

西江枯季径流退水系数与流域特征关系研究

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摘要:文章采用基于遗传算法的经典退水曲线对西江上游主要站点枯季日平均流量进行研究,所率定的退水系数经验证精度较好,能够反映所在流域的径流特性。通过退水系数与流域面积、下垫面性质、植被覆盖度、多年平均径流深等流域特征关系的分析,发现退水系数值(1)对降雨和蒸散发的变化不敏感,整体上随流域面积和植被覆盖度的增加而减小;(2)随地形高差和下垫面透水性的下降而减小;(3)对喀斯特岩溶地貌尤其敏感,表现为退水系数值较非岩溶地区偏大;(4)随多年平均径流深的增大而增大,二者具有指数函数关系。退水系数与流域特征因子的这些规律,可为无资料流域水文预报提供思考和借鉴。

关键词:流域特征;枯季径流;退水系数;无资料流域

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1 引言

枯季径流预报对流域水资源管理与利用、供水安全及生态环境保护具有深远意义。气候变化、人类活动和流域下垫面的变化改变了传统流域的产汇流机制^[1],使原有流域资料的一致性出现偏差,有资料流域向某种意义上的“无资料(或者资料匮乏)流域”的转变正在发生。伴随着全国中小河流建设规划的展开,缺乏水文历史资料的中小河流成为水文预报的真空区。无资料流域的枯季水文预报成为亟待解决的难题,针对这一课题的研究工作意义重大^[2],本文就是针对这一课题展开的探索。

无资料地区的水文预报,前人分别从模型运用、精度提高和新技术运用等方面做了一些探索。甘衍军等人^[3]借助GIS和因子径流场运用SCS模型对无资料流域日径流进行模拟,Ming Li、Teemu S等^[4-5]利用区域化方法对无资料流域进行模拟,David A. Post^[6]用区域化降雨径流模型对澳大利亚干旱地区无资料流域进行模拟,均取得良好结果。Mohamed、舒畅等^[7-8]对遥感气象数据进行再处理,Bocchiola D等^[9]改进分布式水文预报方法,Salvatore等^[10]把反映坡度和土地利用的汇流时间估算模块加入模型,Maitreya等^[11]通过寻找对流

域水文模型精度限制最大的因素,均提高了无资料地区水文预报的精度。Pradhan等^[12]提出单变量径流模型,S. Castiglioni等人^[13-14]运用地理空间插值技术预报无资料流域枯季径流,开创出无资料地区水文预报新途径。Reed等^[15]对无资料流域的洪水运用临界概率方法和分布式水文模型进行研究,发现分布式水文模型精度要高于集中式模型,临界概率方法也有助于提高预报精度。柴晓玲等^[16]运用比较成熟的IHACRES模型对无资料流域进行应用研究,发现对流域属性尤其是流域面积相差不大的流域运用移置法得出的预报精度比相同条件下新安江模型的精度要高。周芬等人^[17-20]运用区域回归方法和线性矩方法对无资料流域设计洪水估算也做了相应的研究和探索。1953年Riggs^[21]介绍了枯水径流的预报方法,并首次对枯水径流的水文过程进行划分。李秀云^[22]等对枯水的形成原理和影响因素作了深入的探讨,指出枯水流量与流域面积具有显著的函数关系;黎坤^[23]等通过对北江天然径流变化规律的分析,从宏观上探讨了大气环流、地形地貌、太阳黑子活动周期等现象对北江径流量变化的影响。殷福才^[24]、黄国如^[25]等分别从不同视角对枯水研究进展进行追踪。

本文通过分析流域属性特征与枯季径流退水系数的关系,探索无资料流域枯季径流预报的途径。

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2 研究区域资料与方法

2.1 研究区域

西江流域地处南亚季风区,多年平均降雨量1470mm,降雨主要集中在汛期4~9月,占全年降水量的80%以上。西江流域枯水期一般为10月至翌年3月,局部河流可延至5月。枯水径流量多年平均值 $803 \times 10^8 \text{m}^3$,占全流域年径流量的24%,如表1、图1所示。

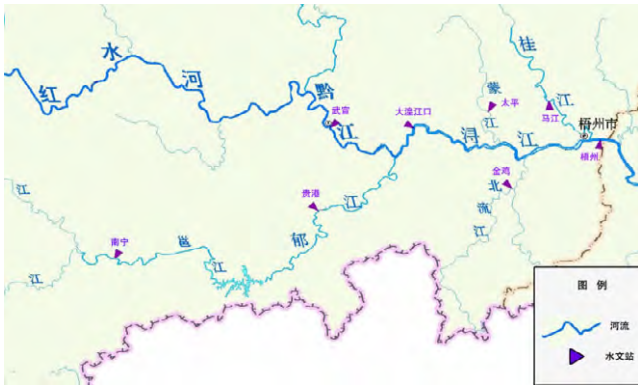


图1 研究流域及站点

Fig.1 The study basin and hydrological stations

2.2 数据说明

本文数据来自水文年鉴,选取1950~1986年西江上游表2中8个水文站点的枯季日平均流量资料进行

研究,其中,1950~1980年资料用于模型参数的率定,1981~1986年的资料用于验证。

2.3 模型方法

本方法使用经典退水曲线,该法在洪枯水预报中被广泛使用。

$$Q_t = Q_0 e^{-\beta t} \quad (1)$$

式中: Q_0 、 Q_t 分别为退水开始时刻的退水流量和 t 时刻退水流量, m^3/s ; β 为退水系数; t 为退水时间。

对式(1)进行变形,用 Q_t 、 Q_0 、 t 的关系来表达 β ,有:

$$\beta = (\ln Q_0 - \ln Q_t) / t \quad (2)$$

模型参数 β 采用遗传算法(GA)在相对残差平方和最小下优化,即求式(3)最小化问题:

$$\min Q(\beta) = \sum_{i=1}^n (y_0 - y_c)^2 / y_0^2 \quad (3)$$

式中: y_0 为实测值; y_c 为拟合值。

采用相对误差和确定性系数作为模型预报的精度评价指标,公式分别为:

$$\delta = \frac{y_0(i) - y_c(i)}{y_0(i)} \times 100\% \quad (4)$$

$$DC = 1 - \frac{\sum_{i=1}^n [y_c(i) - y_0(i)]^2}{\sum_{i=1}^n [y_0(i) - \bar{y}_0]^2} \quad (5)$$

表1 研究区域河流特性

Table1 The characteristics of the rivers in the study basin

级别	河流	流域面积 / km^2	河长 / km	坡降 / ‰	下垫面
干流	黔江	2 210	122	0.0652	丘陵平原、地势低平
	浔江	20 570	172	0.0968	丘陵平原、地势平坦
	桂江	18 800	438	0.0864	低山丘陵、石灰岩地貌
支流	郁江	92 300	1152	0.0895	丘陵平原
	柳江	58 400	724	0.0895	低山丘陵
	北流江	9 359	259	0.0968	低山丘陵
	濛江	3 895	189	0.0968	低山丘陵

表2 研究流域水文站点特性

Table 2 The characteristics of the hydrological stations in the study basin

站点	分级	河流	集水面积 / km^2	多年平均径流深 / mm	多年平均流量 / m^3	多年平均枯水流量 / $\text{m}^3 \cdot \text{s}^{-1}$	多年平均降雨量 / mm	多年平均蒸发量 / mm
梧州	干流	浔江	330 000	627.2	6 640	1 476	1 467.4	5 823.5
武宣		黔江	196 000	612.5	3 480	837.8	1 334.7	5 844.7
大湟江口		浔江	290 760	577.1	5 050	1 084.8	1 684.4	5 919.5
南宁	支流	郁江	75 500	541.5	1 260	262.2	1 256.9	6 861
贵港	支流	郁江	89 235	528.1	1 580	250	1 486.1	5 745.3
金鸡	支流	北流江	8 720	1 008.3	375	45.46	1 604.5	6 764.4
太平	支流	蒙江	3 796	953.7	156	10.964	1 618.1	6 426.7
马江	支流	桂江	18 210	935.7	641	56.86	1 634.3	6 435.6

式中: δ 为相对误差; DC 为确定性系数; $y_0(i)$ 为实测值; $y_c(i)$ 为预报值; \bar{y}_0 为实测值的均值; n 为资料序列长度。

3 基于遗传算法的退水曲线率定与验证

将流量数据代入式(2),采用遗传算法对参数进行优化,目标函数采用式(3),其中GA中 β 的取值范围为(0,1)。运用遗传算法计算出各个站点的退水系数值,率定与验证结果见表3和图2。

从图2和表3中可知计算值与实测序列的变化趋势一致,模拟结果较好。表明GA所获得的退水系数能较好的反映流域区间的特性,可以用于退水系数与流域特征关系的分析。

4 退水系数与流域特征关系分析

4.1 退水系数与流域特征因子的定性分析

由式(2)知,在时间 t 一定的情况下,退水系数值

表3 率定与验证结果

Table 3 The results of calibration and validation

		梧州	武宣	大湟江口	南宁	贵港	金鸡	马江	太平
退水系数	β	0.036	0.039	0.038	0.034	0.039	0.053	0.074	0.047
率定误差	$\delta / \%$	-0.01	-0.02	-0.05	-0.02	-0.13	0.05	0.02	0.14
	DC	0.94	0.95	0.96	0.75	0.72	0.90	0.88	0.85
验证误差	$\delta / \%$	-5.12	-5.21	-5.29	-7.86	-22.80	-5.95	-5.34	-3.73
	DC	0.83	0.89	0.91	0.73	0.70	0.89	0.83	0.80

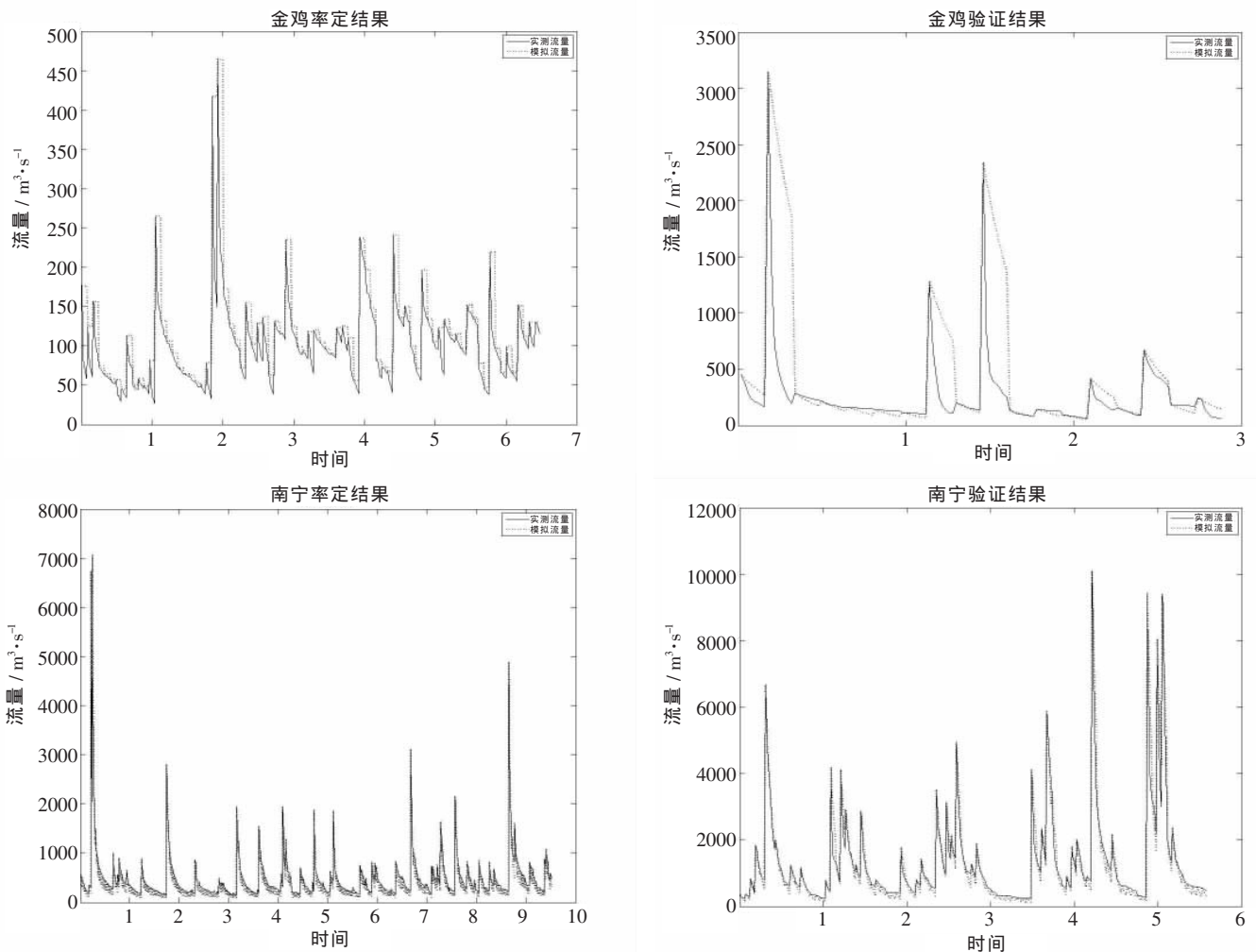


图2 部分站点率定与验证结果

Fig.2 The results of calibration and validation from some stations

表4 退水系数与流域特征关系

Table 4 Correlation between the recession coefficients and catchment characteristics

子流域	集水面积 / km ²	多年平均径流深 / mm	多年平均降雨量 / mm	多年平均蒸发量 / mm	多年平均枯季流量 / m ³	植被覆盖	下垫面	退水系数 β
	18210	935.7	1634.3	6435.6	56.9	差	低山丘陵、喀斯特地貌	0.074
	12516	981	1611.3	6595.6	28.2	一般	低山丘陵	0.05
	164735	740.9	1371.5	6303.2	256	好	丘陵平原	0.0365
	816760	605.6	1495.5	5862.6	1130	中等	低丘平原	0.0377

的大小与径流变化剧烈程度成正比。退水系数越大,径流前后变化越剧烈,反之亦然。研究中发现,在影响退水系数的因素中,地带性因素如降雨和蒸散发对退水系数的影响甚微,非地带因素如多年平均径流深和流域面积对退水系数影响较大。退水系数与多年平均径流深存在较好的正相关,与流域面积总体上呈现负相关。由于同一纬度下气候条件基本相似,加之降雨和蒸散发不直接作用于地下水,所以此二者对退水系数的影响较小。集水面积的增加会带来更多的水源,流域蓄水池内水量变化缓慢,表现为径流变化平缓,退水系数相对较小。

影响退水系数的局地因子中,植被覆盖度、土质条件和地形地貌尤其是喀斯特地貌最为直接。下垫面性质为砾土或漏水的岩溶地区,退水系数较不易漏水土质或非岩溶地质条件下的数值大;植被覆盖率高地区较植被覆盖率低的地区退水系数小。退水系数的这种变化规律呼应了枯水径流形成的物理机制。植被覆盖良好的地区,雨水被植被截留涵养以极缓慢的方式不间断地输送补给地下水;透水的表层覆盖层如沙质土以及漏水的喀斯特岩溶地貌和山区地形,使雨水快速的汇流进入河道,从而使径流表现为快涨快落。如表4所示,马江所处子流域()以低山丘陵为主的岩溶地貌,植被覆盖度差,虽然流域面积大于金鸡-太平子流域,但退水系数明显较大;地形以低山丘陵为主,植被覆盖一般,地表为砾土或沙质土覆盖的金鸡-太平子流域()退水系数为0.05;地表以沙质土盖层,地形以低丘平原为主且植被覆盖度一般的南宁-贵港子流域()退水系数最小为0.0365;植被覆盖良好,表土为冲淤土的武宣-大湟江口-梧州子流域()退水系数数值较子流域()略大为0.0377。这是因为调查中发现子流域()所在西江干流区的上游红水河段为发育成熟的喀斯特岩溶区,红水河上的迁江站与上游的都安站水量平衡常年失衡。

4.2 退水系数与多年平均径流深的定量关系

非地带因素的多年平均径流深对退水系数影响较大,与退水系数存在正相关关系。研究发现二者之间具有指数函数关系,见式(6)、(7)和图3。岩溶地区建议采用式(6)和①线,非岩溶地区采用式(7)和②线。

$$y=0.0109e^{0.002x} \quad (6)$$

$$y=0.0167e^{0.0011x} \quad (7)$$

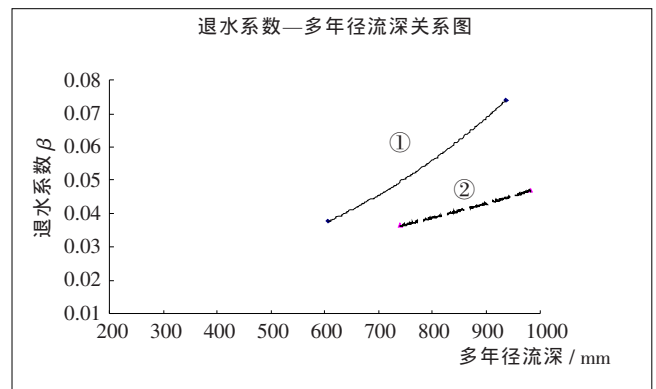


图3 退水系数与多年平均径流深关系图

Fig.3 The relation between the recession coefficients and mean annual runoff

退水系数与多年平均径流深的这种函数关系,可为资料匮乏流域径流预报的参数获取提供方便,但使用中退水系数的选取,应注意结合前面对流域属性特征与退水系数之间关系的定性分析,进行适当调整。

5 结论

运用遗传算法对经典退水曲线参数进行率定,避免了人工率定的盲目性和随意性,较客观地反映了流域的属性。通过对枯水径流退水系数与流域特征关系的分析,发现退水系数与流域特征之间存在一定的关系,具体表现为退水系数值(1)对降雨和蒸散发的变化不敏感,整体上随流域面积和植被覆盖度的增加而减小;(2)随地形高差和下垫面透水性的下降而减小;

(3)对喀斯特岩溶地貌尤其敏感,表现为退水系数值较非岩溶地区偏大;(4)随多年平均径流深的增大而变大,二者具有指数函数关系。退水系数的这些规律可为无资料地区水文参数移置提供一些有益思考,从而使无资料流域的水文预报成为可能。但使用中针对特定流域,应对参数进行适当调整。

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Study on Correlation between Recession Coefficients and Catchment Characteristics in Pearl River

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Abstract: This paper adopted the classical recession curve based on GA to study and analyze the mean daily runoff at some hydrological stations in the Xijiang upstream. The accuracy of verified results demonstrate well with Nash coefficients. Therefore, the obtained coefficient of recession can reflect the characteristics of the study basin. This paper also studied the relation of the coefficients of recession with the catchment area, underlying surface characteristics, degree of vegetation and mean annual runoff, and discovered that (1)The recession coefficients will decrease with the catchment area and vegetation degree increasing;(2)The recession coefficients will decrease with the height difference permeability of underlying reducing;(3)The recession coefficients are especially sensitive to the Karst landform, characterized by being larger than those in the non-Karst area;(4)The recession coefficients will increase with the mean annual runoff increasing, and there is an exponential function relationship between the two. These rules between the recession coefficients and catchment characteristic factors will provide reference for runoff forecasting in ungauged basins.

Key words: catchment characteristics; low flow discharge; parameter of recession; ungauged basin

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A Modified Saturated Storage and Excess Infiltration Watershed Model and Its Application

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Abstract: Saturated storage and excess infiltration of two water resources model was modified for each characteristic and mechanism of saturated storage and excess infiltration model and Tank model, based on the introduction to two models. The model could reflect dynamic change of surface runoff, interflow and groundwater runoff. And it can be applied in flood forecasting, river simulating, and water exploitation. The modified model was applied for the Luanchuan Station in the Yihe River Basin. Three optimization algorithms (Genetic, Rosenbrock and Simplex) for hydrological model calibration were used for calibrating the model parameters. The modified model was compared with the original model. The results show that the modified model has a better goodness-of-fit than the original model, and the model could reflect the process of different runoff composition

Key words: saturated storage and excess infiltration model; water source; modified model