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厦门大学

硕士学位论文

九龙江典型小流域氮输出对土地利用及水文季节性变动的响应

Land-use Effect and Seasonal Hydrologic Controls on Nitrogen Export in Typical Sub-watersheds within Jiulong River Watershed

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摘要

在过去的几十年里，世界范围的大部分地区都经历了由于进入近海的河流氮通量的大量增加而导致的富营养化和其它生态损害。氮、磷作为限制性营养盐，控制着河流－近海系统富营养化，威胁着我们所依赖的生态系统服务与功能。河流营养盐状况是植被、土壤、地形、气候、土地利用状况等自然和人为因素综合作用的结果，这些因素在不同时空尺度内交互作用，使得河流营养盐输出的影响机制研究更具挑战性。本研究开展亚热带流域氮输出对土地利用及水文状况季节性变动的响应，可为流域综合管理和区域用水安全提供科技支撑。

本研究通过现场监测、GIS 技术、数理统计、模型模拟等方法，基于 2015 年 3 月-2016 年 2 月持续一年两周一次的九龙江流域不同土地利用主导（自然、农业和城市三种类型）的典型小流域河流氮指标（总氮、硝态氮、铵态氮、亚硝态氮）浓度监测，探究流域氮浓度与氮输出的时空差异性，揭示亚热带近海流域河流营养盐输出对土地利用和水文季节性变动交互控制的响应机制，取得如下主要结论：

九龙江流域氮指标浓度具有明显的时空动态变化特征。九龙江流域氮指标（TN、NO_3^--N、NO_2^--N、NH_4^+-N）浓度在春季最高，夏季有所降低，秋季最低，冬季又有所升高，但具体到源头小流域时不同氮指标在不同季节表现存在较大差异。三种类型小流域（城市、自然、农业）的 TN、NO_3^--N、NH_4^+-N、NO_2^--N 浓度在对应季节（春、夏、秋、冬）均存在显著的空间差异性；TN 浓度在 3 类流域、NO_3^--N 浓度在自然流域和城市流域、NH_4^+-N 浓度在农业流域、NO_2^--N 浓度在自然流域均存在显著的季节性差异。整体上，九龙江干流氮指标浓度大于支流，农业流域>城市流域>自然流域。源头小流域中，农业流域花山溪的 TN 和 NO_3^--N 浓度最高，龙山溪的 NH_4^+-N 和 NO_2^--N 浓度最高；汇流点中，郑店的 TN 和 NO_3^--N 浓度最高，北 4 的 NH_4^+-N 和 NO_2^--N 浓度最高，且西溪出口郑店的氮指标浓度较北溪出口浦南的高。

九龙江流域的氮输出（总氮、硝态氮、铵态氮、亚硝态氮通量）存在较大的时空差异。研究期间九龙江流域全年总氮输出为 34918 吨，西溪出口郑店占 66%，

北溪出口浦南占 34%，并且位于西溪流域的花山溪总氮输出量为 12435 t，达到西溪输出量的 54%；对于单位面积的流域氮输出而言，西溪各流域仍高于北溪流域，西溪出口郑店的总氮输出量为 6730 kg/km^2/yr，北溪出口浦南的总氮输出量为 1411 kg/km^2/yr，西溪为北溪的 4.8 倍，其中氮输出量最高为农业流域，最低为自然流域。另一方面，城市小流域和自然小流域的氮输出在冬季最高，秋季其次，夏季最低；而在农业小流域中，夏季的氮输出最高，秋冬其次，春季最低，且花山溪对应季节的总氮和硝态氮输出要高于其他各个小流，龙山溪对应季节的铵态氮和亚硝态氮输出较其他各个小流域高；总体来讲，农业小流对应季节的氮输出较城市小流域和自然小流域的高。

九龙江流域氮输出受人为因素和自然因素的综合影响，其中河流流量和土地利用方式对氮输出的影响较大。九龙江流域氮浓度和氮通量与环境变量的 Pearson 相关分析发现：林地比例与总氮和硝态氮浓度及通量均呈显著负相关，而流域内单位面积第一产业 GDP、单位面积氮肥施用量、单位面积径流量以及农业用地比例与氮通量、总氮和硝态氮浓度均呈显著正相关，畜禽养殖量也与铵态氮和亚硝态氮浓度呈显著正相关，且日流量与氮通量有显著的正相关关系。

全球均值法、线性插值法、流量权重法、流量特性曲线法得出的氮通量存在些许差异，但方法变异系数均低于 7%，均可用于九龙江流域的氮通量计算，其中流量特性曲线法对采样频率有较强的依赖性；另一方面，经校验的 Smith 方程也可以用于九龙江流域溶解态无机氮（DIN）通量的计算，Smith 方程得出的 DIN 通量与观测的 DIN 通量线性拟合系数达到 0.81，计算结果良好，可以应用于九龙江流域 DIN 输出预测。

关键词：氮输出；土地利用；水文状况；时空变异性；影响因子

Abstract

Over the past decades, many regions of the world have experienced large increases in riverine nitrogen (N) fluxes to coastal waters, leading to eutrophication in catchment-coast continuum, thereby posing a threat to the local/regional water security and ecosystem services supporting. Riverine nutrient is affected by the combination of natural and anthropogenic factors such as vegetation, soil, topography, climate, land use, and so on. These factors are interacted on different spatial and temporal scales, which make it challenging to explore the mechanisms driving riverine nitrogen export dynamics. This study was carried out to investigate the land use effect and seasonal hydrologic controls on riverine nitrogen export in subtropical sub-watersheds within Jiulong River Watershed (JRW), which can provide scientific support for integrated watershed management and regional drinking water secrurity in the watershed studied.

In-situ monitoring, GIS technology, statistical techniques and models were coupled in this study to explore the land use effect and seasonal hydrologic controls on riverine nitrogen export in Jiulong River Watershed. Surface water samples were first collected bimonthly from nine headwater sub-watersheds which were classified into three types of watersheds (natural, urban and agricultural) and seven mainstream sampling sites during the period from March 2015 to Feb, 2016. Then the spatiotemporal variations of riverine nitrogen export among three types of sub-watersheds within JRW were identified. Finally, we revealed the mechanisms regarding land use effect and seasonal hydrologic controls on riverine nitrogen export in JRW. The major findings of this study are as follows:

Significant spatiotemporal variations of nitrogen concentration were observed in JRW. All of mean concentrations of nitrogen parameters's (namely TN, NO_3^--N, NO_2^--N, NH_4^+-N) were highest in spring, whereas the lowest concentrations were in autumn. However, there were distinct seasonal variations among three types of headwater sub-watersheds. Meanwhile, spatial variations can be discerned among three types of headwater sub-watersheds and seven mainstream sampling sites. Overall, the nitrogen concentrations were higher in main stream than those in branches of Jiulong River, and the extent of nitrogen pollution was in the order of agricultural watersheds>urban watershed>natural watershed. In terms of nine headwater sub-watersheds, the TN and NO_3^--N concentrations were the highest in Huashan sub-watersheds; NH_4^+-N and NO_2^--N concentrations were highest in Longshan sub-watersheds. In terms of seven mainstream sampling sites, TN and NO_3^--N concentrations were the highest in Zhengdian; NH_4^+-N and NO_2^--Nconcentrations were the highest in Beisi; N concentrations was generally higher in West River reach that those in North River reach.

Nitrogen fluxes in Jiulong River showed obvious spatiotemporal variations. The estimated annual TN flux in the entire watershed was 34918 tons, West River outlet, namely Zhengdian, accounted for 66% while North River outlet, Punan, accounted for 34%, and Huashan stream located in West river has 12435 tons of TN flux, accounted for 54% of West River TN annual yield. For nitrogen export in per unit area, nitrogen export in west river's branches were still higher than in north river's branches, TN yield in Zhengdian was 6730 kg/km^2/yr, 1411 kg/km^2/yr in Punan. TN yield in West River is 4.8 times more than North River, and the nitrogen output is the highest in the agricultural watersheds, lowest in the natural watersheds. In addition, the nitrogen fluxes in urban watersheds and natural watersheds were highest in winter, followed by autumn and spring, lowest in summer. In agricultural watersheds, the nitrogen fluxes were highest in summer, then in autumn and winter, lowest in spring. TN and NO_3^--N fluxes in every season were highest in Huashan stream, NH_4^+-N and NO_2^--N fluxes in corresponding season were highest in Longshan stream. In general, N fluxes in the agricultural watersheds were higher than those in urban watersheds and natural watersheds.

The nitrogen yield in Jiulong River was affected by the combination of natural and anthropogenic factors, among which runoff and landuse type are the most important factors. According to Pearson correlation analysis between environment variables and nitrogen concentrations and fluxes, there was a significant negative correlation between the proportion of forest land and N concentrations & fluxes, while there were significant positive correlations between N concentrations and fluxes and the other variables including the primary industry GDP, amount of nitrogen fertilizer and livestock, runoff, the proportion of agriculture land. Moreover, the daily flow was positive correlated with N flux.

The N fluxes calculated by four commonly used methods (i.e. global mean, linear interpolation, flow weighted, and the rating curve method) exhibited some differences, but the variation coefficients of four methods were less than 7%, indicating that four methods all can be applied to the calculation of N fluxes in JRW. Moreover, the linear fit coefficient between estimated DIN flux using the verified Smith equation and the observed value reached to 0.81, suggesting that the verified Smith equation is applicable to estimate DIN flux in JRW.

Key words: Nitrogen export; Landuse; Hydrologic regime; Spatiotemporal variation; Influence factors.

第 1 章 绪论

1.1 研究背景及意义

富营养化日渐严重，水短缺与水污染成为全球重要的议题。据世界水资源评估计划调查，全球水污染仍呈上升趋势[1]。在过去的几十年里，世界范围的大部分地区都经历了由于进入近海的河流氮通量的大量增加而导致的富营养化和其它生态损害[2,3]。据估算，目前全球每年大约有 25 Tg 的溶解态无机氮被输入到河口环境系统中，其中人为氮约占 64%。氮、磷作为限制性营养盐，控制着河流－近海系统富营养化，威胁着我们所依赖的生态系统服务与功能，包括饮用水的供给[4]。

水体富营养化已经成为江河湖泊甚至河口乃至海洋等水体污染十分突出的环境热点问题之一，并且表现出在将来很长一段时间内都存在无法缓和的趋势[5-8]。据统计，21 世纪初全球约有 75%以上的封闭型水体存在富营养化问题[9]，据中国环保部 2014 年中国环境状况公报，2014 年，我国 25% 的国控重点湖库（61 个）为富营养化水体，较 2011 年下降 29%，中营养占 59%[10]。不仅湖库富营养化日益严重，河流也开始出现富营养现象[12]，河流富营养化不仅与营养盐大量输入有关，还与水文水动力条件的改变（如流速、流量、水体扰动）有关[13]。虽然一些技术已被用于控制营养盐的污染，但效果并不明显，因为这些控制多专注于工程项目的末端控制，如建设污水处理厂，在河口或河道开垦人工湿地等[11,14]。因此，需要找到氮磷等营养盐的源及其影响机制并制定相应对策进行全面控制才能解决根本问题。

河流氮磷营养盐状况是植被、土壤、地形、气候、土地利用状况等自然和人为因素综合作用的结果，这些影响因素受到人类活动和气候变化两方面的共同作用[15,16]。人类活动相关的点源与非点源污染被普遍认为是引起河流氮磷浓度增加，水体富营养化的首要原因。并且众多研究发现非点源 N、P 的扩散与排放对水环境的影响更为突出。土地利用方式是影响非点源污染的关键性因素，综合反映人类活动对自然环境作用的土地利用方式对土壤、植被、径流及化学物质输入输出等因素具有重要影响，进而导致不同土地利用类型所产生的非点源污染差异