武汉大学优秀博士学位论文文库

# 大型通江湖泊水沙时空动态遥感研究

## ——以鄱阳湖为例

On the Dynamic Changes of Water and Sediments in Large Lakes Connecting to the Yangtze River: A Remote Sensing Assessment of Poyang Lake

冯炼 著

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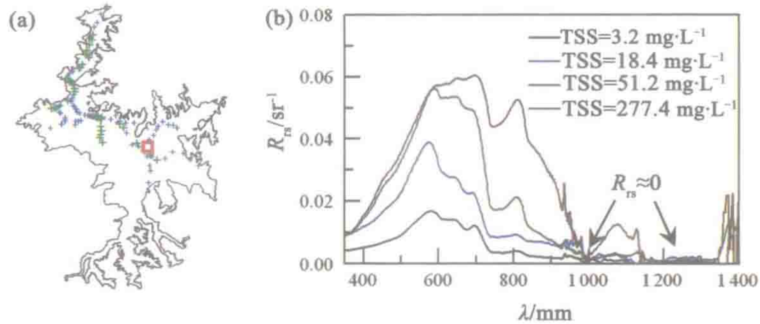


图 4-2　(a)2009 年 10 月与 2011 年 7 月鄱阳湖实测站点位置，其中绿色代表实测值与 MODIS 遥感数据的同步观测站点；(b)鄱阳湖实测光谱数据($R_{rs}$)，其中在 1 000 nm 与 1 150~1 380 nm 的光谱区间内，遥感反射率约为 0，因此可以认为水体在 1 240 nm 波段上对 MODIS 反射率没有贡献

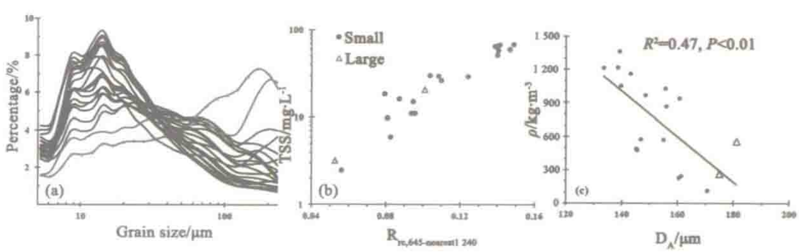


图 4-15　(a)鄱阳湖悬浮泥沙存在两种不同类型的粒径分布，LISST-100X 取样的粒径分布用红点表示；(b)不同粒径分布的悬浮泥沙浓度与 MODIS $R_{rc,645-nearest1\ 240}$之间的关系，大粒径(三角形表示)与其他小粒径颗粒物(黑点表示)之间不存在明显的区分度；(c)表观密度($\rho$)与颗粒物平均面积($D_A$)之间的关系

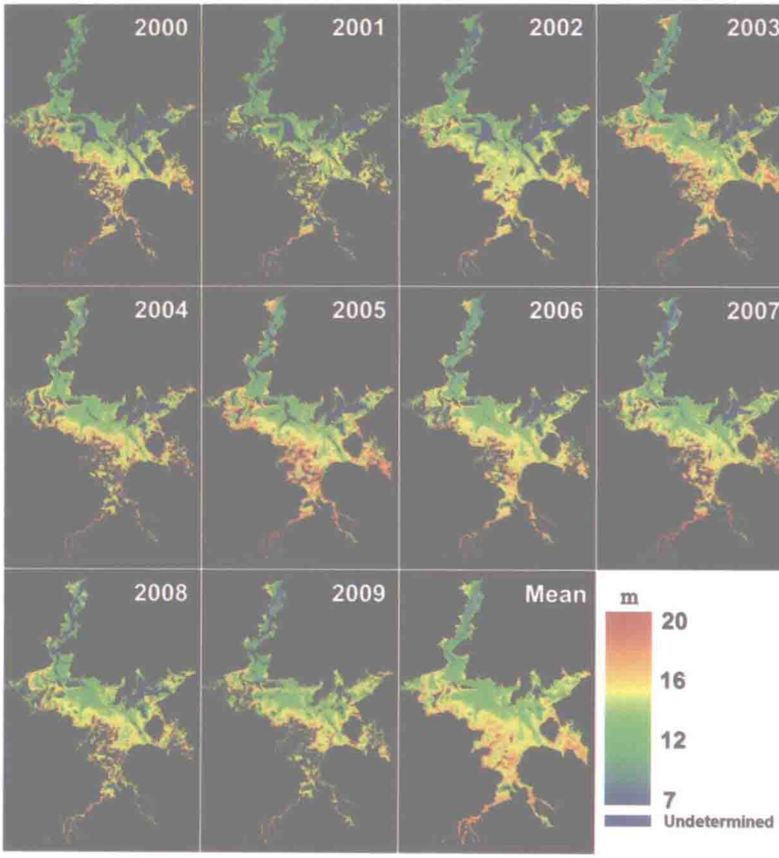


图 5-6 不同年份(2000—2009 年)鄱阳湖的湖底地形图(以吴淞基准面为参考平面),而"Mean"为 10 年的平均值,未确定区域("Undetermined")位于湖泊年最小水体范围以内

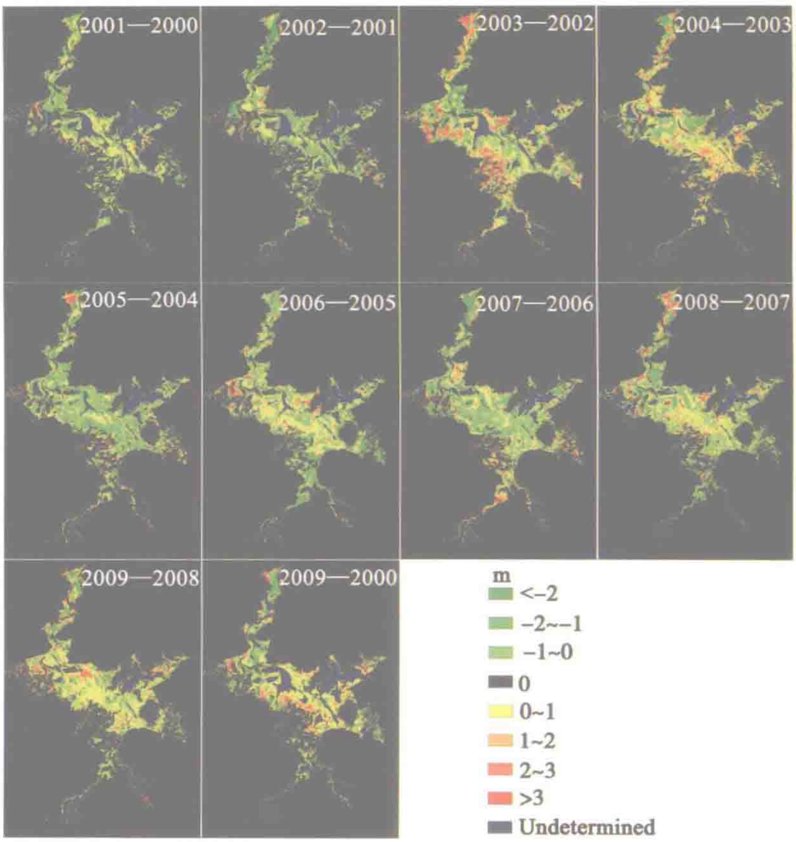


图 5-8　2000—2009 年间鄱阳湖湖底地形在任意连续两年的差异。其中 2002—2004 年的变化最为显著，而 2000 年与 2009 年的差异代表了湖底地形在十年中的总变化量(“2009—2000”)

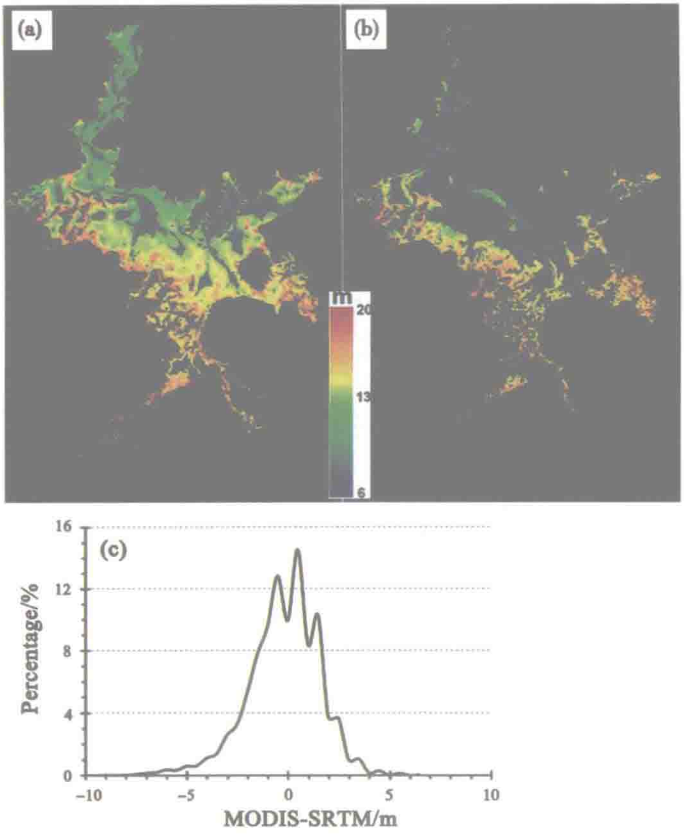


图 5-14　MODIS 提取湖底地形与 SRTM 地形数据比较。(a) 2000 年 MODIS 提取的湖底地形图，其中蓝色为未确定区域("Undetermined")(图 5-6)；(b) SRTM 在鄱阳湖的地形数据，其中蓝色区域为("奋进号"飞行时)鄱阳湖的积水区域；(c) MODIS 提取结果与 SRTM 之间差异(MODIS-SRTM)的直方图分布

# 总　序

创新是一个民族进步的灵魂，也是中国未来发展的核心驱动力。研究生教育作为教育的最高层次，在培养创新人才中具有决定意义，是国家核心竞争力的重要支撑，是提升国家软实力的重要依托，也是国家综合国力和科学文化水平的重要标志。

武汉大学是一所崇尚学术、自由探索、追求卓越的大学。美丽的珞珈山水不仅可以诗意栖居，更可以陶冶性情、激发灵感。更为重要的是，这里名师荟萃、英才云集，一批又一批优秀学人在这里砥砺学术、传播真理、探索新知。一流的教育资源，先进的教育制度，为优秀博士学位论文的产生提供了肥沃的土壤和适宜的气候条件。

致力于建设高水平的研究型大学，武汉大学素来重视研究生培养，是我国首批成立有研究生院的大学之一，不仅为国家培育了一大批高层次拔尖创新人才，而且产出了一大批高水平科研成果。近年来，学校明确将“质量是生命线”和“创新是主旋律”作为指导研究生教育工作的基本方针，在稳定研究生教育规模的同时，不断推进和深化研究生教育教学改革，使学校的研究生教育质量和知名度不断提升。

博士研究生教育位于研究生教育的最顶端，博士研究生也是学校科学研究的重要力量。一大批优秀博士研究生，在他们学术创作最激情的时期，来到珞珈山下、东湖之滨。珞珈山的浑厚，奠定了他们学术研究的坚实基础；东湖水的灵动，激发了他们学术创新的无限灵感。在每一篇优秀博士学位论文的背后，都有博士研究生们刻苦钻研的身影，更有他们的导师的辛勤汗水。年轻的学者们，犹如在海边拾贝，面对知识与真理的浩瀚海洋，他们在导师的循循善

诱下，细心找寻着、收集着一片片靓丽的贝壳，最终把它们连成一串串闪闪夺目的项链。阳光下的汗水，是他们砥砺创新的注脚；面向太阳的远方，是他们奔跑的方向；导师们的悉心指点，则是他们最值得依赖的臂膀！

博士学位论文是博士生学习活动和研究工作的主要成果，也是学校研究生教育质量的凝结，具有很强的学术性、创造性、规范性和专业性。博士学位论文是一个学者特别是年轻学者踏进学术之门的标志，很多博士学位论文开辟了学术领域的新思想、新观念、新视阈和新境界。

据统计，近几年我校博士研究生所发表的高质量论文占全校高水平论文的一半以上。至今，武汉大学已经培育出 18 篇“全国百篇优秀博士学位论文”，还有数十篇论文获“全国百篇优秀博士学位论文提名奖”，数百篇论文被评为“湖北省优秀博士学位论文”。优秀博士结出的累累硕果，无疑应该为我们好好珍藏，装入思想的宝库，供后学者慢慢汲取其养分，吸收其精华。编辑出版优秀博士学位论文文库，即是这一工作的具体表现。这项工作既是一种文化积累，又能助推这批青年学者更快地成长，更可以为后来者提供一种可资借鉴的范式抑或努力的方向，以鼓励他们勤于学习，善于思考，勇于创新，争取产生数量更多、创新性更强的博士学位论文。

武汉大学即将迎来双甲华诞，学校编辑出版该文库，不仅仅是为百廿武大增光添彩，更重要的是，当岁月无声地滑过 120 个春秋，当我们正大踏步地迈向前方时，我们有必要回首来时的路，我们有必要清晰地审视我们走过的每一个脚印。因为，铭记过去，才能开拓未来。武汉大学深厚的历史底蕴，不仅在于珞珈山的一草一木，也不仅仅在于屋檐上那一片片琉璃瓦，更在于珞珈山下的每一位学者和学生。而本文库收录的每一篇优秀博士学位论文，无疑又给珞珈山注入了新鲜的活力。不知不觉地，你看那珞珈山上的树木，仿佛又茂盛了许多！

**李晓红**

2013 年 10 月于武昌珞珈山

# 摘　要

随着全球气候变暖与人类活动的加剧，地球上的许多湖泊面临着面积萎缩、水质下降等一系列日趋恶化的水环境问题，严重阻碍了区域经济发展与湖泊正常的生态功能。作为我国最大的通江湖泊(也是第一大淡水湖泊)，鄱阳湖兼有调蓄、航运及维系流域生态平衡等重要功能。然而，由于鄱阳湖复杂的水文条件，湖泊周边区域一直是我国洪旱灾害最严重的地区之一，而近年来灾害发生的频率及强度都呈明显的增大趋势。另一方面，由于湖泊采砂等人类活动的影响，鄱阳湖水质状况在近年来有明显下降的趋势，且已经给人类及水生物的生存构成了威胁。然而，由于受各种技术手段的限制，到目前为止还没有鄱阳湖水质水量的长时序数据，更无从分析其水文格局变化的各种原因。本文将利用长时序的遥感数据，结合实测气象、水文等辅助数据，系统地研究鄱阳湖水沙的长短期时空动态及其形成机制。研究成果不仅包括了高动态通江湖泊水沙遥感的新方法，并且取得了一系列重要发现，具体内容如下：

利用 MODIS 遥感影像获取鄱阳湖长时间序列(2000—2010 年)的水体范围，并统计分析了水面积的长短期时空动态特征。湖泊水面积呈显著的季节性与年际变化，11 年间最大最小面积分别为 2010 年 8 月份的3 162.9 $km^2$和 2009 年 10 月份的 714.1 $km^2$。任意年份的最大最小面积之比在 2.3~3.2 间，而 11 年的最大可能与最小可能水面积相差约 14 倍，充分表明了鄱阳湖水面积的剧烈变化。2000—2010 年间，年平均与年内最小水面积呈减小的趋势，减小的速率分别为-30.2 $km^2/a$ 和-23.9 $km^2/a$($P<0.05$)。鄱阳湖水面的高动态变化主要受流域降水的影响，而在夏季(7—9 月)，由于湖流受长江高水位的顶托，流域降水的作用趋于不明显状态。本研

究获取的结果为后续监测与评估鄱阳湖水面积的动态过程提供了长时序的历史参考数据。在 11 年历史数据的基础上，定量化评估了 2011 年春季鄱阳湖的干旱程度。

结合两次现场实测数据与 MODIS 遥感影像，提出了一种有效的悬浮泥沙浓度反演算法。该算法主要基于大气校正后的 645 nm 波段反射率，而将1 240 nm 反射率作为气溶胶散射信号，并且用最邻近算法避免了陆地邻近效应的影响。实测悬浮泥沙浓度在 3～200 mg/L 时，本反演算法存在 30%～40% 的误差。对长时序(2000—2010 年)的遥感反演结果进行统计分析表明，鄱阳湖悬浮泥沙浓度时空分布动态十分显著，其北湖区的悬浮泥沙浓度总体上高于南湖区。特别是在 2002 年以后，两个湖区之间的悬浮泥沙平均值相差大于 40 mg/L。分析显示，悬浮泥沙的季节性变化主要归因于湖流的流速变化，而其年际变化主要受采砂活动及相关政策实施的影响。本研究为鄱阳湖的水质动态监测及环境保护提供了重要历史数据，其中提出的一系列方法对其他类似通江湖泊及海岸带的相关研究具有重要借鉴意义。

水下地形数据是湖泊水量估算的前提条件。基于鄱阳湖水体范围的高动态变化特征，结合实测水位数据，提出了一种获取高动态湖泊湖底地形的新方法，此方法弥补了传统的声呐、激光雷达或光学反演在高动态浑浊湖泊的不足。每一景遥感影像提取的水陆边界线可以视作水深线，而用实测水位数据能修正湖泊水边界线的水位差。季节性变化的湖泊水体范围提供了渐进变化的水深线，在此基础上可以获取鄱阳湖的湖底地形。验证结果表明，遥感获取的湖底地形与历史实测数据、SRTM 地形数据之间具有较好的一致性。鄱阳湖绝大部分区域湖底高程分布在 12～17 m 间(以吴淞基准面为参考)。2000—2009 年间，鄱阳湖湖底高程呈显著的时空动态变化，湖盆淤浅区域面积大于冲刷区域面积。分析表明，湖底高程的动态变化受到人类活动(采砂、围堰等)和气候等多重因素等的影响。例如，2002 年的强降水以及 2003 年的三峡大坝截流直接导致了湖盆在 2002—2003 年的淤浅。

结合前面 MODIS 遥感影像获取的鄱阳湖湖底地形及水陆边界

线数据，可以估算任意影像获取时刻的鄱阳湖蓄水量。结合湖泊蓄水量、气象和水文观测等数据，提出一种估算高动态通江湖泊水量收支的新方法，并获取了2000—2009年间，鄱阳湖的水量收支状况。鄱阳湖的水量收支呈显著的年内年际变化，2000—2009年间湖泊的年平均出湖水量为$(1.20\pm0.31)\times10^{11}\ m^3$，并以平均每年$5.7\times10^9\ m^3$的速率减小。本研究最大的发现是三峡截留对鄱阳湖水量平衡的瞬时性影响。2003年6月份的三峡大坝截留蓄水导致了出湖水量的急速增加$(7.6\times10^8\ m^3/d)$，直接致使湖泊蓄水量在较短的时间内减小约$7.86\times10^{10}\ m^3$。

三峡工程建设对下游生态环境的影响，从20世纪90年代以来一直都备受争议。然而，目前还没有科学依据能将下游湖泊水环境的各种变化与三峡工程建设直接联系。上述的研究分析已经发现2003年的三峡大坝截留给鄱阳湖的水量平衡带来了重大影响，在此基础上，本研究结合遥感、实测水文与气象数据，进一步就三峡工程建设对下游湖泊水环境的影响进行了初步分析。研究发现，2003年的三峡大坝截留蓄水后，湖泊水面积呈现显著性的减小趋势(减小速率为3.3%/年)。此外，鄱阳湖流域地表径流系数与大气相对湿度也显著性减小。对洞庭湖的数据进行对比分析表明，两个湖泊的水面积、大气相对湿度等有着类似的变化趋势。鉴于两个通江湖泊具有相似的地理与水文条件，洞庭湖的水文格局变化也从侧面说明了鄱阳湖结果的科学性。本研究通过遥感分析在一定程度上说明了三峡工程建设对长江中下游湖泊产生了影响。然而，获取更多湖泊及长江流域的水文情势数据，是解析三峡水库蓄水对通江湖泊影响机制研究的必要条件。

**关键词**：鄱阳湖；遥感；MODIS；悬浮泥沙；水体面积；湖底地形；水量平衡；三峡工程

# Abstract

Driven by both globe climate change and human activities, many lakes in the world have faced increasingly deteriorated problems in terms of water quantity and water quality, posing threat to their ecological functions and hampering regional economic growth. As the largest freshwater lakes in China, Poyang Lake plays a critical role in modulating local dry/wet conditions, shipping and tansprtation, and the eco-system of the lake's drainage basin. However, due to its complex hydrological properties, the Poyang Lake region has been the most frequently flooded and drought area in China, and the severity of these extreme conditions appeared to have increased in recent years. On the other hand, water quality of Poyang Lake has been reported to have declined recently, causing numerous problems and posing a significant threat to both animals and humans. Despite these known problems, due to technical difficulties, to date long-term, quantitative records of Poyang Lake's water quantity (e. g. , lake size) and water quality are still lacking, let alone the knowledge on what drove the long-term changes. In this study, several techniques were developed to combine long-term remote sensing, meteorological, and hydrological observations to: quantify the spatial and temporal changes of Poyang Lake's volume and water quality; and document and understand how these changes are affected by natural and human forces. The study led to not only new methods and algorithms on remote sensing of lake's environment but also several significant findings, most of which have been published in peer-reviewed literature by myself and my coauthors. The main contents of this

dissertation are separated into several chapters: ①long-term changes in Poyang Lake's inundation area (size); ② long-term changes in Poyang Lake's suspended sediment concentrations (water quality); ③ estimation of Poyang Lake's bottom topography; ④ long-term changes of Poyang Lake's water volume; and finally ⑤ impact of the Three Gorges Dam (TGD) on the downstream environments.

First, using Moderate Resolution Imaging Spectroradiometer (MODIS) medium-resolution (250-m) data collected between 2000 and 2010 and an objective water/land delineation method, I documented and studied the short- and long-term characteristics of Poyang Lake's inundation. Significant seasonality and inter-annual variability were found in the monthly and annual mean inundation areas. The inundation area ranged between 714.1 $km^2$ in October 2009 and 3 162.9 $km^2$ in August 2010, and the inundation area during any particular year could change by a factor of 2.3-3.2. During the 11-year period, the maximum possible inundation area was 14 times the minimum possible inundation area, indicating extreme variability. Both the annual mean and minimum inundation areas showed statistically significant declining trends from 2000 to 2010 ($-30.2$ $km^2/a$ and $-23.9$ $km^2/a$, $P<0.05$). The changes of the inundation area were primarily driven by local precipitation during non-summer months, while during summer months of July to September when the outflow into the Yangtze River was impeded the effect of precipitation became less significant. These results provide long-term baseline data to monitor future changes in Poyang Lake's inundation area in a timely fashion, for example quantifying the extreme drought conditions during spring 2011.

Then, a robust remote sensing algorithm to estimate concentrations of total suspended sediments (TSS) in Poyang Lake was developed using MODIS data from 2000 to 2010 and in situ data collected from two cruise surveys. The algorithm was based on atmospherically corrected surface reflectance at 645 nm, with the 1 240 nm data serving as a reference for

aerosols and a nearest-neighboring method to avoid the land adjacency effect. The algorithm showed an uncertainty of 30% ~ 40% for TSS ranging between 3 – 200 mg · $L^{-1}$. Long-term TSS distribution maps derived from the MODIS data and the customized TSS algorithm showed significant variations in both space and time, with low TSS (< 10 mg · $L^{-1}$) in wet seasons and much higher TSS (> 15–20 mg · $L^{-1}$) in dry seasons for the south lake, and generally higher TSS in the north lake. The TSS difference between the north and the south increased significantly after 2002, with mean TSS often reaching > 40 mg · $L^{-1}$ in the north. While the TSS seasonality was attributed to the seasonal changes of the lake's dominant current, the inter-annual variations were primarily driven by sand dredging activities, regulated by management policies. These case results provide baseline water quality information for future restoration efforts and a general approach to assess water quality changes in other similar water bodies in response to both climate variability and human activities.

In order to estimate Poyang Lake's volume, the first step was to derive its bottom topography. Using MODIS 250-m resolution data, I developed a novel approach to derive the bottom topography of Poyang Lake for every year between 2000 and 2009. The approach differs from other traditional methods (sonar, Lidar, optical inversion, and Radar) but takes advantage of the fast-changing nature of the lake's inundation area. On every image, the water/land boundary is effectively a topographic isobath after correction for the water level gradient. Thus, the about 10/year carefully selected MODIS images provided incremental topographic isobaths, from which bottom topography was derived every year. Such-derived topographic maps were validated using limited historical data and other consistency checks. Most of the lake bottom showed an elevation of 12 m to 17 m (referenced against the elevation reference of the Woosung Horizontal Zero). Significant inter-annual variability of the bottom topography from 2000 to 2009 was found for

some of the lake's bottom, with more areas associated with bottom elevation increases than decreases. The changes and inter-annual variability in the bottom topography were attributed to the combined effect of human activities (e. g. , sand dredging and levee construction) and weather events. One example was the increased bottom elevation from 2002 to 2003, which was apparently due to the excessive precipitation in 2002 and the impoundment of the Three-Gorges Dam in 2003.

The above-derived Poyang Lake bottom topography was combined with the lake's water-land boundary, also derived from MODIS measurements, to estimate the lake's volume at any MODIS measurement time. This information was used together with hydrologic and meteorological data to develop a box model to estimate the water exchange between Poyang Lake and Changjiang (Yangtze) River from 2000 to 2009. Significant intra- and inter-annual variability of the water budget was found, with an annual mean outflow of Poyang Lake of 120. 2 ±31. 2 billion $m^3$ during 2000-2009 and a declining trend of 5. 7 billion $m^3/a$ ($P=0.09$). The impoundment of the TGD on the Changjiang River in June 2003 led to a rapid lake-river outflow of 760. 6 million $m^3 \cdot d^{-1}$, resulting in a loss of 7 864. 5 million $m^3$ of water from the lake in a short period.

Ever since its planning in the 1990s, the TGD caused endless debates in China on its potential impacts on the environments and humans. Yet to date synoptic assessment of environmental changes and their potential linkage with the TGD is still lacking. The above analyses already showed the impact of the TGD on the Poyang Lake's water budget during the TGD impoundment year of 2003, and the impact of the TGD on the downstream water environment is further analyzed here by combing remote sensing, meteorological, and hydrological observations. A 10-year MODIS time-series from 2000 to 2009 revealed significantly decreasing trends (3. 3%/year) in the inundation areas of Poyang Lake