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# 青海湖流域物理侵蚀速率对气候变化的响应

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**摘要:** 气候要素是否影响地表物理侵蚀速率目前还存在诸多争议。以往对此方面的研究均集中在高降雨区域, 而对于低降雨条件下气候因子的控制机制研究目前还很有限。青海湖流域对气候变化十分敏感。本文通过对青海湖流域最大两条河流布哈河和沙柳河每日的温度、降雨、径流和河流悬浮物浓度进行为期一年的持续监测, 探讨干旱/半干旱区气候要素对地表物理侵蚀速率的影响。研究结果显示: 在气候要素中, 降雨以及其产生的径流是青海湖流域物理侵蚀速率最主要的控制因素, 而温度的影响较弱。最重要的是, 降雨强度决定着最终的侵蚀速率。布哈河和沙柳河流域一次瞬时高强度降雨能产生全年侵蚀通量的30%以上。此外, 相同流量条件下, 季风前期的侵蚀速率要高于季风中、后期, 反映了季风前期低温条件下的冰冻作用, 以及春季降尘产生的大量细颗粒物质, 增加了雨季来临时侵蚀物质的输出。这些认识对于理解长时间尺度上青海湖沉积物钻孔中沉积速率和古气候要素的关系具有重要意义。

**关键词:** 物理侵蚀速率; 降雨; 流量; 气温; 青海湖流域

## Response of physical erosion rates to climate changes within the Lake Qinghai catchment

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**Abstract:** *Background, aim, and scope* Whether climate controls erosion rates is still controversial. Some found significant correlations between erosion rates and climate (e.g. precipitation, discharge), and others didn't. In addition, Previous studies were mainly focused on high precipitation and tectonic active regions, such as the Taiwan, Alps, Andes and Himalayas, whereas the study in low precipitation area remains scarce. Lake Qinghai catchment, located in the NE Tibetan Plateau, is quite sensitive to climate changes. The detailed hydrological and meteorological data in the Lake Qinghai catchment provides a good opportunity to in depth understand the effects of climate factors on erosion rate in arid/semi-arid regions. **Materials and methods** The daily air temperature, water discharge, precipitation and suspended particulate material (SPM) were monitored over a whole year period in the Buha River hydrological station in 2007 and the Shaliu River station in 2009. The water discharge was monitored twice a day, and when in flood periods, the monitoring frequency was increased to 4—5 times one day. The daily SPM concentration was measured only from the

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period of May to October, since the SPM was extremely low during dry seasons. The physical erosion rates (PER) were calculated by daily SPM concentration multiplied water discharge. **Results** The results showed that the courses of air temperature, water discharge, precipitation and suspended river sediment in the Buha and Shaliu Rivers exhibited great seasonal variations with their high values during the monsoon seasons and low values during the dry seasons. In the Buha River catchment, the total precipitation was 389.8 mm in 2007, and the mean daily air temperature and water discharge during a year ranged from  $-20.5^{\circ}\text{C}$  to  $16.5^{\circ}\text{C}$  and from  $2 \text{ m}^3 \cdot \text{s}^{-1}$  in February to  $220 \text{ m}^3 \cdot \text{s}^{-1}$  in August, respectively. In the Shaliu River catchment, the annual precipitation was 431 mm in 2009, with the mean daily air temperature and water discharge ranging from  $-25.5^{\circ}\text{C}$  to  $12^{\circ}\text{C}$  and  $0.1 \text{ m}^3 \cdot \text{m}^{-1}$  in February to  $107 \text{ m}^3 \cdot \text{s}^{-1}$  in July, respectively. It is observed that the daily SPM concentrations vary from  $<0.001 \text{ kg} \cdot \text{m}^{-3}$  in the dry season to  $2.280 \text{ kg} \cdot \text{m}^{-3}$  in the monsoon in the Buha River, and from  $<0.003 \text{ kg} \cdot \text{m}^{-3}$  to  $2.350 \text{ kg} \cdot \text{m}^{-3}$  in the Shaliu River. Seasonal PER exhibits significant changes in the Buha and Shaliu Rivers. The SPM fluxes vary from  $<1 \text{ tons} \cdot \text{day}^{-1}$  in the dry season to  $23155 \text{ tons} \cdot \text{day}^{-1}$  in the monsoon in the Buha River, and from  $<1 \text{ tons} \cdot \text{day}^{-1}$  to  $21078 \text{ tons} \cdot \text{day}^{-1}$  in the Shaliu River. **Discussion** The relationships between temperature and erosion rates were weak ( $R^2$  is 0.22 and 0.17 in the Shaliu and Buha River, respectively), whereas the water discharge showed good correlation with erosion rates ( $R^2$  is 0.77 and 0.68 in the Shaliu and Buha River, respectively). In addition, some samples with abnormally high physical erosion rates were corresponded to heavy rain events. In the Shaliu River, a 26 mm rainfall within 5 hours on 15th, July generated 21078 tons of SPM, accounting for 35.2% of the total year flux in 2009, whereas totally 92 mm rainfall in the entire August only contributed 6937 tons. Similarly, a highest daily rainfall (20 mm) in the Buha River brought in a highest SPM flux on 18th July, and produced 22.5% of the total year flux in 2007. Meanwhile, it was also observed that at a given discharge, the suspended sediment flux was generally higher from May to June than from July to October in both river catchments, indicating that freezing processes before monsoon and input of eolian dust in spring season provided large volumes of fine materials which was finally flushed out at the onset of monsoonal rainfall resulting in the high suspended sediment fluxes during the pre-monsoon period. **Conclusions** In the Lake Qinghai catchment, water discharge and precipitation controls erosion rates, but temperature shows only a weak control. The most important is that precipitation intensity rather than total rainfall volume or discharge finally determines the erosion rates. One storm rain event can produce more than 30% of the total yearly suspended river sediment flux. Higher erosion rates during pre-monsoon period than mid- and post-monsoon are ascribed to freezing erosion and eolian dust input. **Recommendations and perspectives** We firstly detailed discussed whether temperature, discharge and precipitation control physical erosion rate in the two largest rivers in the Lake Qinghai catchment, which are critical to explore their relationships at arid/semi-arid climate condition. Also, this study is significant for understanding the relationship between deposition rate of Lake Qinghai sediment and paleoclimate changes over long-time scale.

**Key words:** physical erosion rate; precipitation; water discharge; temperature; Lake Qinghai

厘清到底什么因素控制着地表的侵蚀速率, 对于认识大范围的构造和地形问题至关重要, 例如对侵蚀过程控制机制的认识可用于探究构造隆升和气候之间潜在的相互反馈; 确定极端和频繁事件对地形塑造所起的作用; 以及分辨沉积盆地沉积物的构造和气候信号等 (DiBiase and Whipple, 2011)。已有的研究显示, 地表侵蚀速率强烈依赖于岩性、地形坡度和气候 (Gabet et al, 2008; Pelletier and

Rasmussen, 2009; DiBiase and Whipple, 2011)。在这些因素中, 目前对气候因素的控制作用还颇有争议。Thiede et al (2004) 测试了喜马拉雅山的剥蚀速率, 指出高的侵蚀速率发生在最高的降雨区域, 强调了侵蚀速率随降雨量的增加而增加。其他学者的研究也发现降雨和径流与侵蚀速率之间呈现良好的相关性 (Dadson et al, 2003; Moon et al, 2011)。而另外一部分学者的研究却并未发现侵蚀

速率和降雨或径流之间的相关性，或者认为气候对侵蚀速率仅有微弱的影响 (Riebe et al, 2001; Aalto et al, 2006)。此外，当前对地表侵蚀的研究多集中在构造活动强烈的高降雨区，例如中国台湾，阿尔卑斯山，安第斯山，喜马拉雅山等 (Burbank et al, 2003; Dadson et al, 2003; Gabet et al, 2008; Willett, 2010; Carretier et al, 2013)。但是对干旱 - 半干旱低降雨气候条件下侵蚀过程的机理研究还十分匮乏。

位于青藏高原东北隅的青海湖是我国最大的内陆封闭性微咸水湖，地处东亚季风、印度季风和西风急流的汇聚带，对气候和全球环境变化十分敏感，是开展我国西部环境变化、青藏高原隆升过程、环境效应及它们与全球联系等研究的热点区域。前人通过沉积物钻孔开展了大量青海湖古、现代环境演变的研究 (黄麒, 1988; Lister et al, 1991; 王苏民和施雅风, 1992; 王云飞, 1993; 张彭熹等, 1994; 沈吉等, 2001; 张恩楼等, 2002; 刘兴起等, 2003; Xu et al, 2006; Liu et al, 2009; An et al, 2012; Li et al, 2012; 安芷生等, 2015; Jin et al, 2015)，在这些研究中一项重要的指标就是沉积速率，这是与当地侵蚀速率直接关联的。不同降雨频率和

降雨量条件可能会产生侵蚀通量的差异，最终产生湖泊沉积物中不同的沉积速率。这个侵蚀速率到底是如何受气候因素调控的，目前还不清楚。因此，开展青海湖流域现代侵蚀过程的研究对不同时间尺度气候反演具有重要的现实意义。

## 1 研究区概况

青海湖 ( $36^{\circ}32' - 37^{\circ}15'N$ ,  $99^{\circ}36' - 100^{\circ}47'E$ ) 位于青藏高原东北隅，是我国最大的微咸水湖 (图 1)。2007 年湖面海拔 3194 m，湖区面积  $4260 \text{ km}^2$ ，流域面积  $29660 \text{ km}^2$  (Jin et al, 2009)。湖区地势为西北高而东南低，形成东为日月山、南为青海南山、西为天峻山、北为大通山脉所环绕的内陆湖盆地，海拔多在 4500 m 以上，最高可达 5200 m。湖区山地约占流域面积的 68.6%，其余为河谷和湖积平原。湖区北部大通山走向北西西，山脉基岩裸露。刚察县以西主要为三叠纪砂、页岩，东段则为晚寒武纪变质岩，主要岩性为片岩及片麻岩，并有花岗岩侵入体；湖区西部布哈河谷北侧出露早古生代砂岩、片岩、千枚岩、混合片麻岩和火山岩，并夹结晶灰岩 (中国科学院兰州分院和中国科学院西部资源环境研究中心, 1994)。

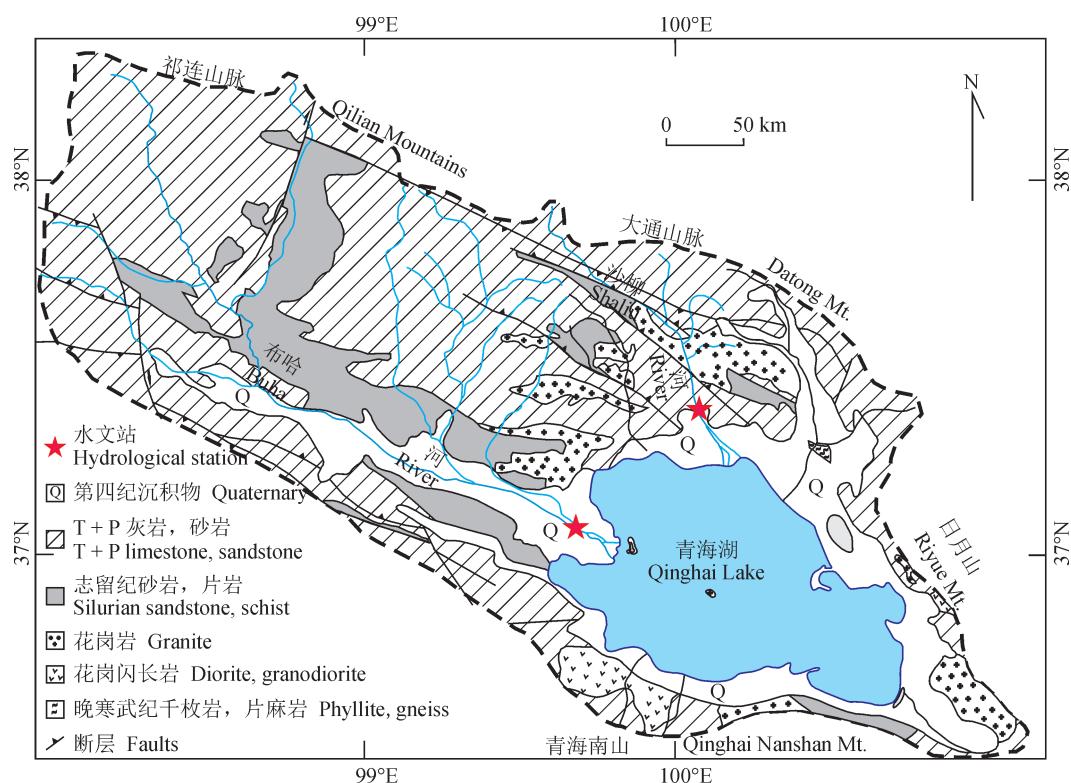


图 1 布哈河和沙柳河水文气象数据监测点位

Fig.1 Monitoring sites of hydrological and meteorological data in the Buha and Shaliu River

青海湖流域为高原大陆性气候, 光照充足, 日照强烈; 冬寒夏凉, 暖季短暂, 冷季漫长, 春季多大风和沙暴; 雨量偏少, 雨热同季, 干湿季分明(中国科学院兰州分院和中国科学院西部资源环境研究中心, 1994; 陈桂琛, 2008)。根据环湖气象站的记录, 青海湖年平均降雨量(1951—2005)为336.6 mm, 蒸发量(1959—2000)约为~925 mm(Jin et al., 2009)。青海湖流域约90%的降水集中在5—9月(1961—2001)。每年平均温度变化为0.9—2.7°C, 记录的最高温度28°C出现在7月, 而月平均温度为12.4°C; 最冷的月份为1月, 其月平均温度为-12.7°C, 最低温度-31°C。布哈河和沙柳河流域多年平均潜在蒸发量为1650 mm和1463 mm。这两个流域的月平均气温最高出现在7月而最低值出现在1月。从10月中旬开始到次年的4月, 气温一般处于0°C(Zhang et al., 2013)。位于湖区西部的布哈河是青海湖流域最大的河流, 贡献了入湖径流量的40%以上。布哈河长286 km, 下游最宽处达22 m, 其流域面积为14337 km<sup>2</sup>, 几乎占了总流域面积的一半。布哈河起源于平均海拔高于4600 m并带有冰川覆盖的疏勒南山, 其2007年的总流量为 $10.05 \times 10^8 \text{ m}^3$ (Zhang et al., 2013)。沙柳河起源于最高海拔在5200 m以上的大通山脉, 长109.5 km, 流域面积1442 km<sup>2</sup>(中国科学院兰州分院和中国科学院西部资源环境研究中心, 1994)。

## 2 样品与方法

本文选取青海湖流域最大的两条河流布哈河和沙柳河进行了为期一年的定点水文气象数据的每日持续监测, 布哈河和沙柳河流域的监测时间分别是2007年和2009年, 监测地点在布哈河水文站和沙柳河的刚察水文站(图1)。监测内容包括每日河流悬浮物浓度(SPM)、河水流量、降雨量和气温。需要说明的是, 在这两个河流流域, 仅监测了5—10月每天的SPM浓度, 这是因为在其余月份(干季), SPM的浓度非常低。

布哈河和沙柳河流域的物理风化速率(PER)通过悬浮颗粒物浓度(SPM)和河水流量的(Discharge)数据估算。计算公式为: PER = SPM×Discharge。

## 3 结果与讨论

### 3.1 日降雨、气温、流量、悬浮物浓度变化特征

根据监测的布哈河和沙柳河水文气象

数据(图2): 布哈河2007年的降雨量为389.8 mm, 当年的日平均温度变化-20.5—16.5°C(图2a)。沙柳河流域2009年的降雨量为431.3 mm, 当年的日平均温度变化-25.5—12.0°C(图2d)。两条河流5—9月的降雨分别形成了布哈河和沙柳河75%和85%的年径流量, 而从12月到次年2月几乎没有降雨产生。在春季, 青海湖流域内的降雨主要以雪和冰雹的形式发生, 此时逐渐增加的气温导致了冰雪的融化, 冰融水开始补给河水。

布哈河2007年的总流量为 $10.05 \times 10^8 \text{ m}^3$ , 每日平均流量从2月的 $2 \text{ m}^3 \cdot \text{s}^{-1}$ 增加到8月的 $220 \text{ m}^3 \cdot \text{s}^{-1}$ (图2b)。沙柳河2009年的总流量为 $4.23 \times 10^8 \text{ m}^3$ , 日平均流量变化从2月的 $0.1 \text{ m}^3 \cdot \text{s}^{-1}$ 到7月的 $107 \text{ m}^3 \cdot \text{s}^{-1}$ (图2e)。

每日SPM浓度监测的数据显示: 布哈河流域SPM浓度的变化从干季的 $<0.001 \text{ kg} \cdot \text{m}^{-3}$ 到季风期的 $2.280 \text{ kg} \cdot \text{m}^{-3}$ , 沙柳河流域的SPM浓度从干季的 $<0.003 \text{ kg} \cdot \text{m}^{-3}$ 到季风期的 $2.350 \text{ kg} \cdot \text{m}^{-3}$ 。

所有这些水文气象数据均显示了一个共性, 即它们的高值出现于雨季, 低值出现于干季。其中两个河流流域气温的变化从1月到12月呈现良好的正态分布, 径流的变化在7月出现第一次峰值, 随后到8月份逐渐降低, 到9月份出现第二次峰值。悬浮物浓度的变化基本与径流变化相似, 一个明显的区别是布哈河流域的悬浮物浓度全年最高值出现在季风来临的初期(图2)。

### 3.2 物理侵蚀速率与气候要素之间的关系

#### 3.2.1 物理侵蚀速率与温度之间的关系

图3a和图3b展示了沙柳河和布哈河流域的日物理侵蚀速率与气温之间的关系。整体上而言, 物理侵蚀速率在雨季达到全年的最高值, 与温度变化相似, 例如两个河流的最高值均出现在7月, 此时的温度也基本上处于全年的最高值。但是物理侵蚀速率的详细变化却未能与温度形成良好的对应, 表现在物理侵蚀速率的变化并不是一个正态分布状态。图4a和图4b显示两个流域的物理侵蚀速率与温度之间呈现指数函数的关系, 相关系数为0.22和0.17, 处于弱正相关关系。这个结果表明, 此区域的物理侵蚀速率对温度变化并不敏感。温度的作用体现在冬季地表冰冻和春季的解冻过程, 这会产生岩石和土壤的破碎松动, 使得地表物质容易被侵蚀出来。

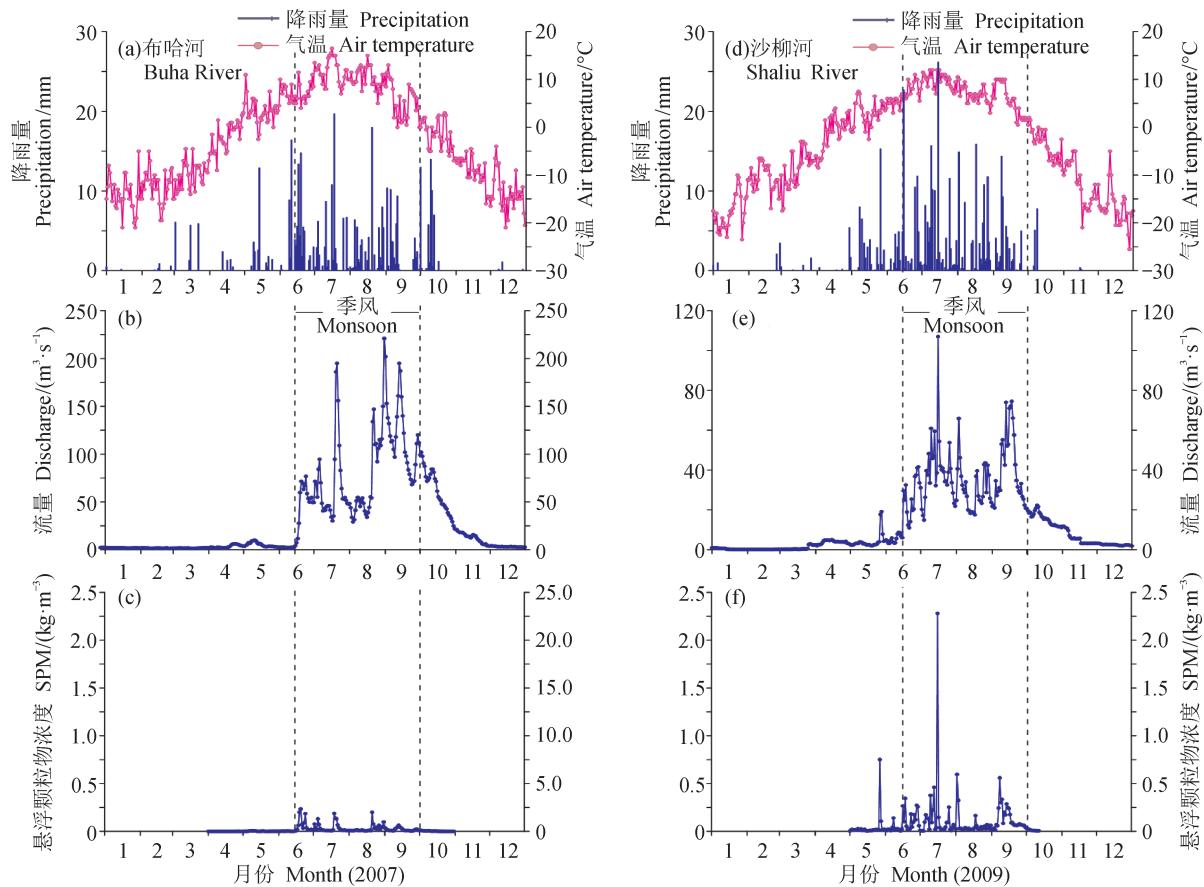


图 2 布哈河 2007 年和沙柳河 2009 年的水文气象参数的日变化

Fig.2 Daily variations of air temperature, precipitation, water discharge and suspended particulate material (SPM) content in the Buha River in 2007 and in the Shaliu River in 2009

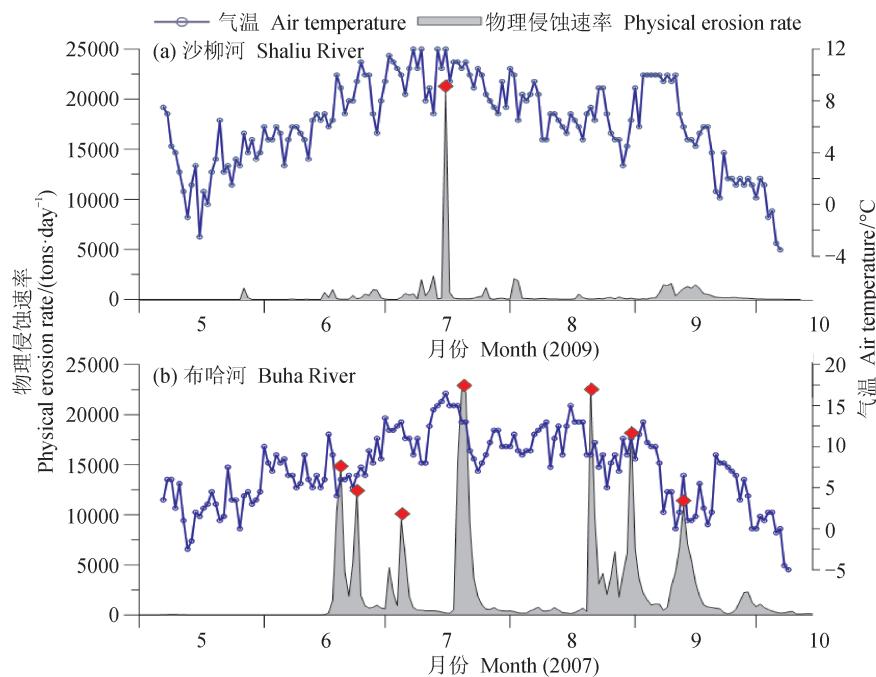


图 3 布哈河 2007 年和沙柳河 2009 年的物理侵蚀速率与气温的日变化

Fig.3 Daily variations of air temperature and physical erosion rate (PER) in the Buha River in 2007 and in the Shaliu River in 2009

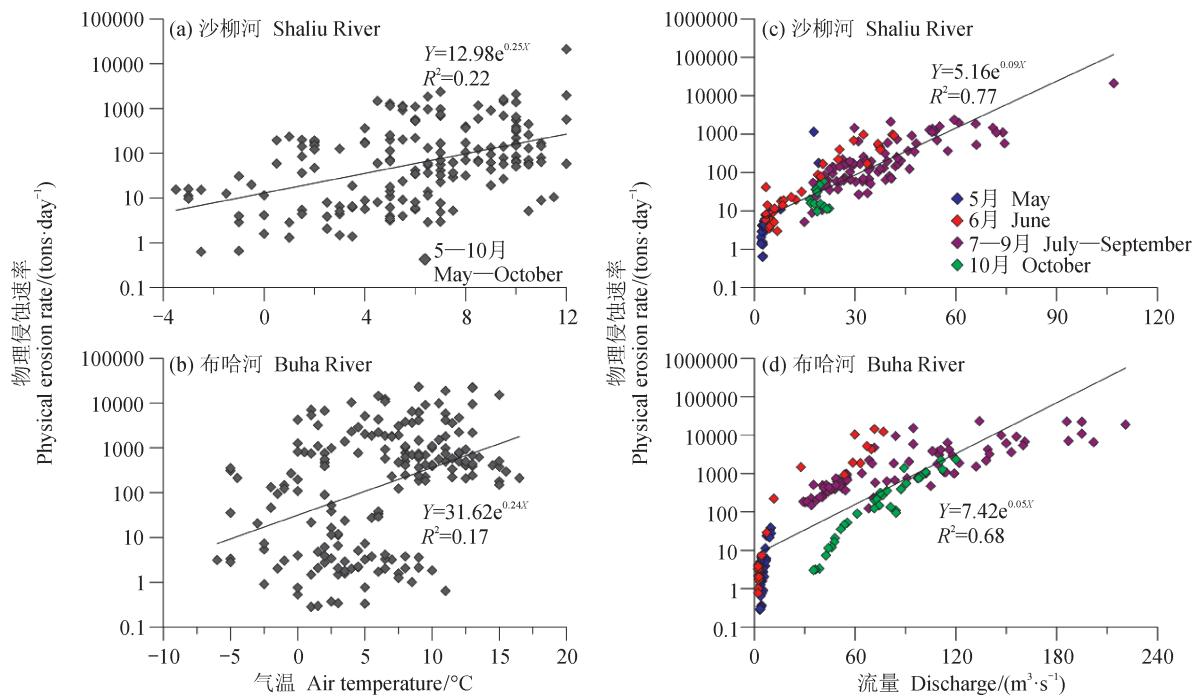


图 4 布哈河 2007 年和沙柳河 2009 年的物理侵蚀速率与气温 (a, b) 和河水流量 (c, d) 的关系

Fig.4 The relationship of daily physical erosion rate (PER) vs. temperature (a, b) and water discharge (c, d) in the Buha River in 2007 and in the Shaliu River in 2009

### 3.2.2 物理侵蚀速率与径流和降雨之间的关系

大气降雨会产生地表冲刷, 侵蚀地表物质。虽然大气降雨是偶然发生的, 但是降雨会产生地表径流, 这个过程会长于降雨过程。因此, 对河水流量的监测是一个连续的过程, 河水中携带的侵蚀物质也能被连续监测到。径流因子从某种程度上讲, 是对大气降雨的一个体现, 可以等同于降雨。图 4c 和图 4d 显示沙柳河和布哈河流域的物理侵蚀速率和流量呈现良好的指数正相关, 相关系数分别为 0.77 和 0.68。这说明两个流域的地表物理侵蚀速率受到径流或者降雨的主要控制。此外, 在相同河水流量条件下, 雨季前期和初期(5—6月)的物理侵蚀速率要高于雨季中、后期(7—10月), 这说明: (1) 5 月前的冰冻和冰融过程产生了大量易侵蚀细颗粒物质; (2) 青海湖流域春季频繁的尘暴事件累积了一定量的大气降尘在地表, 这两个过程, 在雨季来临时被快速冲刷出来。在本文的研究中, 冬季气温变化从  $-10^{\circ}\text{C}$  到  $-25^{\circ}\text{C}$ , 此时地表被冰雪覆盖而处于冰冻状态。在这个过程中, 冰冻侵蚀产生的细颗粒物质最终在季风降雨来临被输出到河流系统, 导致 5—7 月高的河流沉积物通量。关于冰冻过程产生岩石的机械破碎并

产生大量细颗粒物质的现象此前也有学者在全球其他区域观察到(如 Galliardet et al., 1999; Hun and Edmond, 1999)。

此外, 总体而言, 布哈河和沙柳河流域河水流量越大, 物理侵蚀速率越高(图 4c 和图 4d), 反应了气候因素中降雨产生的径流对地表侵蚀的控制作用。但是降雨量与物理侵蚀速率的关系并不是一个简单的正相关关系。图 5a 和图 5b 中显示两个流域均有一些异常高的物理侵蚀速率值(红色方框标记), 而每个异常高值分别对应着一次强降雨。例如: 在沙柳河流域, 2009 年 7 月 15 日 5 小时内发生的一次 26 mm 强降雨产生了 21078 吨的河流悬浮物通量, 本次短时间降雨仅占全年降雨总量的 6.07%, 却产生了高达全年悬浮物通量的 35.2%。相比较而言, 随后整个 8 月份产生的 92 mm 降雨却仅产生了 6937 吨的悬浮物通量, 低于单次 26 mm 强降雨产生悬浮物总量的 1/3。同样, 在布哈河流域 2007 年 7 月 18 日产生的一次 19.7 mm 降雨(占全年降雨量的 5.05%)产生的悬浮物通量高达全年通量的 22.5%。图 5b 中其他用红色方框标记的也各自对应了一次瞬时强降雨事件。

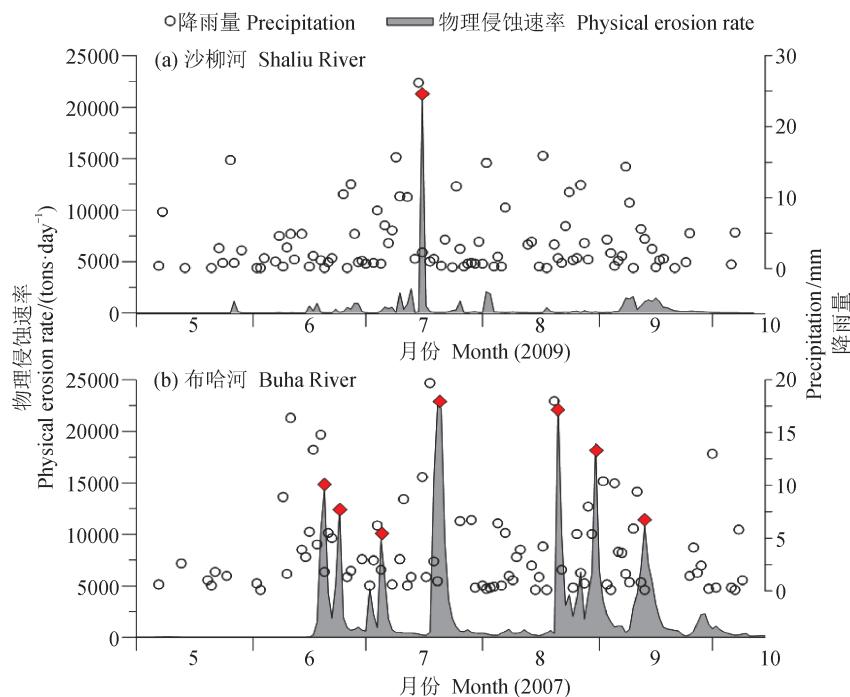


图 5 布哈河 2007 年和沙柳河 2009 年的物理侵蚀速率与降雨的日变化

Fig.5 Daily variations of precipitation and physical erosion rate (PER) in the Buha River in 2007 and in the Shaliu River in 2009

这些结果表明，在干旱半干旱的青海湖流域，地表侵蚀过程受到降雨和径流的影响，但是降雨因素中，降雨的强度是决定侵蚀速率的一个非常重要的因素，一次短时高强降雨时间可能产生全年侵蚀通量的 30% 以上。

#### 4 结论

本文通过对青海湖两条最大河流布哈河和沙柳河流域日气温、降雨、流量以及悬浮物浓度持续一年的监测，分析了气候因素与干旱 / 半干旱区物理侵蚀速率的关系。结果表明，在气候因素中，物理侵蚀速率主要受降雨控制，而气温的影响较弱。更重要的是，单次的瞬时降雨强度而非总降雨量对地表侵蚀速率的主导作用非常明显。这个过程对于理解青海湖湖泊沉积物钻孔中沉积物速率与古气候之间的关系提供了重要的实测数据支持。

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