DOI:10.13476/j.cnki.nsbdqk.2020.0007
孙周亮,刘艳丽,刘冀,等. 1960—2012 年湄公河干流径流时空演变[J]. 南水北调与水利科技,2020,18(1):51-65. SUN Z L, LIU Y L, LIU J, et al. Spatiotemporal evolution of runoff in the mainstream of the Mekong River from 1960 to 20122[J]. South-to-North Water Transfers and Water Science & Technology, 2020, 18(1): 51-65. (in Chinese)

1960—2012 年湄公河干流径流时空演变

孙周亮[1,2,3],刘艳丽[1,2],刘冀[4],唐雄朋[1,2],舒章康[1,2],关铁生[1,2]

(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,南京 210098;2. 水利部应对气候变化研究心,南京 210029;3. 武汉大学 水资源与水电工程科学国家重点实验室,武汉 430072;4. 三峡大学 水利与环境学院,湖北 宜昌 443002)

摘要:根据湄公河干流清盛、琅勃拉邦、穆达汉、上丁 4 个代表性水文站 1960—2012 年的实测日径流资料,采用 Mann-kendall 趋势检验法、Pettitt 突变检验法和不均匀系数 C_V,分析了年径流、汛期和枯期径流、月径流和极值径流等水文要素的演变特征。结果表明,清盛、琅勃拉邦、上丁三站年径流呈下降趋势,穆达汉站年径流为上升趋势,其中穆达汉站年径流在 1994 年发生显著突变;各站汛、枯期径流比值均呈下降趋势,汛、枯期径流分配差异趋于减小;各站年内分配不均匀系数 C_V 均为下降趋势,其中清盛站和上丁站下降趋势达显著水平,各站径流年内分配过程趋于均匀;清盛、穆达汉、上丁三站流量波动区间逐渐减小,琅勃拉邦站流量波动区间逐渐增大。整体上,湄公河流域产水能力的空间差异较大,50 多年来不同河段的径流变化趋势呈现增减相间的格局。

关键词:径流;时空演变;年内分配;湄公河

中图分类号:TV213　　**文献标志码:**A　　**开放科学(资源服务)标识码(OSID):**

水资源合理配置是人-水系统和谐发展的有效手段,而被利用水资源大多数来源于河川径流,同时水量共享利用也是国际河流的高频议题。湄公河是一条贯穿东南亚的重要国际河流,沿岸居民的生产、生活都直接受到湄公河水量变化的影响,因此研究湄公河的径流演变规律对于湄公河水资源合理利用具有重要意义[1]。

湄公河上游为我国的澜沧江,从我国出境后依次流经缅甸、老挝、泰国、柬埔寨和越南。由于湄公河跨越的多个国家之间地理位置、经济水平、科技水平、社会文化等差异较大,导致各国对湄公河水资源的利用及其效益需求也存在明显的差异性[2]。由于湄公河沿岸国家多属不发达国家,经济、技术发展水平较为落后,因此各国在农业灌溉、水电、渔业和生态等方面对湄公河具有较大依赖性[3]。另一方面,湄公河流域范围呈纬向分布,穿越了多个气候带且受季风影响显著,降雨时间分配极不均匀,存在明显的雨旱分化特征,约八成降雨出现在雨季(6 月—11 月)[4-5],因此水资源的变化对开发利用的深远影响是显然的[6]。

当前国内外对于湄公河的径流演变规律的分析和研究还较少[7]。我国较早的有何大明对澜沧江-湄公河流域的自然地理、水文、水资源等特征进行了首次系统的分析,开启了我国研究澜沧江-湄公河问题的先河[8]。周婷等[5,9]先后对湄公河年流域的径流变化趋势、干旱时空分布等特征进行了分析,并定量评价了清盛站年径流、汛期和枯期径流、低流量等方面的趋势与突变特征[10],钟华平等[11]分析了湄公河干流径流的空间变化及其对洞里萨湖和三角洲两地区的水文特征影响,并分析了澜沧江水电开发对

收稿日期:2019-04-19　**修回日期:**2019-12-02　**网络出版时间:**2020-01-02
网络出版地址:http://kns.cnki.net/kcms/detail/13.1334.TV.20200102.1605.002.html
基金项目:国家重点研发计划(2016YFA0601602);国家自然科学基金项目(91747103;51679145;51779146);中央级公益性科研院所基本科研业务费专项(Y518007)
作者简介:孙周亮(1993—),男,湖北咸宁人,博士研究生,主要从事水文水资源研究。E-mail:zlsun17@163.com
通信作者:刘艳丽(1981—),女,河南泌阳人,教授级高级工程师,博士,主要从事气候变化对水文水资源的影响研究。E-mail:ylliu@nhri.cn

下游干流(即相当于湄公河入流)径流调节与时间分配的影响[12]，雷四华等[13]对澜沧江水电开发对出境径流的影响进行了模拟和分析。国际上则研究相对较少，Hoang 等[14]研究了未来气候和人类活动影响下的旱季和雨季径流量变化，Li 等[15]分析了大坝建设对下游流量脉冲特征的影响。以上研究主要集中于径流的总体分布和总量宏观变化特征方面，对于湄公河极值径流，径流年内分配均匀性和空间产水变化等水文特征研究还较少。

为了更加全面地掌握湄公河径流变化特征，本文基于湄公河干流的长系列日径流观测资料对年、月、汛期和枯期、日尺度极值径流等要素进行了分析和研究，从而为水资源合理利用提供支持。

1　数据与方法

1.1　数据来源

对于澜沧江-湄公河流域而言，我国境内部分称为澜沧江，出境后称为湄公河，由于允景洪为我国在澜沧江的最后一个控制站，且距离出境点较近，一般将允景洪站的流量近似作为我国出境流量。本文中的湄公河流域为允景洪站以下的部分，考虑到上丁站流量可达全流域径流量的 90%[11]，因此本文主要考虑以允景洪站至上丁站之间的部分代表湄公河流域。在综合考虑了空间代表性、资料系列长度等因素的基础上，从湄公河干流选取了清盛(Chiang Saen)、琅勃拉邦(Luang Prabang)、穆达汉(Mukdahan)、上丁(Stung Treng)4 个水文站，并收集了各站 1960—2012 年的逐日流量观测资料，数据来源于湄公河委员会，可靠性较高。

1.2　分析方法

本文主要采用了 Mann-kendall 趋势检验法、Pettitt 突变检验法和不均匀系数指标 C_V。

Mann-kendall 趋势检验法(下称 Mann-kendall 法)是水文气象领域广泛应用的一种非参数检验法，通过计算统计量 Z 对序列趋势变化的显著性进行双边检验，当 Z 的绝对值大于一定显著性水平 α 下的临界值时，即可认为所分析序列在统计意义上存在显著性变化趋势。其中 Z 的绝对值大小体现了变化趋势的大小，Z 值的正、负号分别表示上升、下降趋势[16]。

Pettitt 突变检验法(下称 Pettitt 法)也是一种非参数检验法，通过计算统计量 U 及其绝对值最大值处的概率 P 值检验序列最有可能突变点的显著性，当 P 小于给定的显著性水平 α 时，即可认为 U 的绝对值最大值处是统计意义的显著突变点，该值出现的时间即突变发生的时间[17]。

本文定义上述方法采用的显著性水平 $\alpha=0.05$，相应的临界值区间为 $-1.96\sim1.96$。

不均匀系数指标 C_V(变差系数)是对序列波动不均匀性进行量化的常用指标，C_V 值越大表明序列不均匀性越大、波动性越大[18]。

2　结果与分析

2.1　径流年际变化

各站年平均流量年际变化见图 1。从年际变化过程及趋势线上看，清盛、琅勃拉邦、上丁三站年径流均呈下降趋势，穆达汉站年径流为上升趋势，图 1

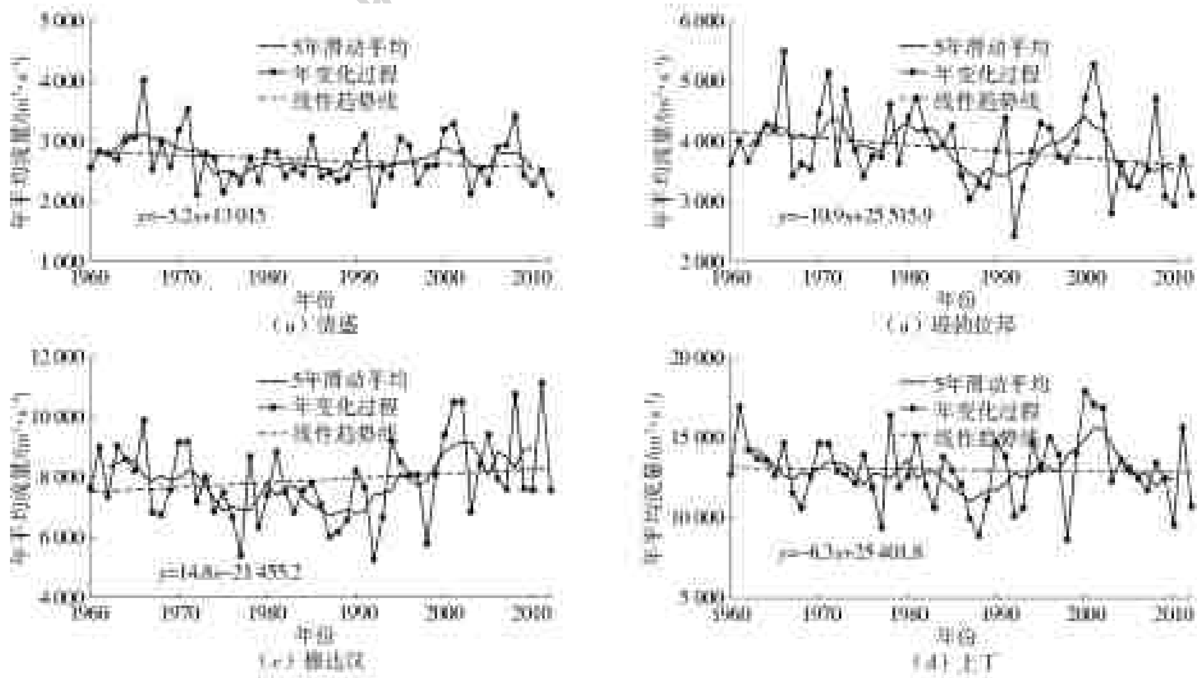

图 1　各站径流年际变化过程

中各站趋势线的线性倾向估计值存在较大差异,依次为－5.2、－10.9、14.8、－6.3,表明总体变化幅度穆达汉站最大,其次是琅勃拉邦站,清盛站和上丁站较为接近。

采用 Mann-kendall 法和 Pettitt 法分别对各站年径流趋势性和突变性进行检验,检验结果见表 1。从 Z 值来看,各站检验结果依次为－1.23、－1.85、0.91、－0.48,Z 值均在临界值区间内,即表示各站年径流变化趋势均不显著。从 P 值来看,清盛、琅勃拉邦、上丁三站检验结果均大于临界值 α,即未发生显著突变,穆达汉站检验结果为 0.049(小于 α),即发生了显著性突变;从时间上看,各站分别在 1972 年、1986 年、1994 年、1994 年发生突变。从 5 年滑动平均过程线不难看出,各站均呈现出前后时期变化趋势发生转折的相似特点,清盛站转折点大约在 1970 年,琅勃拉邦站转折点大约在 1985 年,穆达汉站、上丁站转折点大约在 1995 年,与 Mann-kendall 法检验的转折时间接近。

表 1　各站年径流和不均匀系数序列趋势、突变检验结果

站点	年径流		不均匀系数	
	Z	P	Z	P
清盛	－1.23	0.15(1972)	－2.11	0.02(1972)
琅勃拉邦	－1.85	0.10(1986)	－0.22	0.51(1995)
穆达汉	0.91	0.049(1994)	－1.62	0.26(1976)
上丁	－0.48	0.96(1994)	－2.28	0.08(1998)

注:括号内为突变发生年份,下划线表示突变显著。

2.2　汛、枯期径流变化

湄公河流域径流存在明显的枯期和汛期差异性。为了定量描述这种时期区分,根据文献[5]中的结论,本文将全年按 12 月一次年 5 月、6—11 月分别划分枯期和汛期,分别分析汛、枯期径流及汛、枯期径流比值的变化特征,如 1961 年枯期为 1960 年 12 月—1961 年 5 月,汛期为 6—11 月,各站枯期和汛期径流趋势与突变检验结果见表 2。

表 2　各站汛、枯期径流趋势、突变检验结果

站点	枯期		汛期		汛期/枯期	
	Z	P	Z	P	Z	P
清盛	1.13	0.81(1965)	－1.92	0.07(1971)	－2.30	0.03(1971)
琅勃拉邦	－1.62	0.12(1986)	－1.67	0.16(1985)	－0.51	0.94(2008)
穆达汉	3.35	3.71×10^{-4}(1999)	0.37	0.21(1993)	－1.95	0.27(1981)
上丁	1.71	0.003(1996)	－1.00	1.12(1966)	－2.49	0.05(1995)

注:括号内为突变发生年份,下划线表示突变显著。

从枯期径流来看,清盛、穆达汉、上丁三站均呈增加趋势,且穆达汉站增加趋势显著,并发生了显著突变,结合趋势性可知为突变增加。从汛期径流来看,清盛、琅勃拉邦、上丁三站均呈减少趋势,穆达汉站呈增加趋势,变化趋势均不显著。从汛、枯期径流比值来看,各站均呈下降趋势,且清盛、上丁两站增加趋势显著,其中清盛、上丁两站发生了显著突变,表明各站汛、枯期径流分配差异趋于减小,且清盛、穆达汉、上丁三站差异减小趋势显著或接近显著。

2.3　各月径流变化

径流的年内分配特征是径流的基本特征之一。为了了解径流的年内分配不均匀性情况,首先计算了各站逐年月平均径流的不均匀系数 C_V 序列,其次采用 Mann-kendall 法和 Pettitt 法分别对各站径流年内分配不均匀系数 C_V 序列的趋势性和突变性进行检验,检验结果见表 1。从 Z 值来看,各站年内分配不均匀系数 C_V 均为下降趋势,其中清盛站和上丁站下降趋势达显著水平,表明各站径流年内过程趋于均匀。从 P 值来看,清盛站发生了显著突变,突变时间为 1972 年,与年径流突变时间一致。

为分析各月径流变化的差异性,采用 Mann-kendall 法对各月径流的年际变化趋势进行检验,为了对比年径流量变化对检验结果的影响,其中月径流分别采用绝对径流和相对径流进行对比,绝对径流是指各月的实际平均流量,反映各月份的径流量变化,相对径流是指各月径流占当年全年总径流的比例,反映各月径流全年分配比的变化,各月径流多年变化趋势检验结果见表 3。值得说明的是,当绝对径流和相对径流变化趋势方向一致,即同为上升或下降趋势时,则说明该月径流多年变化幅度(即相对该月的变幅)相对年径流量增加或减少幅度较大。

清盛站绝对径流中 1—5 月为上升趋势,其中 4、5 月上升趋势显著,6—12 月为下降趋势,其中 8 月下降趋势显著。相对径流中 12、1—7 月为上升趋势,其中 3—5 月上升趋势显著,8—11 月为下降趋势,其中 8 月下降趋势显著。绝对径流和相对径流中 1—5 月、8—11 月趋势方向一致,表明 1—5 月径流增加幅度较大,8—11 月径流减小幅度较大。

琅勃拉邦站绝对径流中 4 月总体平稳,5 月为

上升趋势,其余月份均为下降趋势,其中 1、2、8、11、12 月下降趋势显著。相对径流中 3—7 月为上升趋势,其中 5 月上升趋势显著,8—12 月、1—2 月为下降趋势,下降趋势均不显著。绝对径流和相对径流中 1—2 月、8—12 月、5 月趋势方向一致,表明 1—2 月、8—12 月径流减少幅度较大,5 月径流增加幅度较大。

穆达汉站绝对径流中 6、11 月为下降趋势,其余月份均为上升趋势,其中 1—5 月上升趋势显著。相对径流中 1—5 月、7—8 月为上升趋势,其中 3—5 月上升趋势显著,6 月、9—12 月为下降趋势,下降趋势均不显著。绝对径流和相对径流中 1—8 月、1 月趋势方向一致,表明 1—5 月、7—8 月径流增加幅度较大,6—11 月径流减少幅度较大。

上丁站绝对径流中 12 月、1—5 月为上升趋势,其中 4、5 月上升趋势显著,6—11 月为下降趋势,下降趋势均不显著。相对径流中 12、1—5 月、7 月为上升趋势,其中 3—5 月上升趋势显著,6 月、9—11 月为下降趋势,下降趋势均不显著。绝对径流和相对径流中 1—6 月、8—12 月趋势方向一致,表明 12—次年 5 月、径流增加幅度较大,6 月、8—11 月径流减小幅度较大。

表 3　各站不同月份径流趋势检验结果

月份	清盛		琅勃拉邦		穆达汉		上丁	
	绝对径流	相对径流	绝对径流	相对径流	绝对径流	相对径流	绝对径流	相对径流
1	0.58	0.94	-2.17	-0.51	2.00	0.08	0.94	1.19
2	0.04	0.70	-2.46	-1.07	3.23	1.45	1.63	1.40
3	1.93	2.00	-0.91	0.42	4.00	3.21	1.74	2.25
4	2.31	2.48	0.00	1.45	5.65	4.84	3.63	4.49
5	2.40	3.32	1.28	3.09	4.36	4.33	2.95	3.66
6	-0.58	0.41	-1.12	0.05	-0.02	-0.33	-0.71	-0.36
7	-0.56	0.58	-0.22	1.50	1.11	0.68	-0.15	0.33
8	-2.51	-2.65	-1.97	-0.85	0.77	0.12	-0.59	-0.15
9	-0.87	-0.05	-1.35	-0.15	0.06	-1.08	-1.02	-1.13
10	-1.02	-0.05	-1.80	-0.44	0.50	-0.77	-0.08	-0.38
11	-1.62	-0.93	-2.51	-0.93	-0.39	-1.31	-0.59	-0.10
12	-0.27	0.67	-3.11	-1.89	0.28	-1.74	0.12	0.74

注:红色表示上升趋势,蓝色表示下降趋势,加方框表示趋势显著。

湄公河流域是受季风影响的典型地区,因此径流年内分配是影响水资源高效利用的重要影响因素。从表 1 年内各月分配不均匀系数变化趋势来看,各站径流年内分配过程趋于均匀,这增加了径流的可利用性和可控性。结合各月相对径流变化趋势来看,这种年内分配均匀化趋势在各月分配比例变化方面具有空间相似性,即枯期径流占比增加、汛期径流占比减少,尤以 3—5 月径流占比增加、8—11 月径流占比减小为主。但这种均匀化趋势在绝对径流变化方面的表现存在一定空间差异性,其中清盛站和上丁站 1—5 月径流量均表现为增加趋势,6—11 月均表现为减少趋势,两时期的变化趋势均较大且相当,因此月分配不均匀系数减小趋势显著;琅勃拉邦站全年有 10 个月径流均为减少趋势,枯期减少趋势稍大于汛期且均接近显著水平,因此月分配不均匀系数减少趋势较小;穆达汉站则是全年有 10 个月径流为增加趋势,且枯期增加趋势显著,因此月分配不均匀系数减少趋势较大。

2.4　极值径流变化

极值径流是影响洪旱灾害的重要指标,反映了流量波动幅度变化。本文从年统计尺度上考虑最大和最小 1 日、3 日、7 日流量等指标来分析湄公河干流极值径流变化特征,考察各指标序列的趋势变化,检验结果见表 4。

清盛站最大 1 日、3 日、7 日流量和最小 1 日、3 日、7 日流量均呈减少趋势,但最大流量比相应历时最小流量减小趋势大,说明流量波动区间逐渐减小。琅勃拉邦站最大 1 日、3 日、7 日流量和最小 1 日、3 日、7 日流量均呈减少趋势,其中最小 1 日、3 日、7 日流量减少趋势显著,说明流量波动区间逐渐增大。穆达汉站最大 1 日、3 日、7 日流量和最小 1 日、3 日、7 日流量均呈减少趋势,其中最小 1 日、3 日、7 日流量增加趋势显著,说明流量波动区间逐渐减小。上丁站最大 1 日、3 日、7 日流量均为减小趋势,最小 1 日、3 日、7 日流量均为增加趋势,说明流量波动区间逐渐减小。

表 4　各站最大和最小 1 日、3 日、7 日流量趋势检验结果

站点	Max1d	Min1d	Max3d	Min3d	Max7d	Min7d
清盛	-1.55	-0.74	-1.77	-0.31	-1.62	0.18
琅勃拉邦	-1.03	-2.68	-1.20	-2.71	-1.20	-2.40
穆达汉	0.22	4.60	0.15	4.67	0.19	4.71
上丁	-1.79	1.20	-1.70	1.23	-1.93	1.37

注：Max、Min 表示最大、最小值，1 d、3 d、7 d 表示 1 日、3 日、7 日流量。

3　产水变化的空间特征

由于所选的 4 个代表站之间为上下游关系，径流变化规律存在依存关系。为了分析产水量的空间差异性，采用去除上游影响的径流序列分析区间内的产水变化特征。相邻站点之间形成自然产流区间，忽略当前区间（即当前断面与上一断面之间的流域范围）对上游断面来水的调蓄影响，将当前断面径流（观测径流）减去上游断面径流，所得径流差值作为当前区间产水。对比当前断面观测径流与区间产水即可分析得到区间产水变化特征和上断面来水对当前杜断面径流变化特征的影响。将允景洪站（下称景洪）作为湄公河的上游来水断面，分析该站径流变化特征及其对下游径流变化特征的影响。表 5 列出了不同区间在枯期、汛期及全年的来水变化趋势。其中左列为景洪以上以及景洪与下游不同断面区间的径流变化趋势，右列为湄公河干流相邻断面区间的径流变化趋势，结合表 1、2 断面观测径流检验结果分析各区间产水变化特征。由于表 1 中的年径流为自然年，表 5 中的年径流为水文年，经计算得到各断面水文年径流变化趋势检验结果（结果略）与自然年接近，因此下文中的干流站点年径流变化趋势仍然采用表 1 的结果。

景洪以上来水在枯期及汛期均减少，且汛期减少显著从而年径流减少显著。景洪-清盛区间产水在枯期和汛期均为增加趋势，且枯期增加趋势显著，因此清盛站径流减少趋势主要是受景洪汛期径流减少所致。清盛-琅勃拉邦区间产水在枯期和汛期均为减少，且枯期径流减少显著，而景洪-琅勃拉邦区间产水亦为减少趋势，景洪-清盛区间所增加的来水难以补充前后两个区间的来水减少量，因此琅勃拉邦站径流减少趋势受景洪来水减少和清盛-琅勃拉邦区间产水减少的双重影响。琅勃拉邦-穆达汉区间产水增加趋势显著，而琅勃拉邦站径流为显著减少，因此穆达汉站径流增加趋势主要受琅勃拉邦-穆达汉区间产水显著增加的影响。结合景洪-琅勃拉邦、景洪-穆达汉两区间产水以及琅勃拉邦、穆达汉径流变化趋势可知，琅勃拉邦-穆达汉区间产水对湄公河中下游径流变化具有重要影响。穆达汉-上丁区间产水为减少趋势，虽然穆达汉站径流为增加趋势，且枯期径流增加显著而年径流为减少趋势，但上丁站径流为减少趋势，因此其径流减少趋势主要受穆达汉-上丁区间汛期径流减少影响。

表 5　不同区间产水变化趋势检验结果

区间	枯期	汛期	全年
景洪以上	−0.52	−3.01	−2.88
景洪-琅勃拉邦	−1.70	−0.50	−1.00
景洪-穆达汉	3.51	0.77	1.37
景洪-上丁	1.93	−0.64	−0.18
景洪-清盛	2.28	0.31	0.56
清盛-琅勃拉邦	−3.65	−0.70	−1.37
琅勃拉邦-穆达汉	5.15	1.71	2.23
穆达汉-上丁	−0.51	−1.60	−1.60

注：全年指当年枯期和汛期径流之和，此处为上年 12 月至当年 11 月的来水量。

从上述分析结果可知，总体上 5 个区间产水变化趋势呈现增减相间的格局。各个断面的径流变化必然是受到上游断面来水和本地产水的影响，从本文的结果可以得出，上下游相邻断面之间的径流变化趋势可能存在反向性，即区间产水变化完全可以改变下断面的径流变化趋势，相邻断面并不会因为存在上下游关系而必然地出现一致的变化趋势。如琅勃拉邦断面径流为减小趋势，琅勃拉邦-穆达汉区间产水的增加使得穆达汉断面径流为增加趋势，穆达汉-上丁区间产水的减少又使得上丁断面径流为减小趋势。

4　结论与展望

本文以清盛、琅勃拉邦、穆达汉、上丁四个水文站为代表站，基于 1960—2012 年日径流系列资料，采用了 Mann-kendall 趋势检验法、Pettitt 突变检验法和不均匀系数指标 C_V，从年径流、汛期和枯期径流、月径流、极值径流和区间产水等方面分析了湄公河干流的径流演变特征。主要得到以下结论。

（1）清盛、琅勃拉邦、上丁三站年径流均呈下降趋势，穆达汉站年径流为上升趋势，变化趋势均不显著；清盛、琅勃拉邦、穆达汉、上丁四站分别于 1972、1986、1994、1994 年发生突变，其中穆达汉站突变显著。

(2)各站径流年内分配趋于均匀。各月径流分配呈均匀化趋势,以清盛站和上丁站表现最为显著。枯期径流占比增加、汛期径流占比减少,主要体现在 3—5 月径流占比增加、8—11 月径流占比减小。

(3)清盛站、琅勃拉邦站高流量及低流量均呈减小趋势,其中清盛站高流量比低流量减小趋势大,琅勃拉邦站则相反。穆达汉站高流量及低流量均呈增加趋势,低流量比高流量减小趋势大。上丁站高流量呈减小趋势而低流量呈增加趋势。即清盛、穆达汉、上丁三站流量波动区间逐渐减小,琅勃拉邦站流量波动区间逐渐增大。

(4)湄公河干流相邻站点之间的区间产水变化趋势差异较大,从而影响了下游的区间出口断面径流变化特征。从上游到下游,各区间产水变化趋势呈现增减相间的格局。

参考文献:

[1] 李奔,张坤,程天矫. 基于层次分析法的澜沧江-湄公河可消耗水量分配[J]. 武汉大学学报(工学版),2018,51(5):389-393. DOI:10.14188/j.1671-8844.2018-05-003.

[2] 唐海行. 澜沧江—湄公河流域的水资源及其开发利用现状分析[J]. 云南地理环境研究,1999,11(1):16-25.

[3] 赵萍,汤洁,尹笋. 湄公河流域水资源开发利用现状[J]. 水利经济,2017,35(4):55-58. DOI:10.3880/j.issn.1003-9511.2017.04.011.

[4] 杨婧,李铎,毕攀,等. 澜沧江-湄公河流域水资源利用概况[J]. 安徽农业科学,2009,37(16):7569-7570. DOI:10.3969/j.issn.1009-640X.2011.03.007.

[5] 周婷,于福亮,李传哲,等. 1960—2005 年湄公河流域径流量演变趋势[J]. 河海大学学报:自然科学版,2010,38(6):608-613. DOI:10.3876/j.issn.1000-1980.2010.06.002.

[6] HE Y,GUI Z,SU C,et al. Response of sediment load to hydrological change in the upstream part of the Lancang-Mekong River over the past 50 years[J]. Water. 2018,10(7):888. DOI:10.3390/w10070888.

[7] XUE Z,LIU J P,GE Q. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: connection to damming, monsoon, and ENSO [J]. Earth Surface Processes & Landforms,2011,36(3):296-308. DOI:10.1002/esp.2036.

[8] 何大明. 澜沧江-湄公河水文特征分析[J]. 云南地理环境研究,1995,7(1):58-74.

[9] 周婷,李传哲,于福亮,等. 澜沧江-湄公河流域气象干旱时空分布特征分析[J]. 水电能源科学,2011,29(6):4-7,193. DOI:10.3969/j.issn.1000-7709.2011.06.002.

[10] 周婷,于福亮,李传哲,等. 湄公河清盛站水文情势变化分析[J]. 水电能源科学,2011,29(11):15-18. DOI:10.3969/j.issn.1000-7709.2011.11.004.

[11] 钟华平,王建生. 湄公河干流径流变化及其对下游的影响[J]. 水利水运工程学报,2011,32(3):48-52. DOI:10.16198/j.cnki.1009-640x.2011.03.011.

[12] 钟华平,王建生. 澜沧江干流水电开发对径流的影响分析[J]. 水利水电技术,2010,41(12):72-74. DOI:10.3969/j.issn.1000-0860.2010.12.018.

[13] 雷四华,刘静楠,顾颖,等. 澜沧江干流水电站建设前后出境点径流变化分析[J]. 云南大学学报(自然科学版),2010,32(1):58-62. DOI:10.3724/SP.J.1084.2010.00199.

[14] HOANG L P,VAN VLIET M T H,KUMMU M,et al. The Mekong′s future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes[J]. Science of The Total Environment,2019,649:601-609. DOI:10.1016/j.scitotenv.2018.08.160.

[15] LI D,LONG D,ZHAO J,et al. Observed changes in flow regimes in the Mekong River basin[J]. Journal of Hydrology,2017,551(S1):217-232. DOI:10.1016/j.jhydrol.2017.05.061.

[16] 周吉,季永东,白宁明,等. 无锡市水情科学调度的实践与思考[J]. 江苏水利,2014(12):25-28. DOI:10.16310/j.cnki.jssl.2014.12.016.

[17] 李继清,朱一鸣,李建昌,等. 变化环境对潮河下游径流一致性的影响[J]. 南水北调与水利科技,2017,15(3):5-12. DOI:10.13476/j.cnki.nsbdqk.2017.03.002.

[18] 王万瑞,王刘明,张雪蕾,等. 1956—2015 年洮河径流演变特征研究[J]. 西北师范大学学报(自然科学版),2018,54(1):92-99. DOI:10.16783/j.cnki.nwnuz.2018.01.015.

·译文(Translation)·

DOI:10.13476/j.cnki.nsbdqk.2020.0007

Spatiotemporal evolution of runoff in the mainstream of the Mekong River from 1960 to 2012

SUN Zhouliang[1,2,3], LIU Yanli[1,2], LIU Ji[3], TANG Xiongpeng[1,2], SHU Zhangkang[1,2], GUAN Tiesheng[1,2]

(1. Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing 210098, China; 2. Research Center for Climate Change of Ministry of Water Resources, Nanjing 210029, China; 3. State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China; 4. College of Hydraulic and Environment, China Three Gorges University, Yichang 443002, China)

Abstract: This study evaluates the hydrological characteristics such as annual runoff, runoff in flood and dry season, monthly runoff and extreme runoff using daily measured runoff data of Chiang Saen, Luang Prabang, Mukdahan and Stung Treng hydrological stations in the mainstream of Mekong River from 1960 to 2012. For this purpose, the Mann-Kendall trend test, the Pettitt mutation test, and the coefficient of variance (C_V) were used to analyze the evolution characteristics.. The results showed that the annual runoff of Chiang Saen, Luang Prabang, and Stung Treng stations exhibited downward trend, while the annual runoff of Mukdahan stations showed upward trend. Among them, the annual runoff of Mukdahan station had a significant change in 1994. The runoff ratio showed a downward trend, while the difference in runoff distribution during the flood season and dry season tended to decrease. Furthermore, the C_V of each station showed decreasing trend. The declining trend of Chiang Saen and Stung Treng stations was significant, and the runoff distribution of each station was distributed within the year. The flow fluctuation range of three stations (Chiang Saen, Mukdahan, and Stung Treng) was gradually decreased, while the flow fluctuation range of Luang Prabang station increased gradually. On the whole, the runoff change trend showed an increased and decreased pattern at different river sections in the past 50 years which revealed that the spatial difference of water production capacity of the Mekong River Basin is quite large.

Key words: runoff; spatial-temporal evolution; hydrological characteristics; Mekong River

Reasonable allocation of water resources is an effective means for the harmonious development of human-water systems, and most of the water resources used come from river runoff. At the same time, water allocation operation is also a high-frequency issue for international rivers. The Mekong River is an important international river that runs through Southeast Asia. The production and life of residents along the coast are directly affected by changes in the amount of water in the Mekong River. Therefore, the study of the runoff evolution of the Mekong River is of great significance for the rational use of water resources[1].

The upper reach of the Mekong River is Lan-

Received: 2019-04-19 **Revised**: 2019-12-02 **Online publishing**: 2020-01-02
Online publishing address: http://kns.cnki.net/kcms/detail/13.1334.TV.20200102.1605.002.html
Funds: National Key Research and Development Program of China (2016YFA0601602); National Natural Science Foundation of China (91747103; 51679145; 51779146); National Non-profit Institute Basic Research Foundation Funded Special Project (Y518007)
Author brief: SUN Zhouliang(1993-), PhD candidate, mainly engaged in hydrology and water resources research. E-mail: zlsun17@163.com
Corresponding author: LIU Yanli(1981-), professor-level senior engineer, mainly engaged in hydrology and water resources research. E-mail: ylliu@nhri.cn

cang River of China, which flows through Myanmar, Laos, Thailand, Cambodia, and Vietnam after leaving China. Due to the large differences in geographic location, economic level, scientific and technological level, social culture, and other aspects among the countries across the Mekong River, there are also obvious differences in the use of water resources and benefit needs in the Mekong River[2]. Most of the countries along the Mekong River are mostly underdeveloped countries and their economical and technological development levels are relatively low, therefore, these countries are largely depend on the Mekong River in terms of agricultural irrigation, hydropower production, fisheries, and ecology. In addition, the water resources problem is a sensitive factor that can affectthe international relations of countries in the basin[3]. Instead, the Mekong River is crossing multiple climatic zones and is significantly affected by the monsoon. The rainfall distribution is extremely uneven, and there are obvious characteristics of rainfall and drought differentiation, with about 80% of the rainfall occurs in the rainy season (June-November) [4-5]. Therefore, the profound impact of changes in water resources on development and utilization is obvious[6].

At present, there are few analyses and studies on the runoff evolution of the Mekong River at home and abroad[7]. For example, HE systematically analyzed the natural geography, hydrology, and water resources of the Lancang-Mekong River Basin for the first time in China, which opened the precedent to study the Lancang-Mekong River problems[8]. ZHOU et al[5,9] successively analyzed the characteristics of runoff changes in the Mekong River basin, and the spatial and temporal distribution of drought, and quantitatively evaluated the trends and change characteristics of annual runoff, runoff in flood and dry seasons, and low discharge at Chiang Saen[10], Zhong et al[11] analyzed the spatial changes of the Mekong mainstream runoff and its impact on the hydrological characteristics of the Tonle Sap Lake and of the Delta, and examined the impact of the development of Lancang River hydropower on the regulation and distribution time of mainstream runoff (i. e. Equivalent to the Mekong River inflow)[12], Lei et al [13] simulated and analyzed the impact of Lancang River hydropower development on outbound runoff. Internationally, there are relatively few studies. Hoang et al [14] studied the changes in dry season and rainy seasons runoff under the influence of future climate change and human activities. Li et al[15] analyzed the impact of dam construction on the characteristics of downstream flow pulses. The above studies mainly focused on the general distribution of runoff and the characteristics of macroscopic changes in total volume of Mekong River. There are few studies on the hydrological characteristics of extreme runoff of the Mekong River, for example, the uniformity of annual runoff distribution, and the variation of spatial water production.

In order to fully grasp the characteristics of the runoff change in the Mekong River, this paper analyzed the annual runoff, monthly runoff, runoff in flood season and dry season, and daily-scale extreme runoff based on the long-term daily runoff observation data of the Mekong mainstream river, so as to provide support to reasonable use of water resources in the region.

1 Data and methods

1.1 Data

The Lancing River of Lancang-Mekong River basin crossed from China and after crossing the geographical boundary of China it named as the Mekong River. Since Yunjinghong (hereinafter Jinghong) is the last controlled hydrological station in China at the Lancang River and is close to the exit point. The flow at Jinghong is generally taken as China's outbound flow. In this study, the selected Mekong River basin is the part below the Jinghong. Since, the flow of Stung Treng can reach 90% of the whole basin[11], this article mainly considered the part between Jinghong and Stung Treng, representing the Mekong River basin. In this study, a comprehensive consideration of factors such as spatial representation, data series length, four hydrological stations such as Chiang Saen, Luang Prabang, Mukdahan, and Stung Treng were selected. The daily flow observation data for each station from 1960 to 2012 were obtained from Mekong River Commission. The data have high reliability.

1.2　Methods

This paper mainly used the Mann-Kendall trend test method, Pettit mutation test method and the coefficient of variance C_V.

The Mann-Kendall trend test method (hereinafter M-K) is a non-parametric test method widely used in the field of hydrometeorology. It calculate the statistical magnitude *Z-value* for testing the bilateral significance of the trend change in a series. A certain critical value at the significance level α can be regarded as a statistically significant trend in the analyzed sequence. Among them, the absolute value of *Z-value* reflect the size of the changing trend, and the positive and negative signs of the *Z-value* indicate the upward and downward trends, respectively[16].

The Pettit mutation test method (hereinafter Pettit) is also a non-parametric test. The significance of the most likely mutation point of a sequence was tested by calculating the maximum of the statistic U and its probability *P-value*. When *P-value* was less than a given significance level α, it could be considered that the point with a maximum of absolute U was a statistically significant mutation point, and the time when the value appeared was the time when the mutation occurs[17]. This paper defined the significance level $\alpha = 0.05$, and the corresponding critical value range between −1.96～1.96.

The C_V (variation coefficient, or the uneven distribution coefficient) is a commonly used index to quantify the unevenness of sequence fluctuations. A larger C_V value indicate the sequence of greater unevenness and greater volatility[18].

2　Evolution of different runoff indicators

2.1　Variation in annual runoff

The interannual variation in the annual runoff at each station is shown in Fig. 1. From the change within a year and trend line, the annual runoff at Chiang Saen, Luang Prabang, and Stung Treng showed a downward trend, and the annual runoff at Mukdahan was displayed an upward trend. In Fig. 1, the estimated linear tendency of the trend lines at each station, for example, −5.2, −10.9, 14.8, and −6.3, were greatly different, showed that the overall change range was the largest at Mukdahan, followed by Luang Prabang, and Chiang Saen and Stung Treng were similar.

The M-K and Pettitt were used to test the annual runoff trend and mutation point at each station. The test results are shown in Tab. 1. The test

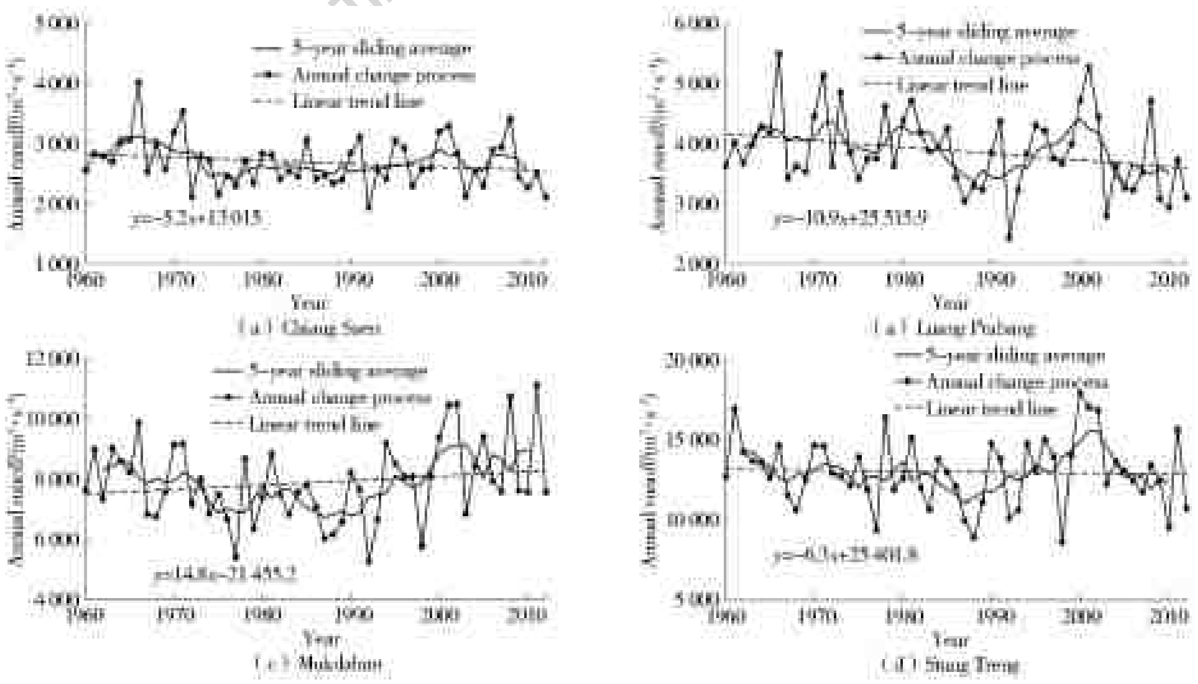

Fig. 1　Temporal variations in annual runoff at each station

Tab. 1 Mann-Kendall and Pettit test values of annual runoff and C_V at each station

Stations	Annual runoff		C_V	
	Z	P	Z	P
Chiang Saen	−1.23	0.15(1972)	−2.11	0.02(1972)
Luang Prabang	−1.85	0.10(1986)	−0.22	0.51(1995)
Mukdahan	0.91	0.049(1994)	−1.62	0.26(1976)
Stung Treng	−0.48	0.96(1994)	−2.28	0.08(1998)

Note: the year in which the mutation occurred is in parentheses, and the underline indicates the mutation is significant

results of each station showed that *Z-values* such as −1.23, −1.85, 0.91, −0.48, were within the critical value interval, which mean that the annual runoff change trend of each station was not significant.

From the *P*-value, the test results of Chiang Saen, Luang Prabang, and Stung Treng were all greater than the critical value α, it revealed that there was no significant mutation occurred. The test result of Mukdahan station was 0.049 (less than α), which showed a significant that at Mukdahan station mutation was occurred. During analysis it was also observed that the runoff mutation were occurred during the year of 1972, 1986, 1994 and 1994, respectively. Based on 5-year moving average line, it was also observed that each station showed similar characteristics of a change in the trend between two periods. The mutation point of Chiang Saen station was occurred during 1970, and in 1985 at Luang Prabang, in 1995 at Mukdahan and Stung Treng, which was close to the change time tested by the M-K.

2.2 Variation in flood season runoff and dry season runoff

There were obvious differences between dry season runoff and flood season runoff of the Mekong River basin. Based on previous study, Ref. [5], this study divided the dry season and flood season (December-May and June-November), to quantitatively describe the division of time. To analyze the flood season runoff, dry season runoff and the ratio, the dry season in 1961 was taken from December 1960 to May 1961 and the flood season from June to November. The runoff trends and mutation test results of the dry season and flood season at each station are shown in Tab. 2.

From the perspective of dry season runoff, Chiang Saen, Mukdahan, and Stung Treng showed an increasing trend, while Mukdahan showed a significant increase trend and displayed a significant mutation point occurred at this station. It can be seen that is was the mutation to increase. From the perspective of flood season runoff, Chiang Saen Sttion, Luang Prabang, and Stung Treng showed a non-significant decreasing trend, while the Mukdahan showed a non-significant increasing trend.

Tab. 2 Mann-Kendall and Pettit test values for annual flood season and dry season at each station

Stations	Dry season runoff		Flood season runoff		RatioZ	
	Z	P	Z	P	Z	P
Chiang Saen	1.13	0.81(1965)	−1.92	0.07(1971)	−2.30	0.03(1971)
Luang Prabang	−1.62	0.12(1986)	−1.67	0.16(1985)	−0.51	0.94(2008)
Mukdahan	3.35	3.71×10^{-4}(1999)	0.37	0.21(1993)	−1.95	0.27(1981)
Stung Treng	1.71	0.003(1996)	−1.00	1.12(1966)	−2.49	0.05(1995)

Note: the year in which the mutation occurred is in parentheses, and the underline indicates the mutation is significant

For the ratio, all stations showed a decline trend, while the trend of Chiang Saen and Stung Treng was significant. Among them, significant changes were occurred at two stations (Chiang Saen and Stung Treng), indicating that the difference of runoff allocation between flood and dry season at each station tended to decrease. The difference between Chiang Saen, Mukdahan, and Stung Treng showed a significant or close to significant decrease trend.

2.3 Variation in monthly runoff

The annual distribution of runoff is one of the basic characteristics of runoff. To understand the uneven distribution of runoff, the annual average of the C_V series of each station was calculated, and then the M-K and Pettit were used to test the trend in C_V series at each station. The test results are shown in Tab. 1. For *Z-value*, the C_V of each station has a downward trend, and the downward trend of Chiang Saen and Stung Treng reached at significant level, indicating that the annual runoff at each station had become uniform. For the *P*-value, a significant mutation point occurred during 1972 at Chiang Saen, which was consistent with the annual runoff mutation time.

To analyze the differences in changes in monthly runoff, the M-K was used to test the variation trends of monthly runoff. To compare the effects of annual runoff changes on the test results, monthly runoff was conductedusing absolute runoff and relative runoff. In contrast, absolute runoff refer to the actual average flow of each month, which reflect the change of runoff in each month, and relative runoff refer to the proportion of each month's runoff to the total runoff of the year and reflect the change in the annual distribution ratio of runoff in each month. Tab. 3 showed the test results of the runoff changes. It was worth noting that when the absolute runoff and relative runoff change in the same direction, they were both up or down, it showed that the annual runoff of the monthly runoff (relative to the month's change) increased or decreased relative to the annual runoff.

Tab. 3 Mann-Kendall test values of monthly runoff at each station

Months	Chiang Saen		Luang Prabang		Mukdahan		Stung Treng	
	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative
1	0.58	0.94	-2.17	-0.51	2.00	0.08	0.94	1.19
2	0.04	0.70	-2.46	-1.07	3.23	1.45	1.63	1.40
3	1.93	2.00	-0.91	0.42	4.00	3.21	1.74	2.25
4	2.31	2.48	0.00	1.45	5.65	4.84	3.63	4.49
5	2.40	3.32	1.28	3.09	4.36	4.33	2.95	3.66
6	-0.58	0.41	-1.12	0.05	-0.02	-0.33	-0.71	-0.36
7	-0.56	0.58	-0.22	1.50	1.11	0.68	-0.15	0.33
8	-2.51	-2.65	-1.97	-0.85	0.77	0.12	-0.59	-0.15
9	-0.87	-0.05	-1.35	-0.15	0.06	-1.08	-1.02	-1.13
10	-1.02	-0.05	-1.80	-0.44	0.50	-0.77	-0.08	-0.38
11	-1.62	-0.93	-2.51	-0.93	-0.39	-1.31	-0.59	-0.10
12	-0.27	0.67	-3.11	-1.89	0.28	-1.74	0.12	0.74

Note: The numbers in red indicate the upward trend, and the blue indicate a downward trend, while a box indicate a significant trend.

At Chiang Saen station, there was an upward trend from January to May in absolute runoff. The results revealed that the upward trend was significant in April and May, while the downward trend was from June to December, of which the downward trend was significant in August. In the relative runoff, the upward trend was from December to January to July, of which the upward trend was significant from March to May, the downward trend was from August to November, and the downward trend was significant from August. Absolute runoff and the relative runoff had the same trend direction from January to May and August to November, indicating that the increase of runoff from January to May was larger and compared to August to November.

Absolute runoff at Luang Prabang station was generally stable in April, with an upward trend in May and a downward trend during the rest of the month, of which a significant downward trend in January, February, August, November, and December. Relative runoff had an upward trend from March to July, of which the upward trend was significant in May, and the downward trend in August to December and January to February and the downward trends were not significant. Absolute runoff and relative runoff had the same trend direction from January to February, August to December and May, indicating that the runoff decreased significantly from January to February, August-December, and increased a lot in May.

Absolute runoff at Mukdahan station had a downward trend in June and November, and the remaining months had upward trends, of which the upward trend was significant from January to May. The relative runoff had an upward trend from January to May and July to August, of which the upward trend was significant from March to May, and had a downward trend from June to September to December. The downward trend was not significant. Absolute runoff and relative runoff had the same trend direction from January to August and January, indicating that the increase of runoff from January to May and July to August was larger compared to June to November.

Absolute runoff at the Stung Treng had an upward trend in December and from January to May, of which the upward trend was significant from April to May, and had and downward trend from June to November. The relative runoff had an upward trend in December, from January to May and in July, the upward trend was significant from March to May, and there was a downward trend in June and from September to November. Absolute runoff and relative runoff had the same trend direction from January to June and August to December, indicating that the runoff increased significantly from December to May, and decreased significantly from June to August.

The Mekong River basin is a typical area affected by the monsoon, so the annual distribution of runoff is an important factor affecting the efficient use of water resources. According to the trend of the uneven distribution coefficient C_V of each month which is presented in Tab. 1, the distribution of runoff at each station tended to be uniform, which increased the availability and controllability of runoff. Given the relative runoff change trends of each month, this uniform distribution trend had spatial similarity in the change of the monthly distribution ratio, the dry runoff proportion increased especially from March to May and the flood runoff proportion decreased especially from August to November. However, there was a certain spatial difference in the homogenization trend in terms of absolute runoff change. For example, the runoff at Chiang Saen and Stung Treng showed an increasing trend from January to May, and a decreasing trend from June to November. The changing trends of the periods were all large and equivalent, so the monthly uneven distribution coefficient significantly decreased.

Luang Prabang station showed decreasing runoff in 10 months. The decreasing trend during the dry season was slightly larger than that in the flood season and was close to a significant level, the decreasing trend of monthly uneven distribution coefficient was smaller. For Mukdahan station, there was increase in runoff during 10 months, and the increasing trend of the dry season was significant, so the monthly uneven distribution coefficient decreased.

2.4 Variation in extreme runoff

Extreme runoff is an important indicator that could affect flood and drought disasters, reflecting changes in the magnitude of flow fluctuations. This paper considered the maximum and minimum 1-day, 3-day and 7-day flow on an annual statistical scale to analyze the changes in the extreme runoff of the Mekong mainstream, and examine the trend changes of each indicator series. The test results are shown in Tab. 4.

The maximum 1-day, 3-day, and 7-day flow and the minimum 1-day, 3-day and 7-day flow at Chiang Saen station showed a decreasing trend, but the trend value of maximum flow was larger than the corresponding minimum flow, indicating that the flow fluctuation interval gradually decreased. At Luang Prabang station, the maximum 1-day, 3-day, and 7-day flow and the minimum 1-day, 3-day, and 7-day flow all showed a decreasing trend. Among them, the minimum 1-day, 3-day, and 7-day flow decreased significantly, indicating that the flow fluctuation interval was gradually increasing. The maximum 1-day, 3-day, and 7-day flow and the minimum 1-day, 3-day and 7-day flow at Mukdahan station showed a decreasing trend. Among them, the minimum 1-day, 3-day, and 7-day flow increased significantly, indicating that the flow fluctuation interval gradually decreased. Stung Treng's station maximum 1-day, 3-day and 7-day flow showed a decreasing trend, while the minimum 1-day, 3-day, and 7-day all showed an increasing trend, indicating that the flow fluctuation interval gradually decreased.

Tab. 4 Mann-Kendall test values of maximum and minimum flow in 1-day、3-day and 7-day at each station

Stations	Max1d	Min1d	Max3d	Min3d	Max7d	Min7d
Chiang Saen	-1.55	-0.74	-1.73	-0.31	-1.62	0.18
Luang Prabang	-1.03	-2.68	-1.20	-2.71	-1.20	-2.40
Mukdahan	0.22	4.66	0.15	4.67	0.19	4.71
Stung Treng	-1.79	1.20	-1.70	1.23	-1.93	1.37

Note: The Max and Min refer to maximum and minimum, and 1d, 3d and 7d refer to flow in 1-day, 3-day, and 7-day.

3 Spatial characteristics of water yield variation

The selected four representative stations are at upstream and downstream, there is a dependent relationship between runoff changes. To analyze the spatial difference of water production, the runoff sequence that remove the upstream influence was used to analyze the characteristics of water production change in the region. A natural runoff region was formed between adjacent stations, ignoring the impact of the current region (the watershed range between the current region and the previous region) on the inflow water from the upstream region. The current section runoff (observed runoff) was subtracted from the upstream section runoff, and the resulting runoff difference was taken as the water yield of the current section. Comparing the runoff observation with the regional water production, we can analyzed and obtained the change characteristics of the regional water production and the water flow from the upper region from the current runoff variation characteristics. The Jinghong was taken as the upstream cross region of the Mekong River, and its runoff change characteristics and influence on downstream runoff change characteristics were analyzed. Tab. 5 lists the trend of inflow in different regions during the dry season, flood season, and throughout the year. The left column is the runoff change trend above Jinghong and the different regions between Jinghong and other stations. The right column is the runoff change trend of the regions in the mainstream of the Mekong River. Combining with Tab. 1 and Tab. 2 to observe the runoff test results and analyzed the change characteristics of water production in each section. Since the annual runoff in Tab. 1 is a calendric year, and the annual runoff in Tab. 5 is a hydrological year, the calculation results of the hydrological annual runoff (the results are omitted) are close to the calendric years. Therefore, the trends of annual runoff at the mainstream stations in the following sections still use the results in Tab. 1.

Tab. 5 Mann-Kendall test values of runoff in different regions

Regions	Dry season	Flood season	Annual
Above Jinghong	−0.52	−3.01	−2.88
Jinghong-Luang Prabang	−1.70	−0.50	−1.00
Jinghong-Mukdahan	3.51	0.77	1.37
Jinghong-Stung Treng	1.93	−0.64	−0.18
Jinghong-Chiang Saen	2.28	0.31	0.56
Chiang Saen-Luang Prabang	−3.65	−0.70	−1.37
Luang Prabang-Mukdahan	5.15	1.71	2.23
Mukdahan-Stung Treng	−0.51	−1.60	−1.60

Note: The annual refers to the sum of runoff in the dry season and flood season of the current year, here the inflow is from December of the previous year to November of the current year.

Inflow water above Jinghong decreased during the dry season and flood season, and the reduction in flood season significantly reduced the annual runoff. Water production in the Jinghong-Chiang Saen region increased during the dry season and flood season, and the increasing trend was significant during the dry season. Therefore, the runoff reduction trend at Chiang Saen was mainly caused by the decrease of flood season runoff at Jinghong. Water production in the Chiang Saen-Luang Prabang region decreased during the dry season and flood season, and the dry season runoff decreased significantly, while water production in the Jinghong-Luang Prabang region also decreased. It was difficult for the inflow water in the Jinghong-Chiang Saen region to replenish the reduction amount of inflow water in the two regions before and after it, so the reduction of runoff at Luang Prabang was affected by both the reduction of Jinghong′s inflow water and the decrease of Chiang Saen-Luang Prabang region′s water production. Luang Prabang-Mukdahan region had a significant increase in water production, while Luang Prabang had a significant decrease in the runoff, so the increase in runoff at Mukdahan was mainly affected by the significant increase in water production in Luang Prabang-Mukdahan region. Combining the water production in the Jinghong-Luang Prabang region, Jinghong-Mukdahan region, and the runoff trends at Luang Prabang and Mukdahan, it can be seen that the water production in Luang Prabang-Mukdahan region had an important impact on the runoff changes in the middle and lower reaches of the Mekong River. Water production in the Mukdahan-Stung Treng region was decreasing. Although the runoff at the Mukdahan region was increasing, and the dry season runoff was increasing significantly while the annual runoff was decreasing, the runoff at Stung Treng was decreasing. Thus, the runoff reduction trend was mainly affected by the reduction of flood season runoff in Mukdahan-Stung Treng region

From the above analysis, it can be seen that, change trends of water production in the five regions showed an increasing and decreasing pattern. The runoff change at each section must be affected by the water inflow from the upstream section and the local water production. From the results, it can be concluded that the runoff change trend between the adjacent sections may be reversed, the regional water production may completely change the runoff change trend of the lower section, and the runoff at adjacent sections will not necessarily show a consistent trend because of the upstream and downstream relationship. For example, the runoff at Luang Prabang was decreasing, the increase in water production at Luang Prabang-Mukdahan section made the runoff in Mukdahan section increasing, and the decrease in water production in Mukdahan-Stung Treng section made the runoff in Stung Treng section decreasing.

4 Conclusions

This paper selected Chiang Saen, Luang Prabang, Mukdahan, and Stung Treng as the representative stations. Based on the daily runoff data from 1960 to 2012, the Mann-Kendall trend test method, Pettit mutation test method and the coefficient of variance C_V were used. The annual runoff, flood season runoff and dry season runoff, monthly runoff, extreme runoff, and regional water production were analyzed in terms of runoff evolutionary characteristics of the Mekong River mainstream. The main conclusions are as follows.

(1) The annual runoff at Chiang Saen, Luang Prabang, and Stung Treng stations showed a downward trend, while the annual runoff at Mukdahan station displayed upward non-significant trend. Mutation point occurred during 1972, 1986, 1994 and 1994, respectively, atr each station, while the mutation point at Mukdahan was significant.

(2) The annual runoff distribution at each station tended to be uniform. The monthly runoff distribution showed a uniform trend, at Chiang Saen and Stung Treng stations showed the most significant performance. The increase of dry season runoff and the decrease of flood season runoff were mainly reflected in the increase of runoff from March to May and the decrease of runoff from August to November.

(3) Both Chiang Saen and Luang Prabang stations, there was a decreasing trend of high and low flow. Among them, the high flow of Chiang Saen station was lower than that of low flow, while the opposite was true for Luang Prabang station. Mukdahan had an increasing trend of both high flow and low flow, and low flow had a greater trend of decreasing than high flow. At Stung Treng station, the high flow was decreasing and the low flow was increasing, the flow fluctuation range of Chiang Saen, Mukdahan, and Stung Treng stations gradually decreased, while at Luang Prabang was increased.

(4) There was a distinct difference in the trend of water production change between adjacent stations on the mainstream of the Mekong River, which affected the runoff variation characteristics of the downstream region. From upstream to downstream, the change trend of water production in each region showed a pattern of increasing and decreasing.

References:

[1] LI B, ZHANG K, CHENG T J. Application of AHP to

Lancang River-Mekong River consumable water distribution[J]. Engineering Journal of Wuhan University, 2018, 51(5): 389-393. (in Chinese) DOI: 10. 14188/j. 1671-8844. 2018-05-003.

[2] TANG H X. Water resources in the Lancang-Mekong river basin and analysis on the present situation of its utilization[J]. Yunnan Geographic Environment Research, 1999, 11(1): 16-25. (in Chinese)

[3] ZHAO P, TANG J, YIN S. Situations of development and utilization of water resources in Mekong River basin[J]. Journal of Economics of Water Resources, 2017, 35(4): 55-58. (in Chinese) DOI: 10. 3880/j. issn. 1003-9511. 2017. 04. 011 .

[4] YANG J, LI D, BI P, et al. Summarization of water resources use in the Lancang-Mekong River basin[J]. Journal of Anhui Agricultural Sciences, 2009, 37(16): 7569-7570. (in Chinese) DOI: 10. 3969/j. issn. 1009-640X. 2011. 03. 007.

[5] ZHOU T, YU F L, LI C Z, et al. Evolution trend of runoff in Mekong River basin during 1960-2005[J]. Journal of Hohai University: Natural Sciences, 2010, 38 (6): 608-613. (in Chinese) DOI : 10 . 3876/j. issn . 1000-1980 . 2010 . 06 . 002.

[6] HE Y, GUI Z, SU C, et al. Response of sediment load to hydrological change in the upstream part of the Lancang-Mekong River over the past 50 years[J]. Water. 2018, 10(7): 888. DOI: 10. 3390/w10070888.

[7] XUE Z, LIU J P, GE Q. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: connection to damming, monsoon, and ENSO [J]. Earth Surface Processes & Landforms, 2011, 36 (3): 296-308. DOI: 10. 1002/esp. 2036.

[8] He D M. Analysis of hydrological characteristics in Lancang-Mekong River[J]. Yunnan Geographic Environment Research, 1995, 7(1): 58-74. (in Chinese)

[9] ZHOU T, LI C Z, YU F L, et al. Spatial and Temporal Distribution Characteristics Analysis of Meteorological Drought in Lancang-Mekong River basin[J]. Water Resources & Power, 2011, 29(6): 4-7, 193. (in Chinese) DOI: 10. 3969/j. issn. 1000-7709. 2011. 06. 002.

[10] ZHOU T, YU F L, LI C Z, et al. Analysis of hydrological regime changes of Chiang Saen station in Mekong River[J]. Water Resources and Power, 2011, 29 (11): 15-18. (in Chinese) DOI: 10. 3969/j. issn. 1000-7709. 2011. 11. 004.

[11] ZHONG H P, WANG J S. An analysis of Mekong River runoff changes and its impact on the Mekong River downstream [J]. Hydro-Science and Engineering, 2011, 32(3): 48-52. (in Chinese) DOI: 10. 16198/j. cnki. 1009-640x. 2011. 03. 011.

[12] ZHONG H P, WANG J S. Impacts from hydropower development of main stream on runoff of Lancangjiang River[J]. Water Resources and Hydropower Engineering, 2010, 41(12): 72-74. (in Chinese) DOI: 10. 3969/j. issn. 1000-0860. 2010. 12. 018.

[13] LEI S H, LIU J N, GU Y, et al. Analysis the effect of the hydropower station building of Lancangjiang mainstream on the change of runoff at leave country section[J]. Journal of Yunnan University (Natural Sciences Edition), 2010 32(1): 58-62. (in Chinese) DOI: 10. 3724/SP. J. 1084. 2010. 00199.

[14] HOANG L P, VAN VLIET M T H, KUMMU M, et al. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes[J]. Science of The Total Environment, 2019(649): 601-609. DOI: 10. 1016/j. scitotenv. 2018. 08. 160.

[15] LI D, LONG D, ZHAO J, et al. Observed changes in flow regimes in the Mekong River basin[J]. Journal of Hydrology, 2017, 551(S1): 217-232. DOI: 10. 1016/j. jhydrol. 2017. 05. 061.

[16] ZHOU J, JI Y D, BAI N M, et al. Practice and thinking of scientific regulation of water resources in Wuxi City[J]. Jiangsu Water Resources, 2014(12): 25-28. (in Chinese) DOI: 10. 16310/j. cnki. jssl. 2014. 12. 016.

[17] LI J Q, ZHU Y M, LI J C, et al. Impacts of changing environment on runoff consistency in the lower reaches of the Chao River[J]. South-to-North Water Transfers and Water Science & Technology, 2017, 15 (3): 5-12. (in Chinese) DOI: 10. 13476/j. cnki. nsbdqk. 2017. 03. 002.

[18] WANG W R, WANG L M, ZHANG X L et al. Changeable characteristics of channel discharge in the Taohe River basin from 1956 to 2015[J]. Journal of Northwest Normal University (Natural Science), 2018, 54 (1): 92-99. (in Chinese) DOI: 10. 16783/j. cnki. nwnuz. 2018. 01. 015.