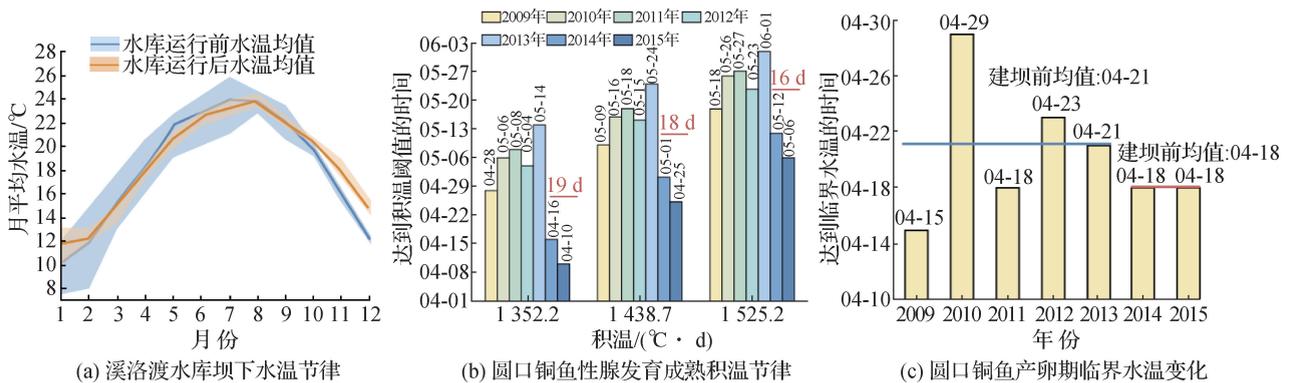


图2 金沙江溪洛渡水库运行影响下坝下水温节律和圆口铜鱼性腺发育积温节律以及产卵期临界水温变化

Fig.2 Changes of water temperature regime and effective accumulated temperature regime for *Coreius guichenoti* gonadal development and critical temperature for *Coreius guichenoti* spawning under the operation of Xiluodu Reservoir in the Jinsha River

从水库不同热分层下泄水体是调节下游河道水温的有效方式^[45-46], 通过有效的调度方案可以实现基于水温的河道生态保护^[64]。但是, 对于存在梯级水库的河流, 水库对河流水温的影响还存在沿程累积效应^[65-66], 在确定梯级水库调度规则时, 需要对其进行系统性模拟分析。

3 水电工程泄水溶解性气体过饱和及其生态影响

高坝泄水导致水体总溶解气体 (Total Dissolved Gas, TDG) 过饱和, 在下游河道中由于气体不能快速释放, 可能对水生生物尤其是鱼类造成损伤, 导致鱼类患“气泡病”, 甚至死亡^[67]。关于大坝泄水 TDG 过饱和问题的研究可以概括为 3 个方面: 泄水近区 TDG 过饱和的发生过程、过饱和 TDG 在下游河道的释放过程、过饱和和气体对鱼类的生态危害。

TDG 过饱和的发生主要受气泡承压的影响, 同时水流紊动强度、气泡滞留时间、水温、掺气浓度及含沙量等也对过饱和 TDG 的生成产生影响, 但是含沙量^[68]影响极小。关于过饱和 TDG 生成过程的研究手段包括原型观测、机理实验、模型实验和数学模型等。Heddam^[69]基于 Columbia 河 Dalles 坝和 John Day 坝上、下游 TDG 饱和度原型监测的数据, 采用广义回归神经网络方法, 建立了大坝泄水上下游饱和度差值预测模型。Li 等^[70]通过在雅砻江、岷江、澜沧江和长江上的 4 座水电站开展过饱和 TDG 原型观测, 分析了其生成影响因素, 并基于一阶传质动力学建立了过饱和 TDG 生成预测机理模型。由于原型观测大多局限于特定坝型或者水动力条件, 建立的预测模型在使用过程中存在局限性。在过饱和 TDG 生成规律机理实验研究方面, DEMoyer 等^[71]通过建立 9.6 m 高水池, 分别探讨了气泡和水面在传质过程中的重要性; Lu 等^[67]利用高压装

置研究了气泡滞留时间与 TDG 饱和度的关系, 建立了基于滞留时间的 TDG 饱和度预测模型。物理模型实验方面, Bagatur 和 Onen^[72]开展了射流传质过程实验, 由于缩尺物理模型未考虑雷诺数和韦伯数, 质量传递过程和气泡尺寸、气泡分布等无法实现模型与原型相似^[73], 较难模拟出原型中的 TDG 浓度分布场, 所以采用物理模型研究过饱和 TDG 生成过程具有局限性。多维、多相流的紊流数学模型已成为研究 TDG 生成过程的重要方法之一。Wang 等^[74]建立了基于流体体积法 (Volume of Fluid, VOF) 的两相流过饱和 TDG 生成模型, 气泡尺寸由气泡数密度函数计算, 并采用考虑了气泡传质过程的输运方程, 模型预测了不同调度方式下 McNary 坝消力池内的 TDG 饱和度分布。目前, 水气两相流模型由于气泡传质机理和气泡尺寸分布等方面的系统性研究较少、消力池流场模拟精度不高等问题限制了模型的应用。

坝下河道 TDG 的释放主要受水深、水温、风速、紊动强度、含沙量和河流形态等的影响。研究发现水深的增大减缓了过饱和 TDG 的释放速率^[75], 在梯级高坝体系中, 上游高坝泄水产生的 TDG 过饱和水体进入到下游深水库区, 可能扩大其生态影响, 如 2014 年发生的溪洛渡泄水造成下游向家坝库区死鱼案例。实验表明, 过饱和 TDG 耗散系数与水温成正比^[76]。过饱和 TDG 在坝下河道中的传质过程主要发生在气液交界面, 风对传质过程具有促进作用, 使过饱和 TDG 加速释放^[77]。研究表明, 水体紊动强度的增加, 加速了过饱和 TDG 的释放^[78]。过饱和 TDG 释放的另一个途径是游离气体分子聚集成核, 形成气泡析出。含沙量的增加, 为游离气体分子聚集成核提供了大量的介质, 使过饱和状态更快降低至平衡态^[79]。复杂的河流形态可造成复杂的流态, 提高了局部的紊动强度, 促进过饱和 TDG 的释放^[80]。为预测过饱和 TDG 在坝下河道中的释放过程, 目前主要采用的手段有原型观测、模型实验和数学模型等。Feng 等^[81]根据金沙江、雅砻江、岷江等河道 TDG 饱和度原型观测结果和明渠水槽实验结果, 建立了基于摩阻流速和弗劳德数等水动力因子与 TDG 释放过程的定量关系; Kamal 等^[75]对比了 Columbia 河和 Kootenay 河的释放过程, 结果表明河道水深与流速的比值越大, TDG 释放越慢。在模型实验方面, Ou 等^[76]研究了水温对过饱和 TDG 释放过程的影响, 提出了温度修正系数; Huang 等^[77]开展了风速对过饱和 TDG 释放的影响, 建立了过饱和 TDG 释放过程与风速的定量关系。但是对于天然河道, TDG 释放影响因素较多, 模型试验结果的应用效果有待进一步验证。在数学模型方面, 国内外重点研究了溶解氧或二氧化碳在水气界面的传质理论及其系数确定, 研究成果多属于由欠饱和态向饱和平衡态转变过程, 并不适合 TDG 由过饱和态向饱和平衡态转变过程。过饱和 TDG 释放过程计算流体动力学模型主要分为单相流模型和多相流模型。在单相流模型方面, TDG 输运方程中源项的计算主要采用传质系数经验方程。Johnson 等^[82]采用二维水动力水质模型 MASS2 模拟了 Bonneville 和 Ice Harbor 坝下河道内 TDG 分布规律, 其中输运方程中 TDG 源项的传质系数采用 O'Connor^[83]提出的与风速相关的方程。Shen 等^[84]采用三维紊流模型模拟研究了支流与干流交汇处 TDG 的分布, 其中自由界面传质系数采用与涡黏系数和平均水深相关的方程。多相流模型能对 TDG 模型进行改进, 可以很好模拟自由液面的变化、气泡运动过程、水气界面传质过程等。Fu 等^[85]采用非恒定流条件下三维两相流过饱和 TDG 预测模型, 模拟葛洲坝下游 3.1 km 范围内的过饱和 TDG 输运释放过程, 其中水气交界面传质系数的计算采用溶解氧复氧系数方程。Politano 等^[86]采用两相流模型模拟了 Wells 坝下游 5 km 范围内的 TDG 输运过程, 其中传质方程为气泡大小和气体体积分数的函数。三维水气两相流模型具有很多优点, 但是比较适用于局部精细化模拟, 当计算区域范围较大时, 模型计算速度及收敛性有待解决。

针对 TDG 过饱和对鱼类的危害, 重点研究了鱼类气泡病及其症状^[87-88]、气泡病的致病因素^[89-90]、鱼类对过饱和 TDG 的耐受性^[91], 从而评价高坝泄水过饱和 TDG 的生态风险^[92], 如图 3(a)。这方面更多的涉及鱼类生理等相关内容, 本文不做详细陈述。值得特别一提的是水深的增加可减弱 TDG 过饱和对鱼类的影响, 这对采取补偿水深降低甚至规避大坝泄水产生的过饱和 TDG 对鱼类的危害具有较强的指导意义。梯级开发后形成水库之间首尾相连的格局, 上一梯级泄水产生的过饱和 TDG 在下一梯级释放缓慢(如图 3(b)), 导致影响持续至大坝下游数十甚至数百公里^[92], 因此需要特别关注过饱和 TDG 在下游水体中的释放过程及规律研究, 尤其是初始饱和度的精确确定和沿程饱和度变化的准确预测。不过, 由于梯级水库之间的水域水深较大, 为鱼类进行深度补偿提供了有利条件, 如图 3(c)。但是, 最后一级水库的下游主河槽泄水期流速较大,

喜好静水的鱼类往往栖息于流速较小的滩地或近岸浅水区,不利于鱼类进行深度补偿,需要对最后一级电站坝下近区的 TDG 过饱和度提出比中间梯级电站更严格的限制标准。因此,需要精确测定近区 TDG 初始含量,深入研究 TDG 过饱和的发生过程及其机制,从而为防控近区 TDG 过饱和提供依据。

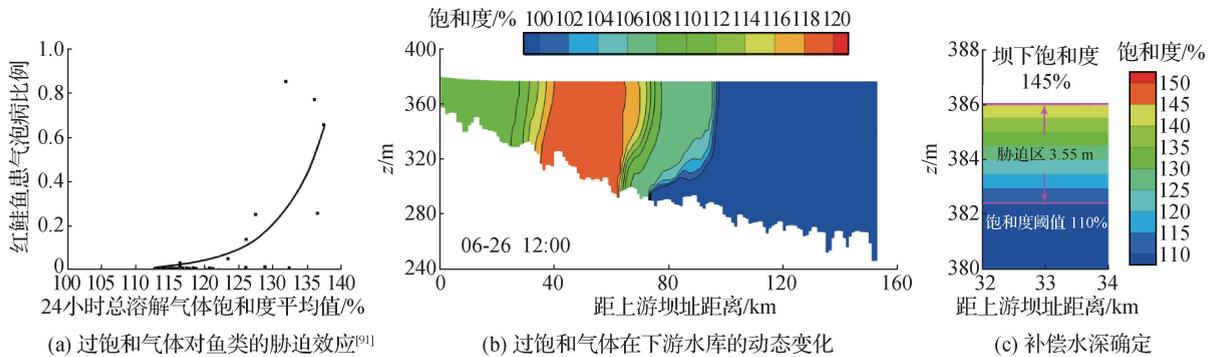


图3 过饱和气体对鱼类的胁迫效应和在下游水库的动态变化以及补偿水深确定

Fig. 3 Stress effect of TDG on fish and the dynamic of TDG in the downstream reservoir and the determination of compensation water depth

4 水电工程对河流底栖动物群落结构及分布的影响

梯级水库建设阻隔了河流的连通性,且库与库之间受下级水库的顶托作用改变了河流的自然形态,形成了坝前湖相、库尾河相相互交替的格局^[93-94]。河湖分相使得天然河道的水流形态发生了变化,天然的河相长度缩减,坝前形成了水深流缓的湖库,河湖相生境差异导致底栖动物群落组成、结构及空间分布在水库干支流河段形成显著差异^[95-96],如金沙江梯级蓄水后干支流底栖动物群落出现显著分异(图4)。

大型底栖动物的生长繁殖主要受水文水动力、水环境和自然地理等因子的影响。水文水动力因子包括水深、流速、水温等;水环境因子主要包括营养盐、溶解氧、pH值、重金属、悬浮物等;自然地理因子包括河床底质、河岸地貌、纬度、海拔等^[97]。水深变化往往伴随着水温、溶解氧等在垂向上发生分层现象,直接或间接对底栖动物群落结构、密度、生物量产生影响,研究表明水深与生物多样性、生物量等均呈现负相关关系^[98-99]。Nelson和Lieberman^[100]发现流速是影响底栖动物群落结构变化的主要变量,由于流速快慢会影响水体中溶解氧的含量,因此静水或缓流区适宜对氧气需求较低的底栖动物生存,而急流区较适宜好氧型底栖动物的生存^[101-102]。温度对生物的新陈代谢起着重要作用,底栖动物的生长和发育均会随着温度的升降变化^[103]。研究发现,当水体温度过高或过低时都会对底栖动物的生长发育产生抑制作用,温度通过影响喜温和喜冷生物的生存进而对底栖动物群落结构产生作用^[104]。

不同的底栖动物物种对水体溶解氧含量要求不同,其中清洁型种类(如毛翅目等)对溶解氧的要求较高,而耐污型种类(如颤蚓类、摇蚊幼虫等)能够适应极低的溶解氧环境^[105-106]。水体中的氮、磷等营养盐的含量也会直接影响底栖动物的群落结构,研究表明水体中营养盐浓度的过低或过高,都会使底栖动物群落结构简单化,前者会使生产者的生产力下降,而后者可能导致水体溶解氧降低从而引起物种多样性降低^[107-109]。在水库中,重金属离子多沉积于底泥,由于不同底栖动物对重金属的耐受性不同,底泥中重金属的富集也会改变底栖动物群落结构组成^[110-111]。

此外,河流底质的结构、粒径大小、稳定性和有机质含量等差异均会导致底栖动物群落结构的不同^[112-113]。研究表明,不同类群的底栖动物会选择不同的河流底质类型进行栖息,如寡毛纲和摇蚊幼虫比较喜欢生活在黏土和淤泥底质中,软体动物门喜欢生活在卵砾石底质中^[114]。海拔属于宏观尺度自然地理因

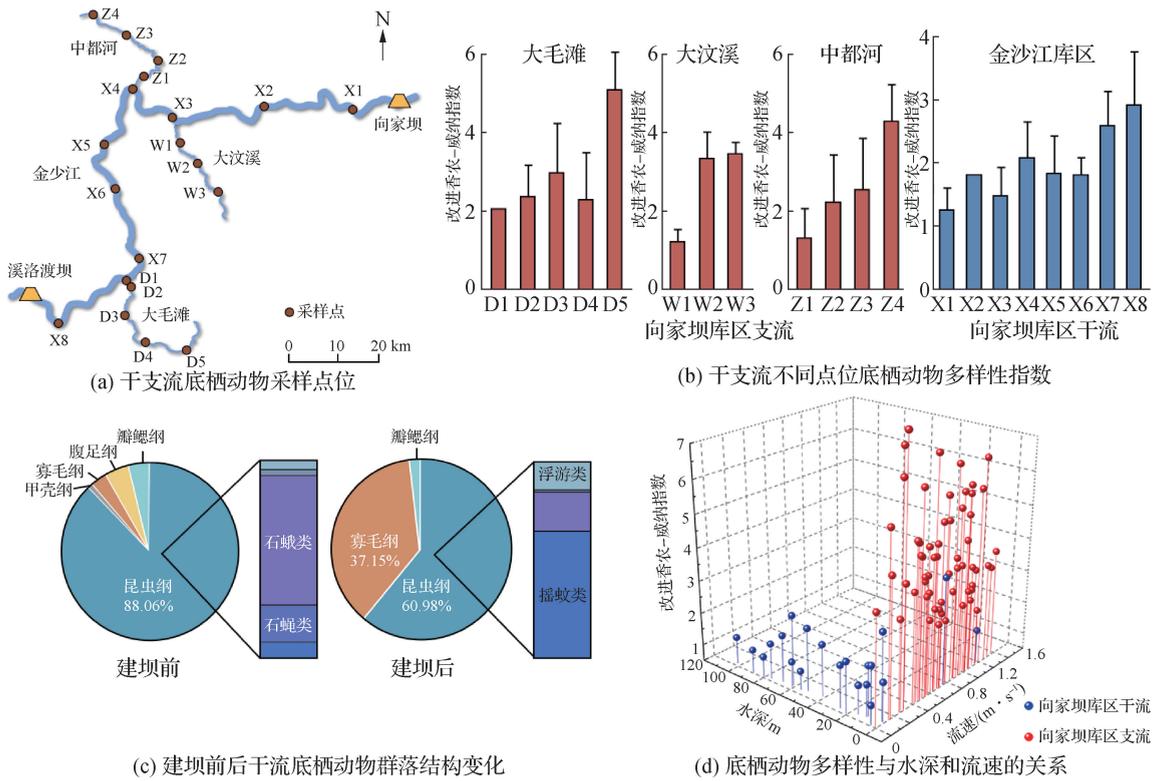


图4 金沙江溪洛渡和向家坝梯级间干支流底栖动物群落结构特征

Fig. 4 The community composition of zoobenthos in the mainstream and tributaries between Xiluodu and Xiangjiaba cascade reservoirs in Jinsha River

子, 海拔的差异可能引起水文水动力、水质条件等其他因素的改变。例如, 河流的流向均是由高向低, 因此在海拔跨度较大的山区型河流中, 海拔对底栖动物群落的影响较为显著^[115-117]。

水库建设, 尤其是梯级水库建设, 对河流水文水动力和水环境均产生较大的影响, 使得水系大型底栖动物生物多样性呈现出明显的空间差异性。水库建设使得底质环境差异减小, 例如金沙江下游原本是长江干流宜昌站泥沙的主要来源, 梯级水库的建设具有为三峡水库拦沙的作用^[118], 导致三峡库内底质均质化严重, 以淤泥为主, 致使库内底栖动物物种多样性显著下降, 且均匀性显著增加。金沙江支流为典型山区河流, 河道底质类型丰富, 包括卵石、粗沙、细沙、淤泥等, 且水流流态相较于干流更为丰富, 从而致使物种多样性大, 均匀性小^[119]。与建坝前相比, 库区干流的底栖动物在建坝后群落结构变化最为显著, 一般表现为物种种类减少, 主要以耐低氧、对环境变化适应能力强的摇蚊类为主, 而在建坝前主要以喜急流、富氧的石蛾类为主。主要原因是水库蓄水所引起的生境条件急剧改变^[120], 水深增加, 流速减缓, 库区干流形成缓流静水河段, 改变了建坝前山区型河流的流场多样性(激流、缓流、河湾、深潭), 生境多样性的丧失使底栖动物的生物多样性也相应减小, 并使适应静水生存的底栖动物物种逐渐替代适应急流生存的物种^[121]。

5 水电工程建设运行对鱼类的影响及保护措施

河流建坝对鱼类的影响是水电工程生态环境效应研究最为关注和最为深入的方面, 主要包括鱼类洄游通道阻隔及过鱼技术、鱼类繁殖与增殖放流、鱼类栖息地(产卵场、越冬场、索饵场)保护与替代生境、生态流量过程与生态调度等。

虽然欧美和日本的一些过鱼设施, 尤其是低水头过鱼设施, 表现出很好的效果, 但是中国目前的报道显

示绝大部分大坝的过鱼设施效果不佳。Shi 等^[122]系统分析了中国大坝过鱼设施的现状,指出了存在的3个主要问题:①缺乏督促业主接受并执行过鱼设施规划、设计和效果评价的流程;②缺乏对洄游性鱼类生命史中运动、行为和游泳能力的充分认知;③鱼类生物学家未能和水利工程专家深度融合以形成一个有效的过鱼设施工作组。该研究最后提出了包括教育、管理、标准规范等在内的一序列建议以及集运鱼、鱼梯、船闸过鱼等针对高坝的新型过鱼方式。

大型河流的开发通常以梯级的方式展开,形成特殊的河湖分相格局。李婷等^[123]调查研究了金沙江溪洛渡至向家坝河段水电梯级开发下鱼类种群分布及生态类型变化,发现梯级水库建设后溪洛渡至向家坝鱼类的种类数,尤其是土著鱼类减少,而产漂流性卵的四大家鱼等大型鱼类的种类数占比呈增长趋势;梯级之间河相段和湖相段鱼类的生态类型差异较大,土著鱼类如铜鱼和裂腹鱼集中在河相段,放流的四大家鱼集中在湖相段和过渡段,如图5。王沛芳等^[124]提出了基于河流自然生境和原生生态及物种保护的生态水头的概念,建议河流梯级水电开发水头与生态水头协同的原则。梯级水库建设形成河相湖相分区,鱼类生境破碎化,若梯级之间留出足够的河相段,即一定的生态水头,可形成河相段产卵、过渡区与库中育肥的生境格局,可为土著鱼类等提供虽然狭小但能赖以生存繁衍的空间。

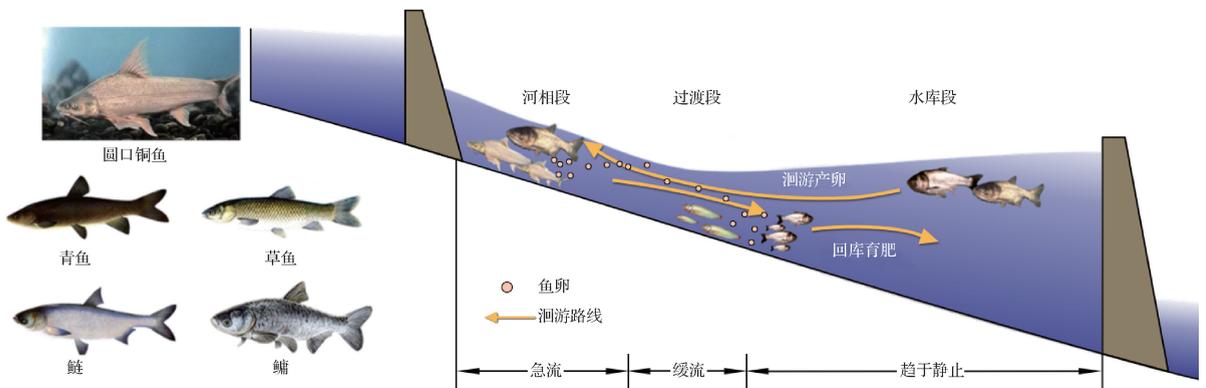


图5 金沙江溪洛渡和向家坝梯级间鱼类生境河湖分相及鱼类增殖放流的影响

Fig.5 Riverine zone and lacustrine zone of fish habitat between Xiluodu and Xiangjiaba cascade reservoirs in the Jinsha River, the effect of fish breeding and releasing

针对鱼类栖息地保护和生态流量需求及生态调度,陈求稳进行了系统性的阐述^[31],包括鱼类生态水力学物理模型实验理论与方法以确定鱼类对关键水动力指标的喜好^[125],鱼类栖息地评价模型以及景观生态学理论方法的引入^[126],基于个体模式的鱼类行为与栖息地趋好模拟^[125],生态流量推求方法,如水文学法、水力学法、栖息地法和综合法,尤其是生态流量过程概念和方法的提出^[127-128],梯级水库/水库群“水文情势最小干扰度约束”^[129]和“坝下生态流量过程约束”^[130]两种生态调度模式以保障目标鱼类繁殖的生态流量需求。生态调度在执行过程中一个难点是可能影响发电效益,春夏之交的枯水期,既是生态流量关键需求时期,也是电价高值期;而在丰水期,生态流量一般均能够满足,此时水库因防洪调度需要以及上网电价偏低,产生大量弃水。因此,提高中长期水文预报能力,有效分析来水的不确定性,实现不确定性条件下的日尺度生态调度,对于同时保障生态流量和发电效益至关重要,成为需要重点研究的难题,这一问题在梯级水库系统中更为复杂^[131]。更多的研究表明生态调度不仅是水量问题,还需要考虑水温的问题,也就是同时满足下游鱼类繁殖的水文和水温过程的生态调度。水库叠梁门和控制幕等分层取水是实现水温调度的重要方式^[132-133],但是工程实践显示,叠梁门分层取水工程投入很大,操作复杂,使用频率和效果有限。一些产漂流性卵的鱼类在产卵期需要一定的流速刺激和持续涨水过程,如长江四大家鱼产卵^[127],为此,在常规的生态流量调度基础上针对特殊时期的需求提出了脉冲流量的生态调度。Chen 等^[134]针对宜都四大家鱼产卵场,通过室内物理模型实验,结合多年现场试验性调度数据,确定了宜都产卵场四大家鱼产卵的触发流速、流速

涨率、喜好流速, 根据断面特征, 提出了促进四大家鱼产卵的起始流量 12 500 m³/s、流量日涨率平均 1 200 m³/s(可能因断面不规则形状而有所变化)、持续涨水时间 4.5 d, 试验调度效果显著, 如图 6。

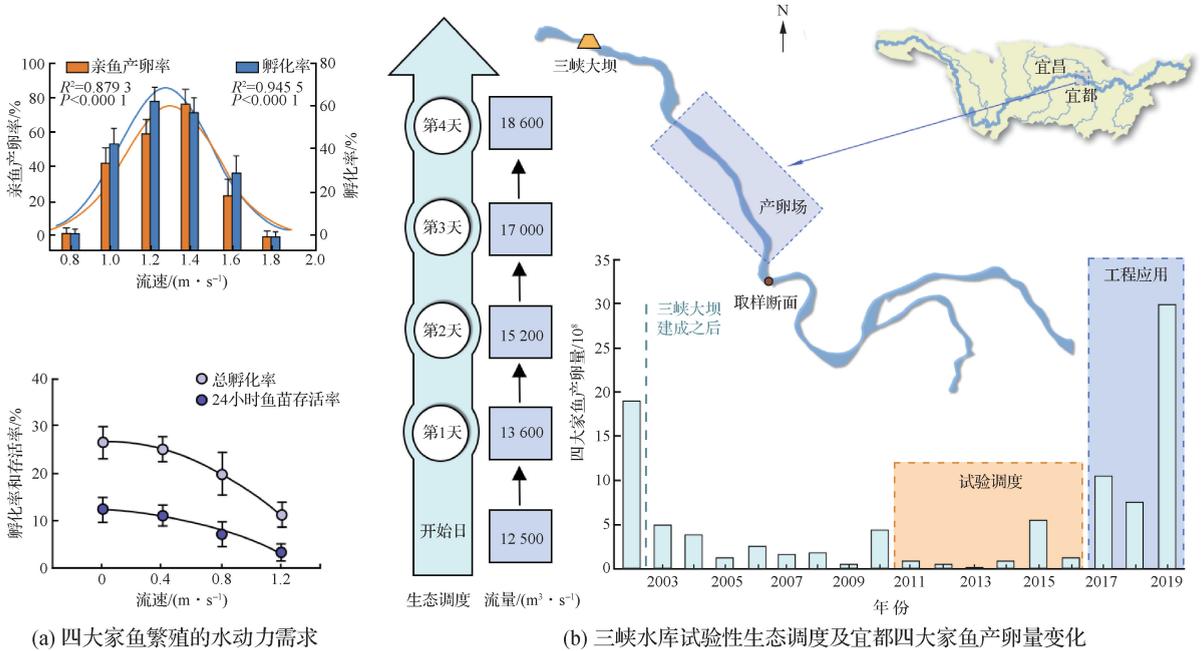


图 6 四大家鱼繁殖的水动力需求和三峡水库试验性生态调度及其促进下游四大家鱼产卵的效果

Fig.6 Flow requirements for Chinese carp reproduction and the experimental eco-operation of the Three Gorges Reservoir for Chinese carps spawning in Yidu section

近年来在“干流开发、支流保护”的新思路指导下, 同时由于一批小水电先后接近服役期限, 支流拆坝和生境替代日益成为鱼类栖息地保护的重要方式。Lovett^[135] 总结分析了美国大量小型旧坝拆除后的生态效应, 指出拆坝后使得河川径流自由流动, 河流生态系统重新变得年轻活力, 水生植被迅速恢复, 鱼类短期内已经成功洄游上溯。但是同时指出: 需要密切关注短期内下泄洪水和泥沙对下游生态系统的冲击; 不仅需要关注对鱼类的影响, 也要关注对底栖动物和水生昆虫的影响, 从而为洄游鱼类提供足够食物; 指出个案无法形成普适性原则, 建议开展系统性研究和观测。Kim 等^[136] 研究了低水头小坝拆除后河貌及岸边带植被的变化, 重点是建立并率定了数值预测模型, 从而为今后拆坝提供生态影响分析工具和工程指导。Magilligan 等^[137] 研究了美国某支流上游小坝拆除后短期内河道地形、水生生物生境、鱼类群落的变化, 指出在拆坝前后开展短期和长时期河貌演变及其生态影响监测与评价的重要性。从以上的研究可以看出, 通过支流拆坝进行河流生态修复的核心是河貌演变及相应的植被和鱼类生境的变化, 如图 7。

中国近年来依托重大水电工程建设和病险水库退役等需求, 开展了支流拆坝方面的研究。高婷等^[138] 针对实施支流生境替代提出了“生态功能持续化、经济代价合理化、保护活动规范化”的基本原则, 杨青瑞等^[139] 建立了包含水文情势、河流水质、生物群落和物理结构 4 个一级指标和 10 个二级指标的支流生境替代效果评价指标体系, 采用了层次分析和专家赋分的评价方法, 并通过澜沧江支流罗梭江生境替代工程进行了应用检验。唐磊等^[140] 以贵州西河水坝为例, 采用数学模型模拟并预测了小型水坝拆除后库内和下游河道河貌的短期及长期演变特征, 为拆坝河流的河道治理及水生生物栖息地修复提供了重要方法。林育青等^[141] 梳理了国内外有关拆坝对河流泥沙地貌、岸边带植物、鱼类和底栖动物群落等影响的评估方法, 可为今后支流拆坝和生境替代提供参考。

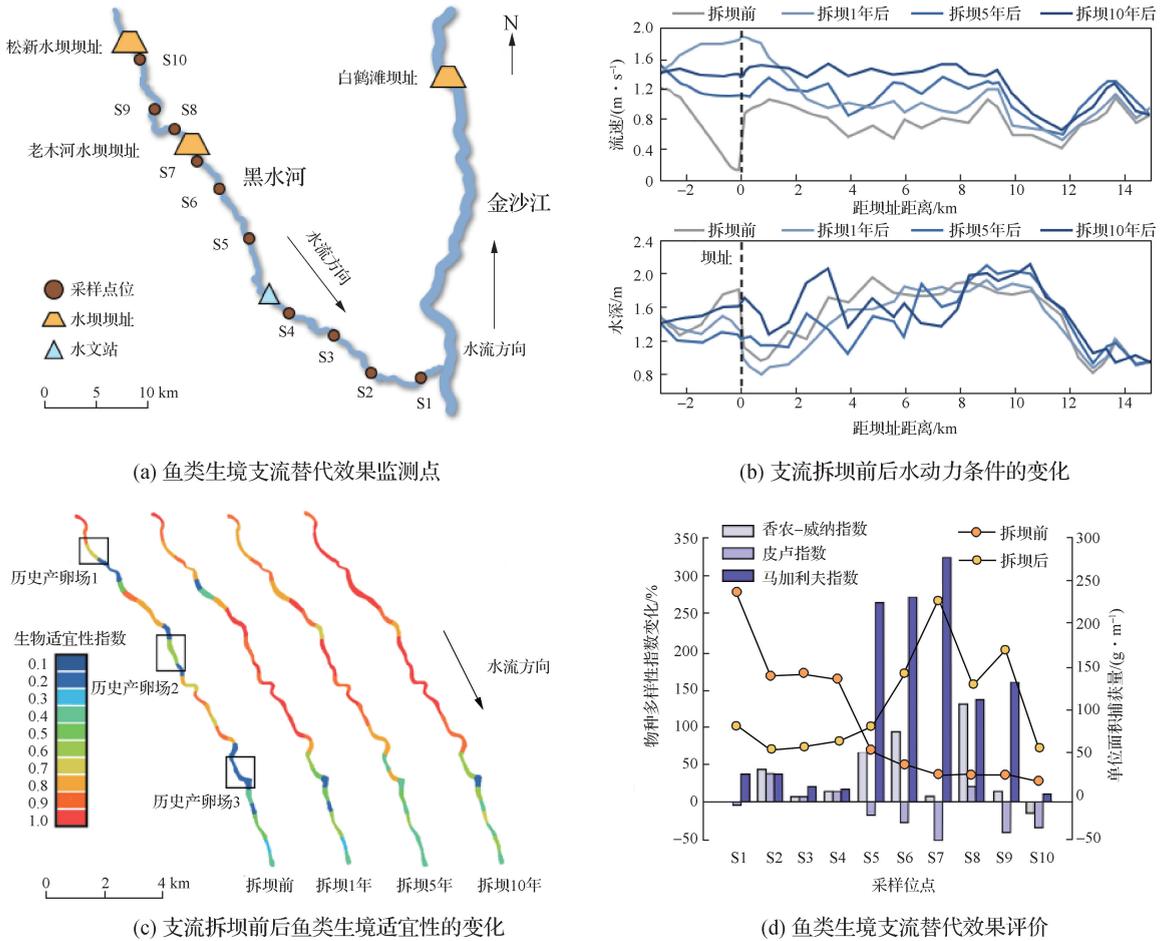


图7 金沙江溪洛渡和向家坝梯级间支流拆坝后河貌变化及鱼类生境替代效果评价
 Fig. 7 Changes of tributary morphology after dam removal and the assessment on its effect for fish habitat compensation between Xiluodu and Xiangjiaba cascade reservoirs in Jinsha River

以上的分析表明应当理性建设高坝过鱼设施和叠梁门等水温调控设施，避免因为一刀切的盲目要求造成低效浪费；河湖分相可能给增殖放流的外来物种如四大家鱼创造适宜的生存与繁殖条件，从而进一步影响土著鱼类的生存空间，因此必须严格规范增殖放流的种类，避免外来物种入侵而进一步损害土著鱼类多样性；支流生境修复可为干流土著鱼类提供有效的替代生境，但替代效果具有局部性，并受支流修复程度和干流梯级进一步开发的影响；加强鱼类各种保护措施效果的定量化跟踪评价，从而使得鱼类保护具有可持续性和经济合理性，如近年来快速发展的环境DNA(eDNA)定量评价技术。

6 结论与展望

通过对近年来国内外有关水电工程生态环境效应研究进展的整理分析，认为尚存在以下几个关键的知识缺口需要深入探究。

(1) 关于大坝对河流生源要素的拦截及生态系统的影响，目前的主要方法是概念模型，或者基于对泥沙的拦截估算对其携带的营养盐的截留，或者是基于下游鱼获量的变化，缺乏长序列观测数据的支撑和内在机制的揭示。

(2) 水库水温调节及其生态效应亟需突破，当前关于水库水温变异对鱼类的影响几乎都集中在繁殖期临

界水温对鱼类产卵的效应,但鱼类繁殖不仅受产卵时水温的影响,更受性腺发育整个时期积温的影响,如何确定生物零度、阐明积温与临界水温节律的变化对目标鱼类繁殖的影响是水库水温效应与调控的核心挑战。

(3) 生态流量的重要性日益突出,但生态流量及其变化过程的生态学基础尚不健全,目前基于水文水力学方法或者物理生境评价方法的流量过程在生物学和生态学意义上的阐释依然不足;而且当前的水库生态调度一般只考虑了坝下生态流量的需求,尚未综合考虑气体过饱和和控制和水温节律调节的需求。

(4) 虽然目前全球有6万多座大坝(坝高15 m以上),但是高坝大库仅占4.5%,广泛分布在支流的小水坝量大面广,这些水坝建设技术相对落后,而且比较缺乏对生态保护的考虑;溪流是生物生境多样性和物种多样性较高的区域,贯彻“干流开发、支流保护”的整体理念,实现溪流生态恢复,科学支撑支流生境替代是当前河流生态保护的迫切需求。

(5) 生态保护措施效果缺乏定量化评价方法,急需建立目标物种在生境、种群、个体、组织、分子、基因组学(eDNA)等层次的量化评价方法,系统分析工程开发前、工程运行后、生态保护措施后目标生物资源及生境状况的变化,合理评价生态保护投入(过鱼设施、增殖放流、栖息地修复、生态调度、替代生境)的绩效,指导重大水电工程影响下水生态环境保护措施的投资和技术筛选与组合。

参考文献:

- [1] HARMAN C, STEWARDSON M. Optimizing dam release rules to meet environmental flow targets[J]. *River Research and Applications*, 2005, 21: 113-129.
- [2] CHEN W, OLDEN J D. Designing flows to resolve human and environmental water needs in a dam-regulated river[J]. *Nature Communications*, 2017, 8: 2158.
- [3] SCHMITT R J P, BIZZI S, CASTELLETTI A, et al. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong[J]. *Nature Sustainability*, 2018(1): 96-104.
- [4] MAAVARA T, PARSONS C T, RIDENOUR C, et al. Global phosphorus retention by river damming[J]. *PNAS*, 2015, 112: 15603-15608.
- [5] MAAVARA T, LAUERWALD R, REGNIER P, et al. Global perturbation of organic carbon cycling by river damming[J]. *Nature Communications*, 2017, 8: 15347.
- [6] CHEN Q, SHI W, HUISMAN J, et al. Hydropower reservoirs on the upper Mekong River modify nutrient bioavailability downstream[J]. *National Science Review*, 2020. [doi: 10.1093/nsr/nwaa026]
- [7] MAAVARA T, CHEN Q, van METER K, et al. River dam impacts on biogeochemical cycling[J]. *Nature Reviews Earth and Environment*, 2020, 1(2): 103-116.
- [8] SHI W Q, CHEN Q W, ZHANG J Y, et al. Nitrous oxide emissions from cascade hydropower reservoirs in the Upper Mekong River[J]. *Water Research*, 2020. [doi: 10.1016/j.watres.2020.115582]
- [9] ORR S, PITTOCK J, CHAPAGAIN A, et al. Dams on the Mekong River: lost fish protein and the implications for land and water resources[J]. *Global Environment Change*, 2012, 22: 925-932.
- [10] MORAN E F, LOPEZ M C, MOORE N, et al. Sustainable hydropower in the 21st century [J]. *PNAS*, 2018, 115: 11891-11898.
- [11] PAN B Z, YIN X A, WANG H Z, et al. An exploratory analysis of ecological water requirements of macroinvertebrates in the Wuhan branch of the Yangtze River[J]. *Quaternary International*, 2015, 380: 256-261.
- [12] STONE R. Dam-building threatens Mekong fisheries[J]. *Science*, 2016, 354: 1084-1085.
- [13] WINEMILLER K O, MCINTYRE P B, CASTELLO L, et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong[J]. *Science*, 2016, 351: 128-129.
- [14] MCINTYRE P B, LIERMANN C A R, REVENGA C. Linking freshwater fishery management to global food security and biodiversity conservation[J]. *PNAS*, 2016, 113: 12880-12885.
- [15] BROWNELL R L, REEVES R R, THOMAS P O, et al. Dams threaten rare Mekong dolphins [J]. *Science*, 2017, 355: 805-806.
- [16] GRUMBINE R E, XU J. Mekong hydropower development[J]. *Science*, 2011, 332: 178-179.

- [17] NGOR P B. Mekong's dams damn fisheries[J]. *Nature*, 2018, 563: 184.
- [18] MURCHIE K J, HAIR K P E, PULLEN C E. Fish response to modified flow regimes in regulated rivers: research methods, effects and opportunities[J]. *River Research and Applications*, 2008, 24(2): 197-217.
- [19] POFF N L, SCHMIDT J C. How dams can go with the flow[J]. *Science*, 2016, 353: 1099-1100.
- [20] SYMPHORIAN G R, MADAMOMBE E, van der ZAAGP. Dam operation for environmental water releases: the case of Osborne Dam, save catchment, Zimbabwe[J]. *Physics and Chemistry of the Earth*, 2003, 28: 985-993.
- [21] LI R, CHEN Q, HAN R, et al. Determination of daily eco-hydrography by the fish spawning habitat suitability model and application to reservoir eco-operation[J]. *Ecohydrology*, 2016, 9(6): 973-981.
- [22] HUANG Z, WANG L. Yangtze dams increasingly threaten the survival of the Chinese sturgeon[J]. *Current Biology*, 2018, 28: 1-8.
- [23] CHEN Q, CHEN D, LI R, et al. Adapting the operation of two cascaded reservoirs for ecological flow requirement of a de-watered river channel due to diversion-type hydropower stations[J]. *Ecological Modelling*, 2013, 252: 266-272.
- [24] WANG L, MO K, CHEN Q, et al. Estimating ecological flows for fish overwintering in plain rivers using a method based on water temperature and critical water depth[J]. *Ecohydrology*, 2019, 12: e2098.
- [25] WANG Y, RHOADS B, WANG D. Assessment of the flow regime alterations in the middle reach of the Yangtze River associated with dam construction: potential ecological implications[J]. *Hydrological Processes*, 2016, 30(21): 3949-3966.
- [26] PARK Y S, CHANG J B, LEK S, et al. Conservation strategies for endemic fish species threatened by the three Gorges Dam[J]. *Conservation Biology*, 2003, 17(6): 1748-1758.
- [27] YI Y, SUN J, ZHANG S. A habitat suitability model for Chinese sturgeon determined using the generalized additive method[J]. *Journal of Hydrology*, 2016, 534: 11-18.
- [28] YU J, ZHANG J, CHEN Q, et al. Dramatic source-sink transition of N_2O in the water level fluctuation zone of the Three Gorges Reservoir during flooding-drying processes[J]. *Environmental Science and Pollution Research*, 2018, 25(20): 20023-20031.
- [29] LIU L, LIU D, JOHNSON D M, et al. Effects of vertical mixing on phytoplankton blooms in Xiangxi Bay of Three Gorges Reservoir: implications for management[J]. *Water Research*, 2012, 46(5): 294-302.
- [30] 董哲仁. 生态水工学探索[M]. 中国水利水电出版社, 2007. (DONG Z R. Exploration of eco-hydraulic engineering[M]. China Water & Power Press, 2007. (in Chinese))
- [31] 陈求稳. 生态水力学及其在水利工程生态环境效应模拟调控中的应用[J]. 水利学报, 2016, 47(3): 413-423. (CHEN Q W. Discipline of ecohydraulics and the application to modeling and mitigating eco-environmental effects of hydraulic works[J]. *Journal of Hydraulic Engineering*, 2016, 47(3): 413-423. (in Chinese))
- [32] YI Y, CHEN X, YANG Z, et al. Evaluating the ecological influence of hydraulic projects: a review of aquatic habitat suitability models[J]. *Renewable and Sustainable Energy Reviews*, 2017, 68: 748-762.
- [33] HU Y, CHENG H. The urgency of assessing the greenhouse gas budgets of hydroelectric reservoirs in China[J]. *Nature Climate Change*, 2013, 3: 708-712.
- [34] 赵炎, 曾源, 吴炳方, 等. 水库水气界面温室气体通量监测方法综述[J]. 水科学进展, 2011, 22(1): 135-146 (ZHAO Y, ZENG Y, WU B F, et al. Review of methods for measuring green houses flux from the air water interface of reservoirs[J]. *Advances in Water Science*, 2011, 22(1): 135-146. (in Chinese))
- [35] SHI W, CHEN Q, YI Q, et al. Carbon emission from cascade reservoirs: spatial heterogeneity and mechanisms[J]. *Environmental Science & Technology*, 2017, 51(21): 12175-12181.
- [36] 姬雨雨, 陈求稳, 施文卿, 等. 水库运行对漫湾库区洲滩水热交换影响[J]. 水科学进展, 2018, 29(1): 73-79. (JI Y Y, CHEN Q W, SHI W Q, et al. Influence of reservoir operation on water and heat exchange in the Manwan's island[J]. *Advances in Water Science*, 2018, 29(1): 73-79. (in Chinese))
- [37] MAO G, WANG S, TENG Q, et al. The sustainable future of hydropower: a critical analysis of cooling units via the theory of inventive problem solving and life cycle assessment methods[J]. *Journal of Cleaner Production*, 2017, 142(4): 2446-2453.
- [38] 崔彦萍, 王保栋, 陈求稳, 等. 三峡水库三期蓄水前后长江口硅酸盐分布及其比值变化[J]. 环境科学学报, 2013, 33(7): 1974-1979. (CUI Y P, WANG B D, CHEN Q W, et al. Distribution of dissolved silicate and changes of Si-N and Si-P ratio in Yangtze River estuary after impoundment of Three Gorges Reservoir[J]. *Acta Scientiae Circumstantiae*, 2013, 33(7):

1974-1979. (in Chinese))

- [39] WANG L, CHEN Q, HAN R, et al. Responses of phytoplankton community in Yangtze River estuary and adjacent sea areas to the impoundment of the Three Gorges Reservoir[J]. *International Journal of Limnology*, 2017, 53: 1-10.
- [40] STONE R. Mayhem on the Mekong[J]. *Science*, 2011, 333: 814-818.
- [41] HEGGENES J, ALFREDSEN K, BUSTOS A A, et al. Be cool: a review of hydro-physical changes and fish responses in winter in hydropower-regulated northern streams[J]. *Environmental Biology of Fishes*, 2018, 101(1): 1-21.
- [42] TAO Y, WANG Y, RHOADS B, et al. Quantifying the impacts of the Three Gorges Reservoir on water temperature in the middle reach of the Yangtze River[J]. *Journal of Hydrology*, 2020, 582: 124476.
- [43] YIGZAW W, LI H, FANG X, et al. A multilayer reservoir thermal stratification module for earth system models[J]. *Journal of Advances in Modeling Earth Systems*, 2019, 11(10): 3265-3283.
- [44] LIU M, ZHANG Y, SHI K, et al. Thermal stratification dynamics in a large and deep subtropical reservoir revealed by high-frequency buoy data[J]. *Science of the Total Environment*, 2019, 651: 614-624.
- [45] KEDRA M, WIEJACZKA L. Climatic and dam-induced impacts on river water temperature: assessment and management implications[J]. *Science of the Total Environment*, 2018, 626: 1474-1483.
- [46] DANIELS M E, DANNER E M. The drivers of river temperatures below a large dam[J]. *Water Resources Research*, 2020, 56(5): e2019WR026751.
- [47] FARMER T M, MARSCHALL E A, DABROWSKI K, et al. Short winters threaten temperate fish populations[J]. *Nature Communications*, 2015, 6: 7724.
- [48] MCBRIDE R S, SOMARAKIS S, FITZHUGH G R, et al. Energy acquisition and allocation to egg production in relation to fish reproductive strategies[J]. *Fish and Fisheries*, 2015, 16: 23-57.
- [49] LUGG A, COPELAND C. Review of cold water pollution in the murray-darling basin and the impacts on fish communities[J]. *Ecological Management and Restoration*, 2014, 15(1): 71-79.
- [50] DADRAS H, DZYUBA B, COSSON J, et al. Effect of water temperature on the physiology of fish spermatozoon function: a brief review[J]. *Aquaculture Research*, 2017, 48(3): 729-740.
- [51] KING H R, PANKHURST N W, WATTS M, et al. Effect of elevated summer temperatures on gonadal steroid production, vitellogenesis and egg quality in female Atlantic salmon[J]. *Journal of Fish Biology*, 2003, 63(1): 153-167.
- [52] HONSEY A E, VENTURELLI P. A, LESTER N P. Bioenergetic and limnological foundations for using degree-days derived from air temperatures to describe fish growth[J]. *Canadian Journal of Fisheries and Aquatic Science*, 2019, 76(4): 657-669.
- [53] BELDADE R, BLANDIN A, O'DONNELL R, et al. Cascading effects of thermally-induced anemone bleaching on associated anemonefish hormonal stress response and reproduction[J]. *Nature Communications*, 2017, 8: 716-725.
- [54] GILLOOLY J F, CHARNOV E L, WEST G B, et al. Effects of size and temperature on developmental time[J]. *Nature*, 2002, 417(6884): 70-73.
- [55] KOCOVSKY P M, CHAPMAN D C, MCKENNA J E. Thermal and hydrologic suitability of Lake Erie and its major tributaries for spawning of Asian carps[J]. *Journal of Great Lakes Research*, 2012, 38: 159-166.
- [56] DURANT J M, HJERMANN D, OTTERSEN G, et al. Climate and the match or mismatch between predator requirements and resource availability[J]. *Climate Research*, 2002, 33(3): 271-283.
- [57] KING J, CAMBRAY J A, DEAN I N. Linked effects of dam-released floods and water temperature on spawning[J]. *Hydrobiologia*, 1998, 384(1): 245-265.
- [58] MARTIN H, PAUL B, MATHIEU D, et al. Survey timing vs. ecosystem scheduling: degree-days to underpin observed interannual variability in marine ecosystems[J]. *Progress in Oceanography*, 2018, 166: 30-40.
- [59] MOTOS L, URIARTE A, VALENCIA V. The spawning environment of the bay of Biscay anchovy (*Engraulis encrasicolus* L.) [J]. *Scientia Marina*, 1996, 60: 117-140.
- [60] PAWIROREDJO P, LAMOUREUX J, HALL S G, et al. Degree-days as a tool to determine the heating requirement for channel catfish spawning in earthen ponds[J]. *North American Journal of Aquaculture*, 2008, 70: 328-337.
- [61] MAZZEO I, PEÑARANDA D S, GALLEGO V, et al. Temperature modulates the progression of vitellogenesis in the European eel [J]. *Aquaculture*, 2014, 434: 38-47.

- [62] REGNIER T, GIBB F M, WRIGHT P J. Understanding temperature effects on recruitment in the context of trophic mismatch[J]. *Scientific Reports*, 2019, 9: 15179.
- [63] ROGERS L A, DOUGHERTY A B. Effects of climate and demography on reproductive phenology of a harvested marine fish population[J]. *Global Change Biology*, 2019, 25: 708-720.
- [64] KING A J, GWINN D C, TONKIN Z, et al. Using abiotic drivers of fish spawning to inform environmental flow management[J]. *Journal of Applied Ecology*, 2016, 53: 34-43.
- [65] 梁瑞峰, 邓云, 脱友才, 等. 流域水电梯级开发水温累积影响特征分析[J]. *四川大学学报(工程科学版)*, 2012(增刊2), 221-227. (LIANG R F, DENG Y, TUO Y C, et al. Analysis on characteristics of water temperature's cumulative effects of river cascade hydropower stations[J]. *Journal of Sichuan University (Engineering Science Edition)*, 2012(Suppl2): 221-227. (in Chinese))
- [66] 纪道斌, 龙良红, 徐慧, 等. 梯级水库建设对水环境的累积影响研究进展[J]. *水利水电科技进展*, 2017, 37(3): 7-14. (JI D B, LONG L H, XU H, et al. Advances in study on cumulative effects of construction of cascaded reservoirs on water environment[J]. *Advances in Science and Technology of Water Resources*, 2017, 37(3): 7-14. (in Chinese))
- [67] LU J, LI R, MA Q, et al. Model for total dissolved gas supersaturation from plunging jets in high dams[J]. *Journal of Hydraulic Engineering*, 2019, 145(1): 04018082.
- [68] 曲璐. 高坝工程总溶解气体过饱和与水体含沙量关系[J]. *水科学进展*, 2011, 22(6): 839-843. (QU L. Relation of total dissolved gas supersaturation and suspended sediment concentration of high-dams[J]. *Advances in Water Science*, 2011, 22(6): 839-843. (in Chinese))
- [69] HEDDAM S. Generalized regression neural network based approach as a new tool for predicting total dissolved gas (TDG) downstream of spillways of dams: a case study of Columbia River basin dams, USA[J]. *Environmental Processes*, 2017, 4(1): 235-253.
- [70] LI R, LI J, LI K, et al. Prediction for supersaturated total dissolved gas in high-dam hydropower projects[J]. *Science China Technological Sciences*, 2009, 52(12): 3661-3667.
- [71] DEMOYER C, SCHIERHOLZ E, GULLIVER J, et al. Impact of bubble and free surface oxygen transfer on diffused aeration systems[J]. *Water Research*, 2003, 37(8): 1890-1904.
- [72] BAGATUR T, ONEN F. Prediction of flow and oxygen transfer by a plunging water jets with genetic expression programming (GEP) models[J]. *Arabian Journal for Science and Engineering*, 2014, 39(6): 4421-4432.
- [73] CHANSON H, AOKI S, HOQUE A. Physical modelling and similitude of air bubble entrainment at vertical circular plunging jets [J]. *Chemical Engineering Science*, 2004, 59(4): 747-758.
- [74] WANG Y, POLITANO M, WEBER L. Spillway jet regime and total dissolved gas prediction with a multiphase flow model[J]. *Journal of Hydraulic Research*, 2019, 57(1): 26-38.
- [75] KAMAL R, ZHU D, ASCE M, et al. Dissipation of supersaturated total dissolved gases in the intermediate mixing zone of a regulated river[J]. *Journal of Environmental Engineering*, 2018, 145(2): 04018135.
- [76] OU Y, LI R, HODGES B, et al. Impact of temperature on the dissipation process of supersaturated total dissolved gas in flowing water[J]. *Fresenius Environmental Bulletin*, 2016, 25(6): 1927-1934.
- [77] HUANG J, LI R, FENG J, et al. Relationship investigation between the dissipation process of supersaturated total dissolved gas and wind effect[J]. *Ecological Engineering*, 2016, 95: 430-437.
- [78] 冯镜洁, 李然, 李克锋, 等. 高坝下游过饱和 TDG 释放过程研究[J]. *水力发电学报*, 2010, 29(1): 7-12. (FENG J J, LI R, LI K F, et al. Study on release process of supersaturated total dissolved gas downstream of high dam[J]. *Journal of Hydroelectric engineering*, 2010, 29(1): 7-12. (in Chinese))
- [79] 冯镜洁, 李然, 唐春燕, 等. 含沙量对过饱和总溶解气体释放过程影响分析[J]. *水科学进展*, 2012, 23(5): 702-708. (FENG J J, LI R, TANG C Y, et al. Experimental study on the sediment effect on releasing process of supersaturated total dissolved gas[J]. *Advances in Water Science*, 2012, 23(5): 702-708. (in Chinese))
- [80] 王琳, 冯镜洁, 李然. 鱼道内过饱和总溶解气体释放规律的试验研究[J]. *工程科学与技术*, 2017, 49(6): 30-37. (WANG L, FENG J J, LI R. Experimental study on dissipation of supersaturated total dissolved gas in a fishway[J]. *Advanced Engineering Sciences*, 2017, 49(6): 30-37. (in Chinese))

- [81] FENG J, LI R, MA Q, et al. Experimental and field study on dissipation coefficient of supersaturated total dissolved gas[J]. Journal of Central South University, 2014, 21(5): 1995-2003.
- [82] JOHNSON E, CLABOUGH T, PEERY C, et al. Estimating adult chinook salmon exposure to dissolved gas supersaturation downstream of hydroelectric dams using telemetry and hydrodynamic models[J]. River Research and Applications, 2007, 23(9): 963-978.
- [83] O'CONNOR D. Wind effects on gas-liquid transfer coefficients[J]. Journal of Environmental Engineering, 1983, 109(3): 731-752.
- [84] SHEN X, LI R, HODGES B, et al. Experiment and simulation of supersaturated total dissolved gas dissipation: focus on the effect of confluence types[J]. Water Research, 2019, 155: 320-332.
- [85] FU X, LI D, ZHANG X. Simulations of the three-dimensional total dissolved gas saturation downstream of spillways under unsteady conditions[J]. Journal of Hydrodynamics, 2010, 22(4): 598-604.
- [86] POLITANO M, AMADO A, BICKFORD S, et al. Investigation into the total dissolved gas dynamics of wells dam using a two-phase flow model[J]. Journal of Hydraulic Engineering, 2011, 137(10): 1257-1268.
- [87] SMILEY J, OKIHIRO M, DRAWBRIDGE M, et al. Pathology of ocular lesions associated with gas supersaturation in white seabass[J]. Journal of Aquatic Animal Health, 2012, 24(1): 1-10.
- [88] DENG Y, CAO C, LIU X, et al. Effect of total dissolved gas supersaturation on the survival of bighead carp (*Hypophthalmichthys Nobilis*)[J]. Animals, 2020, 10(1): 166.
- [89] SMILEY J, DRAWBRIDGE M, OKIHIRO M, et al. Acute effects of gas supersaturation on juvenile cultured white seabass[J]. Transactions of the American Fisheries Society, 2011, 140: 1269-1276.
- [90] 彭天辉, 潘连德, 唐绍林. 大口黑鲈慢性气泡病的组织病理观察以及水体分层对发病的影响[J]. 大连海洋大学学报, 2013, 28(6): 578-584. (PENG T H, PAN L D, TANG S L. Pathological observation of chronic gas bubble disease and influence of water stratification on the incidence in largemouth bass *Micropterus salmoides* [J]. Journal of Dalian Ocean University, 2013, 28(6): 578-584. (in Chinese))
- [91] WANG Y, LI Y, AN R, et al. Effects of total dissolved gas supersaturation on the swimming performance of two endemic fish species in the Upper Yangtze River[J]. Scientific Reports, 2018, 8(1): 10063-10071.
- [92] MA Q, LI R, FENG J, et al. Cumulative effects of cascade hydropower stations on total dissolved gas supersaturation[J]. Environmental Science and Pollution Research, 2018, 25(14): 13536-13547.
- [93] SÁ-OLIVEIRA J C, HAWES J E, ISAAC-NAHUM V J, et al. Upstream and downstream responses of fish assemblages to an eastern Amazonian hydroelectric dam[J]. Freshwater Biology, 2015, 60(10): 2037-2050.
- [94] AGOSTINHO A A, GOMES L C, SANTOS N C L, et al. Fish assemblages in neotropical reservoirs: colonization patterns, impacts and management[J]. Fisheries Research, 2016, 173: 26-36.
- [95] MARDEN S L, WALDECY A, RICARDO R, et al. Small hydropower dam alters the taxonomic composition of benthic macroinvertebrate assemblages in a neotropical river[J]. River Research and Applications, 2019, 35(6): 725-735.
- [96] DOS SANTOS N C L, de SANTANA H S, DIAS R M, et al. Distribution of benthic macroinvertebrates in a tropical reservoir cascade[J]. Hydrobiologia, 2016, 765: 265-275.
- [97] MBAKA J G, MWANIKI M W. A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates[J]. Environmental Reviews, 2015, 23(3): 257-262.
- [98] BEISEL J N, USSEGLIO-POLATERA P, THOMAS S, et al. Stream community structure in relation to spatial variation: the influence of mesohabitat characteristics[J]. Hydrobiologia, 1998, 389(1/2/3): 73-88.
- [99] 马徐发, 熊邦喜, 王明学, 等. 湖北道观河水库大型底栖动物的群落结构及物种多样性[J]. 湖泊科学, 2004, 16(1): 49-55. (MA X F, XIONG B X, WANG M X, et al. The community structure and biodiversity of macrozoobenthos in Daoguanhe Reservoir, Hubei Province[J]. Journal of Lake Sciences, 2004, 16(1): 49-55. (in Chinese))
- [100] NELSON S M, LIEBERMAN D M. The influence of flow and other environmental factors on benthic invertebrates in the Sacramento River, USA[J]. Hydrobiologia, 2002, 489(1): 117-129.
- [101] BEAUGER A, LAIR N, REYES-MARCHANT P, et al. The distribution of macroinvertebrate assemblages in a reach of the River Allier (France), in relation to riverbed characteristics[J]. Hydrobiologia, 2006, 571(1): 63-76.

- [102] 任海庆, 袁兴中, 刘红, 等. 环境因子对河流底栖无脊椎动物群落结构的影响[J]. 生态学报, 2015, 35(10): 3148-3156. (REN H Q, YUAN X Z, LIU H, et al. The effects of environment factors on community structure of benthic invertebrate in rivers[J]. *Acta Ecologica Sinica*, 2015, 35(10): 3148-3156. (in Chinese))
- [103] 李仁熙. 水温对正颤蚓繁殖的影响[J]. 水生生物学报, 2003, 27(4): 443-444. (LI R X. Effects of water temperature on reproduction of tubifex muller[J]. *Acta Hydrobiologica Sinica*, 2003, 27(4): 443-444. (in Chinese))
- [104] 段学花, 王兆印, 徐梦珍. 底栖动物与河流生态评价[M]. 北京: 清华大学出版社, 2010. (DUAN X H, WANG Z Y, XU M Z. Benthic macroinvertebrate and application in the assessment of stream ecology[M]. Beijing: Tsinghua University Press, 2010. (in Chinese))
- [105] MANDAVILLE S M. Benthic macroinvertebrates in freshwaters; taxa tolerance values, metrics, and protocols[M]. Nova Scotia: Soil & Water Conservation Society of Metro Halifax, 2002
- [106] 任淑智. 京津及邻近地区底栖动物群落特征与水质等级[J]. 生态学报, 1991, 11(3): 262-268. (REN S Z. The characteristics of benthic macroinvertebrate community and water quality in Beijing-Tianjin area[J]. *Acta Ecologica Sinica*, 1991, 11(3): 262-268. (in Chinese))
- [107] FROUIN P. Effects of anthropogenic disturbances of tropical soft-bottom benthic communities[J]. *Marine Ecology Progress Series*, 2000, 194: 39-53.
- [108] 龚志军, 谢平, 唐汇涓, 等. 水体富营养化对大型底栖动物群落结构及多样性的影响[J]. 水生生物学报, 2001, 25(3): 210-216. (GONG Z J, XIE P, TANG H J, et al. The Influence of eutrophication upon community structure and biodiversity of macrozoobenthos[J]. *Acta Hydrobiologica Sinica*, 2001, 25(3): 210-216. (in Chinese))
- [109] 吴东浩, 于海燕, 吴海燕, 等. 基于大型底栖无脊椎动物确定河流营养盐浓度阈值: 以西苕溪上游流域为例[J]. 应用生态学报, 2010, 21(2): 483-488. (WU D H, YU H Y, WU H Y, et al. Estimation of river nutrients thresholds based on benthic macro invertebrate assemblages: a case study in the upper reaches of Xitiao stream in Zhejiang China[J]. *Chinese Journal of applied Ecology*, 2010, 21(2): 483-488. (in Chinese))
- [110] SLOANE I W, NORRIS R H. Relationship of AUSRIVAS-based macroinvertebrate predictive model outputs to a metal pollution gradient[J]. *Journal of the North American Benthological Society*, 2003, 22(3): 457-471.
- [111] 徐霖林, 马长安, 田伟, 等. 淀山湖沉积物重金属分布特征及其与底栖动物的关系[J]. 环境科学学报, 2011, 31(10): 2223-2232. (XU L L, MA C A, TIAN W, et al. The distribution of heavy metals in surface sediment of Lake Dianshan and its correlations with macrozoobenthos[J]. *Acta Scientiae Circumstantiae*, 2011, 31(10): 2223-2232. (in Chinese))
- [112] GRAÇA M A S, PINTO P, CORTES R, et al. Factors affecting macroinvertebrate richness and diversity in portuguese streams: a two-scale analysis[J]. *International Review of Hydrobiology*, 2004, 89(2): 151-164.
- [113] BUSS D F, DARCÍLIO F B, NESSIMIAN J L, et al. Substrate specificity, environmental degradation and disturbance structuring macroinvertebrate assemblages in neotropical streams[J]. *Hydrobiologia*, 2004, 518(1/2/3): 179-188.
- [114] TEWS J, BROSE U, GRIMM V, et al. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures[J]. *Journal of Biogeography*, 2004, 31(1): 79-92.
- [115] WANG J, SOININEN J, ZHANG Y, et al. Contrasting patterns in elevational diversity between microorganisms and macroorganisms[J]. *Journal of Biogeography*, 2011, 38(3): 595-603.
- [116] 许亚红, 郑子叶, 王建柱, 等. 高岚河大型底栖动物时空分布及影响因子研究[J]. 生物资源, 2019, 41(5): 426-433. (XU Y H, ZHENG Z Y, WANG J Z, et al. Temporal and spatial distribution and impact factors of macrobenthos in Gaolan River[J]. *Biotic Resources*, 2019, 41(5): 426-433. (in Chinese))
- [117] 陈丽, 王东波, 君珊. 拉萨河流域大型底栖动物群落结构及其与环境因子的关系[J]. 生态学报, 2019, 39(3): 757-769. (CHEN L, WANG D B, JUN S. Macroinvertebrate community structure and relationships with environmental factors in the Lhasa River basin[J]. *Acta Ecologica Sinica*, 2019, 39(3): 757-769. (in Chinese))
- [118] 朱玲玲, 董先勇, 陈泽方. 金沙江下游梯级水库淤积及其对三峡水库影响研究[J]. 长江科学院院报, 2017, 34(3): 1-7. (ZHU L L, DONG X Y, CHEN Z F. Sediment deposition of cascade reservoirs in the Lower Jinsha River and its impact on Three Gorges Reservoir[J]. *Journal of Yangtze River Scientific Research Institute*, 2017, 34(3): 1-7. (in Chinese))
- [119] 陈浒, 李厚琼, 吴迪, 等. 乌江梯级电站开发对大型底栖无脊椎动物群落结构和多样性的影响[J]. 长江流域资源与环境, 2010, 19(12): 1462-1470. (CHEN H, LI H Q, WU D, et al. Effects of step hydroelectric exploits on community struc-

- ture and biodiversity of macroinvertebrates in Wujiang River[J]. Resources and Environment in the Yangtze Basin, 2010, 19(12): 1462-1470. (in Chinese))
- [120] 张敏, 蔡庆华, 渠晓东, 等. 三峡成库后香溪河库湾底栖动物群落演变及库湾纵向分区格局动态[J]. 生态学报, 2017, 37(13): 4483-4494. (ZHANG M, CAI Q H, QU X D, et al. Macroinvertebrate succession and longitudinal zonation dynamics in Xiangxi Bay, after impoundment of the Three Gorges Reservoir[J]. Acta Ecologica Sinica, 2017, 37(13): 4483-4494. (in Chinese))
- [121] BAXTER R M. Environmental effects of dams and impoundments[J]. Annual Review of Ecology and Systematics, 1977, 8(1): 255-283.
- [122] SHI X, KYNARD B, LIU D, et al. Development of fish passage in China[J]. Fisheries, 2015, 40(4): 161-169.
- [123] 李婷, 唐磊, 王丽, 等. 水电开发对鱼类种群分布及生态类型变化的影响: 以溪洛渡至向家坝河段为例[J]. 生态学报, 2020, 40(4): 1473-1485. (LI T, TANG L, WANG L, et al. Distribution characteristics and ecological types changes in fish communities under hydropower development from Xiluodu to Xiangjiaba reach[J]. Acta Ecologica Sinica, 2020, 40(4): 1473-1485. (in Chinese))
- [124] 王沛芳, 王超, 候俊, 等. 梯级水电开发中生态保护分析与生态水头理念及确定原则[J]. 水利水电科技进展, 2016, 36(5): 1-7. (WANG P F, WANG C, HOU J, et al. Ecological protection analysis of cascade hydropower development and concept and principle for definition of ecological water head[J]. Advances in Science and Technology of Water Resources, 2016, 36(5): 1-7. (in Chinese))
- [125] HAN R, CHEN Q, LI R, et al. Investigation on *Spinibarbus hollandi* behaviors to flow conditions by laboratory physical model and numerical simulations[J]. Ecohydrology, 2013, 6(4): 586-597.
- [126] LI W, CHEN Q, CAI D, et al. Determination of an appropriate ecological hydrograph for a rare fish species using an improved fish habitat suitability model introducing landscape ecology index[J]. Ecological Modelling, 2015, 311: 31-38.
- [127] LI M, DUAN Z, GAO X, et al. Impact of the Three Gorges Dam on reproduction of four major Chinese carps species in the middle reaches of the Changjiang River[J]. Chinese Journal of Oceanology and Limnology, 2016, 34: 885-893.
- [128] WANG L, CHEN Q, ZHANG J, et al. Incorporating fish habitat requirements of the complete life cycle into ecological flow regime estimation of rivers[J]. Ecohydrology, 2020. [doi: 10.1002/eco2204]
- [129] CHEN Q, CHEN D, LI R, et al. Optimizing the operation of the Qingshitan Reservoir in the Lijiang River for multiple human interests and quasi-natural flow maintenance[J]. Journal of Environmental Sciences, 2012, 24(11): 1923-1928.
- [130] CHEN D, LI R, CHEN Q, et al. Deriving optimal daily reservoir operation scheme with consideration of downstream ecological hydrograph through a time-nested approach[J]. Water Resources Management, 2015, 29: 3371-3386.
- [131] CHEN D, LEON A S, GIBSON N L, et al. Dimension reduction of decision variables for multi-reservoir operation: a spectral optimization model[J]. Water Resources Research, 2016. [doi: 10.1002/2015WR017756]
- [132] DENG Y, TUO Y, LI J, et al. Spatial-temporal effects of temperature control device of stoplog intake for Jinping I hydropower station[J]. Science China Technological Sciences, 2011, 54: 83-88.
- [133] HE W, LIAN J, YAO Y, et al. Modeling the effect of temperature-control curtain on the thermal structure in a deep stratified reservoir[J]. Journal of Environmental Management, 2017, 202: 106-116.
- [134] CHEN Q, ZHANG J, CHEN Y, et al. Manipulating flow velocity to manage fish reproduction in dammed Rivers[J]. Engineering, 2020. [doi: 10.1016/j.eng.2020.06.013]
- [135] LOVETT RA. Rivers on the run[J]. Nature, 2014, 511: 521-523.
- [136] KIM S N, TODA Y, TSUJIMOTO T. Effects of a low-head dam removal on river morphology and riparian vegetation: a case study of Gongreung River[J]. Journal of Water Resource and Protection, 2014, 6(18): 1682-1690.
- [137] MAGILLIGAN F J, NISLOW K H, KYNARD B E, et al. Immediate changes in stream channel geomorphology, aquatic habitat, and fish assemblages following dam removal in a small upland catchment[J]. Geomorphology, 2016, 252: 158-170.
- [138] 高婷, 李翀, 廖文根. 实施支流生境替代保护的基本原则[J]. 中国水利水电科学研究院学报, 2012, 10(4): 267-272. (GAO T, LI C, LIAO W G. The basic principles in applying tributary habitat alternative protection[J]. Journal of China Institute of Water Resources and Hydropower Research, 2012, 10(4): 267-272. (in Chinese))
- [139] 杨青瑞, 陈声威, 何建宽, 等. 支流生境替代保护效果评价指标体系与评价方法研究[J]. 中国水利水电科学研究院学

报, 2015, 13(6): 408-420. (YANG Q R, CHEN S W, HE J K, et al. A study on organoleptic chromaticity-based quantitative assessment method for landscape quality of sandy water[J]. Journal of China Institute of Water Resources and Hydropower Research, 2015, 13(6): 408-420. (in Chinese))

[140] 唐磊, 何术锋, 莫康乐, 等. 小型水坝拆除后河貌演变模拟分析: 以西河水坝为例[J]. 水科学进展, 2019, 30(5): 699-708. (TANG L, HE S F, MO K L, et al. Simulation analysis of river channel evolution after small dam removal: a case study of Xihe dam[J]. Advances in Water Science, 2019, 30(5): 699-708. (in Chinese))

[141] 林育青, 马君秀, 陈求稳. 拆坝对河流生态系统的影响及评估方法综述[J]. 水利水电科技进展, 2017, 37(5): 9-21. (LIN Y Q, MA J X, CHEN Q W. Research on effects of dam removal on river ecosystem and review of its assessment methods [J]. Advances in Science and Technology of Water Resources, 2017, 37(5): 9-21. (in Chinese))

Effects of hydropower development on aquatic eco-environment and adaptive managements*

CHEN Qiuwen^{1,2}, ZHANG Jianyun^{1,2}, MO Kangle³, CHEN Yuchen³, GUAN Tiesheng¹,
WANG Guoqing¹, LIN Yuqing^{2,3}

(1. State Key Laboratory of Hydrology-Water Resources & Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210029, China; 2. Yangtze Institute for Conservation and Green Development, Nanjing 210098, China; 3. Center for Eco-Environmental Research, Nanjing Hydraulic Research Institute, Nanjing 210029, China)

Abstract: Eco-environmental conservation has been a long challenge and even bottleneck for sustainable hydropower development. This study comprehensively reviewed the advances of researches on river damming impacts on biogeochemical cycling and thereby the aquatic eco-environment effects, zoobenthos habitat, fish habitat and migration routes, as well as structure and non-structure conservation measures. It analyzed the current challenges in fundamental researches and engineering applications as well as the underlying reasons, and highlighted the core aspects for future investigations. These include: ① Long-term in-situ monitoring to discover the interception, transformation and transport processes of biogenic elements, and reveal the associated mechanism as well as the accumulated eco-environmental impacts; ② Reservoir induced changes in effective accumulated temperature regime for fish gonadal development and critical temperature regime for fish spawning, and consequently their joint effects on fish reproduction. In particular, the study pointed out the irrationality of some mandatory measures for indigenous fish conservation at present, and proposed the options such as ecological flow and tributary habitat compensation for high dams, and finally it provided some novel technologies to quantitatively assess the efficiency of conservation measures.

Key words: hydropower; eco-environmental effects; modelling and assessment; adaptive management

* The study is financially supported by the National Key R&D Program of China (No. 2016YFC0502205) and the National Natural Science Foundation of China (No. 91547206).