第 46 卷第 2 期　　生　态　学　报　　Vol.46,No.2
2026 年 1 月　　ACTA ECOLOGICA SINICA　　Jan.,2026

DOI: 10.20103/j.stxb.202502240387

于道平, 连玉喜, 陈敏敏, 张晓可, 杨晓鸽.河流交汇水域的水力特征与生态功能.生态学报,2026,46(2)

Yu D P, Lian Y X, Chen M M, Zhang X K, Yang X G.Characteristics of hydrodynamics and ecological functions in river confluence.Acta Ecologica Sinica,2026,46(2)

河流交汇水域的水力特征与生态功能

于道平[1,2,*], 连玉喜[1,2], 陈敏敏[1,2], 张晓可[1,2], 杨晓鸽[1,2]

1 水生生物保护与水生态修复安徽省高校工程技术研究中心,安庆　246133

2 安庆师范大学生命科学学院,安庆　246133

摘要:河流交汇水域是大型河网及其附属水体连接的重要节点,是物质运输、能量转化、生物汇聚与扩散的枢纽。从水力特征的角度,分析交汇水域对群落结构,物种多样性维持的驱动机制有助于更好地理解其生态功能,为长江水生濒危物种保护和生态系统修复提供理论依据。本文根据河流交汇水域的最新研究成果,从交汇水域生境异质性、流态多样性和生物多样性的角度系统阐述了其水力特征和生态功能:(1)交汇水域是由浅滩与深潭序列组成的河流非连续体的物理模板,结构复杂,生境异质性高,为水生生物重要的庇护所和适宜栖息地;(2)交汇水域具有复杂的水力形态,剪切层、二次流、分层效应与河床相互作用,共同主导了区域内的流态特征、泥沙输送和河床形态,以及物质运输和能量转化,并驱动着水生生物聚集与扩散;(3)交汇水域具有吸附过滤和滞留效应,不同的流态中汇聚了众多水生生物,长江江豚则能利用环境涡量更容易捕获在上下游或支流与湖泊之间移动的鱼类。总之,河流交汇水域具有多样的地貌、复杂的水动力特征和独特的生态功能,是河流生态系统和生物多样性保护的关键水域。

关键词:河流地貌学;水动力学;交汇水域;生物多样性

Characteristics of hydrodynamics and ecological functions in river confluence

YU Daoping[1,2,*], LIAN Yuxi[1,2], CHEN Minmin[1,2], ZHANG Xiaoke[1,2], YANG Xiaoge[1,2]

1 *Research Center of Aquatic Organism Conservation and Water Ecosystem Restoration in Anhui Province*, *Anqing* 246133, *China*

2 *College of Life Science*, *Anqing Normal University*, *Anqing* 246133, *China*

Abstract: The river confluence serves as critical nodes connecting large river networks and their affiliated waters, acting as hubs for material transport, energy transformation, and biological aggregation and dispersal. From the hydraulic perspective, analyzing the driving mechanisms of the confluence waters on the community structure and the maintenance of biodiversity helps to better understand their ecological functions and provide theoretical foundations for the conservation of endangered aquatic species and ecosystem restoration in the Yangtze River. This paper summarized the latest research on the river confluence, and expound their hydraulic characteristics and ecological functions systematically from the perspectives of habitat heterogeneity, flow regime diversity and biodiversity of the confluence. (1) The confluence formed a physically discontinuous template composed of shallow beaches and deep pools, characterized by complex structures and high habitat heterogeneity, and can serving as vital refuges and suitable habitats for aquatic organisms; (2) The confluence featured with complex hydraulic flow patterns, where shear layers, second flows, and stratification interact with the riverbed, jointly influenced the flow regime, sediment transport and riverbed morphology within the region, as well as material transportation and energy conversion, thereby acting as key drivers of biological aggregation and dispersal; (3) The confluences sustained

基金项目:国家自然科学基金项目(32470539);安徽省教育厅水生生物保护创新团队专项基金项目(070-185003);安徽省教育厅科研项目(2023AH030072)

收稿日期:2025-02-24

* 通讯作者 Corresponding author.E-mail: ahyudp@163.com

exceptionally high biodiversity. Factors such as habitat heterogeneity, substrate particle filtration, bioflocculation-driven aggregation, and bed shielding collectively promote the diversity and abundance of invertebrates, while abundant prey resources and energy-efficient flow conditions made these zones crucial for fish and freshwater cetaceans in terms of breeding, foraging, migration, or dispersal. The confluence performed functions of adsorption-filtration and nutrient retention effects, where diverse flow regimes aggregate numerous aquatic organisms. Additionally, the Yangtze finless porpoise captured fish which moving between upstream-downstream or tributary-lake more efficiently by taking advantage of the vortices. In conclusion, the confluences exhibited diverse geomorphic features, complex hydrodynamic characteristics and pivotal ecological functions, making them essential areas for river ecosystem conservation and biodiversity protection.

Key Words: fluvial geomorphology; hydrodynamics; river confluence; biodiversity

河流是气候在地球上留下的烙印,是陆地表面上经常或间歇有水流动的线形天然水道,是溪、川、江、河等的总称[1]。湿润地区河网密集、径流充分,干旱地区河网稀疏、径流贫乏,因此河网形态与分布受气候和地理条件严格制约[2]。河流生态系统包括高海拔河源区、河源至大海之间的线性河道、季节性淹没的河岸带和泥沙淤积的洪泛平原,并涉及流域地下水和近岸相通的湖泊等,统称河流生态系统[3]。

人类择水而栖,向水而生,创造出辉煌夺目的大河流域文明[4]。现代大都市几乎都建立在河流交汇水域,如中国重庆、加拿大蒙特利尔、塞尔维亚贝尔格莱德等,或河流入海口,如上海、广州等。在漫长的历史中,人类承蒙了河流的巨量惠泽,也遭受过河流的无情打击。人类社会发展与河流休戚相关,在与河流相互作用的过程中,对河流生态价值的认知也不断提升,日渐关注河流生态修复和关键水域的生态保护[5]。

交汇水域是指具有能量差异的水体汇合后其具有开尔文—赫姆霍兹不稳定现象[6]。从热电厂排水口、城市排污口到河流进入湖泊或水库、两条河流或干流与支流在洲尾汇合,都能形成从几米到几公里不等,与水环境自然景观有明显区别的交汇水域,其范围主要取决于两种水体动能[7]。根据宽深比(W/H),交汇水域通常划分为小型(<10)、中型($10<W/H<50$)和大型(>50)3 种类型[8]。空间尺度较大的交汇水域,常见的有:溪流与江河交汇,如皖河口;江河与湖泊交汇,如鄱阳湖口,河流入海;如长江口和珠江口。此外,大型河流的分汊在江心洲尾汇合,也形成交汇水域。

长江是世界第三大河流,唯一能同时生活 2 种大型哺乳动物长江江豚(*Neophocaena asiaeorientalis*)和白鱀豚(*Lipoter vexillifer*),表明长江曾经拥有的极高生物多样性和稳定的生态系统[9]。长江中下游是以河网结构为主要特征的江湖复合型生态系统,沿岸有大量支流和湖泊,河道中有众多江心洲,形成系列的交汇水域,为稚仔鱼进出相邻水体或湖泊提供临时庇护或短暂休憩场所[10]。长江两岸 10 km^2 以上的通江湖泊至少 100 个,然而,半个多世纪以来,除鄱阳湖、洞庭湖和石臼湖外,97 个通江湖泊都已建立涵闸,相应的交汇水域遭到毁坏[11]。长江许多涉水工程,如航道整治、桥梁、引水工程等,不同程度地改变了长江干支流分流比、断面平均流速和输沙率,导致在江心洲下游交汇水域栖息活动的长江江豚数量降低或消失[12]。

早期关注交汇水域的是工程技术人员,在防洪工程设计中需要考虑交汇水域紊流的冲刷作用[13]。上世纪 80 年代,运用室内水槽实验和野外观察数据,开展了多项涉及交汇水域平面形态、流量、汇流角等因子对城市排污口、引水口及防洪设计的影响的研究工作[14—16]。近 20 年,交汇水域在河网生态系统时空格局与异质性中的作用[17—18],以及交汇水域作为鱼类在河网之间往返迁移活动的节点逐渐得到关注[19]。随着野外测量仪器的发展和计算机技术的广泛应用,三维流场结构得以精确捕捉和描述,交汇水域的不同地貌单元和水力单元逐渐被揭示[20—21]。

然而,天然河流交汇水域的形态结构和水力特征处于动态变化中,很难有一个完美理论系统地总结所有的交汇水域特征。由于交汇水域涉及地貌学和流体力学,且汇入流的通量存在差异,如流量、密度、水温等,以及气候和人类活动的强烈扰动,因此生物地化过程复杂,许多生态驱动机制至今尚不清楚[22]。本文仅回顾河流交汇水域的最新研究成果,从地貌多样性、流态多样性和生物多样性角度,阐述大型河流交汇水域的特殊生

态功能,为长江水生濒危物种保护和生态系统修复提供理论依据。

1　生境异质性

1.1　地貌单元

河流生态系统具有多层次的自然景观,地貌单元(Geomorphic units)是河流的基本组成部分,包括河漫滩等地貌景观,又称之生境单元(habitat units)或形态单元(morphologic units)[23—24]。交汇水域是河流中常见的自然景观,其河床由特征鲜明的地貌亚单元构成(图 1),包括雪崩面、冲坑和沙滩[25]。其中冲坑与沙滩构建的深潭-浅滩序列,是河流非连续体理论的核心内容[26—27]。

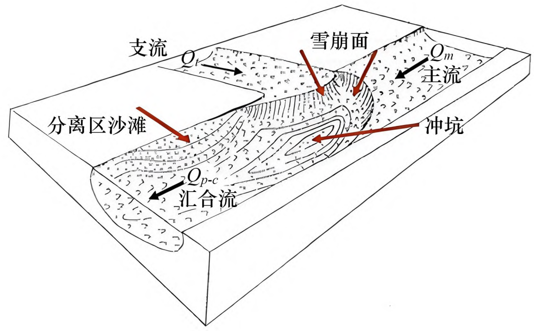

图 1　交汇水域形态模型

Fig.1　Morphologic descriptive model in river confluence

Q_t: 支流流量;Q_m: 主流流量;Q_{p-c}: 汇合流流量,参考[25]

为了简化研究,实验室通常模拟高程相同,含沙量一致的顺直河道开展水槽实验[14, 16, 28],但真实河流宽深比范围大、地质结构、断面形态和糙率差异大,因此天然河流交汇水域地貌特征与水力条件差异明显[29]。大型河流的交汇水域,河床高程通常不一致[30]。如皖河、九华河等支流在长江干流入口处有几米高的雪崩面,汇入的水流动能强,汇流区水动力响应与水槽实验结果往往不完全一致[31]。虽然鄱阳湖出口河床高程与长江相当,但高流量作用下,类似于河床不一致的效应,混合层受到抑制,结果分离区萎缩[8, 32]。对于交汇水域地貌环境的认识,主要来自实验室[14—16]和中小型辫状河流的观察[33],近年来,世界大型冲积河流的交汇水域研究明显增多[34—36],为研究濒危物种选择利用交汇水域栖息地提供了有价值的资料。

1.2　冲坑

冲坑是交汇水域常见的河床形态,Mosley 首次在室内对冲坑进行详细研究[14]。当汇流角和流量比增加时,冲坑深度会发展,野外测量与实验水槽模拟的结果较一致[15]。两条支流的流量接近时,冲坑深度最大,反之则下降[25]。低汇流角,冲坑呈细长沟状;高汇流角,冲坑似盘状[37]。当两个支流的流量接近时,冲坑长轴方向会平分切入的汇流角。反之,冲坑长轴偏向流量大的一侧[38]。

Ghobadian 对河床一致的交汇水域进行广泛实验,发现当交汇水域下游的密度弗劳德(*Fr*)系数、流量比和汇流角的增加,冲坑深度也会增加[39]。Biron 等在野外测量 60°的汇流角,也发现河床不一致河流交汇处没有冲坑[33]。然而,随着河流宽深比或粒径增大时,冲坑深度会降低[40]。在低流量条件下,能看到冲坑,可能与螺旋涡环存在有关。然而高流量会出现反向螺旋环,下游远处的冲坑会消失[8]。但泥沙含量高的河流,高流量冲坑会扩大,如黄河[34]。

上述有关冲坑的形态、深度和位置及发展动力机制,大部分来自于实验模型或者小型辫状河网的研究。近年来涉及到大型冲积河流的交汇水域如长江鄱阳湖口和亚马逊的 Negro-Solimões 河口,但是很少关注河流中江心洲交汇水域的地貌环境。例如,中华鲟(*Acipenser sinensis*)是一种古老珍稀的硬骨鱼,生活在近海大陆架水域,成熟个体沿河道深槽长距离溯河至长江上游繁殖,长江口成为中华鲟迁移的关键通道[41],而沿途的所有洲尾冲坑可能为远距离溯河繁殖的个体提供庇护。

1.3　沙滩

交汇水域下游河道形状和沉积物,通过对流量、推移质和上游河道形状响应进行调整[42]。辫状河道更新与交汇水域下游水流扩张和沙洲移动或推移质穿过汇入流有联系[43]。汇入流中横向移动可能加快点状沙洲复合体的堆积,而汇入流向下游移动,往往会侵蚀或完全清除现存的沙洲[44]。除了汇入流移动引起沙滩变化外,流量或推移质输送率也起作用。如冲坑轴旋转,汇入流调整和沉积物移动,导致沙滩撕裂[45]。总流量变化能引起冲刷区域扩张或收缩,可能会导致交汇河道中冲坑的消失[46]。局部冲刷与沉积,会导致河床不均

匀,曲率快速变化,加快了自然河道剧烈弯曲效应[32].

决定交汇水域河床形态和泥沙输送的主要是汇流角,其次是流量比。起初输送的泥沙大部分沉积在分离区沙滩迎面,后来移到沙滩背处[25]。当汇流角和流量比增加时,交汇河道内泥沙分布逐渐地滞留在汇流角的通道上,向周边输送而不是穿过汇流中心[16]。伴随着主河道雪崩面从交汇水域中退缩,泥沙滞留在下游连接角的支流一侧,形成河岸分离区边滩[33]。亚马逊河的 Negro -Solimoes 交汇水域的分离区大小随着汇入流量增加而增大,长度由 2.5 km 增加到 4 km[47]。

2 流态多样性

2.1 水力单元

水力单元(hydrodynamic unit)是水流形式(flow pattern)及其相应的地貌单元共同构建的流场(flow construct),又称之为流态(flow regime)。从宏观到微观不同尺度上,河流包含了许多异质性或斑块状的水力单元[24]。河流空间上能量梯度和涡度,可以用于判别不同河段或河道中不同地貌单元的水力特征[48—49]。此外,水力特征还可以用切应力、雷诺数、弗劳德数等水力参数描述[50]。

两条水流携带不同动能汇合,经常在下游产生受 Kelvin-Helmholtz(*KH*)不稳定驱动的剪切层,在空间发展成对涡环,紊动能增强,促进了能量和其它物质混合与交换[51]。Best 提出交汇水域经典模型概念(图 2),汇流水力区(Confluence hydrodynamic zone;CHZ)明确包括 6 个水力子单元(流态),即滞留区、偏转区、分离区、加速区、恢复区和剪切层(或混合层)[25]。此后,从辫状河网到大型冲积河流,该模型不断得到验证和完善[52]。

自然界所有河流交汇水域在河床形态、泥沙输送和水力动态上有差异,影响因子有平面对称性、连接角度、两个河流能量比和通量差(水温、密度)、河床高程一致性等[54]。常见的流量与速度表达的动能比(M_r)公式如下[55]:

$$M_r = \frac{\rho_1 Q_1 U_1}{\rho_2 Q_2 U_2}$$

式中,ρ 是水体密度(kg/m^3),Q 是流量(m^3/s),U 是断面平均速度(m/s),下标 1 和 2 分别代表支流和干流。

2.2 剪切层

剪切层定义为狭窄带状高强度湍流或紊流动能[32],交汇水域的剪切层是因为两股汇合水流动能差异大,从汇流角开始向下延伸类似一个涡量平面[56]。剪切层具有强大的涡通量和切应力,并呈现高度自主的水流结构[57]。剪切层中湍流有 2 种类型,当动能比(M_r)接近 1 时,属于冯·卡门涡街[52]。当动能比(M_r)远大于或小于 1 时,属于开尔文—赫姆霍兹(*KH*)类型[57]。开尔文—赫姆霍兹(*KH*)模型中有连续相同方向的成对涡流,切应力比较大,不稳定性是产生大尺寸旋转涡环的主要原因。冯·卡门涡街模型能看到两个方向相反的旋转涡环,产生机制是汇流角类似钝形物体两侧水流分离的结果[58]。野外测量表明交汇水域混合界面和滞留区的水面形态明显升高并有压力梯度[59]。根据无人机影像,Biron 等发现在中等交汇水域动能比在 0.09—1.02范围中,基本都是 *KH* 涡量模式[60]。*KH* 模式涡量级别和发生率比冯·卡门流模式更强,在混合界面(*MI*)两侧局部动能比值随水流方向在变化,因此有时候两种涡流模型会同时出现在 *MI* 不同位置上[52]。

交汇水域平面形状和河床形态能显著影响剪切层位置和形态。河床不一致通常指两个河流河床高程存在差异,Best 和 Roy 首次报道河床不一致交汇水域下游连接角出现上升水流[61],能扭曲准二维混合界面并导致剪切层变形,结果影响泥沙输送和河床形态[33, 62]。在非一致性交汇水域,侧向支流河床高程一般高于主流上下游,水流通过侧向支流出口的台阶,产生强烈湍流,导致混合界面中剪切层发生变形并向支流入口倾斜[33, 61],原因是流体沿支流入口突兀台阶背侧断面压力梯度横向运动[63]。结果下游河道混合速度加快[64],混合距离比以前报道的要缩短 5—10 倍[65]。弯曲的汇流河道,诱导的螺旋运动与高连接角不对称的交汇水域有相似的剪切层。此外,粗糙河床的摩擦力增加,能减缓汇流之间动量交换,河床形态突然变化也能导致混

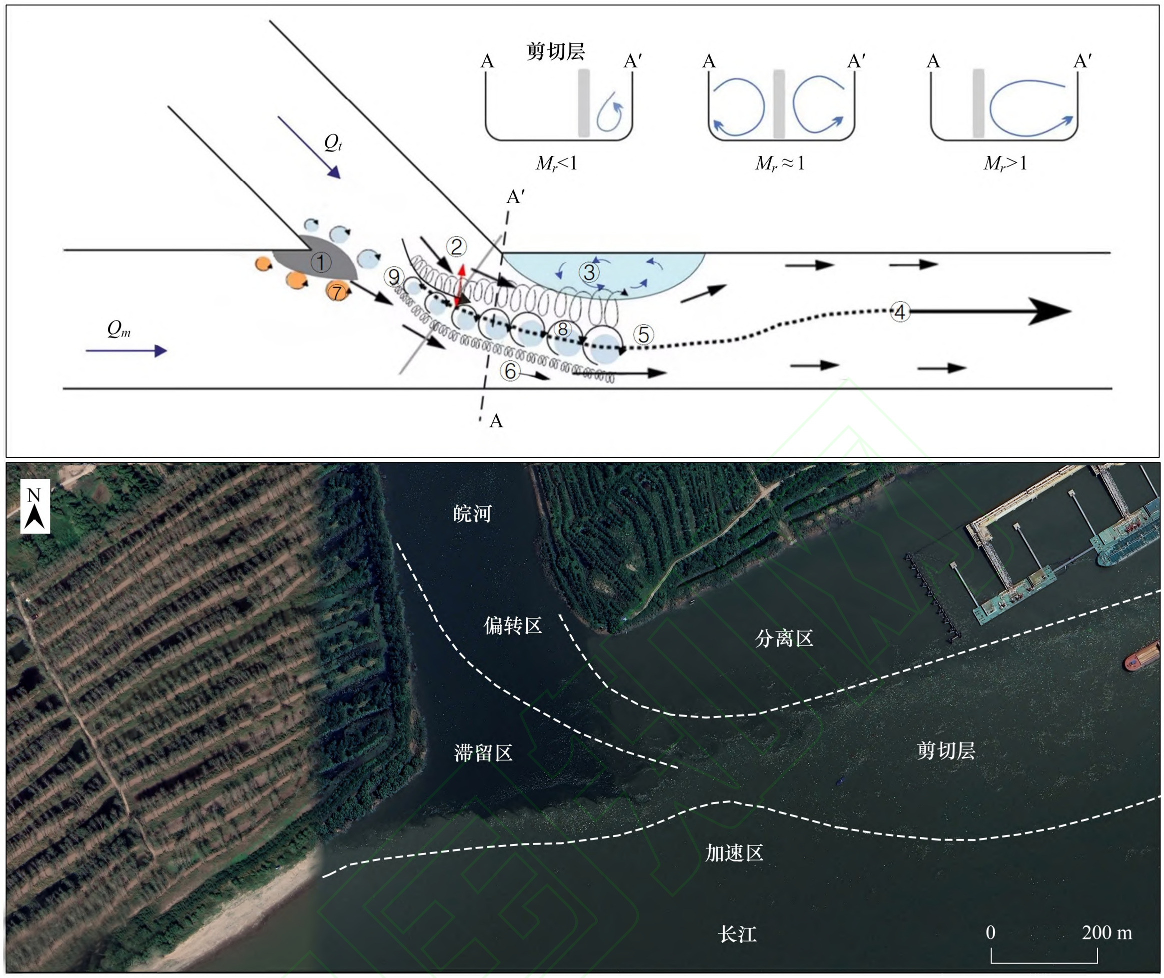

图 2　汇流水力区流态、二次流示意图及皖河口流态实际表征

Fig.2　Sketch showing flow regime and second flow in confluence hydrodynamic zone (CHZ), and the actual flow patterns at the estuary of Wan River

①: 滞留区;②: 偏转区;③: 分离区;④: 恢复区;⑤: 剪切层;⑥: 加速区;⑦: 卡门涡环;⑧: *KH* 涡环;⑨: 水流向涡环;Q_m: 主流;Q_t: 支流;参考[25]、[52]和[53]

合层变形[61]。

2.3　二次流

野外和实验室测量近乎瞬时波动的流速并用涡流解析数值方法进行模拟,都已阐明了交汇水域有不同类型的二次流[66]。经常讨论的 4 种结构,螺旋环(直径相当于支流宽度)、垂直方向的开尔文—赫姆霍兹(*KH*)涡环(切应力沿混合界面诱导的不稳定)、机制不清楚的间歇脉冲[67]和水流向涡环(SOV)。

最常见的二次流是水流向涡环(SOV),位于剪切层两侧,转动轴平行于混合界面,类似一个连续,沿水流方向滚动的环。Mosley 首次在小水槽实验中对这种螺旋环的二次流进行详细研究[14]。这种在混合层两侧或一侧,出现与汇入水流偏转方向相反的表面流以及向河岸底部流动的闭环旋转现象,形成机制归因于向外的离心力和向内的压力梯度[7]。一般通过平面曲率增加,促进抬高的水面向底部流动[68]。近期数值模拟[52, 69]基本证实了至少在河床一致的交汇水域中,涡环(SOV)在冲坑发生和汇流动力区(CHZ)泥沙向外输送起重要作用[70]。数值研究显示水流向涡环(SOV)能与混合界面(*MI*)切应力和水平面涡环发生复杂的相互作用,主要原因是两股水流碰撞汇合区中双峰振荡效应引起的[52]。野外调查长江和鄱阳湖交汇水域,发现高流量情况下会出现双向反向旋转涡流,而低流量仅有单个涡流[8]。河床不一致增加了紊流强度,增强了汇流动力

区(CHZ)上升水流(即从主河道向支流侧流动),而且有些交汇水域中没有水流向涡环(SOV),原因不清楚[55, 71]。

交汇水域下游连接角附近出现了一个水平面旋转环并有强烈的逆向水流,这种二次流是支流从加速区分离汇聚形成一个陡峭的压力梯度的产物[63]。受 *MI* 中螺旋流挟持作用,分离区旋转环在深水河道明显,距离混合界面越远越小[66]。当水流携带足够动能脱离主河道,在分离区形成的旋转环,强度随着流量比和汇流角增大而增加[72]。然而,河床不一致会明显增强支流下游拐角的上升流强度,导致分离区变形或压缩[32]。亚马逊流域的 Negro-Blanco 河流交汇水域,由于汇流顶低流速中存在强大的回水效应,促进支流洪漫滩形成,给下游带来了复杂的水力和混合过程[73]。

交汇水域另一个重要二次流是剪力层的湍流(或紊流),主要特征是由具有垂直轴的大型二维涡旋结构组成,来源于剪力层的开尔文—亥姆霍兹不稳定性。随着距离的增加,通过横向扩展,演变成相同方向一对或合并成单个水平面涡环。不一致河床诱导横断面压强梯度扭曲混合界面(*MI*)和内部平流涡量核心[55,63],明显不同于一致交汇水域的混合机制[65]和沉积物输送形式[71]。

由于河床摩擦力影响 *MI* 发育,相对浅的水流从 *MI* 内部和附近形成大范围连续湍流,一旦涡量直径是水深 2 倍以上,水动力明显受损[72]。在河床高程一致的情况下,而且交汇水域水深足够,*MI* 内部产生垂直方向湍流,在两股水流物质与能量互换发挥重要作用[7, 52]。

2.4 分层

如果两条支流的温度、盐度或悬浮泥沙浓度有差异,那么两条支流的密度就有差异,在汇流顶点下游会存在一个垂直密度界面。由于其两侧的静水压力不同,这种密度界面是不稳定的。如果两条支流密度比值足够大,产生与惯性力相当的浮力,密度界面会从汇流顶点开始向下游变形,混合界面(*MI*)发生剧烈倾斜,密度差异效果明显[73]。靠近河床密度大的水体开始向对岸流动而靠近水面密度小的水体则相反,相当于水流在空间进行了锁交换,到达河岸后双层水流趋于平稳[74]。在汇流区内水流快速成为稳定分层是受理查森系数控制的($Ri = g'D/U_0^2$),其中重力下降$g' = (\Delta\rho/\rho_0)g$,$\rho_0$是两条水流密度均值,$g$ 是重力加速度。密度弗劳德系数与理查森系数有内在联系($Fr_\rho = 1/Ri^{1/2}$)。两个系数都用汇流河道的平均速度(U_0)定义,汇流河道的平均水流深度(D),输入水流密度差异为 $\Delta\rho$。

两个河流水温相差 $\Delta T = 4.7°C$,流量比大且河床不一致。当 $Ri = 1.89$,模拟发现两股水流密度不同比密度相同的混合速度要快[75]。长江夏季水温低于鄱阳湖,而冬季则相反。当水温相差 $\Delta T = 2.5°C$,出现了与天然小型河流交汇水域相反的情况,即混合界面(*MI*)附近的水流向涡环(SOV)消失。主要原因是两股水流密度差异大,密度大的水流靠近河床流动,导致混合层边界倾斜,不仅影响混合界面(*MI*)位置和宽度以及其中的紊流与汇流顶端的尾流脱落涡量的能量,而且还影响弯曲河道产生的螺旋涡环[76]。亚马逊流域的 Solimões-Negro 交汇水域,来自 Andes 山区 Solimões 河含侵蚀性沉积物高,而穿过森林的 Negro 河中沉积物少。两条河流的温度、营养物和氧气含量存在显著差异,会发生世界最为壮观的长达 6 km 混合层[77]。近期研究发现流速快密度大的支流倾向形成连续顺时针 SOV,而流速慢密度大的支流导致混合界面不稳定。因此,支流速度与密度锋面的传播相反,改变了二次流性质[78]。河流中释放高温水体也能引起局部分层,例如 Mississippi 河与 Meramec 河交汇处的 Meramec 热电厂热源排放,除了影响汇流水流结构外,还危及许多鱼类和贝类生活史关键阶段[75]。

很显然,分层不仅能影响汇流动力区(CHZ)的水动力[76]和泥沙输送[77],而且还能影响物质和能量交换[78],是河流水生生物在交汇水域聚集与扩散的重要驱动因子,但生态过程和机理目前很少研究。对于受季风显著影响的长江中下游,年内降雨季节性变化明显,泥沙输送时空动态差异显著,交汇水域分层效应及生物群落的响应机制都是未来亟需研究的内容。

3 生物多样性

通过连接不同规模与水文过程的河流,交汇水域成为河网系统重要的环境异质资源[79]。河网结构中,流

量和空间配置不同的河流交汇产生边际效应,生物与非生物过程相互作用,塑造物种丰度和群落组成的显著梯度[80]。如悬移质含量高的 Bermej 河与 Paraguay 河交汇水域,输入细沙对流体环境中底栖生物分布和运动的潜在影响,体现出物理过程中的阻碍与过滤作用[81]。从支流带来的粗糙有机质、沙粒和木屑,丰富了交汇水域的底质多样性[82]。栖息地的多样性进而驱动无脊椎动物通过丰度和密度对鱼类等高营养级消费者的数量增长产生影响[18]。

3.1　无脊椎动物

大型无脊椎动物对河流生态系统的物质通量和生态过程有重要影响,并促进河流生物多样性[83]。河流交汇水域大型底栖无脊椎动物的多样性通常要高于河段上下游[84]。天然石砾河流中,因交汇水域下游底质粒径和河床稳定性增加,促使下游大型无脊椎动物增加,并向大型滤食性石蛾比例占优的群落结构演替[84]。研究表明,美国林业保护区内干支流交汇水域双翅目、大型石蛾和幼鱼的数量显著增加[82]。支流携带的粗糙生物质和大型无脊椎动物可以为干流的鱼类和其他消费者提供食物[85]。交汇水域低流速区的存在和水生植物的庇护作用,使许多个体大小介于支流和下游的浮游动物得以生存[86]。交汇水域的一些水文"盲区",如滞留区和回水区,能够满足浮游植物分布水深及透光条件,完成光合作用、增殖和生长[87]。长江与皖河交汇水域,洪水期(5—7 月)浮游动物种类最多,达 53 种,数量与生物量明显高于其它区域样点,底栖动物种类和数量也显著高于邻近水域[88]。然而,夏季皖河口鲜有长江江豚觅食[89],无脊椎动物作为长江江豚饵料鱼的食物资源,在该水域的上行效应并不明显[88]。

以往在通过水生无脊椎动物时空格局或物种多样性来评估河流水生态环境质量,并研判人类活动影响的研究中,关于流域内无脊椎动物的监测,几乎都只是在不同级别的河流(从河源到河口)设置断面[90],近年来才开始研究交汇水域水生生物聚集与扩散的生态功能。但并未考虑交汇水域地貌单元、水力单元与生物多样性之间的关系,如交汇水域滞留区和分离区内细沙粒沉积过程的生物絮凝对浮游生物和底栖生物的聚集作用[91],河床粗糙率对底栖动物的屏护作用等[92],这些都是将来研究需要关注的科学问题。

3.2　鱼类

大型河流汇合区有宽泛的入流条件,如流量、水质、沉积物,成就了交汇水域中多样的栖息地和复杂的水力生物区,为鱼类纵向与侧向移动提供重要节点[93],许多鱼类生活史的完成,需要选择利用交汇水域[94]。密西西比河支流交汇水域,为多种鱼类提供低流量下的适宜栖息地,与索饵、休息和繁殖密切相关[95]。孟加拉国 Padma-Meghna 河交汇水域中至少有 199 种鱼,其中极危鱼类 6 种,成为该国鱼类资源和生物多样性保护的重要水域[96]。在皖河口,尽管渔获物数量和重量与周边水域无显著差异,但鱼类种类最多,中上层小型鱼类比例更高,如鳌(*Hemiculter leucisculus*)、贝氏鳌(*Hemiculter bleekeri*)等,为长江江豚偏好的饵料鱼[97]。eDNA 和鱼探仪监测表明,长江与鄱阳湖交汇水域鱼类密度、大小和种类空间异质高,夏季高流量小型鱼类数量基本上高于鄱阳湖低速出口水域[36]。

鱼类是河流食物网中的高营养级生物,物种及群落时空分布受诸多因子驱动,其中水流速度对鱼类生理过程十分重要[98]。交汇水域滞留区和分离区,为一些小型鱼类和稚仔鱼提供低流速的栖息地,因为这些鱼在生理代谢和运动解剖方面不适应高速水流[99—100]。洪水暴涨季节交汇水域雪崩面为鱼类提供临时庇护所[101],而冲坑类似水缓的深潭为鱼类提供越冬场所[102]。交汇水域的水流结构为大鳞钩吻鲑(*Oncorhynchus tshawytscha*)前往繁育场发挥了积极作用[19]。被动集成发射器跟踪发现,目标鱼进入支流繁殖和索饵,而交汇水域异质栖息地提供了通道作用[103]。

许多研究者在实验室水槽对鱼类游泳速度[104]、涡量[105]和集群[106]的水动力机制进行研究。运用 k-ω 紊流模型,发现高流速比或者较大汇流角会增加紊流强度,明显影响鱼游泳速度[107]。涡流大小与鱼大小的比值、"动量比"(涡流动量与鱼动量之比)以及涡流与鱼之间的相互作用时间,在确认鱼的姿势和轨迹阈值十分重要[108]。运用声学仪器和数值模拟技术,研究鱼类在长江和鄱阳湖之间洄游和繁殖的水力特征取得了部分进展[36]。然而,传统网具在固定样点捕鱼,无法与栖息地的物理特性和水力特征相匹配[53]。随着人工智能

技术进步,在无人艇装上鱼探仪或多谱勒流速仪,可以深入开展这方面研究。

3.3 淡水豚

现存的 7 种淡水鲸类动物,均分布于世界热带雨林和季风区的大型河流中[109]。据报道白鱀豚经常在洲尾交汇水域的混合层或礁石下游深潭中活动[110—111]。亚马逊河的亚河豚(*Inia geoffrensis*)和 Tucuxi(*Sotalia fluviatilis*)偏爱河流交汇水域[112]。研究人员发现恒河豚(*Platanista gangetica*)在交汇水域中活动,呈斑块状分布于印度、尼泊尔和孟加拉国境内的恒河[113—114]。拉河豚(*Pontoporia blainvillei*)也全年在河口活动,如阿根廷的 Bahía San Blas、Bahía Anegada 和 Rio Negro 河口[115—116]。虽然湄公河伊河豚(*Orcaella brevirostiris*)雨季活动范围较大,但旱季集中于沙洲交汇水域的深潭中[117]。在长江干流部分江心洲尾部交汇水域中,全年都有长江江豚活动记录,而河口却有明显的季节性差异[118]。水位急剧变化时,东洞庭湖长江江豚活动于下游扁山水域,而水位稳定时,则在鲶鱼口交汇水域聚集[119]。鄱阳湖有 5 条重要支流,在湖区汇合处称之为尾闾水域,是江豚低水位期的重要栖息地[120]。在鄱阳湖与长江交汇水域中,当湖水与江水温差大于 2.5℃时,断面螺旋流形成的涡流,影响着热量交换与生物聚集[121],小型鱼类数量高[36],因此夏季长江江豚在鄱阳湖口聚集活动明显增多[122],但是皖河口与长江交汇水域却相反,仅仅枯水期有江豚聚集活动,其它月份几乎看不到[89, 123]。究其原因,除食物资源外,水动力对江豚及其猎物的驱动作用不可忽视。

鱼类为了提升游动能力,从环境涡量中获得能量已是普遍认可的水动力机制[124]。由于交汇水域广泛存在着涡流,鱼类可以感知并沿着分离区与剪切层之间移动[100]。而且交汇水域雷诺数较高,喜欢在这些水域聚集活动的鲸类,水体中的阻力系数(*Cd*)较低,因此能耗相对较低[125]。近期,运用 MIKE21 水力模型模拟枯水期皖河口交汇水域涡量空间分布图,并将野外记录的江豚数据进行关联分析,发现长江江豚偏爱的涡量值为 1.0—1.5 $\times 10^{-3}$ s^{-1},主要分布在汇流角附近[126],与 Chen 报道的江豚活动水域较为一致[89],推测汇流角有卡门涡街存在,小型鱼聚集在钝形障碍体下游,利用涡流能降低运动能耗[127]。

淡水鲸类依赖的交汇水域经常受人类强烈活动影响[128]。涉水工程主要包括大坝、拦河坝、堤岸加固和河道整治[129]。印河豚和恒河豚已受 20 个大坝和 50 个大规模拦河坝灌溉系统影响,导致沙洲、江心洲、回水区和深潭可利用栖息地面积减少[130—131]。三峡大坝、葛洲坝及其它小型坝体、拦水坝、支流与附属湖泊的护岸工程,已被确定为导致交汇水域淡水豚栖息地减少的主要因素[132—134]。长江下游太子矶江段炸礁后,白鱀豚在交汇水域活动范围明显收缩,活动次数与时间急剧下降[135]。东流江段航道整治后,洲尾交汇水域江豚活动虽有所恢复,但仍低于施工前[136]。长江众多涉水工程,改变了分汊河段的流量比与输沙率,加快了河道演替进程,最终会影响分汊河流交汇水域的水力条件[137]。然而,交汇水域中涡量斑块发生、发展和毁坏过程对淡水鲸类动物聚集的影响尚无研究。

4 结束语

交汇水域是河流景观异质性最强,物化最活跃的地貌单元,能够接收瞬息万变的流量、水温、沉积物等,改变并重塑变化的河流栖息地,并为水生生物提供纵向和侧向迁移通道,是维系健康的河流生态系统关键水域,也是研究流体中动物运动、河流生态系统物质通量生态过程与演化机制的科学模板。从三江源至长江入海口,其间有数以万计、大小不等的交汇水域,由于人为活动的影响,大部分结构和功能遭到削弱或破坏。明确交汇水域的水力特征和生态功能,结合鱼类、淡水豚类的繁殖、索饵、洄游或迁移等习性,适时开启闸门,调节流量,促进已受损的江湖交汇水域结构和生态功能的恢复,对全流域生态修复与水生生物多样性保护、水生态安全和区域经济发展有积极作用。

参考文献(References):

[1] Dooge J C I. Sensitivity of runoff to climate change: a hortonian approach. Bulletin of the American Meteorological Society, 1992, 73(12): 2013-2024.

[2] Teng J, Vaze J, Chiew F H S, Wang B, Perraud J M. Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling

climate change impact on runoff. Journal of Hydrometeorology, 2012, 13(1): 122-139.

[3] Ward J V, Tockner K, Arscott D B, Claret C. Riverine landscape diversity. Freshwater Biology, 2002, 47(4): 517-539.

[4] Liu Y, Tian F, Hu H, Sivapalan M. Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River basin, Western China: the Taiji-Tire model. Hydrology and Earth System Sciences, 2014, 18(4): 1289-1303.

[5] He F Z, Thieme M, Zarfl C, Grill G, Lehner B, Hogan Z, Tockner K, Jähnig S C. Impacts of loss of free-flowing rivers on global freshwater megafauna. Biological Conservation, 2021, 263: 109335.

[6] Winant C D, Browand F K. *Vortex* pairing: the mechanism of turbulent mixing-layer growth at moderate Reynolds number. Journal of Fluid Mechanics, 1974, 63(2): 237-255.

[7] Constantinescu G, Miyawaki S, Rhoads B, Sukhodolov A, Kirkil G. Structure of turbulent flow at a river confluence with momentum and velocity ratios close to 1: Insight provided by an eddy-resolving numerical simulation. Water Resources Research, 2011, 47(5): 2010WR010018.

[8] Yuan S Y, Tang H W, Li K, Xu L, Xiao Y, Gualtieri C, Rennie C, Melville B. Hydrodynamics, sediment transport and morphological features at the confluence between the Yangtze River and the Poyang Lake. Water Resources Research, 2021, 57(3): e2020WR028284.

[9] Campbell E, Alfaro-Shigueto J, Aliaga-Rossel E, Beasley I, Briceño Y, Caballero S, da Silva V, Gilleman C, Gravena W, Hines E, Khan M S, Khan U, Kreb D, Mangel J C, Marmontel M, Mei Z, Mintzer V J, Mosquera-Guerra F, Oliveira-da-Costa M, Paschoalini M, Paudel S, Sinha R K, Smith B D, Turvey S T, Utreras V, Van Damme P A, Wang D, Whitty T S, Thurstan R H, Godley B J. Challenges and priorities for river cetacean conservation. Endangered Species Research, 2022, 49: 13-42.

[10] Ren P, Hou G, Schmidt B V, Fang D, Xu D P. Longitudinal drifting pattern of larval assemblages in the lower reach of the Yangtze River: Impact of the floodplain lakes and conservation implementation. Ecology of Freshwater Fish, 2022, 31(2): 410-423.

[11] Chen J. Evolution and Water Resources Utilization of the Yangtze River. Wuhan, Changjiang Press Co., Ltd. & Springer Nature Singapore Pte Ltd, 2020, 341-383.

[12] 连玉喜, 杨晓鸽, 陈娜, 王云生, 李世健, 陈敏敏, 于道平. 航道整治期间长江江豚临时庇护所建设及效果评估. 生态学报, 2024, 44(12): 5185-5193.

[13] Lee L H Y, Clark J A. Angled Injection of jets into a turbulent boundary layer. Journal of Fluids Engineering, 1980. 102:211-218.

[14] Mosley M P. An experimental study of channel confluences. Journal of Geology, 1976, 84(5): 535-562.

[15] Ashmore P, Parker G. Confluence scour in coarse braided streams. Water Resources Research, 1983, 19(2): 392-402.

[16] Best J L, Reid I. Separation zone at open-channel junctions. Journal of Hydraulic Engineering, 1984, 110(11): 1588-1594.

[17] Lee B D, Poff N L, Miller D, Dunne T, Reeves G, Pess G, Pollock M. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience, 2004, 54(5): 413.

[18] Boddy N C, Booker D J, McIntosh A R. Heterogeneity in flow disturbance around river confluences influences spatial patterns in native and non-native species co-occurrence. Biological Invasions, 2020, 22(11): 3457-3475.

[19] Luis S M, Pasternack G B. Local hydraulics influence habitat selection and swimming behavior in adult California Central Valley Chinook salmon at a large river confluence. Fisheries Research, 2023, 261: 106634.

[20] Bradbrook K F, Lane S N, Richards K S. Numerical simulation of three-dimensional, time-averaged flow structure at river channel confluences. Water Resources Research, 2000, 36(9): 2731-2746.

[21] Lewis Q W, Rhoads B L. Rates and patterns of thermal mixing at a small stream confluence under variable incoming flow conditions. Hydrological Processes, 2015, 29(20): 4442-4456.

[22] Gualtieri C, Filizola N, de Oliveira M, Santos A M, Ianniruberto M. A field study of the confluence between Negro and solimões rivers. part 1: hydrodynamics and sediment transport. Comptes Rendus Geoscience, 2018, 350(1/2): 31-42.

[23] Duncan W W, Poole G C, Meyer J L. Large channel confluences influence geomorphic heterogeneity of a southeastern United States river. Water Resources Research, 2009, 45(10): W10405.

[24] Belletti B, Rinaldi M, Bussettini M, Comiti F, Gurnell A M, Mao L C, Nardi L, Vezza P. Characterising physical habitats and fluvial hydromorphology: a new system for the survey and classification of river geomorphic units. Geomorphology, 2017, 283: 143-157.

[25] Best J L. Sediment transport and bed morphology at river channel confluences. Sedimentology, 1988, 35(3): 481-498.

[26] O'Neill M P, Abrahams A D. Objective identification of pools and riffles. Water Resources Research, 1984, 20(7): 921-926.

[27] Ward J V, Stanford J A. The serial discontinuity concept: extending the model to floodplain rivers. Regulated Rivers-research & Management, 1995, 10: 159-168.

[28] Ashmore P E. Laboratory modelling of gravel braided stream morphology. Earth Surface Processes and Landforms, 1982, 7(3): 201-225.

[29] Rice S P, Kiffney P, Greene C, Pess G R. The ecological importance of tributaries and confluences. In: Rice SP, Roy AG, Rhoads B (eds) River confluences, tributaries and the fluvial network. Wiley, Chichester, 2008.

[30] Kennedy B A. On Playfair's law of accordant junctions. Earth Surface Processes and Landforms, 1984, 9(2): 153-173.

[31] Park E, Latrubesse E M. Surface water types and sediment distribution patterns at the confluence of mega rivers: The Solimões-Amazon and Negro Rivers junction. Water Resources Research, 2015, 51(8): 6197-6213.

[32] Biron P, Best J L, Roy A G. Effects of bed discordance on flow dynamics at open channel confluences. Journal of Hydraulic Engineering, 1996, 122(12): 676-682.

[33] Biron P, Roy A, Best J L, Boyer C J. Bed morphology and sedimentology at the confluence of unequal depth channels. Geomorphology, 1993, 8(2/3): 115-129.
[34] Zhang T, Feng M Q, Chen K L. Hydrodynamic characteristics and channel morphodynamics at a large asymmetrical confluence with a high sediment-load main channel. Geomorphology, 2020, 356: 107066.
[35] Luz L D, Szupiany R N, Parolin M, Silva A, Stevaux J C. Obtuse-angle *vs.* confluent sharp meander bends: insights from the Paraguay-Cuiabá confluence in the tropical Pantanal wetlands, Brazil. Geomorphology, 2020, 348: 106907.
[36] Yuan S Y, Qiu J J, Tang H W, Xu L, Xiao Y, Liu M Y, Rennie C, Gualtieri C. Fish community traits near a large confluence: Implications for its nodal effects in the river ecosystem. Journal of Hydrology, 2023, 626: 130335.
[37] Best J L, Ashworth P J. Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. Nature, 1997, 387(6630): 275-277.
[38] Best J L, Rhoads B L. Sediment transport, bed morphology, and the sedimentology of river channel confluences. In: Rice S P, Roy A G, Rhoads B L. (Eds.), River Confluences, Tributaries and the Fluvial Network, Wiley, Chichester, 2008: 45-72.
[39] Ghobadian R, Bajestan M S. Investigation of sediment patterns at river confluence. Journal of Applied Sciences, 2007, 7(10): 1372-1380.
[40] Bejestan M S, Hemmati M. Scour depth at river confluence of unequal bed level. Journal of Applied Sciences, 2008, 8(9): 1766-1770.
[41] Zhu J Z, Guo W T, Li Z Y, Jiang W. First insights into the migration route and spatial distribution of the endangered Chinese sturgeon (*Acipenser sinensis*) in the Yangtze River Estuary. Fishes, 2024, 9(8): 321.
[42] Ashworth P J, Best J L, Roden J E, Bristow C S, Klaassen G J. Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. Sedimentology, 2000, 47(3): 533-555.
[43] Ashmore P. Anabranch confluence kinetics and sedimentation processes in gravel-braided streams. Geological Society, London, Special Publications, 1993, 75(1): 129-146.
[44] Ashworth P J. Mid-channel bar growth and its relationship to local flow strength and direction. Earth Surface Processes and Landforms, 1996, 21(2): 103-123.
[45] Ferguson R I. Understanding braiding processes in gravel-bed rivers: progress and unsolved problems. Geological Society, London, Special Publications, 1993, 75(1): 73-87.
[46] Rhoads B L, Riley J D, Mayer D R. Response of bed morphology and bed material texture to hydrological conditions at an asymmetrical stream confluence. Geomorphology, 2009, 109(3/4): 161-173.
[47] Gualtieri C, Martone I, Filizola N PJr, Ianniruberto M. Bedform morphology in the area of the confluence of the Negro and solimões-Amazon rivers, Brazil. Water, 2020, 12(6): 1630.
[48] Crowder D W, Diplas P. Evaluating spatially explicit metrics of stream energy gradients using hydrodynamic model simulations. Canadian Journal of Fisheries and Aquatic Sciences, 2000, 57(7): 1497-1507.
[49] Crowder D W, Diplas P. Vorticity and circulation: spatial metrics for evaluating flow complexity in stream habitats. Canadian Journal of Fisheries and Aquatic Sciences, 2002, 59(4): 633-645.
[50] Moir H J, Soulsby C, Youngson A. Hydraulic and sedimentary characteristics of habitat utilized by Atlantic salmon for spawning in the Girnock Burn, Scotland. Fisheries Management and Ecology, 1998, 5(3): 241-254.
[51] Rhoads B L, Sukhodolov A N. Field investigation of three-dimensional flow structure at stream confluences: 1. Thermal mixing and time-averaged velocities. Water Resources Research, 2001, 37(9): 2393-2410.
[52] Constantinescu G, Miyawaki S, Rhoads B, Sukhodolov A. Numerical analysis of the effect of momentum ratio on the dynamics and sediment-entrainment capacity of coherent flow structures at a stream confluence. Journal of Geophysical Research: Earth Surface, 2012, 117(F4): 2012JF002452.
[53] Yuan S Y, Xu L, Tang H W, Xiao Y, Gualtieri C. The dynamics of river confluences and their effects on the ecology of aquatic environment: A review. Journal of Hydrodynamics, 2022, 34(1): 1-14.
[54] Constantinescu G, Gualtieri C. River confluences: a review of recent field and numerical studies. Environmental Fluid Mechanics, 2024, 24(6): 1143-1191.
[55] De Serres B, Roy A G, Biron P M, Best J L. Three-dimensional structure of flow at a confluence of river channels with discordant beds. Geomorphology, 1999, 26(4): 313-335.
[56] Sukhodolov A N, Rhoads B L. Field investigation of three-dimensional flow structure at stream confluences: 2. Turbulence. Water Resources Research, 2001, 37(9): 2411-2424.
[57] Rhoads B L, Sukhodolov A N. Lateral momentum flux and the spatial evolution of flow within a confluence mixing interface. Water Resources Research, 2008, 44(8): 2007WR006634.
[58] Rhoads B L, Sukhodolov A N. Spatial and temporal structure of shear layer turbulence at a stream confluence. Water Resources Research, 2004, 40(6): 2003WR002811.
[59] Cheng Z Y, Constantinescu G. Stratification effects on flow hydrodynamics and mixing at a confluence with a highly discordant bed and a relatively low velocity ratio. Water Resources Research, 2018, 54(7): 4537-4562.
[60] Biron P M, Buffin-Bélanger T, Martel N. Three-dimensional turbulent structures at a medium-sized confluence with and without an ice cover. Earth

Surface Processes and Landforms, 2019, 44(15): 3042-3056.

[61] Best J L, Roy A G. Mixing-layer distortion at the confluence of channels of different depth. Nature, 1991, 350(6317): 411-413.

[62] Sukhodolov A N, Krick J, Sukhodolova T A, Cheng Z Y, Rhoads B L, Constantinescu G S. Turbulent flow structure at a discordant river confluence: Asymmetric jet dynamics with implications for channel morphology. Journal of Geophysical Research: Earth Surface, 2017, 122(6): 1278-1293.

[63] Bradbrook K F, Biron P M, Lane S N, Richards K S, Roy A G. Investigation of controls on secondary circulation in a simple confluence geometry using a three-dimensional numerical model. Hydrological Processes, 1998, 12(8): 1371-1396.

[64] Bradbrook K F, Lane S N, Richards K S, Biron P M, Roy A G. Role of bed discordance at asymmetrical river confluences. Journal of Hydraulic Engineering, 2001, 127(5): 351-368.

[65] Gaudet J M, Roy A G. Effect of bed morphology on flow mixing length at river confluences. Nature, 1995, 373(6510): 138-139.

[66] Shaheed R, Yan X H, Mohammadian A. Review and comparison of numerical simulations of secondary flow in river confluences. Water. 2021, 13(14): 1917.

[67] Sabrina S, Lewis Q, Rhoads B. Large-scale particle image velocimetry reveals pulsing of incoming flow at a stream confluence. Water Resources Research, 2021, 57(9): e2021WR029662.

[68] Sukhodolov A N, Sukhodolova T A. Dynamics of flow at concordant gravel bed river confluences: effects of junction angle and momentum flux ratio. Journal of Geophysical Research: Earth Surface, 2019, 124(2): 588-615.

[69] Constantinescu G. LE of shallow mixing interfaces: a review. Environmental Fluid Mechanics, 2014, 14(5): 971-996.

[70] Paola C. When streams collide. Nature, 1997, 387(6630): 232-233.

[71] Leite Ribeiro M, Blanckaert K, Roy A G, Schleiss A J. Flow and sediment dynamics in channel confluences. Journal of Geophysical Research: Earth Surface, 2012, 117(F1): 2011JF002171.

[72] Cheng Z, Constantinescu G. Spatial development of a constant-depth shallow mixing layer in a long channel//River Flow 2014. Boca Raton: CRC Press, 2014: 155-161.

[73] Sukhodolov A N, Shumilova O O, Constantinescu G S, Lewis Q W. Mixing dynamics at river confluencees governed by intermodal behaviour. Nature Geoscience, 2023, 16: 89-93.

[74] Cheng Z Y, Constantinescu G. Shallow mixing interfaces between parallel streams of unequal densities. Journal of Fluid Mechanics, 2022, 945: A2.

[75] Cheng Z Y, Constantinescu G. Stratification effects on hydrodynamics and mixing at a river confluence with discordant bed. Environmental Fluid Mechanics, 2020, 20(4): 843-872.

[76] Lyubimova T P, Lepikhin A P, Parshakova Y N, Kolchanov V Y, Gualtieri C, Roux B, Lane S N. A numerical study of the influence of channel-scale secondary circulation on mixing processes downstream of river junctions. Water, 2020, 12(11): 2969.

[77] Szupiany R N, Amsler M L, Parsons D R, Best J L. Morphology, flow structure, and suspended bed sediment transport at two large braid-bar confluences. Water Resources Research, 2009, 45(5): W05415.

[78] Lewis Q W, Rhoads B L. Resolving two-dimensional flow structure in rivers using large-scale particle image velocimetry: an example from a stream confluence. Water Resources Research, 2015, 51(10): 7977-7994.

[79] Rice S P, Greenwood M T, Joyce C B. Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrate fauna along river systems. Canadian Journal of Fisheries and Aquatic Sciences, 2001, 58(4): 824-840.

[80] Czeglédi I, Sály P, Takács P, Dolezsai A, Nagy S A, Erös T. The scales of variability of stream fish assemblages at tributary confluences. Aquatic Sciences, 2016, 78(4): 641-654.

[81] Blettler M C M, Amsler M L, Ezcurra D D I, Grago E, Paira A, Espinola I A, Eberle E, Szupiany R. Fine sediment input and benthic fauna interactions at the confluence of two large rivers. International Journal of Environmental Research, 2016, 10(1): 65-76.

[82] Kiffney P M, Greene C M, Hall J E, Davies J R. Tributary streams create spatial discontinuities in habitat, biological productivity, and diversity in mainstem rivers. Canadian Journal of Fisheries and Aquatic Sciences, 2006, 63(11): 2518-2530.

[83] Clarke A, Mac Nally R, Bond N, Lake P S. Macroinvertebrate diversity in headwater streams: a review. Freshwater Biology, 2008, 53(9): 1707-1721.

[84] Knispel S, Castella E. Disruption of a longitudinal pattern in environmental factors and benthic fauna by a glacial tributary. Freshwater Biology, 2003, 48(4): 604-618.

[85] Wipfli M S, Gregovich D P. Export of invertebrates and detritus from fishless headwater streams in southeastern Alaska: implications for downstream salmonid production. Freshwater Biology, 2002, 47(5): 957-969.

[86] Bolotov S E, Tsvetkov A I, Krylov A V. Zooplankton in the zones of confluence of unregulated rivers. Inland Water Biology, 2012, 5(2): 184-191.

[87] Descy J P, Servais P, Smitz J S, Billen G, Everbecq E. Phytoplankton biomass and production in the river Meuse (Belgium). Water Research, 1987, 21(12): 1557-1566.

[88] Zhang X K, Wang H L, Wan A, Chen M M, Wang K X, Yu D P. Effects of macrozoobenthos and zooplankton on the occurrence of Yangtze finless porpoise *via* the bottom-up force at a confluence of rivers. Nature Environment and Pollution Technology, 2018, 17: 175-182.

[89] Chen M M, Zhang X K, Wang K X, Liu Z G, Wan A, Yu D P, Ji H, Peng F Z. Spatial and temporal distribution dynamics of the Yangtze finless porpoise at the confluence of the Yangtze and wanhe rivers: implications for conservation. Pakistan Journal of Zoology, 2017, 49(6): 2263-2269.

[90] Barsukova N N, Bazhenova O P, Kolesnichenko L G. Phytoplankton as an indicator of the current ecological status of the Ob River. Acta Biologica Sibirica, 2021, 7: 573-591.

[91] Blettler M C M, Amsler M L, Ezcurra de Drago I, Espinola L A, Eberle E, Paira A, Best J L, Parsons D R, Drago E E. The impact of significant input of fine sediment on benthic fauna at tributary junctions: a case study of the Bermejo-Paraguay River confluence, *Argentina*. Ecohydrology, 2015, 8(2): 340-352.

[92] Zanke U, Roland A, Wurpts A. Roughness effects of subaqueous ripples and dunes. Water, 2022, 14(13): 2024.

[93] Röpke C P, Amadio S A, Winemiller K O, Zuanon J. Seasonal dynamics of the fish assemblage in a floodplain lake at the confluence of the Negro and Amazon Rivers. Journal of Fish Biology, 2016, 89(1): 194-212.

[94] Li H F, Yu X J, Wu B B, Yu L X, Wang D Q, Wang K, Wang S, Chen D Q, Li Y F, Duan X B, Li J. Temporal and spatial distribution characteristics of fish resources in a typical river-lake confluence ecosystem during the initial period of fishing ban. Fishes, 2024, 9(12): 492.

[95] Braaten P J, Guy C S. Relations between physicochemical factors and abundance of fishes in tributary confluences of the lower channelized Missouri River. Transactions of the American Fisheries Society, 1999, 128(6): 1213-1221.

[96] Azadi M, Sarker M M. Fish fauna of the Padma-Meghna River confluence of Bangladesh. Journal of Biodiversity Conservation and Bioresource Management, 2015, 1(2): 31-40.

[97] 张晓可, 于道平, 王慧丽, 万安, 蒋泽球, 陈寿文.长江安庆段江豚主要栖息地鱼类群落结构. 生态学报, 2016, 36(7): 1832-1837.

[98] Power M E, Jr Dietrich W E. Food webs in river networks. Ecological Research, 2024, 17: 451-471.

[99] Smith D L, Brannon E L, Odeh M. Response of juvenile rainbow trout to turbulence produced by prismatoidal shapes. Transactions of the American Fisheries Society, 2005, 134(3): 741-753.

[100] Yuan S Y, Xu L, Tang H W, Xiao Y, Whittaker C. Swimming behavior of juvenile silver carp near the separation zone of a channel confluence. International Journal of Sediment Research, 2022, 37(1): 122-127.

[101] Webb P W. Use of fine-scale current refuges by fishes in a temperate warm-water stream. Canadian Journal of Zoology, 2006, 84(8): 1071-1078.

[102] Rakowitz G, Berger B, Schludermann E, Tritthart M, Habersack H, Keckeis H. Deep pools of the Danube River: ecological function or turbulent sink Hydrobiologia, 2014, 729(1): 143-159.

[103] Cathcart C N, Gido K B, McKinstry M C, MacKinnon P D. Patterns of fish movement at a desert river confluence. Ecology of Freshwater Fish, 2018, 27(1): 492-505.

[104] Lauder G V. Fish locomotion: recent advances and new directions. Annual Review of Marine Science, 2015, 7: 521-545.

[105] Cotel A J, Webb P W. The challenge of understanding and quantifying fish responses to turbulence-dominated physical environments. Natural Locomotion in Fluids and on Surfaces. New York, NY: Springer, 2012: 15-33.

[106] Ashraf I, Bradshaw H, Ha T T, Halloy J, Godoy-Diana R, Thiria B. Simple phalanx pattern leads to energy saving in cohesive fish schooling. Proceedings of the National Academy of Sciences of the United States of America, 2017, 114(36): 9599-9604.

[107] Yan J F, Chu W H, Cao Y, Zhou Q L. Hydrodynamic analysis of fish swimming behavior in turbulent river confluences. Physics of Fluids, 2024, 36(12): 121904.

[108] Cote A J, Webb P W. Living in a turbulent world-a new conceptual framework for the interactions of fish and eddies. Integrative and Comparative Biology, 2015, 55(4): 662-672.

[109] Smith B D, Reeves R R. River cetaceans and habitat change: generalist resilience or specialist vulnerability Journal of Marine Biology, 2012, 2012: 718935.

[110] Hua Y Y, Zhao Q Z, Zhang G C. The habitat and behavior of Lipotes vexillifer. In: Perrin W F, Brownell R L Jr Zhou K Y eds. Biology and Conservation of the River Dolphins. Oceasional Papers of IUCN/SSC,1989.

[111] Zhang X, Wang D, Liu R, Wei Z, Hua Y, Wang Y, Chen Z, Wang L. The Yangtze River dolphin or Baiji (*Lipotes vexillifer*): population status and conservation issues in the Yangtze River, China. Aquatic Conservation: Marine and Freshwater Ecosystems, 2003, 13(1): 51-64.

[112] Martin A R, da Silva V M F, Salmon D L. Riverine habitat preferences of botos and tucuxis in the central Amazon. Marine Mammal Science, 2004, 20(2): 189-200.

[113] Bashir T, Khan A, Gautam P, Behera S K. Abundance and prey availability assessment of Ganges river dolphin (*Platanista gangetica gangetica*) in a stretch of upper Ganges river, India. Aquatic Mammals, 2010, 36(1): 19-26.

[114] Sinha R K, Kannan K. Ganges river dolphin: an overview of biology, ecology, and conservation status in India. AMBIO, 2014, 43(8): 1029-1046.

[115] Failla M, Seijas V A, Espósito R, Iñíguez M A. Franciscana dolphins, *Pontoporia blainvillei*, of the río Negro Estuary, *Patagonia*, *Argentina*. Marine Biodiversity Records, 2012, 5: e102.

[116] Wells R S, Cremer M J, Berninsone L G, Albareda D, Wilkinson K A, Stamper M A, Paitach R L, Bordino P. Tagging, ranging patterns, and behavior of franciscana dolphins (*Pontoporia blainvillei*) off *Argentina* and Brazil: Considerations for conservation. Marine Mammal Science, 2022, 38(2): 571-605.

[117] Stacey P, Hvenchaard G. Habitat use and behavior of Irrawaddy dolphins (*Orcaella brevirostris*) in the Mekong River of Lao. Aquatic Mammals,

2002, 28(1): 1-13.

[118] 王子璇, 陈敏敏, 王康伟, 连玉喜, 于道平. 不同流态中长江江豚的栖息活动比较. 兽类学报, 2022, 42(2): 152-158.

[119] 王崇瑞, 索纹纹, 蒋国民, 李昊旻, 梁志强, 杨鑫, 袁希平, 李鸿, 廖伏初, 葛虹孜, 张辉, 伍远安. 东洞庭湖长江江豚及其与鱼类资源相关性. 中国环境科学, 2019, 39(10): 4424-4434.

[120] Li Q Y, Lai G Y, Liu Y, Devlin A T, Zhan S P, Wang S. Identifying the seasonal characteristics of likely habitats for the Yangtze finless porpoise in Poyang Lake. Aquatic Conservation: Marine and Freshwater Ecosystems, 2022, 32(3): 523-536.

[121] Jiang C Y, Constantinescu G, Yuan S Y, Tang H W. Flow hydrodynamics, density contrast effects and mixing at the confluence between the Yangtze River and the Poyang Lake channel. Environmental Fluid Mechanics, 2023, 23(2): 229-257.

[122] Kimura S, Akamatsu T, Li S H, Dong L J, Wang K X, Wang D, Arai N. Seasonal changes in the local distribution of Yangtze finless porpoises related to fish presence. Marine Mammal Science, 2012, 28(2): 308-324.

[123] Zhang X K, Yu D P, Wang H L, Wan A, Chen M M, Tao F, Song Z R. Effects of fish community on occurrences of Yangtze finless porpoise in confluence of the Yangtze and Wanhe Rivers. Environmental Science and Pollution Research, 2015, 22(12): 9524-9533.

[124] Harvey S T, Muhawenimana V, Müller S, Wilson C A M E, Denissenko P. An inertial mechanism behind dynamic station holding by fish swinging in a *Vortex* street. Scientific Reports, 2022, 12: 12660.

[125] Fish F E. Power outpot and propulsive efficiency of swimming bottlenose dolphins (Tursiops truncatus). Journal of Experimental Biology, 1993, 185:179-193.

[126] Ding R, Zhang X K, Chen M M, Lian Y X, Yu D P. Vorticity preference of the Yangtze finless porpoise (*Neophocaena asiaeorientalis*) during the dry season at the Wanhe River Estuary confluence. Ecological Modelling, 2023, 485: 110504.

[127] Liao J C, Beal D N, Lauder G V, Triantafyllou M S. The *Kármán* gait: novel body kinematics of rainbow trout swimming in a *Vortex* street. Journal of Experimental Biology, 2003, 206(Pt 6): 1059-1073.

[128] Castello L, McGrath D G, Hess L L, Coe M T, Lefebvre P A, Petry P, Macedo M N, Renó V F, Arantes C C. The vulnerability of Amazon freshwater ecosystems. Conservation Letters, 2013, 6(4): 217-229.

[129] Reeves R, Smith B, Kasuya T. Biology and conservation of freshwater cetaceans in Asia. Occasional Paper of the IUCN Species Survival Commission, Gland and Cambridge, 2000.

[130] Reeves R R, Chaudhry A A, Khalid U. Competing for water on the Indus Plain: is there a future for Pakistan's River dolphins Environmental Conservation, 1991, 18(4): 341-350.

[131] Paudel S, Timilsina Y P, Lewis J, Ingersoll T, Jnawali S R. Population status and habitat occupancy of endangered river dolphins in the Karnali River system of Nepal during low water season. Marine Mammal Science, 2015, 31(2): 707-719.

[132] Braulik G T, Arshad M, Noureen U, Northridge S P. Habitat fragmentation and species extirpation in freshwater ecosystems; causes of range decline of the Indus river dolphin (*Platanista gangetica* Minor). PLoS One, 2014, 9(7): e101657.

[133] López-Pujol J, Ren M-X. Biodiversity and the Three Gorges Reservoir: a troubled marriage. Journal of Natural History, 2009, 43(43/44): 2765-2786.

[134] Fang H W, He G J, Han D, Duan J H, Huang L, Chen M H. Fluvial processes and their impact on the finless porpoise's habitat after the Three Gorges Project became operational. Science China Technological Sciences, 2014, 57(5): 1020-1029.

[135] 于道平, 王江. 铜陵江段白鱀豚生态环境与行为的变化. 浙江海洋学院学报(自然科学版), 1999, 18(3): 227-231.

[136] 陈敏敏, 张康, 张平, 严燕, 张四刚, 王康伟, 于道平. 长江安庆段航道整治对长江江豚数量和分布的时空影响. 生态学报, 2023, 43(10): 4242-4249.

[137] Konsoer K M, Rhoads B L. Spatial-temporal structure of mixing interface turbulence at two large river confluences. Environmental Fluid Mechanics, 2014, 14(5): 1043-1070.