上方来水来沙的异位侵蚀效应研究进展

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摘要： 上方来水来沙作为上下不同地貌部位之间水流能量传递的媒介和泥沙输移的载体，对下游侵蚀产沙过程具有重要影响，是土壤侵蚀研究的关键环节。以往研究多侧重于小流域泥沙来源以及上方来水来沙的异位沉积效应，对上方来水来沙的异位侵蚀效应研究相对较少。本文回顾了上方来水来沙异位侵蚀效应的研究方法，在总结归纳前人研究成果的基础上，首次提出了"异位侵蚀"的概念，从异位径流特征、侵蚀产沙等方面，分析了裸露坡面上方来水来沙的异位侵蚀效应，并对水土保持措施异位减蚀作用的研究进展进行了综述。在此基础上，进一步探讨了异位侵蚀研究中的热点和难点问题，提出可从明确异位侵蚀效应概念、探索异位侵蚀影响因素及其机理、阐明上方来水来沙异位侵蚀过程中水沙和能量传递特征、量化水土保持措施异位减蚀作用等 4 个方面进一步深入研究上方来水来沙的异位侵蚀效应。

关键词： 上方来水来沙；土壤侵蚀；异位侵蚀效应；水土保持措施；研究进展
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Review on the off-site erosion effect of up-slope runoff and sediment

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Abstract: [**Background**] Up-slope runoff and sediment play an important role in energy deliver and sediment transport between the adjacent section. The change of up-slope runoff and sediment will affect the soil erosion process of down-slope. Thus, it is the vital content of soil erosion to study the up-slope runoff and sediment. However, previous studies mainly focused on the sediment sources of small watershed and the off-site depositional effects of up-slope runoff and sediment, while less studies focused on the off-site erosional effect of up-slope runoff and sediment. [**Methods**] This paper reviewed the study methods of the off-site erosional effect of up-slope runoff and sediment. Based on the previous research, the "off-site erosion" was firstly proposed in this paper. And then, it summarized the research achievements of predecessors. In terms of the characteristics of off-site runoff and sediment yield, the paper summarized the off-site erosional effect of up-slope runoff and sediment on the bare slope, and the research progress of the influence of soil and water conservation on the off-site erosional effect. Furthermore, it discussed the hotspots, challenges, and the future research directions of the off-site erosional effect. [**Results**] "Off-site erosion" refers to the change of downslope runoff characteristics and

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the sediment yield caused by up-slope runoff and sediment. The up-slope runoff and sediment joined into the down-slope and increased the runoff energy of down-slope. Besides, the runoff velocity, hydraulic radius, Reynolds number and Froude number increased, while resistance coefficient decreased. Based on the analysis of observed data and simulation experiments, the up-slope runoff and sediment would increase the sediment yield of down-slope. However, when the sediment concentration of runoff came to the sediment carrying capacity of runoff, the runoff with sediment couldn't erosive the down-slope soil, and even to deposit. The soil and water conservation measures on slope decreased runoff amount and sediment yield entering the down-slope. Some scholars thought soil and water conservation on slope decreased the off-site sediment yield, while others drew the opposite conclusion. Engineering measures, such as dams, drastically cut the runoff erosional energy, thus they had the decreased effect on off-site.

[Conclusions] "Off-site erosion" is a relatively spatial concept, but how to reasonably define the up-slope and down-slope regions, there is still no clear definition. Up-slope runoff and sediment, erosion pattern evolution process and erosion process interacted with each other. Meantime, off-site erosional effect of up-slope runoff and sediment would be impacted by the dynamic change, such as rainfall intensity, underlying surface, sediment concentration and sediment carrying capacity. Further research of the off-site erosional effect of up-slope runoff and sediment could be conducted in confirming the concept of "off-site erosion", exploring the influence factors and mechanism of off-site erosion, illuminating the transfer characteristics of sediment and runoff energy during the off-site erosional process of up-slope runoff and sediment, as well as quantitating the off-site less erosional effect of soil and water conservation.

Keywords: up-slope runoff and sediment; soil erosion; off-site erosional effect; soil and water conservation; research advance

土壤侵蚀是导致土地资源退化的主要原因之一[1]。高均凯[2]依据效应发生的部位不同，将其分为原位效应和移位效应。认为：原位效应是指在土壤侵蚀过程及侵蚀部位所引起的环境变化，如土壤退化和可利用土地丧失；移位效应指在土壤侵蚀输移过程及堆积部位所产生的环境效应，如泥沙淤积、道路破坏、洪水灾害加剧等[3]。以往研究以小流域泥沙来源为主[4-5]，研究坡沟系统产沙关系，多关注上方水沙在异位的沉积效应[6-8]，较少研究上方来水来沙在下方的侵蚀效应。上方来水来沙作为流域不同地貌部位的联系媒介，是能量传递和泥沙输移的载体，从根本上改变了输入至下方的水沙条件，调节径流侵蚀力的分配[9]，改变了侵蚀产沙的发展过程，不同的上方来水来沙量在下方会引起不同的"净侵蚀产沙量"，即不同的上方来水来沙具有不同的异位侵蚀能力。如陈浩[10]和肖培青[11]的研究发现上方来水来沙量会对下方的侵蚀产沙量产生重要影响。此外，水土保持措施不仅可以较好的保持水土资源[12-14]，还可以改变输入至下游的径流量和含沙量，调节对下游的侵蚀过程[15]，水土保持措施综合布设，可起到"1 + 1 > 2"的减蚀作用[16]。然而，径流潜在的异位侵蚀效应仍容易被忽视，径流的异位水沙效应定量化计算还尚未得到充分重视。

1 概念

陈浩[17]和肖培青等[18]分别提出的"净产沙增量"和"净侵蚀产沙量"的概念，表征上方来水来沙在其下方的增沙效应，其为"异位效应"的具体表现之一。在前人研究的基础上，综合上方来水来沙在下方引起的径流特征改变，笔者提出"异位侵蚀"的概念——一定空间形成的径流在形成径流区域之外的径流路径区域所引起的径流特征改变及侵蚀产沙。它是一个相对空间的概念，原位和异位范围的合理选取，则视研究目标而定。

2 研究方法

目前研究方法主要有以下 4 方面：1) 双土槽试验模型[18]，由供沙土槽和试验土槽组成，可通过控制双槽的分/合观测接受/不接受上方来水来沙的土槽侵蚀量。通过改变降雨强度及供沙土槽塑料膜覆盖情况改变输入至下游的水沙情况。2) 径流冲刷与人工降雨复合试验[19]，以放水冲刷模拟上方来水

量,人工降雨模拟本坡位降雨条件,以有/无放水冲刷来模拟接受/不接受上方来水来沙时的侵蚀产沙情况,通过改变放水流量改变输入至下游的径流特征。3) 基于在相同试验条件(降雨强度、坡度、土壤性质等条件) 下,相同坡长的土槽产生相同侵蚀量的基本假设,孔亚平等[20]进行不同坡长土槽的室内模拟降雨实验,研究上方来水来沙的异位侵蚀效应,通过不同坡长的组合,研究不同来水来沙量对下方的影响。4) 利用水文站观测数据采用系统法[21]、成因分析法[10]考虑坡面水下沟时对沟道侵蚀产沙的影响,即坡面径流的异位侵蚀效应。

模拟试验装置较为简便,操作简单,并能直接计算上方来水来沙在下方引起的异位效应; 但是模拟试验中上方来水来沙的模拟,以及下方下垫面微地形等因素的变化可能与实际情况有所不同,尤其是径流冲刷与人工降雨复合试验,仅考虑上方来水量,清水与浑水的异位侵蚀特征存在差异。水文站观测范围大,采用水文站数据反演坡面的贡献,可研究较大范围内的异位侵蚀效应; 但由于野外观测难度大,数据精确度不高,对异位侵蚀效应估算的准确性有待提高,因此,如何实现更大尺度上的研究分析,仍是目前局限之一。

3 裸露坡面上方来水来沙的异位侵蚀效应

3.1 对异位径流特征的影响

上方来水来沙改变了下方的径流量和流速,显著影响了异位的径流特征和动力学特性。在同一坡度条件下,上方来水来沙汇入到下坡位,以含沙水流为载体,携带能量进入下方,增加了下坡位的径流能量,使下坡位水流流速、水力半径、雷诺数和弗劳德数增大,而细沟水流阻力系数相对减少[22]。车小力等[23]采用野外放水冲刷试验,得出在试验条件下,上方来水来沙的汇入使浅沟雷诺数、弗劳德数、水流功率和剪切力分别增大 33% ~76%、21% ~47%、29% ~72% 和 18% ~42%,阻力系数减少 11% ~13%。肖培青等[24]建立坡沟系统概化模型,发现上方汇水在坡沟系统也存在水流雷诺数和弗劳德数明显增大,水流流态由缓流演变为急流,坡面水流阻力系数明显减小的现象。

目前的研究多侧重于上方来水来沙对径流水动力学特征的影响,对异位径流特征影响因素及量化表达等方面的研究关注不足,异位径流特征对上方来水来沙的响应机制仍需进一步研究。

3.2 对异位侵蚀产沙的影响

上方来水来沙通过改变输入至下方的径流特征,对异位侵蚀产生深刻的影响。根据实测资料整理分析,当接受上方来水来沙时,董庄沟冲刷模数增加 1.26 ~1.4 倍[25]; 羊道沟沟谷地径流、泥沙分别增加 1.4 和 3.5 倍[15]; 黄土丘陵区沟间地径流下沟使沟谷地侵蚀量增加 1 倍以上[21]。研究学者发现在流域尺度沟间地水沙下沟会大大增加沟谷地的侵蚀量,增加的比例略有不同,这与其降雨、地形、土壤等条件有关。

肖培青等[26]采用双土槽的人工模拟降雨试验,发现对于疏松土和紧实土处理,上方汇流引起坡下方的净侵蚀产沙量分别占试验土槽全部产沙量的 31.1% ~97.3% 和 45.1% ~89.7%。王文龙等[27]采用多坡段人工模拟降雨试验,得出上坡来水使梁峁坡和谷坡产沙量增大 20.2% ~ 63.5% 和 42.9% ~60.5%。郑粉莉等[28]指出上方来水来沙可使细沟侵蚀带和浅沟侵蚀带的侵蚀产沙分别增加 30.5% ~37.7% 和 16.7% ~80.6%。武敏等[29]采用双土槽径流小区的人工模拟降雨试验,得出坡面浅沟侵蚀过程以侵蚀-搬运过程为主,当降雨强度为 64 mm/h 和 116 mm/h 时,坡面汇水使坡下方浅沟侵蚀产沙量分别增大 26.2% ~ 82.5% 和 23.5% ~ 58.7%,坡面汇水引起坡下方的净侵蚀产沙量随坡面汇水含沙量的减少和降雨强度的增加而增大等[30]。模拟试验中上方来水来沙在下方引起的增沙效应低于野外观测,上部径流的汇入,使得径流冲刷能力增大,流域侵蚀方式发生演变,加剧了上方来水来沙的增沙效应。

肖培青等[31]认为上方汇水增加侵蚀产沙量是通过增加坡下方径流量及其挟沙能力而实现,其结果表现为增加水流含沙量。ZHENG 等[32]研究发现上方水沙的汇入会加剧溯源侵蚀,增加泥沙输送能力。由于研究手段不一,关注的主要影响因素不同,不同研究所得到的水沙关系并不一致。孔亚平认为产沙量随上方来水量的增加呈线性增加[20]; 谭贞学等发现坡面上坡位汇流、下坡位产流和坡面上坡位输沙对坡面下坡位侵蚀模数的影响可用二元线性方程很好地描述[33]; 蔡强国等[34]根据野外试验小区和小流域的实际观测资料分析,得出在黄土丘陵沟壑区沟坡侵蚀产沙模数与上方来水量和来沙量呈幂函数关系。

土壤侵蚀是一个做功耗能的过程,在侵蚀输沙过程中,用于侵蚀和输送泥沙的能量将会出现此消

彼长的情况,分离过程受输沙过程影响[35];因此,上方来水来沙所能引起的异位侵蚀并不会单一地呈增加趋势,当径流含沙量达到径流挟沙力,含沙水流将不再对土壤进行剥蚀,甚至出现沉积现象[31]。ZHENG 等[32]认为不同土壤条件(干、湿、结皮)下,上方来水来沙的净侵蚀产沙能力和输沙能力会有所不同。HUANG 等[36]研究发现在 5% 坡度和小降雨强度下,上方来水来沙在试验土槽发生了沉积现象,随坡度和降雨强度的增大,上方来水来沙在试验土槽逐渐转变为侵蚀过程为主。

4 水土保持措施的异位减蚀作用

坡面水土保持措施,可使径流就地入渗,防止梁坡径流下沟[37],从而减少输入至下方的径流侵蚀能量。陈浩等[38]发现杨家沟坡面植被率平均达 70% 以上可以使流域和沟道侵蚀产沙分别减少 92% 和 75% 以上,即坡面水土保持措施可在沟坡起到异位减蚀的作用,但也有学者提出不同的观点,丁文峰等[39]采用坡沟系统,研究发现坡面植被盖度为 90% 时沟坡侵蚀量大于坡面无植被覆盖时的沟坡侵蚀量。郑明国等[40]发现,坡面布设植被措施并没有改变流域水沙关系,在坡面减少的含沙量会在沟道部分获得补充,即上方布设的水土保持措施,可能会加剧沟道的侵蚀。

淤地坝可减少地表径流[41],削峰滞洪,减缓放水流速[42],即会改变输入至下游径流特征,从而改变对下游的异位侵蚀能力。冉大川等[43]认为淤地坝减沙量包括淤地坝的拦泥量、减轻沟蚀量以及由于坝地滞洪及流速减小对坝下游沟道侵蚀量的影响减少量,而其削峰滞洪对下游沟道的影响减少量还无法计算,即淤地坝具有异位减蚀作用,但目前其量化研究仍稍显薄弱,仍有待进一步的研究。

水土保持措施除在布设区域具有减水减沙作用外[44-46],还可改变输入至下方的径流特征和含沙量,对下方有潜在的影响,而在目前水土保持措施的异位减蚀作用及其异位侵蚀阻控机制并未受到足够的重视,研究较为零散,异位减沙效应机理未形成系统的认识,缺乏水土保持措施异位减沙效应的有效计算方法,影响了水土保持措施的减沙效益评估。

5 存在问题及展望

坡面下坡位侵蚀模数随降雨强度、坡度的变化较上坡位更为复杂[33],如何界定上方下方更为合理,仍未有统一标准。且来水来沙、侵蚀方式演变与侵蚀过程互相影响[47-48],上方来水来沙的异位侵蚀效应还与降雨强度、下垫面、来水含沙量、径流挟沙力等动态变化密切相关[26,49],而挟沙力研究多在河道上进行,适用于坡面的挟沙力公式仍在探索阶段,加大了上方来水来沙的异位侵蚀效应的研究难度。

水土保持措施的异位减蚀作用仍缺少定量化研究,如何正确认识,以及量化水土保持措施的异位减蚀作用,还需要更加深入的研究。

自 20 世纪 70 年代以来,学者们对上方来水来沙的异位侵蚀效应,以及水土保持措施的异位减蚀作用进行了开创性研究。但由于上方来水来沙的异位侵蚀效应复杂程度高,许多问题仍需进一步研究。今后的研究工作可从以下几方面开展:1) 明确异位侵蚀效应概念,筛选影响异位侵蚀的参数,构建异位侵蚀估算模型;2) 开展模拟试验,探索异位侵蚀影响因素及其机理;3) 研究上方来水来沙异位侵蚀过程中水沙和能量传递特征;4) 从水土保持措施分散削减径流侵蚀能量角度出发,量化水土保持措施,尤其是工程措施的异位减蚀作用。

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