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气候变化对湖库水环境的潜在影响研究进展*

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摘　要:本文着重归纳气候变化对湖库热力特性、冰期、溶解氧、营养盐、浮游植物和水生植物等方面的影响规律,探讨气候变化对湖库水环境潜在影响的区域差异,讨论现有研究方法的优缺点和发展前景. 研究表明,气候变暖对湖库物理过程的影响最为显著;热带草原气候和温带海洋性气候对于气候变暖和降雨变化的响应较其他气候类型突出;气候变化对湖库水环境的影响效果具有两面性. 通过分析各气候类型中气候变暖对磷水平的潜在影响差异表明,亚热带季风气候的湖库更可能受气候变暖的影响趋于富营养状态. 在今后研究中,建议深入开展各气候类型中区域性气候变化对湖库水环境影响的实例研究.
关键词:气候变化;气候类型;水环境;区域差异;湖泊;水库;潜在影响

A review of the potential impacts of climate change on water environment in lakes and reservoirs

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Abstract: The objective of the study is to review the research advances in potential impacts of climate change on water environment in lakes and reservoirs. The paper generalizes the effect of climate change on thermal stratification, ice duration, dissolved oxygen, nutrients, phytoplankton, and structure and function of ecosystem in lakes and reservoirs, as well as differences of climate-related responses to water environment are influenced in lakes and reservoirs. The advantages, disadvantages and development of methods in existing studies are discussed. The processes of potential impacts of climate change on water environment of lakes and reservoirs in climate zones are also discussed. It is significant impact of global warming on physical processes in lakes. The responses to global warming and change of rainfall in savannah climate and temperate maritime climate are higher than other climate zones. There are negative and positive impacts of climate change on water environment. The potential impacts of global warming on total phosphorus in each climate zones are analyzed. The result shows that lakes are tend to be eutrophic due to global warming in subtropical monsoon climate. Considering the spatial variations of climatic factors, regional impacts of climate change of different climate zones on water environment in lakes and reservoirs as the perspective on the subject is provided.
Keywords: Climate change; climate zone; water environment; differences in regions; lakes; reservoirs; potential impacts

"气候变化"是当今各国学者研究的热点问题. 政府间气候变化专门委员会(IPCC)认为人类活动已经且持续改变着地表和大气组成,这些变化直接或间接地影响了地球能量平衡,进而引起气候变化[1],即人类活动不可避免地引起了气候变化[2]. 湖库作为淡水生态系统的载体,被喻为气候变化的岗哨,对气候变化有指示、记录和调节作用;另一方面,气候变化直接和间接交互影响着湖库水文、水环境和生态系统功能与服务[3]. 气候变化引起流域径流变化,改变湖库水位和面积[4-5];气候变暖影响湖库热力分层结构和热稳定性,延长分层期,减弱对流混合[6-7];气候变化引起溶解氧下降[5],强化溶解氧分层[8],加剧湖泊富营养化[9-10];气候变化还改变浮游植物春季物候[11]、更易导致浮游植物繁生[12].

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20 世纪末,随着人们对水域生态环境的关注不断提高,科学家们将研究气候变化的影响从水量延伸至水质[13-14]. 我国开展此领域的研究工作晚于欧美发达国家约 15~20 年,主要侧重于气候变化对我国流域或局部地区水文水资源的影响及适应对策方面[15-18],而对地表水环境质量的潜在影响方面处于起步阶段[9,19],除综述外[20-23],已有一些实例研究[7,11]. 气候变化已经且持续影响着湖泊水环境[24],湖泊物理、化学和生物特性对气候变化能做出迅速反应[25],揭示气候变化对湖库水环境的影响机制是亟需解决的重要科学问题. 因此,本文重点综述气候变暖和降雨变化对湖库水环境潜在影响方面的研究进展及主要研究方法.

1 气候变化对湖库水环境的潜在影响规律

气候变化的内涵很丰富,包括气候长期缓慢的变化、极端气候事件、季节交替的年际差异等. 气候变化对湖库影响表现在气候变暖、降雨和风速等其他气候要素变化对湖库物理、化学和生物过程的直接和间接影响. 气候变暖通过改变湖库热力和溶解氧分层(直接影响)进而影响湖库生物过程和生态系统结构与功能(间接影响)[23];降雨变化通过改变流域径流量影响湖库水位和入湖物质负荷进而影响湖库化学和生物过程;风速变化通过改变湖库垂向扰动速度和物质通量进而影响湖库化学和生物过程. 同时,水库相对于自然湖泊,受运行调度等人为因素的干扰更大,两者在气候变化的影响机制上可能存在一定差别.

1.1 气候变暖对湖库热力特性和冰期等物理过程的影响

全球气候变暖已是不争的事实,气候变暖影响着湖库热力分层结构、分层期和热稳定性等热力特性,引起水流垂向对流混合的改变. 位于东非大裂谷地区的 Tanganyika 湖是世界第二古老湖和深水湖,近 100 a 内气候变暖引起上层水体温度升高(约每 0.1℃/(10 a)),导致该湖底层与表层密度差显著升高,阻滞了水体垂向混合,减小混合层和温跃层深度,热稳定性增加了近 1 倍[26-27]. 研究表明在 Zurich 湖[8]、流溪河水库[19]和 Shimajigawa 水库[28]的热力特性也有着相似的响应变化. 气候变暖对热力特性的影响一般性规律表现为,气候变暖使湖库的表层变温层和底层滞温层温度均升高,冬春温度升高提前使得分层提前发生,但往往前者增温幅度较后者大,延缓了秋冬分层期的结束,热稳定性增加,温跃层深度显著降低. 但也有相反的观测结论,如非洲的 Victoria 湖[29]和 Kariba 湖[30],气候变暖引起的底层温度增幅高于表层,减弱了热力分层和热稳定性;温跃层深度变化受风速[31]、透明度[32]等其他因素影响,如 Shimajigawa 水库温跃层深度反而增加[28].

气候变暖引起湖库冰期改变. 冬季冰盖时形成稳定的垂向水温和水下光照,而气候变暖引起冰期缩短[33-34]、冰层厚度减少[35],透光系数改变[36],如韩国 Paldang 湖破冰提前[37].

1.2 气候变化对湖库溶解氧和营养盐等化学过程的影响

气候变暖和降雨减少均引起湖库溶解氧降低. 一方面,伴随着气候变暖引起的热力分层加强,含氧层深度随之降低[8],减弱的水体垂向混合使得滞温层中有机物浓度较高,耗氧加快,形成厌氧条件[28]. 2006 年夏季,由于长时间的热力分层,德国 Müggelsee 湖曾持续 9 d 滞温层溶解氧浓度小于 5 mg/L[6]. 在我国千岛湖[38]相应的研究也得到相同规律. 值得注意的是,气候变暖也有可能利于表层溶解氧穿透至湖底,补偿底部缺氧[29]. 另一方面,大气环流的变化引起降雨减少进而影响湖库溶解氧浓度. 研究发现,地中海湖库受厄尔尼诺南方涛动(ENSO)的影响,降雨和径流减少与溶解氧降低有着显著的一致性[5].

气候变化影响湖库营养盐浓度和营养状况. 气候变暖强化了湖泊热力分层,底层更易形成厌氧条件,促进位于水-土界面沉积物中营养盐释放[19,28],表层水体营养盐浓度提高[6],加速水体富营养化[9],如 Müggelsee 湖和泸沽湖的观测分析结果已证实[6,9]. 降雨变化也会影响湖库营养负荷,可能引起营养盐浓度提高[39-40],如石头口门水库[41]夏季增大的径流量对总磷浓度的贡献较大. 然而,不同区域对于降雨的响应过程可能不尽相同. 在地中海气候区,模拟研究表明未来夏季不断升高的气温将导致 Pareja 水库径流减少,水位降低,营养盐浓度和营养水平提高[39].

1.3 气候变化对湖库浮游植物和水生植物等生物过程的影响

气候变化影响湖库浮游植物的群落结构、春季物候和初级生产力,邓建明等[22]详细地归纳了相关研究成果. 即,在全球变暖的大背景下,淡水湖泊中浮游植物群落结构正朝着蓝藻占优势的方向发展;气温升高、分层期提前、冰期缩短均造成浮游植物春季物候提前;在营养盐充足的湖泊,气候变暖通过延长生长季节使得初级生产力提高,而在贫营养湖泊(如 Tanganyika 湖[26])初级生产力受其影响反而降低. 例如,德国 Saidenbach 水库[42],气候变暖(暖冬和春季的延长)使热力分层提前发生,浮游植物物候提前,硅藻提前达到峰值,水库营养水平提高约 20%. 另有一些相反的研究结论,在英国 Windermere 湖[43]和 Loch Leven 湖[44],湿润的冬季延缓了春季藻类生长,春季升高的温度使水蚤密度增加,从而降低叶绿素浓度.

相比浮游植物,气候变化对大型水生植物(如沉水植物)的影响表现得并不显著. 早期的一些研究发现,水温升高可能影响水生植物群落的物种组成、提高生产力、加快生命周期[45-46],但其驱动力可能是热分层流而非气候变暖[47]. 仅有少量研究证实,生长季节初期的气温升高使水生植物生物量显著增加[48]. Mckee 等[47]利用桶式实验装置模拟得到了沉水植物对气候变暖的响应较小,持续升温改变物种比例,适应性沉水植物生长率和丰度提高的结论. 有学者[49-50]认为大型水生植物对温度升高的响应较浮游植物小,随着气候变暖浮游植物春季物候提前,先于其他水生植物,消耗水体中大量的营养盐,可能使水生植物占优势的清水稳态趋向藻型浊水稳态发展.

2 气候变化对湖库水环境潜在影响的区域差异

2.1 不同气候类型湖库水环境的响应差异案例

前文分析中发现,湖库的热稳定性、温跃层深度、滞温层溶解氧、浮游植物春季物候等对气候变化的响应因区域不同而有所差异. 已有研究实例中,除热带雨林气候类型鲜有报道外,其余 10 种气候类型中均有代表性湖库的相关研究成果. 各气候类型湖库水环境潜在气候影响要素作用过程和效果见表 1.

热带草原、亚热带季风、3 种温带气候和地中海气候的湖库水环境对气候变暖有着相似的响应. 气候变暖影响深水湖库热力分层结构[26-27],引起混合层和含氧层深度变化[8],厌氧条件下底部沉积物中营养盐释放[19,28],表层水体营养盐浓度提高,致使浮游植物繁生[12,28],加速富营养化趋势[9];对于浅水湖库的影响更为突出[10,51],分层期延长[6],滞温层溶解氧下降,营养水平提高,更易诱发水华现象[11]. 有研究表明,气候变暖更易促进温带湖库富营养化趋势,威胁清水稳态[52].

降雨变化对热带沙漠、热带季风、3 种温带气候、地中海气候和寒带气候的湖库水环境也造成一定影响. 降雨减少影响水体自净作用[53],引起湖库萎缩[4]、溶解氧浓度降低[5];季节性降雨变化影响湖库营养负荷来源[40];气候暖干化、干旱频发加速湖泊衰老[54]. 同时,气温和降雨变化的综合作用也可能增加湖库非点源污染负荷量[41],引起营养盐浓度升高[39]或咸化[55]. 此外,风速变化影响湖库污染物的再悬浮[26],日照变化也会影响湖库水生植物的生长[47],极端气候如持续攀升的历史高温[19,26]、频发的洪涝或干旱[56]、增加的台风强度[57]等都有可能造成湖库水环境的恶化.

一般认为气候变化对湖泊水环境造成负面影响,但是气温和季节性降雨变化也会有积极的一面,气候变化对湖库水环境的影响效果具有两面性. 如温带海洋性气候中 Windermere 湖[43],湿润的冬季降低叶绿素浓度,延缓春季藻类生长;暖春也增加 Loch Leven 湖的水蚤密度,降低叶绿素浓度,有利于水质保持[44]. 同样,高原山地气候中一些湖泊受气候变化的影响变得更为清澈[32].

统计分析上述实例和 IPCC AR5 Regional Aspects 报告[58]中的部分实例研究成果,不同气候类型湖库水环境对气候变化的响应存在一定区域差异(图 1). 总体而言,湖库水环境对于气候变暖的响应较降雨变化和其他气候因素突出,其中气候变暖对湖库物理过程的影响最为显著,表现在湖库热力特性的变化;热带草原气候和温带海洋性气候对于气候变暖和降雨变化的响应较其他气候类型突出. 可能的原因是,近赤道的热带草原气候干、热、雨三季的交替变化,温带海洋性气候区气温变幅相对较大(约 1.25~1.50℃,GISS 1901—2012[1]);湖库形态相对集中,如热带草原气候中较典型的深水湖及温带海洋性气候中分布较多的浅水湖库,客观上又促进了此响应表现.

2.2 不同气候类型中气候变暖和湖库总磷关系差异分析

由于气候变暖是较突出的影响因素,而磷被认为是湖泊富营养化的主要限制因子,因此以气候变暖和总磷为例,探讨各气候类型中气候变暖和湖库总磷浓度的差异(图 2). 结果表明,在所选取分析的湖泊中,热带草原气候的湖泊温度升幅较小,平均气温升幅为 0.183℃/(10 a),总磷浓度小于 10 μg/L;亚热带季风气候的湖泊温度升幅较大,平均气温升幅为 0.565℃/(10 a),总磷浓度相对较高,为 6~130 μg/L;温带季风气候、温带海洋性气候和地中海气候的湖库气温升幅平均约为 0.45℃/(10 a),总磷浓度处于 5~80 μg/L;温

表 1 不同气候类型湖库水环境潜在气候影响要素作用过程和效果

Tab.1 Processes of potential impacts of climate change on water quality of lakes and reservoirs in climate zones

气候类型	代表性湖库	国家	气候影响要素及作用过程	效果
热带草原气候	Tanganyika 湖	刚果等	气候变暖增大表底层密度差,阻滞垂向混合,降低初级生产力[26-27]	负面
	Kariba 湖	赞比亚等	气候变暖和降雨减少使得水位降低,入库营养负荷减少,热力分层结构改变,表层水体营养水平降低,浮游植物生物量降低[59]	正面
	Ziway-Shalla 湖	埃塞俄比亚	湖水位对气候变化较为敏感[60]	—
热带沙漠气候	Eyre 湖	澳大利亚	干旱频发导致农业用水紧缺及水质恶化[56]	负面
热带季风气候	Tonle Sap 湖	柬埔寨	降雨增多使湖面扩张,也可能引起洪灾[61]	负面
亚热带季风气候	太湖	中国	暖春促使蓝藻提前暴发[11]	负面
	泸沽湖	中国	气候变暖加速水体富营养化[9]	负面
	流溪河水库	中国	气候变暖影响热力分层结构,促进沉积物中污染物释放[19]	负面
	Feitsui 水库	中国	台风强度增加使水库悬浮物通量增大[57]	负面
	Shimajigawa 水库	日本	气候变暖影响热力分层结构,浮游植物繁生[28]	负面
温带季风气候	松嫩平原湖区	中国	气候变暖引起湖区水环境不断恶化[62]	负面
	石头口门水库	中国	气候变化增大非点源污染负荷量[41]	负面
	Paldang 湖	韩国	气候变暖加速水体富营养化[37]	负面
温带大陆性气候	Redberry 湖	加拿大	降雨变化影响水体自净(稀释)作用[53]	—
	Woods 湖	加拿大	气候变暖引起浮游植物(硅藻)繁生[12]	负面
	Winnipeg & Manitoba 湖	加拿大	降雨减少引起水位下降,湖泊萎缩[4]	负面
	Diefenbaker 湖	加拿大	气候变暖可能使菌类超标[63]	负面
	Great 湖	美国	气候变暖增加湖泊分层期,提高滞温层厌氧风险[64]	负面
	Wachasett 水库	美国	季节性降雨变化影响营养负荷输入[40]	—
	Ashokan 水库	美国	气候变暖使水库浊度增加[65]	负面
	呼伦湖	中国	气候暖干化加速湖泊衰老进程[54]	负面
	Müggelsee 湖	德国	气候变暖加速水体富营养化[6]	负面
温带海洋性气候	Loenderveen 湖	荷兰	气候变暖加速水体富营养化[51]	负面
	Veluwe 湖	荷兰	气候变暖降低湖泊生态系统稳态转换营养阈值,更可能向浊水状态发展[10,66]	负面
	Ijsselmeer 湖	荷兰	气候变化引起水库咸化[55]	负面
	Windermere 湖	英国	湿润的冬季叶绿素 a 浓度较低,延缓春季藻类生长[43]	正面
	Loch Leven 湖	英国	暖春增加水蚤密度,降低叶绿素浓度[44]	正面
	Zurich 湖	瑞士	气候变暖影响热力分层结构,暖冬使表温层水温升高[8]	负面
地中海气候	Sau 水库	西班牙	降雨减少引起溶解氧浓度降低[5]	负面
	Pareja 水库	西班牙	气候变化引起水库营养盐浓度提高[39]	负面
	Mogan 湖	土耳其	降雨减少和蒸发量增大引起水体营养盐浓度升高[67]	负面
高原山地气候	Pipit 湖	加拿大	冬季气温下降减少浮游植物生物量,湖水更清澈[32]	正面
寒带气候	Flora & Fauna 湖	格陵兰岛	气候变暖使水温升高,进而影响水生动植物[68]	负面
	Beall 湖、Holl 湖、'Lake M'湖	南极地区	气候变暖和风速提高导致湖水盐度上升[69]	负面

—表示未见正面或负面效果.

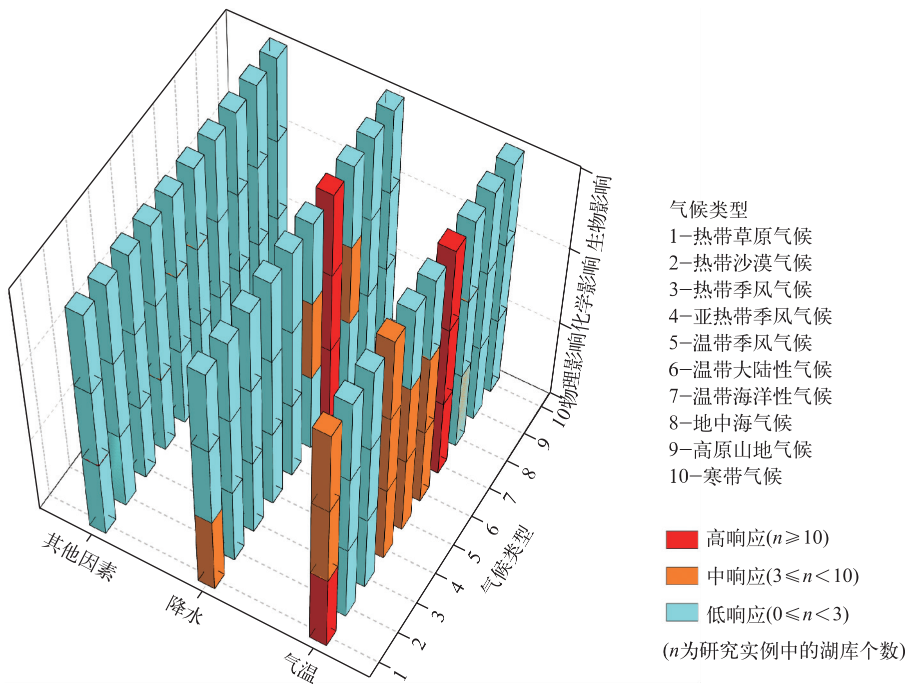

图 1 不同气候类型湖库水环境的响应差异

Fig.1 The differences of climate-related responses to water environment of lakes and reservoirs in climate zones

带大陆性气候由于横跨亚欧及美洲大陆,气温变幅差异较大,气温升幅为 0.064~0.37℃/(10 a),总磷浓度为 8~90 μg/L(图 2). 由此,亚热带季风气候的湖库更易受气候变暖的影响趋于富营养化,而温带季风、大陆性气候中的湖库在气候变暖的驱动下存在向富营养状态发展的潜在风险.

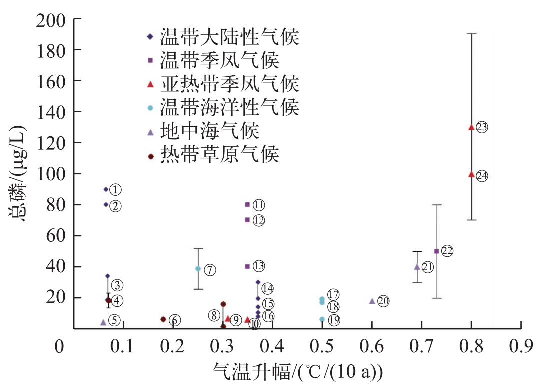

图 2 气温升幅对总磷浓度的潜在影响(①Murry 湖[70],②Jackfish 湖[70],③Rainbow 湖[71],④Tanganyika 湖[72],⑤Ohrid 湖[73],⑥Malawi 湖[74],⑦Neuchatel 湖[75-76],⑧Kivu 湖[77-78],⑨Biwa 湖[79],⑩泸沽湖[80],⑪昆明湖[81],⑫北海[81],⑬前海[81],⑭Erie 湖[82-83],⑮Huron 湖[82-83],⑯Ontario 湖[82-83],⑰Geneva 湖[76],⑱Bourget 湖[76],⑲Annecy 湖[76],⑳Garda 湖[84],㉑Pedina 湖[85],㉒于桥水库[86-87],㉓梅梁湾[11,88],㉔太湖[88])

Fig.2 The potential impact of global warming on total phosphorus concentration

3 研究方法和存在的问题

研究气候变化对湖库水环境影响的方法包括长期监测、数理统计、数值模拟和控制实验方法.

长期监测是获取数据最直接的方式. 研究中所用历史数据的时间尺度长达近百年(Pipit 湖[32]、泸沽湖[9]、Tanganyika 湖[26-27]等)或 50 a 左右(流溪河水库[19]、Sau 水库[5]等),短则 20~30 a(Müggelsee 湖[6]等). 除此之外,还可采用卫星遥感反演[89]、分子化学[90]等新技术方法获得. 气候变化对湖库水环境的潜在影响可在 30 a 或更长时间尺度有所表现.

数理统计方法通常是利用实测数据对湖库的特性要素与气候要素建立关系,采用统计学方法分析变化规律,从而揭示气候变化对湖库水环境的影响及作用过程[8,19,26,91]. 该方法较为直观、理论性强、应用广泛,但研究过程中需要系统的数据积累,且不易获取. 对于国内一些重点湖库,在水质数据整编和管理上仍需完善.

利用数学模型研究气候变化对湖库水环境的影响是一种高效、有前景的方法. 此类方法的研究模式可归纳为三步:先利用大气环流模型(GCMs)输出研究区域的气候变化情景[14,28,92-93];再将其作为边界条件输入至水文模型[18,39-40]、水动力模型[19]、水质模型[65,94]、水生态模型[51,95]进行模拟;最后通过原值比较对气候变化引起的水环境变化进行定量评价[19,39,55,92]. 其优点为,气候情景易于假定,可预测未来气候变化引起的水环境变化趋势[14,55,65];模拟过程中可综合考虑土地利用[18,40,92]、水库运行方式[19,94]等人为因素的影响. 然而,模拟研究中存在 3 点突出不足:①由于 GCMs 输出结果尺度较大,采用降尺度技术[28,93]以满足流域水文模型的需求,但降尺度仍难以满足水质或水生态模型进行精细模拟. 研究中必须先借助水文模型进行产汇流或污染负荷的计算,而后再进行水质模拟[65];或者忽略前两步计算,简化气候因素变化条件,直接进行水质或水生态模拟[51,95]. ②气候变化情景的不确定性[19]、模型参数的不确定性[96]、模型误差引起的预测结果的不确定性[28]仍需更深入的研究. ③模拟可能发生的极端气候对湖库水环境造成的影响程度鲜有报道.

采用控制实验模拟的方法也可研究气候要素变化对水质的影响及其机制,但气候要素在实验中再现和控制难度较大,且考虑的气候要素往往较为单一,研究成果相对较少[47,97-98].

4 结论与展望

通过对比各气候类型中气候要素的影响作用过程,分析气候变化对湖库水环境潜在影响的区域差异. 研究表明,气候变暖对湖库物理过程的影响最为显著;热带草原气候和温带海洋性气候对于气候变暖和降雨变化的响应较其他气候类型突出. 亚热带季风气候的湖库更易受气候变暖的影响趋于富营养化,而温带季风、大陆性气候中的湖库在气候变暖的驱动下存在向富营养状态发展的潜在风险. 气候变化对湖库水环境的影响效果具有两面性.

我国所处温带大陆性、温带季风、亚热带季风、高原山地、热带季风气候,各气候类型中气温、降雨、风速等要素变化特征不同,建议深入开展区域性气候变化对湖库水环境影响的实例研究.

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