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基于 Budyko 假设的滦河流域上游径流变化归因识别

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摘要：近 50 年来，气候变化和人类活动在不同程度上对滦河流域水文过程产生了影响，为了识别径流变化的主要原因，以滦河流域上游地区为研究区，利用 Mann-Kendall 检验法等分析研究区 1966—2015 年气象及水文要素变化趋势，同时建立基于 Budyko 假设的水热耦合平衡方程，运用弹性系数法对研究区径流变化的影响因素进行敏感性分析，并对各要素对径流变化的贡献进行定量评估。结果表明，1966—2015 年滦河流域上游地区年径流深呈显著减少趋势，年降水与年潜在蒸散发均无显著变化趋势。同基准期（1966—1979 年）相比，下垫面变化是径流减少的主要影响因素，1980—1997 年（影响Ⅰ期）与 1998—2015 年（影响Ⅱ期）下垫面变化对径流变化的贡献率分别为 52.68%、88.12%。在气候要素中，降水对径流变化的影响大于潜在蒸散发的影响。

关键词：滦河上游；气候变化；人类活动；径流变化；Budyko 假设；弹性系数

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流域水文循环是一个相当复杂的过程，其中气候变化和人类活动是两大影响因素[1]，径流、降水和蒸发则是水文循环的主要环节。气候变化直接影响降水、蒸发、径流、土壤湿度等，进而导致流域水资源总量及其时空变化[2-3]，人类活动如修建大型水利工程、大规模水土保持措施的实施等通过引起流域下垫面条件变化，使产汇流过程发生改变[4]。因此，对径流变化进行主要驱动力的识别是理解流域可利用水资源变化的关键[5]，变化环境下的径流变化归因识别也逐渐成为近年来的热点研究问题之一[6]。

目前，国内外定量区分各影响因素对径流变化贡献的研究方法主要有水文模型模拟法和气候弹性系数法[7]。其中，水文模拟法是一种建立在良好的物理基础上的研究方法，常用的水文模型有 SWAT (soil and water assessment Tool)模型、VIC(variable infiltration capacity)模型等，Onstad 等[8]最早开始利用水文模型法来预测土地利用/覆被变化对径流变化的影响，此后国内外学者相继开展了许多相关研究。但由于模型参数和输入数据较多，运算过程复杂[9]，且模型参数及结构等因素均存在一定的不确定性[10]，可能使模拟结果产生较大的误差。基于 Budyko 理论[11]的弹性系数法主要适用于年尺度上的分析研究，对历史数据的要求较低[12]，且能直接对各因素的影响程度进行单独估算[13]，是一种简单有效的分析方法，近年来被国内学者广泛应用于相关研究中，在许多流域都得到了较好的适用性验证。例如张丽梅等[14]对渭河径流减少进行了归因分析，结果表明下垫面变化的贡献率大于 60%。夏军等[7]对汉江上游进行了气候和人类活动对水文过程影响的定量评估，发现人类活动是导致径流减少的主要因素，贡献率为

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56.5%～57.2%。

自 20 世纪 50 年代以来，滦河流域水循环过程和水量平衡在气候和人类活动的综合影响下发生了不容忽视的变化[15]，对流域内的生态环境产生了极大的影响。目前学者们在滦河流域开展的研究主要采用水文模型模拟的方法，但研究结果存在较大的差异，如刘晨[15]基于 SWAT 模型建立了滦河流域内气候变化及人类活动影响下的径流响应模型，结果表明在 1980—2008 年，人类活动是引起径流减少的主要影响因素，占 71%；刘学锋等[16]利用 HBV 模型(hydrologiska fyrans vattenbalans model)还原人类活动影响期内(1980—2007 年)的天然径流量，发现气候变化对地表径流的影响占 55%；陈鑫等[17]基于 SWAT 模型发现，近 60 年来三道河子以上流域径流变化主要受气候变化影响，贡献率为 89%；王亮等[18]利用 SWAT 模型分析了气候和人类活动对滦河流域内蒙段径流变化的影响，结果表明人类活动的贡献率为 60.8%。

由于不同学者在进行模型模拟时，选取的模型种类、参数设定及率定方法等不尽相同，对滦河流域近年来径流变化的原因难以得出一致的结论。此外学者们在分析气候变化影响程度时，往往将气候因素作为整体来计算其贡献量，对具体气象因子的影响分析研究较少[19]。因此，本文以滦河流域上游地区为研究区，采用弹性系数法分析流域径流对气候及下垫面变化的敏感性，同时分离气候因素中两个主要影响因子，进一步定量评估气候变化和人类活动对径流变化的贡献。

1　研究区概况与数据

1.1　研究区概况

滦河流域位于华北平原东北部，是海河流域三大水系之一，也是京津冀都市圈最前沿的生态屏障。其上游段发源于河北省张家口地区的巴彦古尔图山麓，至承德市滦平县张百湾镇止，全长 513 km，流域面积25 367 km^2，包括闪电河、小滦河、伊逊河等主要支流。滦河上游地区属典型的温带半干旱大陆性季风气候区，流域多年平均气温为 5.99 ℃，多年平均降雨量为 300～600 mm，冬季寒冷干燥，夏季温暖多雨。滦河上游流经滦河上游国家级自然保护区及塞罕坝国家级自然保护区，具有重要的生态战略地位。

1.2　数据来源与数据处理

本文选取滦河上游三道河子及韩家营水文站作为流域的流量控制站点，径流数据来源于《中华人民共和国水文年鉴》及河北省水文局统计整理。研究区气象数据来源于中国气象科学数据共享服务网(http://data.cma.cn)，包括多伦、围场、丰宁、承德 4 个气象站点 1966—2015 年的逐日日照、降水、气温、风速数据等。研究区潜在蒸散发(ET_0)采用 FAO(Food and Agriculture Organization，联合国粮食及农业组织)56 推荐的 Penman-Monteith 公式(式 1)的计算获得。进一步运用反距离权重法(IDW，inverse distance weighted)插值得到流域形心处潜在蒸散发量，代替研究区的潜在蒸散发。利用现有气象数据分析 1970—2001 年月尺度滦河流域上游潜在蒸散发和蒸发皿蒸发量的相关关系，二者相关系数 R^2 为 0.973 2，具有较高的一致性，表明潜在蒸散发的计算结果能够代表研究区的平均潜在蒸散发[20](图 1)。此外本文采用中国科学院资源环境科学数据中心(http://www.resdc.cn)提供的分辨率为 1 km 的 1980 年、2000 年和 2015 年 3 期土地利用及土地变化(LUCC)数据集以分析研究区土地利用情况。

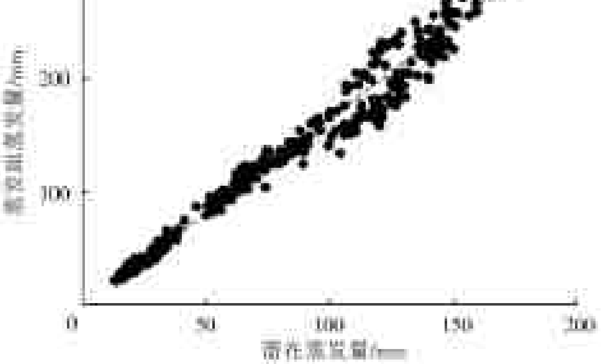

图 1　**1970—2001 年潜在蒸散发量与小型蒸发皿蒸发量相关关系**

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T_{mean}+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{1}$$

式中：ET_0 为潜在蒸散量，mm/d；R_n 为作物面净辐射量，MJ/(m^2·d)；G 为土壤热通量，MJ/(m^2·d)，取 0；γ 为湿度计常数，kPa/℃，取 0.665；Δ 为饱和水汽压与温度关系曲线的斜率，kPa/℃；T_{mean} 为空气平均温度，℃；u_2 为在地面以上 2 m 处的风速，m/s；e_s 为空气饱和水汽压，kPa；e_a 为空气实际水汽压，kPa。

2　研究方法

2.1　水文要素趋势分析及突变检验方法

本文采用被广泛使用的 Mann-Kendall[21-22] 非参数检验方法分析滦河上游地区 1966—2015 年气象、水文数据的变化趋势。同时结合降水-径流双累积曲线法[23] 与滑动 t 突变检验法识别年径流序列的突变点，依此划分不同水文阶段。

2.2　径流变化归因识别

受气候变化和人类活动的综合作用影响，研究区径流量在不同时间段表现出不同的变化特征。本文主要采用基于 Budyko 假设的弹性系数法，评价径流对各环境因子的敏感性，定量分析气候变化和人类活动对径流变化的贡献。

Budyko[11] 认为在一个较长的时间尺度上，流域实际蒸散发量 E 主要受水分供应条件（降水量 P）和能量供应条件（潜在蒸散发 ET_0）控制：$E/P=f(ET_0/P)$，Choudhury[24] 和 Yang[25] 在 Budyko 假设的基础上，推导出流域水热耦合平衡方程。Choudhury-Yang 公式揭示了在一定的气候和植被条件下，流域水文气候特征服从的水分和能量平衡关系为

$$E=\frac{P\times ET_0}{(P^n+ET_0^n)^{\frac{1}{n}}} \tag{2}$$

式中：E 为多年平均实际蒸散发量，mm；P 为多年平均降水量，mm；ET_0 是多年平均潜在蒸散发量，mm；n 为反映流域下垫面特征的参数。

长时间水文序列下，水量平衡方程可以写作 $P=E+R$（式中：R 为多年平均径流量），结合式(2)，可以求得下垫面参数 n。同时可以用微分方程来表示不同因子对径流变化的贡献

$$\mathrm{d}R'=\frac{\partial f}{\partial P}\mathrm{d}P+\frac{\partial f}{\partial ET_0}\mathrm{d}ET_0+\frac{\partial f}{\partial n}\mathrm{d}n \tag{3}$$

根据弹性系数[26] 的定义，各影响因子 x 的弹性系数可以表示为

$$\varepsilon_{x_i}=\frac{\partial R}{\partial_{x_i}}\times\frac{x_i}{R} \tag{4}$$

式中：ε_{x_i} 为各影响因子 x_i 的弹性系数。假设 $\varnothing=\frac{ET_0}{P}$，可以得出各影响因子的弹性系数计算公式为[27]

$$\varepsilon_P=\frac{(1+\varnothing^n)^{1/n+1}-\varnothing^{n+1}}{(1+\varnothing^n)[(1+\varnothing^n)^{1/n}-\varnothing]} \tag{5}$$

$$\varepsilon_{ET_0}=\frac{1}{(1+\varnothing^n)[1-(1+\varnothing^{-n})^{1/n}]} \tag{6}$$

$$\varepsilon_n=\frac{\ln(1+\varnothing^n)+\varnothing^n\ln(1+\varnothing-^{n})}{n(1+\varnothing^n)[1-(1+\varnothing^{-n})^{1/n}]} \tag{7}$$

结合式(4)，(3)可以改写为

$$\mathrm{d}R'=\varepsilon_P\frac{R}{P}\mathrm{d}P+\varepsilon_{ET_0}\frac{R}{ET_0}\mathrm{d}ET_0+\varepsilon_n\frac{R}{n}\mathrm{d}n \tag{8}$$

则各影响因子对径流变化的贡献量 $\mathrm{d}R_{x_i}$ 和贡献率 C_{x_i} 为

$$\mathrm{d}R_{x_i}=\varepsilon_{x_i}\frac{R}{x_i}\mathrm{d}x_i \tag{9}$$

$$C_{x_i}=\frac{\mathrm{d}R_{x_i}}{\mathrm{d}R'}\times100\% \tag{10}$$

3　结果与分析

3.1　研究区水文气象特征

图 2 显示了滦河上游 1966—2015 年降水、潜在蒸散发与径流年际变化趋势。同时对年降水、年潜在蒸散发及年径流数据进行 Mann-Kendall 趋势检验，结果表明，滦河流域上游年径流变化呈显著减少趋势（$P<0.01$），降水与潜在蒸散发变化呈不显著减少趋势。

结合双累积曲线法及滑动 T 检验法对流域水文关系变化的关键点进行识别。由图 3 所示滦河上游降水-径流双累积曲线可看出，降水径流累积曲线于 1980 年以及 1998 年发生明显偏移，结合 5 年滑动 t 检验结果（图 4），将 1980 年及 1998 年作为降雨径流关系的突变点，将 1966—1979 年视为滦河上游径流变化基准期，1980—2015 年视为环境变化的影响期（其中 1980—1997 年为影响Ⅰ期，1998—2015 年为影响Ⅱ期）。偏移后曲线斜率变小，说明环境变化使研究区径流量不断减小[23]。

3.2　研究区土地利用变化特征

有研究表明，滦河所在的海河流域受人类活动影响颇为严重[28]。本文选取 1980 年、2000 年和 2015 年 3 期土地利用数据，分别代表基准期（1966—1979 年）、影响Ⅰ期（1980—1998 年）和影响Ⅱ期（1999—2015年）的土地利用状况。研究区土地利用类型总体上变化不大，以草地为主，林地、耕地次之，分别占研究区总面积的 35%，32%和 24%。

图 5 反映了影响期相对基准期不同土地利用类型之间的转化情况，在影响Ⅰ期，研究区耕地面积增加了 106 km^2（1.73%），林地和草地面积分别减少了 46 km^2（0.55%）和 92 km^2（1.04 %），研究区耕地的主要转入来源是草地与未利用土地，反映出这一阶段人类活动主要为开垦草地、荒地用于粮食种植等农业活动。与基准期相比，影响Ⅱ期耕地和城乡及建设用地面积分别增加了64 km^2（1.04%）和56 km^2（26.17%），未利用土地减少了133 km^2（8.85%），这

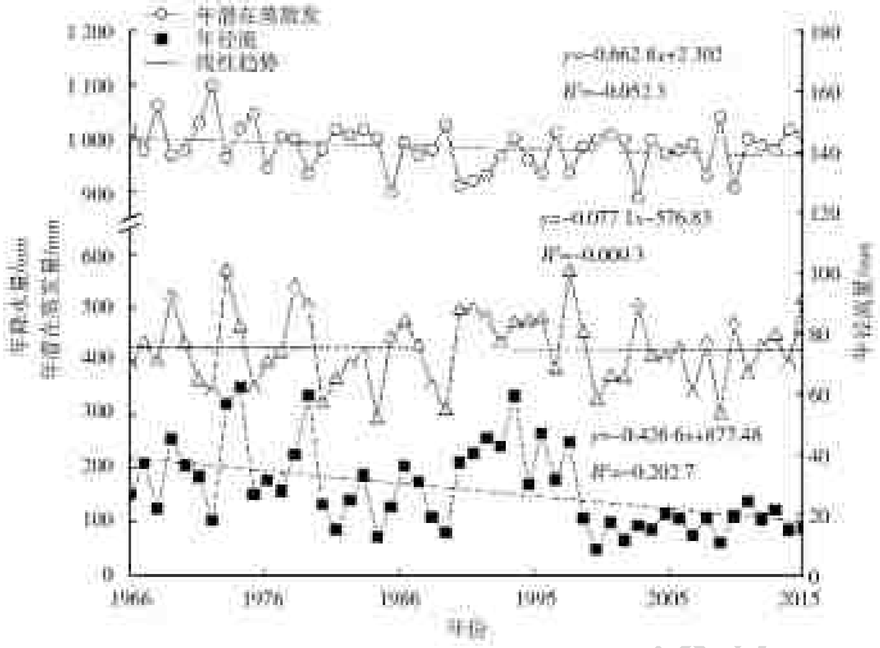

图 2　滦河流域上游 1966—2015 年降水、径流深及潜在蒸散发年际变化趋势

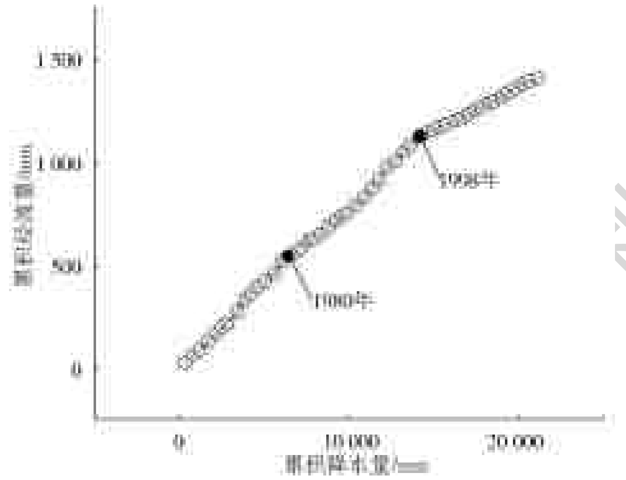

图 3　研究区降水-径流双累积曲线

图 4　研究区径流滑动 t 检验

一时期研究区内的城镇化建设水平得到了提高，城乡及建设用地主要由耕地与草地转化而来。

3.3　径流变化归因识别

3.3.1　敏感性分析

由式(5)至(7)求得 1966—2015 年滦河上游年径流对降雨量、潜在蒸散发及下垫面参数的年弹性系数(图 6)。分析其在人类活动影响期内的变化趋势可知，下垫面特征参数弹性系数的变化幅度比降水及潜在蒸散发弹性系数的变化幅度大得多，这表明在 1980—2015 年内研究区径流对下垫面变化敏感性更高。

表 1 为气候及地表条件不同时期的水文特征参数，可以看出变化期的年平均降水、年均径流深及年均潜在蒸散发较基准期均有所减少；干旱指数(ET_0/P)[29] 较基准期增大，且均大于 1.0，表明研究区为干燥地区，且干燥情况逐年加深。根据各因素的弹性系数，滦河上游径流变化与降水呈正相关、与潜在蒸散发和下垫面条件呈负相关，具体表现为当降水增加 1 mm 时，会导致径流增加 2.74～3.33 mm，潜在蒸散发增加 1 mm 会导致径流减少1.74～2.33 mm，下垫面特征参数增加 1 将会导致径流减少 2.40～2.95 mm。

3.3.2　径流变化归因探究

采用弹性系数法计算气候及下垫面参数对径流变化的影响程度，结果显示(表 2)，1980—1997 年气候变化对径流变化的贡献率为 47.32％(其中降水贡献率为 80.41％，潜在蒸散发贡献率为－33.09％)，下垫面参数对径流变化的贡献率为 52.68％；1998—2015 年气候变化对径流变化的贡献率为 11.88％(其中降水贡献率为 18.52％，潜在蒸散发贡献率为－6.64％)，下垫面参数对径流变化的贡献率为 88.12％。计算所得径流深变化与实际径流深变化的差值很小，可以证明本文在进行径流归因识别时所用方法可靠、有效。由此可见，人类活动引

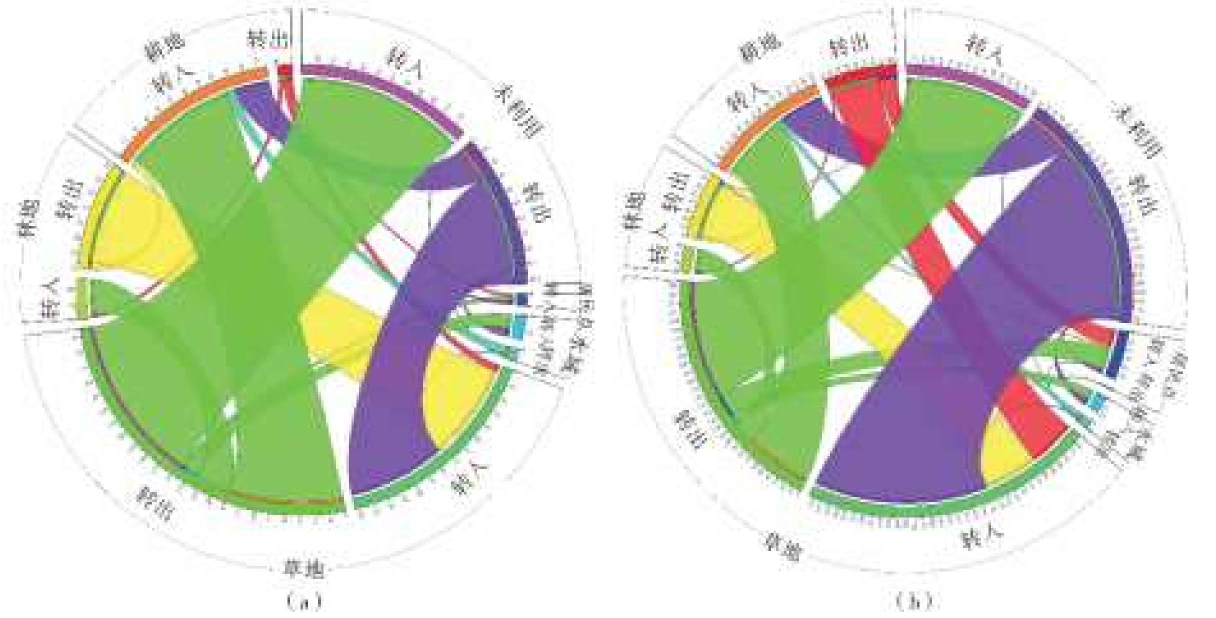

图 5　**1980—2000 年(a)、1980—2015 年(b)土地利用类型转化情况**

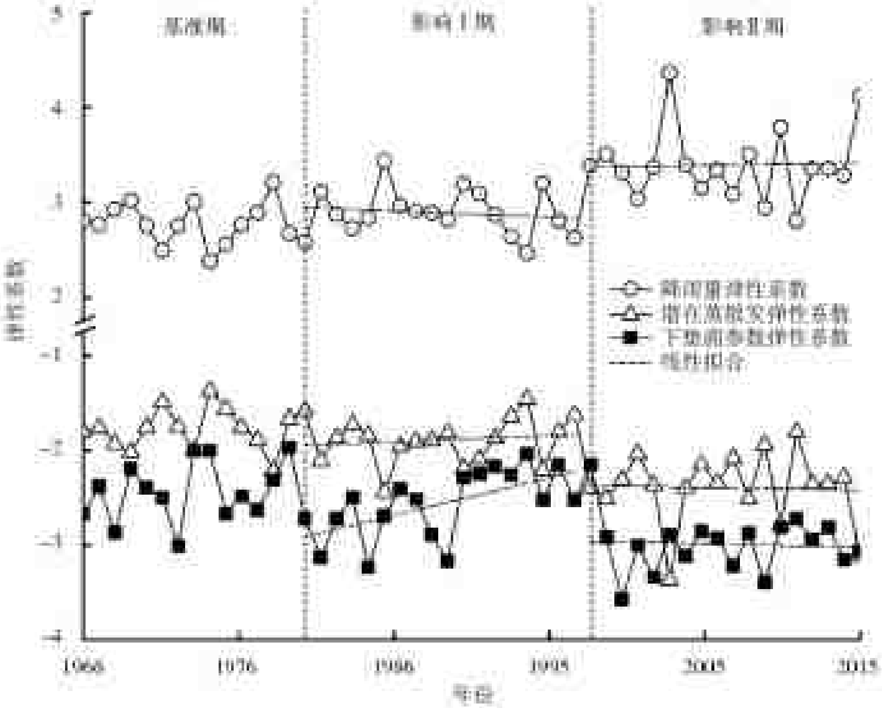

图 6　**各要素弹性系数年际变化趋势**

表 1　**滦河流域上游 1966—2015 年气象水文变量特征值**

时间	P/mm	R/mm	ET_0/mm	n	ET_0/P	弹性系数		
						ε_P	ε_{ET_0}	ε_n
1966—1979 年	437.69	37.258	1 001.90	1.985 2	2.289 2	2.740 0	−1.740 0	−2.397 3
1980—1997 年	417.35	31.345	972.56	2.062 3	2.330 3	2.831 4	−1.831 4	−2.510 9
1998—2015 年	418.41	18.173	977.68	2.516 0	2.336 7	3.328 1	−2.328 1	−2.953 8

起的下垫面变化是滦河上游径流减少的主要因素，对径流减少起正贡献作用；在气候因子中，降雨量变化的贡献率最大，为正贡献，潜在蒸散发次之，为负贡献。

人类活动对径流的影响主要体现在下垫面特征条件的改变，通过分析土地利用类型的变化情况可知，影响期农业活动及城市化建设进程的快速发展对研究区下垫面条件造成了一定了影响。此外，由于研究区存在以风蚀为主的土壤侵蚀现象，因此流域内进行的水土保持措施也是一项不容忽视的人类

表 2　滦河流域上游径流变化归因分析

时间	贡献量/mm			dR'/mm	dR/mm	δ/mm	贡献率/%		
	P	ET_0	n				P	ET_0	n
1980—1997 年	−3.994	1.644	−2.617	−4.967	−5.912	0.94	80.41	−33.090	52.68
1998—2015 年	−3.787	1.357	−18.010	−20.440	−19.080	−1.36	18.52	−6.640	88.12

注:表中 δ 为计算所得径流深变化量 dR' 与实际多年平均径流深变化量 dR 的差值。

活动[30]。经过数十年的治理,流域内水土流失面积已得到初步控制,据统计,至 21 世纪初,承德市内流域累计治理面积达12 985.92 km^2(治理率 57%),平均保水率为 6.33%,滦河流域森林覆盖率达到 43.5%,这对减缓研究区水土流失趋势,改善生态环境起到了重要作用[31]。

在水土保持措施中,修建梯田会减缓耕地坡度,从而促进土壤渗透能力,并最终降低径流速度;植树种草措施则通过截留降水、增加蒸发、改善土壤结构和增强过滤能力来减少径流[32],植被覆盖率的显著增加也可导致蓄水量的加强,进而使径流减少[33]。结合前文对研究区土地利用类型的分析可知,长期水土保持措施及其他人类活动可能使流域下垫面条件发生较大的改变[34],进而对地表产汇流特征等造成影响[35]。

目前在滦河流域开展的大多数研究均表明人类活动是径流变化的主要因素,其中王博威等[36]对滦河流域潘家口水库上游进行径流变化归因识别,发现人类活动影响对径流减少的贡献率大于 65%,气候变化贡献率小于 35%,与本文的结论类似。

4　结　论

本文以 Budyko 水热耦合模型为基础,对滦河上游径流变化进行定量归因识别,主要结论如下。

(1)对滦河流域上游地区 1966—2015 年间气象数据及年径流深进行趋势检验,结果表明年降水与年潜在蒸散发均无显著变化趋势,年径流深则呈显著减少趋势。根据降水-径流双累积曲线及滑动 t 突变检验,确定滦河上游基准期为 1966—1979 年,人类活动影响期为 1980—2015 年(其中 1980—1997 为影响Ⅰ期,1998—2015 为影响Ⅱ期)。

(2)通过基于 Budyko 水热耦合模型的弹性系数法,对径流变化进行归因分析,结果表明下垫面变化是引起径流变化的主要因素,对径流减少起正贡献作用,在 1980—1997、1998—2015 年的贡献率分别为 52.68%、88.12%。气候要素中,降雨量变化对径流减少的影响较大,为正贡献,潜在蒸散发影响较小,为负贡献。

(3)目前 Budyko 假设中下垫面参数的具体影响因素尚未明确,在未来的研究中应进一步区分量化其可能的影响因子,以便更准确地探究人类活动对径流变化的影响机制。

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Attribution identification of runoff changes based on the Budyko hypothesis in the upper reaches of the Luan River basin

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Abstract: In the past 50 years, evidence showed that climate change and human activities have affected the hydrological processes in the Luan River basin. In order to identify the main causes for runoff changes, the upper reaches of the Luan River basin are taken as the research area, and the Mann-Kendall test method is used to analyze the trend of meteorological and hydrological factors from 1966 to 2015 in the study area. Simultaneously, the hydrothermal coupling equilibrium equation based on the Budyko hypothesis is established. The elastic coefficient method is used to calculate the sensitivity coefficient of the influencing factors to runoff change. Furthermore, a quantitative contribution assessment of each factor to runoff change is also carried out in the study area. The results show that the annual runoff decreased significantly from 1966 to 2015, and there is no significant change in annual precipitation and annual evapotranspiration in the upper reaches of the Luan River basin. Compared with the base period (1966-1979), the change of the underlying surface is the main influencing factor of runoff reduction. The contribution rate of underlying surface change to runoff change in 1980-1997 (phase I) and 1998-2015 (phase II) is 52.68% and 88.12%, respectively. Among the climatic factors, the impact of precipitation on runoff changes is more significant compare to potential evapotranspiration.

Key words: upstream of Luan River; climate change; human activity; runoff change; Budyko hypothesis; elastic coefficient

The hydrological cycle is a quite complicated process in a river basin, wherein runoff, precipitation, and evaporation are the main contributors while climate change and human activities act as two major influencing factors[1]. Climate change directly affects precipitation, evaporation, runoff, soil humidity, etc., and its spatiotemporal variations which lead to a change in the total amount of water resources in the basin[2-3]. Human activities, such as the construction of large-scale water conservancy projects and the implementation of large-scale soil and water conservation measures can cause changes in underlying surface conditions and can change the process of production and convergence in the basin[4]. Therefore, the identification of the main driving forces of runoff change is vital to understand the change of available water resources in the basin[5]. In recent years, attribution identification

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of runoff changes under changing environment has gradually become one of the hot research issues[6].

At present, the research methods such as hydrological model simulation method and climate elasticity coefficient method used for quantitatively distinguishing the contribution of various influencing factors to runoff changes at home and abroad[7]. Among them, the hydrological simulation method is a good physical foundation research method. The SWAT (Soil and Water Assessment Tool) model and the Variable Infiltration Capacity (VIC) model are the commonly used hydrological models. For the first time, Onstad et al.[8] use the hydrological model method to predict the impact of land use/cover change on runoff change. Since then, domestic and foreign scholars have carried out many related studies. However, the calculation process is complicated due to a large number of model parameters and input data[9], and there are certain uncertainties in the parameters and structure of the model[10], which may cause large errors in the simulation results. The elasticity coefficient method based on the Budyko theory is a suitable method for analysis and research on an annual scale[11]. It requires less historical data[12] and can directly estimate the degree of influence of various factors[13]. Recently, the simple and effective analysis method has been widely used by domestic scholars in related research, and well verified in many river basins. For example, Zhang Limei et al.[14] conduct an attribution analysis on the runoff reduction in the Weihe River, and the document that the contribution rate of the underlying surface change is greater than 60%. Xia Jun et al.[7] conduct a quantitative assessment of the impact of climate and human activities on the hydrological process in the upper reaches of the Han River and find that human activities are the main factors leading to the reduction of runoff, with a contribution rate of 56.5% to 57.2%.

Since the 1950s, the water cycle process and water balance have undergone undeniable changes by the combined effects of climate and human activities which have greatly affected the ecological environment in the Luanhe River basin[15]. At present, scholars mainly adopt the hydrological model simulation method in the Jinghe River basin, but the research results have large differences. For example, Liu Chen[15] estimates the runoff based on the SWAT model under the influence of climate change and human activities in the Luohe River basin. The results show that human activity is the main influencing factor of runoff reduction, accounting for 71% from 1980 to 2008. Liu Xuefeng et al.[16] use the HBV model (Hydrologiska Fyrans Vattenbalans model) to study the influence of human activity based on natural runoff from 1980-2007 and find that the impact of climate change on surface runoff accounts for 55%. Chen Xin et al.[17] use the SWAT model and conclude that in the past 60 years runoff changes in the basins above Sandaohe are mainly affected by climate change, with a contribution rate of 89%. Wang Liang et al.[18] analyze the impact of climate and human activities on runoff changes using SWAT models in the Luanhe River basin, Inner Mongolia, and find that the contribution rate of human activities is 60.8%.

Different scholars use different types of models, parameter settings, and calibration methods when performing the model simulations, therefore, it is difficult to reach a reliable conclusion on the causes of runoff changes in the Luanhe River basin. Moreover, when scholars analyze the impact of climate change, they often use climate factors as a whole to calculate their contribution, and there is less research on the impact of specific meteorological factors[19]. Therefore, this paper takes the upper reaches of the Luanhe River basin as the research area and uses the elastic coefficient method to analyze the sensitivity of the river runoff to climate and underlying surface changes. Simultaneously, it separates the two main influencing climate factors to further quantitatively assess climate change and human activities and their contribution to runoff change.

1 Research area overview and dataset

1.1 Overview of the study area

Luanhe River basin, located in the northeast of

North China Plain, is one of the three major water systems in Haihe River basin, and also the most advanced ecological barrier in Beijing-tianjin-hebei metropolitan area. Its upstream section originates from the foothills of Bayanguertu mountain in the Zhangjiakou area, Hebei Province, and ends at Zhangbaiwan Town, Luanping county, Chengde city. It has a total length of 513 km and a drainage area of 25,367 km^2, including the Shandian River, Xiaolu River, Yisun River, and other major tributaries. The upper reaches of the Luanhe River are a typical temperate and semi-arid continental monsoon climate zone. The average annual temperature is 5.99 ℃, while the average annual rainfall is 300-600 mm in the basin. It is cold and dry in winter and warm and rainy in summer. The upper reaches of the Luanhe River flow through the upper Luanhe National Nature Reserve and Saihanba National Nature Reserve and has an important ecological strategic position.

1.2 Data sources and processing

In this paper, Sandaohezi and Hanjiaying hydrological stations in the upper reaches of the Luanhe River are selected as the flow control stations. Runoff data obtained from the Hydrological Yearbook of the People′s Republic of China. The statistical data is compiled by the Hebei Hydrological Bureau. The daily meteorological data of sunshine, precipitation, temperature, and wind speed for four meteorological stations (Duolun, Weichang, Fengning, and Chengde) from 1966 to 2015 is obtained from China Meteorological Science Data Sharing Service Network (https://data.cma.cn). The potential evapotranspiration (ET_0) is calculated using the Penman-Monteith formula (Eq. 1) recommended by the Food and Agriculture Organization-56 (FAO-56) in the study area. Furthermore, Inverse Distance Weighted (IDW) interpolation is used to obtain the potential evapotranspiration at the centroid of the watershed in the study area. The correlation between potential evapotranspiration and evaporation from the evaporation pan using existing meteorological data is analyzed from 1970 to 2001 in the upper reaches of the Luan River basin. The correlation coefficient R^2 between the two is 0.973 2, which has high consistency, indicating that the calculation results of the potential evapotranspiration can represent the average potential evapotranspiration in the study area (Fig. 1)[20]. In addition, the three-stage land use and land change (LUCC) datasets from 1980, 2000, and 2015 with a resolution of 1 km provided by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) to analyze the land use change in the study area.

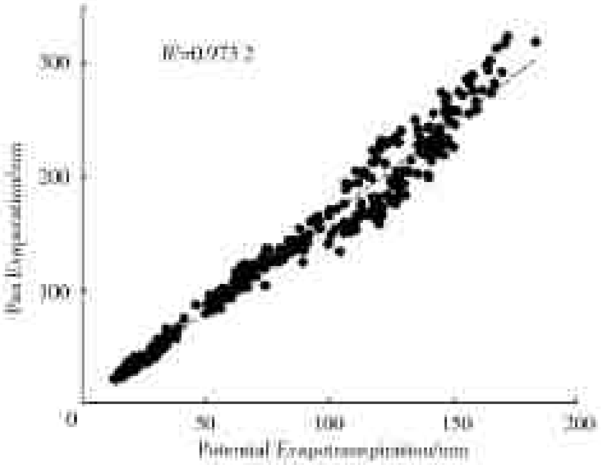

Fig. 1 Relationship between ET_0 and Epan during 1970-2001

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T_{mean}+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{1}$$

where, ET_0 is the potential evapotranspiration (mm/d); R_n is the net radiation on the crop surface[MJ/(m^2 · d); G is the soil heat flux[MJ/(m^2 · d)], 0 is taken; γ is the hygrometer constant (kPa/℃), 0.665 is taken; Δ is the slope of the curve between saturated vapor pressure and temperature (kPa/℃); T_{mean} is the average air temperature (℃); u_2 is the wind speed (m/s) at 2 m above the ground; e_s is the saturated vapor pressure of air (kPa); e_a is the actual vapor pressure of air (kPa).

2 Research methods

2.1 Trend analysis of hydrological variables and mutation test method

In this paper, the widely used Mann Kendall[21-22] nonparametric test method is adopted to analyze the trend in meteorological and hydrological data in the upper reaches of the Luanhe River from 1966 to 2015. Simultaneously, the combined precipitation-runoff double mass curve method[23] and moving the t-mutation test method are used to identify the abrupt change points in the annual runoff series. Besides, different hydrological stages are divided based on the T-mutation test method.

2.2 Attribution identification of runoff changes

The runoff displays different characteristics in different periods due to the combined effects of climate change and human activities in the study area. This paper uses the elasticity coefficient method based on the Budyko hypothesis to evaluate the sensitivity of runoff to various environmental factors and to quantitatively analyze the contribution of climate change and human activities to runoff change.

Budyko[11] believes that on a long time scale, the actual evapotranspiration E in the river basin is mainly controlled by water supply conditions (precipitation amount P) and energy supply conditions (potential evapotranspiration ET_0): $E/P = f(ET_0/P)$, Choudhury[24] and Yang[25] assume the water-heat coupling equilibrium equation based on the Budyko hypothesis. The Choudhury-Yang formula reveals that under certain climatic and vegetation conditions, the relationship between water and energy in the hydrological and climatic characteristics of the basin is subject to the following balance

$$E = \frac{P \times ET_0}{(P^n + ET_0^n)^{\frac{1}{n}}} \tag{2}$$

where: E is the annual average actual evapotranspiration, mm; P is the annual average precipitation, mm; ET_0 is the annual average potential evapotranspiration, mm; n is the parameter reflecting the characteristics of the underlying surface of the basin.

Under a long-term hydrological series, the water balance equation can be written as $P = E + R$ (where: R is the multi-year annual average runoff), and the underlying surface parameter n can be obtained by combining formula (2). Simultaneously, the differential equation can be used to express the contribution of different factors to runoff change

$$\mathrm{d}R' = \frac{\partial f}{\partial P}\mathrm{d}P + \frac{\partial f}{\partial ET_0}\mathrm{d}ET_0 + \frac{\partial f}{\partial n}\mathrm{d}n \tag{3}$$

According to the definition of elastic coefficient[26], the elastic coefficient of each influencing factor x can be expressed as

$$\varepsilon_{x_i} = \frac{\partial R}{\partial_{x_i}} \times \frac{x_i}{R} \tag{4}$$

where ε_{x_i} is the elastic coefficient of each influencing factor x_i. Assuming $\varnothing = \frac{ET_0}{P}$, the elastic coefficient calculation formula of each influence factor can be obtained[27]

$$\varepsilon_P = \frac{(1+\varnothing^n)^{1/n+1} - \varnothing^{n+1}}{(1+\varnothing^n)[(1+\varnothing^n)^{1/n} - \varnothing]} \tag{5}$$

$$\varepsilon_{ET_0} = \frac{1}{(1+\varnothing^n)[1-(1+\varnothing^{-n})^{1/n}]} \tag{6}$$

$$\varepsilon_n = \frac{\ln(1+\varnothing^n) + \varnothing^n \ln(1+\varnothing^{-n})}{n(1+\varnothing^n)[1-(1+\varnothing^{-n})^{1/n}]} \tag{7}$$

The equation can be written by combining formula (4), formula (3) as

$$\mathrm{d}R' = \varepsilon_P \frac{R}{P}\mathrm{d}P + \varepsilon_{ET_0}\frac{R}{ET_0}\mathrm{d}ET_0 + \varepsilon_n \frac{R}{n}\mathrm{d}n \tag{8}$$

The contribution of each influencing factor to runoff change, $\mathrm{d}R_{x_i}$ and contribution rate, C_{x_i}, are as follows

$$\mathrm{d}R_{x_i} = \varepsilon_{x_i}\frac{R}{x_i}\mathrm{d}x_i \tag{9}$$

$$C_{x_i} = \frac{\mathrm{d}R_{x_i}}{\mathrm{d}R'} \times 100\% \tag{10}$$

3 Results and analysis

3.1 Hydrometeorological characteristics of the study area

Fig. 2 shows the interannual trends of precipitation, potential evapotranspiration, and runoff in the upper reaches of the Luan River from 1966 to 2015. Simultaneously, the Mann-Kendall trend test is performed on annual precipitation, annual potential evapotranspiration, and annual runoff, respectively. The results show that the annual runoff change in the upper reaches of the Luanhe River basin displays a significant decrease ($P<0.01$), while the precipitation and potential evapotranspiration change show a non-significant decreasing trend.

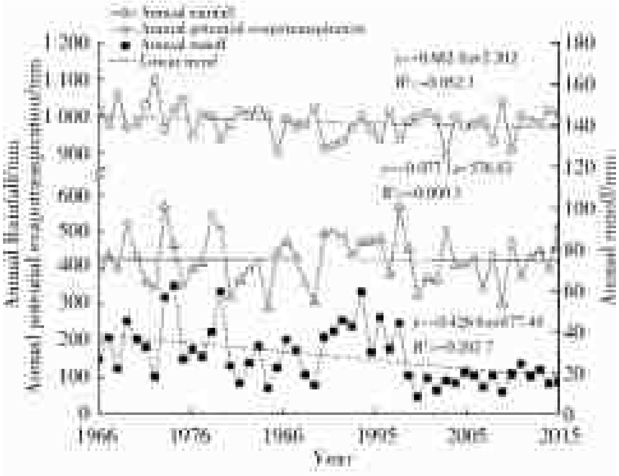

Fig. 2 Variation of precipitation, runoff, ET_0 in the upper reaches of the Luan River basin during 1966-2015

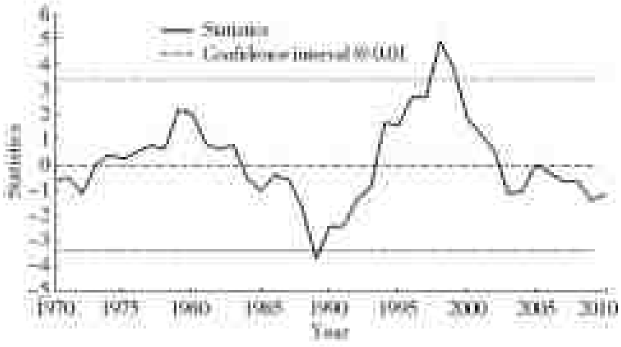

Fig. 4 Variation of moving t-test for interannual runoff at the research area

The key change points of the hydrological relationship are identified using the double mass curve method and the moving T-test method in the river basin. The precipitation-runoff double mass curve in the upper reaches of the Luan River is shown in Fig. 3. It can be seen that the precipitation-runoff mass curve deviates significantly in 1980 and 1998. Combining the 5-year moving t-test results (Fig. 4), 1966-1979 as the base period of runoff change of the upper reaches of Luanhe River, 1980 and 1998 are regarded as the mutation points of the rainfall-runoff relationship, and 1980-2015 is considered as the impact period of environmental change (including 1980-1997 as the impact period I and 1998-2015 as the impact period II). The slope of the curve becomes smaller after the mutation period , which indicates that the runoff decreases continuously due to environmental changes in the study area[23].

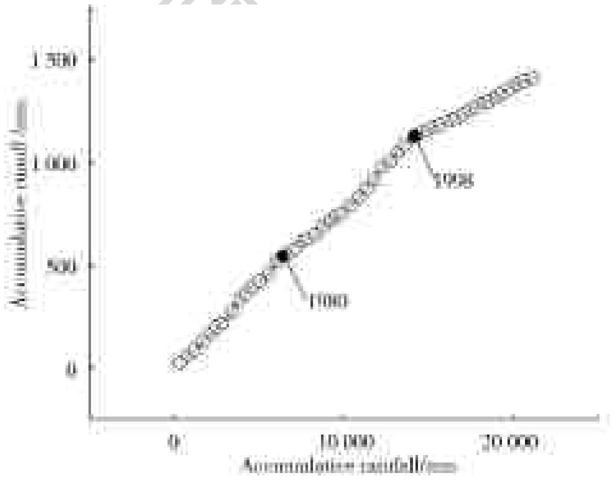

Fig. 3 Double mass curve analysis between cumulative runoff and precipitation in the Luan River basin

3.2 Characteristics of land use change in the study area

Studies have shown that the Haihe River basin where the Luanhe River is located is quite seriously affected by human activities[28]. This article selects the land use data for three periods of 1980, 2000 and 2015, which presents the land use status of the base period (1966-1979), impact period I (1980-1998) and impact period II (1999-2015), respectively. The land use types in the study area generally have little change, mainly grassland, followed by forest land and arable land, which account for 35%, 32%, and 24% of the total area of the study area, respectively.

Fig. 5 shows the conversion between different land use types in the impact period relative to the base period. During impact period I, the cultivated area increased by 106 km^2 (1.73%), and the forest and grassland areas decreased by 46 km^2 (0.55%), and 92 km^2 (1.04%), respectively. The main transfer sources of cultivated land are grassland and unused land, reflecting that at this stage human activities are mainly agricultural activities such as grassland reclamation and wasteland for food crop plantation. Compared with the reference period, the area of cultivated land, urban and rural areas, and construction land affected by Phase II increased by 64 km^2 (1.04%) and 56 km^2 (26.17%), and unused land decreased by 133 km^2 (8.85%), respectively. During this period, the level of urbanization construction has been improved in the study area, and the urban-rural land and construction land mainly converted from cultivated land and grassland.

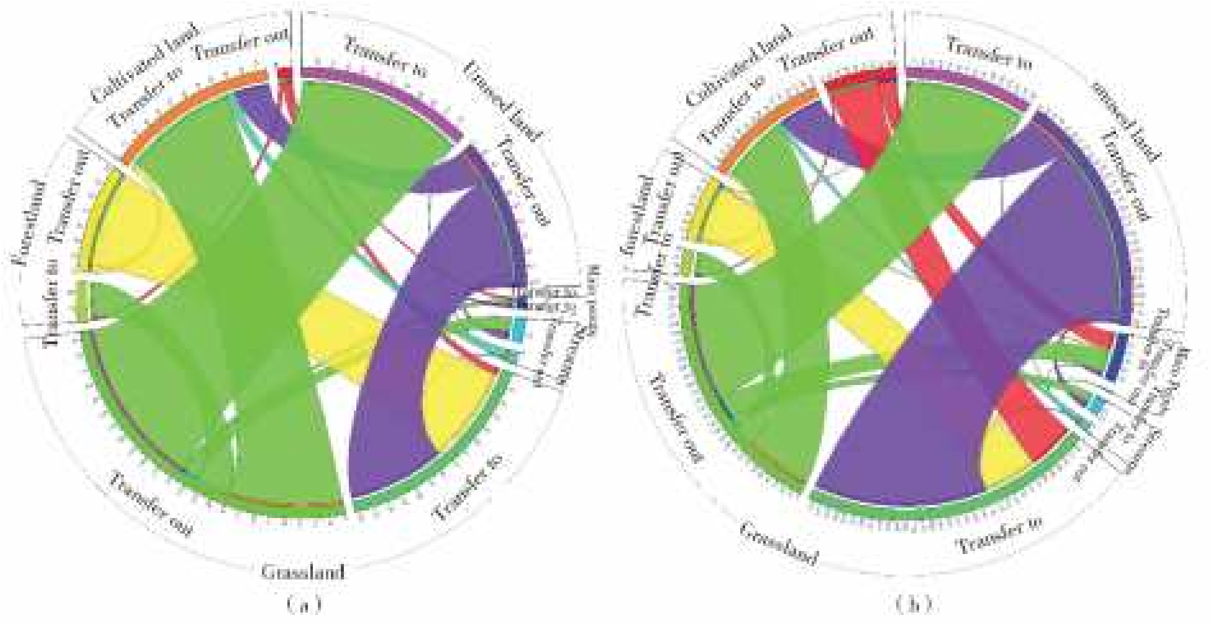

Fig. 5　LUCC conversion during 1980-2000 (a), 1980-2015 (b)

3.3　Attribution identification of runoff changes

3.3.1　Sensitivity analysis

From Eq. (5) to (7), the annual elastic coefficients of annual runoff versus rainfall, potential evapotranspiration, and underlying surface parameters from the upper reaches of the Luan River from 1966 to 2015 are obtained (Fig. 6). It can be seen from the analysis in the impact period of human activities, the elasticity coefficient of the underlying surface characteristic parameter changes much more than the precipitation and potential evapotranspiration elasticity coefficient, which shows that the runoff in the study area is more sensitive to the change of underlying surface in 1980-2015.

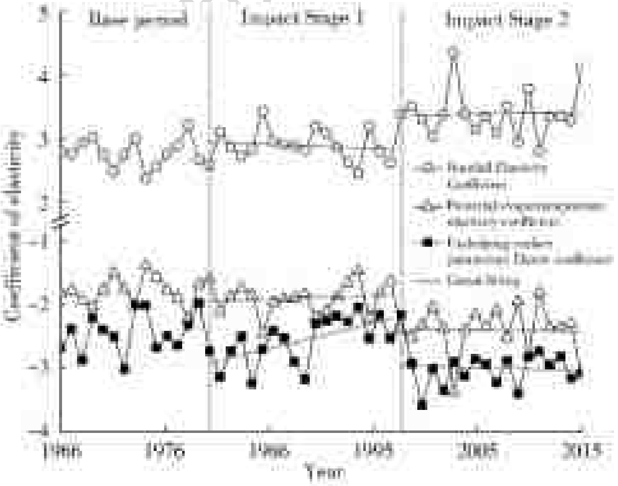

Fig. 6　Interannual variation trend of elastic coefficients of various factors

Tab. 1 shows the hydrological characteristics of the climate and surface conditions in different periods. It can be seen that the annual average precipitation, the annual average runoff depth, and the average annual evapotranspiration during the changing period are all decreased compared to the baseline period. The drought index (ET_0/P)[29] is larger than the reference period, and both are greater than 1.0, indicating that the study area is dry, and the dryness is deepening year by year. According to the elastic coefficients of various factors, the runoff change in the upper reaches of the Luan River is positively related to precipitation and negatively related to potential evapotranspiration and underlying surface conditions. The specific manifestation is that when precipitation increases by 1 mm, it leads to an increase in the runoff of 2.74 to 3.33 mm, while an increase of 1 mm in evapotranspiration leads to a decrease in the runoff of 1.74 to 2.33 mm, and an increase in the characteristic parameters of the underlying surface leads to a decrease in the runoff of 2.40 to 2.95 mm, respectively.

3.3.2　Attribution of runoff changes

The elastic coefficient method is used to calculate the degree of influence of climate and underlying

Tab. 1 Statistics in hydro-climatic variables in the upper reaches of the Luan River basin during 1966-2015

Year	P/mm	R/mm	ET_0/mm	n	ET_0/P	Elasticity coefficient		
						ε_P	ε_{ET_0}	ε_n
1966-1979	437.69	37.258	1 001.90	1.985 2	2.289 2	2.740 0	-1.740 0	-2.397 3
1980-1997	417.35	31.345	972.56	2.062 3	2.330 3	2.831 4	-1.831 4	-2.510 9
1998-2015	418.41	18.173	977.68	2.516 0	2.336 7	3.328 1	-2.328 1	-2.953 8

surface parameters on runoff changes. The results are presented in Tab. 2. The contribution rate of climate change to runoff change from 1980 to 1997 is 47.32% (among which, the contribution rate of precipitation is 80.41%, and the evapotranspiration contribution rate is -33.09%), underlying surface parameters contribute to runoff change account for 52.68%, respectively. Likewise, from 1998-2015, climate change contribution rate to runoff change is 11.88% (among which, the precipitation contribution rate is 18.52%, the potential evapotranspiration contribution rate is -6.64%), and the contribution rate of underlying surface parameters to the change of runoff is 88.12%, respectively. The difference between the calculated runoff depth change and the actual runoff depth change is small, which proves that the method used in the identification of runoff attribution is reliable and effective. It can be seen that the underlying surface change caused by human activities is the main factor behind the runoff reduction in the upper reaches of the Luanhe River, and has a positive contribution to the runoff reduction. Among the climate factors, the contribution rate of rainfall change is the largest, which has a positive contribution, followed by potential evapotranspiration, which has a negative contribution.

Tab. 2 Analysis of the change of runoff in the upper reaches of the Luan River basin

Year	Contribution/mm			dR'/mm	dR/mm	δ/mm	Contribution rate/%		
	P	ET_0	n				P	ET_0	n
1980-1997	-3.994	1.644	-2.617	-4.967	-5.912	0.94	80.41	-33.090	52.68
1998-2015	-3.787	1.357	-18.010	-20.440	-19.080	-1.36	18.52	-6.640	88.12

Note: δ in the table is the difference between calculated runoff depth change dR' and actual multi-year average runoff depth change dR.

The impact of human activities on runoff is mainly reflected in changes in the characteristics of the underlying surface. By analyzing the changes in land use types, the rapid development of agricultural activities and urbanization in the impact period has affected the underlying conditions in the study area. In addition, due to soil erosion which is mainly dominated by wind erosion in the study area, therefore, soil and water conservation measures are also a human activity that cannot be ignored[30]. After decades of governance, the area of water and soil loss has been preliminarily controlled in the basin. According to statistics, the cumulative area under control in Chengde city is reached by 12 985.92 km^2 (the governance rate is 57%), and the average water retention rate is 6.33% by the beginning of the 21st century. The forest coverage reached 43.5%, which played an important role in slowing the soil and water loss trend and improving the ecological environment in the study area[31].

Among the water and soil conservation measures, the construction of terraces can slow down the slope of cultivated land, thus promoting the soil permeability and ultimately reducing the runoff rate. The planting of trees and grass measures can reduce runoff by intercepting precipitation, increasing evaporation, improving the soil structure and enhancing the filtration capacity[32]. The significant increases in vegetation coverage rate can also lead to the enhancement of water storage, thus reduces the runoff[33]. Based on the above analysis of land use types in the study area, it can be seen that long-term soil and water conservation measures and other human activities may greatly change the underlying surface conditions of the basin[34], and affect the characteristics of surface runoff and convergence[35].

At present,most of the previous studies show that human activities are the main factors of runoff change in the Luanhe River basin. Wang Bowei et al.[36] identify the cause of runoff change in the upper reaches of Panjiakou Reservoir in Luanhe River basin and finds that the contribution rate of human activities to runoff reduction is more than 65%,and the contribution rate of climate change is less than 35%,which is similar to the conclusion of this paper.

4　Conclusions

In this paper, Budyko coupled model is employed to identify and to quantitatively attribute the runoff change in the upper reaches of Luanhe River. The main conclusions are as follows:

(1) The trend test of the meteorological data and annual runoff depth from 1966 to 2015 in the upper reaches of the Luanhe River basin show that there is no significant change in annual precipitation and annual potential evapotranspiration, while the annual runoff depth shows a significant decrease. Based on the precipitation-runoff double mass curve and the moving *t*-mutation test, it is identified that the baseline period of the upper reaches of Luanhe River is 1966-1979,and the impact period of human activities is 1980-2015 (among which 1980-1997 is the impact period I,1998-2015 is the impact period II).

(2) Attribution analysis of runoff changes by the elastic coefficient method based on the Budyko hydrothermal coupling model shows that the underlying surface change is the main factor causing runoff change,and it has a positive contribution to runoff reduction. The contribution rates in 1980-1997 and 1998-2015 are 52.68% and 88.12% respectively. Among the climatic factors, rainfall changes have a greater impact on runoff reduction with a positive contribution, and potential evapotranspiration has a smaller impact with a negative contribution,respectively.

(3) At present, the specific influencing factors of underlying surface parameters in the Budyko hypothesis are not clear. In future research,we should further distinguish and quantify the possible influencing factors,to more accurately explore the mechanism of human activities on runoff change.

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