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干旱传播研究进展与展望Ⅱ

——影响因素与干旱传播研究展望

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摘要: 针对影响干旱传播的 3 个方面因素, 将气候因素分成降水、气温、风向和大气环流, 将下垫面因素分成地质与地貌、植被与土壤, 将人类活动因素分成土地利用与变化、水资源开发利用, 系统地回顾了控制与影响干旱传播的有关因素及在不同国家和不同区域的变化, 特别指出气候及下垫面因素在不同地点和时间对干旱传播过程可能会呈现出明显的差异性影响。干旱传播过程及其影响因素与机制的深入探讨, 有助于提高干旱监测与预警水平, 减少干旱灾害对经济、社会和生态环境等带来的负面影响。此外, 从多源数据多模型融合、干旱传播三维建模、干旱传播驱动机理和干旱灾害链条延伸等方面进行了展望。

关键词: 干旱传播; 影响因素; 进展; 展望

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干旱是对人类社会影响最为广泛的自然灾害之一。因频率大、持续时间长和影响范围广的特点, 干旱具有高危害性, 持续的旱灾会明显制约社会经济的可持续发展[1]。干旱的 4 种类型(气象干旱、农业干旱、水文干旱和社会经济干旱)之间存在水量与能量的联系。用于表征水分缺失信号在不同类型干旱间依次传递的“干旱传播”, 近些年受到了国内外的广泛关注, 并得到了比较深入的研究。这几种不同类型的干旱之间, 可形成以大气圈异常要素为推力, 以水圈异常要素为纽带, 以岩石圈差异为条件, 以生物圈客体为影响对象的干旱演变态势[2]。

本文属于 2 篇连载论文的第 2 篇。第 1 篇——《干旱传播研究进展与展望Ⅰ》[3] 从干旱传播的含义、特征、类型和研究方法等方面介绍了干旱传播的研究进展。在第 1 篇的基础上本文对干旱传播影响因素及干旱传播研究的热点与难点进行归纳和总结, 并指出现有研究仍存在的主要问题和未来研究发展趋势。

1　干旱传播的影响因素

干旱通过水循环传播, 主要受到气候因素、下垫面(地表)因素及人类活动 3 个方面的控制及影响。3 种因素共同作用, 进而影响干旱传播的时间、频次和严重程度。气候是干旱传播的关键与主要控制因素之一, 例如, 降水短缺导致的气象干旱, 通过影响水循环过程以及干旱响应时间的非线性累积特征, 进一步发展为农业和水文干旱[4-5]。下垫面及流域地表特征包括海拔、坡度、土地覆盖和含水层状况等, 这些参数在农业、水文干旱对气象干旱的响应中起着重要作用。此外, 人类活动通过土地利用与水利工程等影响水循环, 从而影响干旱传播进程。

1.1　气候因素

气候与水文有着非常密切的关系。著名的俄罗斯气候学家沃叶伊科夫, 1884 年在《全球气候及俄

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国气候》一书中提出了“河流是气候的产物”之科学论断[6-7]，强调气候对于水文及河流形成的关键作用。干旱传播与气象、水文变量异常变化密切相关[8]。影响干旱传播过程的通常是多个气象气候因素的共同作用，例如温度升高、辐射加强、相对湿度降低及潜在蒸散发增加等[9-10]。下面就降水、气温、风向和大气环流4个方面进行重点阐述。

1.1.1　降水

马岚[11]发现，在渭河流域，春季降水对干旱传播时间的影响最大，与传播时间呈显著的负相关，且超过了99%的置信度检验。朱业玉等[12]对河南省旱灾产生的原因进行了分析和探讨，结果表明该省干旱频发主要是由于降雨在年内极度分配不均而导致的。Lin等[13]利用SPI指数与SRI指数，对华南的西江流域1961—2013年的气象干旱、水文干旱传播特征进行了研究，并将传播规律应用于2021—2050年的水文干旱预测，其结果表明：气象干旱的时空格局是引发干旱传播的关键因素，气象干旱面积、干旱严重程度、干旱持续时间、干旱空间集中度和干旱持续时间的影响依次增加。

1.1.2　气温

刘永佳等[1]以黄土高原为例，发现干旱传播速率与气温、蒸发和土壤湿度相关。Dai等[14]发现在渭河流域，气温升高、降水减少和土壤湿度降低对干旱传播的影响较大，灌溉用水影响较小。谢安等[15]研究表明，全球平均温度上升1℃，中国东北区干旱化程度则增加5%~20%。杨淑萍等[16]对2004—2005年宁夏特大干旱事件进行诊断分析，认为降雨量减少或者气温升高是导致该次干旱发生的主要原因。

1.1.3　风向

关于风向与干旱传播特征的关系，Herrera - Estrada等[17]使用1980—2016年北美再分析数据，建立水分跟踪模型探索干旱传播过程中的水分输送减少的原因，发现农业干旱与逆风陆地的水汽输送减少有关。Schumacher等[18-19]通过拉格朗日(Lagrange)含水量追踪法，针对全球最近40次最严重干旱案例，分离土壤水分干旱对顺风降水的影响，研究发现：俄罗斯东部干旱对下风向水汽影响可忽略，北美与俄罗斯西部干旱对下风向水汽的影响较小，南非和澳大利亚干旱对下风向水汽的影响显著。

1.1.4　大气环流

干旱事件与大气环流异常密切相关[20]，大气环流对干旱传播时间的影响主要是通过影响降水及蒸散发来实现的[5,21]。Gibson等[22]利用澳大利亚东部2个农业集水区的长期观测记录——降雨量(1908—2015年)、流量(1901—2014年)研究了该区域的干旱传播，认为干旱的开始和传播与大规模海洋-大气气候驱动因素(如厄尔尼诺-南方涛动、印度洋偶极子和南半球环状模)的组合状态密切相关，而干旱的终止是由持续的天气系统(如低压槽)引起的。Han等[23]以珠江流域为例，发现太平洋年代际涛动是加快干旱传播的主要因素。Zhou等[24]的研究表明，除太平洋年代际涛动以外，厄尔尼诺-南方涛动由于其与蒸散发密切相关，也是影响珠江流域干旱传播时间的重要因素之一。Ma等[25]发现遥相关因子对渭河流域的秋季干旱传播影响较大，其中北极涛动、厄尔尼诺-南方涛动和太平洋年代际涛动，通过影响降水、土壤湿度等变量间接改变渭河流域的干旱传播过程。

1.2　下垫面因素

由于下垫面因子的差异，气象干旱可能会转化为不同程度的农业、水文干旱，海拔、坡度、流域面积、植被、土壤、岩性与地下水等集水区相关的地质地貌条件，都会对干旱传播产生影响。气象因素与下垫面因素，在不同地点、时间及季节也会呈现出影响的差异性。比如，马岚[11]研究了渭河流域的干旱传播影响因子，发现春季、夏季影响气象干旱和水文干旱相依关系的主导因素是气象因子，秋季的主导因子是下垫面特征和气象因子，冬季的主导因子是遥相关因子和流域下垫面特征。下面分为地质与地貌因素及植被与土壤因素两个方面归纳下垫面对干旱传播的影响。

1.2.1　地质与地貌

Veettil等[26]发现流域面积和海拔对美国萨凡纳河流域水文干旱平均持续时间影响显著。Yang等[27]以我国西南地区龙川江流域为例，发现海拔是影响干旱传播的重要因素，农业干旱在高海拔地区向水文干旱传播，而在低海拔地区则相反。Apurv等[28]发现并区分了3种干旱传播机制，认为它们产生了不同的水文干旱特点：第一种机制涉及季节性地下水补给循环，这种循环持续存在于低降水量时期，与气象干旱相比，水文干旱时间更短；第二种机制是季节性地下水补给循环在低降水量期间受到抑制，导致水文干旱比气象干旱更长；第三种机制是地下水补给缺乏季节性，导致与气象干旱持续时间相似的水文干旱。在干旱滞后性研究中，区域下垫

面条件对干旱滞后性的影响是当今干旱传播过程研究中的热点[29]，如我国南方喀斯特地区因其特殊的地貌特点，即便降水丰富也有发生水文干旱的可能。张浪等[30]研究了贵州省黔中水利工程区后发现，各下垫面条件对干旱传播过程的影响程度依次为地表切割深度>岩溶发育强度>高程>地形地貌，其中干旱传播特征与地表切割深度呈显著的负相关，与岩溶发育强度、高程、地形地貌呈正相关。

1.2.2　植被与土壤

植被通过截留降水和植物叶片蒸腾作用影响蒸散发，从而影响干旱传播。Vicente-Serrano 等[31]在研究植被对干旱的反应时发现，由于植被的适应特征，不同的生物群落对干旱的时间尺度反应不同。Peña-Angulo 等[32]发现，1961—2013 年西班牙盆地上游水文干旱持续时间、严重程度、频率的增加可能与森林总面积和森林密度的增加有关。Wu 等[33]发现，森林和草地显著改变了黄土高原干旱传播时间，森林覆盖面积大的地区干旱传播的时间长，草地的干旱传播时间短。Ding 等[34]利用太阳诱导叶绿素荧光(SIF)和归一化差异植被指数(NDVI)探讨了植被对干旱的影响程度和传播时间，研究表明：SIF 和 NDVI 在中国总体上具有较高的一致性，不同植被类型的 NDVI 的归一化值分布水平高于 SIF；干旱通常对中国北方的植被产生负面影响，对中国南方的植被产生积极影响；基于 NDVI 的干旱传播时间大于基于 SIF 的干旱传播。Warter 等[35]发现：从沿海地区的黏壤土到内陆地区的壤土不等，南加州草原的干旱状况在秋季表现出明显的季节性时间模式，低于植被胁迫阈值，因此可归因于土壤保水能力和干燥度(aridity)的差异；内陆地区的土壤饱和度在超过一半(64%)的模拟时间内低于指定阈值，而沿海地区的这一比例约为 47%。

1.3　人类活动因素

人类活动可以通过土地利用、城市化和森林砍伐等影响地表径流和下渗，通过水库蓄水、引水和灌溉等影响水资源储存和消耗[36]。高强度人类活动通过改变大气成分(主要通过温室气体排放)引起全球或区域性水循环过程的变化，导致气象干旱时空特性变化，从而间接影响到水文干旱的形成发展；通过改变河流蓄存状态与水力联系(主要通过蓄、引、提、调水工程)以及用水特性变化，改变河流与地下水系统调蓄功能与产汇流过程，从而直接影响到气象干旱向水文干旱的传递过程以及水文干旱的发展过程[37]。下面分别就土地利用与变化、水资源开发利用对干旱传播的影响进行概括与介绍。

1.3.1　土地利用与变化

Veettil 等[26]指出，土地利用在控制流域水文干旱方面发挥着重要作用。例如，牧场增加了蒸散量，降低了产水量。黎云云[38]量化了气象、农业和水文干旱的驱动归因贡献率发现，大气环流异常和土地利用变化对气象干旱的相对影响贡献率约为 95% 和 5%，气候和土地利用变化对农业干旱的相对影响贡献率约为 75% 和 25%，水资源开发利用、气候变化和土地利用变化对水文干旱的相对影响贡献率约为 50%、30% 和 20%。杨志远[39]评价了气候和土地利用对黑土区典型流域干旱的影响，认为与气候变化相比，以土地利用变化为主的人类活动对农业干旱和水文干旱的历时和强度贡献相对较大，是农业干旱和水文干旱的重要影响因素。

1.3.2　水资源开发利用

代萌[40]发现，春秋季人类用水显著增加是渭河流域部分地区 1960—2010 年干旱传播时间由长变短的驱动力之一。Xu 等[41]探讨了滦河流域气象、水文干旱传播特征并发现：由于不断变化的环境和上游地区的农业活动，干旱传播时间在 12 月至次年 6 月，从 4~9 个月延长到 5~12 个月；而在下游地区，10 月至次年 4 月的干旱传播时间，则缩短了 1~2 个月。他们认为这可能是由于生活供水量的增加和城市扩建造成的。Ma 等[42]发现黑河流域干旱传播的时间变化具有显著的季节特征，在夏季和初秋时节传播时间较短，他们认为这与人类活动(如灌溉和水库)有关。

吴杰峰等[43-44]基于晋江流域两个水文站数据及流域的气象数据，探讨了气象干旱向水文干旱的传播，发现因有水库蓄洪补枯的存在，与未受水库影响的站点相比，流域下游受到影响的石砻站水文干旱历时缩短、烈度降低，相应地改变了水文干旱对气象干旱的响应关系及其临界条件，使得气象干旱演进为水文干旱的临界条件降低。Wang 等[45]以滦河流域为例，发现在水库的影响下，干旱传播的频率降低，但由气象干旱演变的水文干旱的平均持续时间、平均亏缺量均有明显的增加，干旱传播时间平均值、中值和最小值变短。

Wang 等[46]探讨了淮河流域 16 个子流域的农田灌溉对水文干旱传播的影响。他们对农田灌溉、地形指数(TI)与水文干旱进行偏相关分析，发现灌

溉对水文旱情的影响小于流域特征的影响。Li 等[47]设置情景 1（地下水埋深 19.4 m，不灌溉）、情景 2（地下水埋深 2 m，不灌溉）和情景 3（地下水埋深 19.4 m，灌溉），基于 SPEI 和土壤水分亏缺指数（SWDI）研究了河北省石津灌区灌溉和地下水位变化对干旱发展和蔓延的影响，发现在情景 1 下，农业干旱响应对气象干旱持续时间和强度的临界值分别为 4.9 和 0.9；在情景 2 下，临界值增加到 5.1 和 2.0。这表明当地下水位上升到适当的位置时，气象干旱向农业干旱的传播将减缓。

2　干旱传播部分热点与难点问题

关于干旱传播的展望及未来的研究挑战，已有一些文章[48-49]进行了各具特色的阐述 。此处结合国内外干旱传播研究的热点与难点问题，有重点地进行述评。

2.1　多源数据多模型融合研究

开发与集成更长期、更可靠的一系列干旱数据，并定量评估数据的不确定性。在现有干旱传播研究中，大多选择单一资料，未来宜将站点观测数据、再分析资料、遥感卫星数据和水文模型模拟数据等进行综合运用或融合，并进行对比分析，以提高干旱监测、预测的准确度。在目前相对独立与离散的气候模式、水文模型运用基础上，探索与推进气候水文模型耦合的集成，提升模拟精度与时效性。

2.2　干旱传播三维建模研究

干旱传播不仅是不同干旱类型间的单向度传播，三维空间维度上的干旱传播时空一体化研究还需要进一步深入。可以从传播方向、距离和影响范围等方面展开，结合时空维度更完整地刻画与探析干旱传播过程及规律。可针对不同气候区探究干旱传播的空间表达与量化，构建不同干旱类型形成与发展的路径与干旱演变的时空格局。可利用虚拟现实技术、人工智能和大数据技术等实现干旱传播过程可视化。

2.3　干旱传播驱动机理研究

干旱传播受到气候变化、下垫面特征及人类活动的影响，各个因素都对干旱传播造成直接或间接的影响，有关因子之间也存在反馈作用。它们之间的相互作用给干旱传播研究带来了更多的不确定性，干旱传播的影响与驱动因子及其贡献还需要深入研究。对社会经济影响明显的骤发干旱，其干旱传播过程尤其值得注意[50-51]。干旱传播的干旱传播特征及影响机制的揭示，可以促进气象干旱、农业干旱和水文干旱预警预报系统的开发与完善，有助于减缓干旱对农业及社会经济产生的不利影响。

2.4　干旱灾害链条延伸研究

干旱传播具有一定的滞后性，气象干旱发生后，需要一定的时间才能传播为更严重的农业、水文干旱，并对生态环境和人类生活造成威胁。因此，应当注重干旱灾害链的全过程研究，特别是加强干旱传播对生态系统与人居环境影响的研究。此外，干旱灾害链的研究需借鉴其他灾害链领域的研究方法，在学科交叉的基础上进一步探索与揭示干旱传播灾害链的本质规律。

3　结 论

本文根据气候因素、下垫面因素和人类活动因素 3 个方面，系统地回顾了控制与影响干旱传播的有关因素的研究文献。将气候因素分成降水、气温、风向和大气环流，将下垫面因素分成地质与地貌、植被与土壤，将人类活动因素分成土地利用与变化、水资源开发利用，在条分缕析的同时，指出气象及下垫面因素在不同地点、时间及季节对干旱传播过程可能会呈现出明显的差异性影响。对干旱传播影响因素的进一步研究有助于探析干旱传播的孕育机理及揭示其演变规律。

此外，就干旱传播研究中有待深入的若干重要方面——多源数据融合、多种模型融合、三维干旱传播建模及灾害链条延伸等在干旱传播领域的应用前景，进行了展望。

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• 译文 •

Progress and prospects in drought propagation research part II: Influencing factors and research prospects

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Abstract: Regarding the three factors that affect drought propagation, climate factors are divided into precipitation, temperature, wind direction, and atmospheric circulation. Underlying surface factors are divided into geology and landforms, vegetation, and soil、Human activity factors are divided into land use and change and water resource development and utilization. A systematic review is conducted on the relevant factors that control and affect drought propagation and their change in different countries and regions. It is particularly pointed out that climate and underlying surface factors may exhibit significant differences in the impact of drought propagation processes at different locations and time. The in-depth investigation of the drought propagation process and its influencing factors and mechanism can help to promote the level of drought monitoring and early warning and reduce the negative impacts of drought disasters on the economy, society, and ecological environment. Furthermore, prospects are made for the integration of multi-source data and multiple models, three-dimensional drought propagation processes, drought propagation driving mechanisms, and extension of the drought disaster chain.

Key words: drought propagation; influencing factor; progress; prospect

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Drought is one of the most widespread natural disasters that profoundly affect human society. Due to their high frequency, long duration, and wide impact range, droughts are highly hazardous and significantly constrain sustainable socioeconomic development [1]. Droughts consist of four types (meteorological, agricultural, hydrological, and socioeconomic droughts) that are interconnected by water and energy. The process of water deficit signal transfer between different types of droughts, referred to as drought propagation, has garnered extensive attention both domestically and internationally in recent years and has been subject to in-depth research. Among the different types of droughts, a complex evolution pattern of droughts can be formed, driven by abnormal atmospheric elements, linked by hydrological anomalies, conditioned by lithosphere differences, and influenced by the biosphere [2].

This paper is the second part of a two-part series. The first part, *Progress and prospects in drought propagation research part* I, introduces the research progress of drought propagation from its definition, characteristics, types, and research methods [3]. Building upon the first part, this paper summarizes the influencing factors of drought propagation and the hotspots and challenges in drought propagation research. It also identifies the main problems in existing research and outlines future research trends.

1 Influencing factors of drought propagation

Drought propagation is mainly controlled and influenced by three factors: climate, underlying surface (land surface), and human activities. These three factors interact to affect the timing, frequency, and severity of

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Author's brief: ZHI Xiefei (1965–), male, native of Yancheng, Jiangsu, professor, Ph.D., mainly engaged in numerical weather forecasting and short-term climate prediction research. E-mail: zhi@nuist.edu.cn drought propagation. The climate is a key and primary controlling factor in drought propagation. For example, precipitation deficits lead to meteorological drought, which, through the nonlinear cumulative characteristics of water cycle processes and drought response time, further develops into agricultural and hydrological droughts [4–5]. The underlying surface and catchment surface characteristics, such as altitude, slope, land cover, and aquifer conditions, play important roles in the response of agricultural and hydrological droughts to meteorological droughts. Furthermore, human activities influence the water cycle through land use changes and water resource development, thus affecting the process of drought propagation.

1.1 Climate factors

The climate is closely related to hydrology. The renowned Russian climatologist Voeikov proposed in his book *Global Climate and Russian Climate* in 1884 that "rivers are the product of climate", emphasizing the crucial role of climate in hydrology and river formation [6–7]. Drought propagation is closely related to anomalous changes in meteorological and hydrological variables [8]. Various meteorological and climatic factors usually interact to influence the process of drought propagation, such as rising temperatures, increased radiation, decreased relative humidity, and increased potential evapotranspiration [9–10]. The following sections focus on precipitation, temperature, wind direction, and atmospheric circulation.

1.1.1 Precipitation

Ma et al. [11] found that in the Weihe River basin, spring precipitation has the greatest impact on the propagation time of drought, showing a significant negative correlation and exceeding a 99% confidence level. Zhu et al. [12] analyzed the causes of droughts in Henan Province, revealing that the frequent droughts in the province were mainly due to extremely uneven rainfall distribution throughout the year. Lin et al. [13] studied the characteristics of meteorological and hydrological drought propagation in the Xijiang River basin in south China from 1961 to 2013 using the SPI index and the SRI index. The results indicated that the spatial and temporal patterns of meteorological drought were the key factors triggering drought propagation, with the impact of meteorological drought area, severity, duration, spatial concentration, and duration increasing in order.

1.1.2 Temperature

Liu et al. [1], using the Loess Plateau as an example, found that the propagation rate of drought was related to temperature, evaporation, and soil moisture. Dai et al. [14] discovered that in the Weihe River basin, the impact of rising temperatures, reduced precipitation, and decreased soil moisture on drought propagation was significant, while the influence of irrigation water was relatively small. Xie et al. [15] found that a 1°C increase in the global average temperature led to a 5%–20 % increase in drought severity in northeast China. Yang et al. [16] conducted a diagnostic analysis of the severe drought event in Ningxia form 2004 to 2005, indicating that reduced rainfall and higher temperatures were the main causes of the drought.

1.1.3 Wind direction

Regarding the relationship between wind direction and drought propagation characteristics, Herrera-Estrada et al. [17] used North American reanalysis data from 1980 to 2016 to establish a moisture tracking model to explore the reasons for reduced water vapor transport during drought propagation. They found that agricultural drought was related to reduced water vapor transport from upwind land. Schumacher et al. [18–19], using the Lagrangian method, studied the impact of soil moisture drought on downwind precipitation for the 40 most severe global drought cases. They discovered that the impact of drought in eastern Russia on downwind water vapor was negligible, while the impact of drought in North America and western Russia was relatively small, and the impact of drought in South Africa and Australia was significant.

1.1.4 Atmospheric circulation

Drought events are closely related to anomalous atmospheric circulation [20], and the impact of atmospheric circulation on drought propagation mainly occurs through its influence on precipitation and evapotranspiration [5, 21]. Gibson et al. [22], using long-term observation records of rainfall (1908–2015) and streamflow (1901–2014) in two agricultural watersheds in eastern Australia, studied the propagation of drought in the region. They found that the onset and propagation of drought were closely related to the combined state of large-scale ocean-atmosphere climate drivers (such as El Niño-Southern Oscillation, Indian Ocean Dipole, and Southern Hemisphere Annular Mode), while the termination of drought was caused by persistent weather systems (such as low-pressure troughs). Han et al. [23], using the Pearl River basin as an example, found that the Pacific Decadal Oscillation was the main factor accelerating drought propagation. Zhou et al. [24] found that besides the Pacific Decadal Oscillation, the El Niño-Southern Oscillation was also an important factor influencing the propagation time of drought in the Pearl River basin due to its close relationship with evapotranspiration. Ma et al. [25] found that teleconnection factors had a significant impact on the autumn drought propagation in the Weihe River basin. Among them, the Arctic Oscillation, El Niño-Southern Oscillation, and Pacific Decadal Oscillation indirectly changed the drought propagation process in the Weihe River basin by affecting variables such as precipitation and soil moisture.

1.2 Underlying surface factors

Due to the differences in underlying surface factors, meteorological drought may transform into varying degrees of agricultural and hydrological drought. Geomorphological conditions such as altitude, slope, watershed area, vegetation, soil, rock types, and groundwater in the catchment area all have an impact on drought propagation. Meteorological and underlying surface factors also exhibit variability in their influence at different locations, time, and seasons. For instance, Ma [11] studied the factors influencing drought propagation in the Weihe River basin and found that in spring and summer, meteorological factors played a dominant role in the dependence between meteorological drought and hydrological drought. In autumn, both meteorological and underlying surface characteristics were significant, while in winter, teleconnection factors and watershed underlying surface characteristics were the main drivers. Thus, we can summarize the impact of underlying surface factors on drought propagation into two aspects: geological and geomorphological factors and vegetation and soil factors.

1.2.1 Geological and geomorphological factors

Veettil et al. [26] found that watershed area and altitude significantly influenced the average duration of hydrological drought in the Savannah River basin in the United States. Yang et al. [27] used the Longchuan River basin in southwest China as an example and identified altitude as an important factor affecting drought propagation. Agricultural drought propagated towards hydrological drought in high-altitude regions, but the opposite occurred in low-altitude areas. Apurv et al. [28] distinguished three drought propagation mechanisms, which led to different hydrological drought characteristics: the first mechanism involved seasonal groundwater replenishment cycles, which existed continuously during periods of low precipitation, resulting in shorter hydrological drought compared to meteorological drought; the second mechanism was the inhibition of seasonal groundwater replenishment during low precipitation periods, leading to longer hydrological drought compared to meteorological drought, and the third mechanism was the lack of seasonal groundwater replenishment, resulting in hydrological drought durations similar to those of meteorological drought. In the study of drought lag, the influence of regional underlying surface conditions on drought lag has become a hot topic in current drought propagation research [29]. For example, in the karst regions of southern China, hydrological drought can occur even in the presence of abundant precipitation due to their unique geomorphological characteristics. Zhang et al. [30] studied the Guizhou Province’s middle reaches of water conservancy projects and found that the degree of impact of various underlying surface conditions on the drought propagation process was in the following order: surface cutting depth > karst development intensity > altitude > topography and geomorphology. Among them, drought propagation characteristics showed a significant negative correlation with surface cutting depth and positive correlations with karst development intensity, altitude, and topography and geomorphology.

1.2.2　Vegetation and soil

Vegetation influences evapotranspiration by intercepting rainfall and plant leaf transpiration, thereby affecting drought propagation. Vicente-Serrano et al. [31], while studying the response of vegetation to drought, found that due to the adaptive characteristics of vegetation, different biomes responded to drought at different temporal scales. Peña-Angulo et al. [32] found that the increase in the duration, severity, and frequency of hydrological drought in the upstream of the Spanish basin from 1961 to 2013 might be related to the increase in forest area and forest density. Wu et al. [33] discovered that forests and grasslands significantly altered the drought propagation time in the Loess Plateau, with areas of extensive forest cover experiencing longer drought propagation time, while grasslands showed shorter drought propagation time. Ding et al. [34] investigated the influence and propagation time of drought on vegetation using solar-induced chlorophyll fluorescence (SIF) and normalized difference vegetation index (NDVI). They found that SIF and NDVI generally exhibited high consistency in China, with the normalized values of NDVI at different vegetation types higher than those of SIF. Drought generally had a negative impact on vegetation in northern China but a positive impact on southern China. The drought propagation time based on NDVI was longer than that based on SIF. Warter et al. [35] observed that from coastal regions with clay loam to inland regions with loam, the drought condition of southern California grassland exhibited a pronounced seasonal time pattern during autumn, which was below the vegetation stress threshold. This phenomenon was attributed to differences in soil water retention capacity and aridity. Moreover, it was noted that the soil saturation rate in inland areas was below the specified threshold in over half (64%) of the simulated time, while this proportion was approximately 47% in coastal regions.

1.3　Human activity factors

Human activities can significantly influence drought propagation through various means, such as land use changes, urbanization, deforestation, and water resource management practices [36]. The intensity of human activities can cause changes in the composition of the atmosphere, primarily through greenhouse gas emissions, leading to alterations in global or regional water cycle processes. These changes can indirectly affect the formation and development of meteorological droughts. Moreover, human activities can directly impact the transfer process from meteorological to hydrological droughts by altering the storage status and hydraulic connections of rivers through water reservoirs, diversion, extraction, and water management projects [37]. Below, we will provide a summary and introduction of the impact of land use and water resource development on drought propagation.

1.3.1　Land use and changes

Veettil et al. [26] pointed out that land use plays a significant role in controlling hydrological drought in watersheds. For example, pastures increase evapotranspiration and reduce water yield. Li[38] quantified the driving attribution contributions to meteorological, agricultural, and hydrological droughts and found that the relative impact contribution of atmospheric circulation anomalies and land use changes to meteorological drought was approximately 95% and 5%, respectively. The relative impact contribution of climate and land use changes to agricultural drought was about 75% and 25%, respectively, while water resources development and utilization, climate change, and land use changes had relative impact contributions to the hydrological drought of approximately 50%, 30%, and 20%, respectively. Yang [39] evaluated the impacts of climate and land use on typical watershed drought in the black soil region and concluded that compared to climate change, human activities mainly driven by land use changes had a relatively greater impact on the duration and intensity of agricultural and hydrological droughts and were essential influencing factors for these types of droughts.

1.3.2　Water resources development and utilization

Dai [40] found that significant increases in human water consumption during spring and autumn were one of the driving forces for shortening drought propagation time in some areas of the Weihe River basin from 1960 to 2010. Xu et al. [41] studied the characteristics of meteorological and hydrological drought propagation in the Luanhe River basin and found that due to changing environmental conditions and agricultural activities in the upstream area, the drought propagation time from December to June increased from 4-9 months to 5-12 months. In contrast, in the downstream area, the drought propagation time from October to April was shortened by 1-2 months. This change was attributed to increased domestic water supply and urban expansion. Ma et al. [42] found that the time variation of drought propagation in the Heihe River basin exhibited significant seasonal characteristics, with shorter propagation time in summer and early autumn. They attributed this to human activities such as irrigation and reservoirs.

Wu et al. [43– 44], based on data from two hydrological stations in the Jinjiang River basin and meteorological data of the basin, investigated the propagation of meteorological drought to hydrological drought. They found that the presence of reservoir flood regulation significantly reduced the hydrological drought duration and intensity at the Shilong station downstream, which was influenced by the reservoir, and consequently altered the response relationship and critical conditions between hydrological drought and meteorological drought. This led to a decrease in the critical condition for meteorological drought evolving into hydrological drought. Wang et al. [45], using the Luanhe River basin as an example, found that under the influence of reservoirs, the frequency of drought propagation decreased, but the average duration and deficit of hydrological drought evolved from meteorological drought increased significantly. The average, median, and minimum values of drought propagation time became shorter.

Wang et al. [46] investigated the impact of farmland irrigation on the propagation of hydrological drought in 16 sub-basins of the Huaihe River basin. They performed a partial correlation analysis between farmland irrigation, topographic index (TI), and hydrological drought and found that irrigation had a smaller impact on hydrological drought than the basin characteristics. Li et al. [47] designed three scenarios (Scenario 1: groundwater depth of 19.4 m, no irrigation; Scenario 2: groundwater depth of 2 m, no irrigation; Scenario 3: groundwater depth of 19.4 m, irrigation) and studied the impact of irrigation and changes in groundwater level in the Shijun irrigation district of Hebei Province on the development and spread of drought based on the standardized precipitation evapotranspiration index (SPEI) and the soil water deficit index (SWDI). They found that: under Scenario 1, the critical values for the response of agricultural drought to the duration and intensity of meteorological drought were 4.9 and 0.9, respectively; under Scenario 2, these critical values increased to 5.1 and 2.0. This indicated that when the groundwater level rose to an appropriate position, the propagation of meteorological drought to agricultural drought would slow down.

2 Hotspots and challenges in drought propagation research

Looking into the future and the challenges in drought propagation research, several articles have provided unique insights [48–49]. Here, we will focus on the hotspots and challenges in drought propagation research, considering both Chinese and international studies.

2.1 Multi-source data and multi-model integration research

Developing and integrating a longer-term and more reliable series of drought data and quantitatively assessing data uncertainties are essential. In current drought propagation research, most studies tend to use a single data source. However, in the future, it is necessary to comprehensively utilize or fuse station observation data, reanalysis data, remote sensing satellite data, and hydrological model simulation data for comparative analysis, to enhance the accuracy of drought monitoring and prediction. Additionally, exploring and promoting the integration of climate-hydrological models based on the existing relatively independent and discrete climate and hydrological models can improve simulation accuracy and timeliness.

2.2 Three-dimensional modeling of drought propagation

Drought propagation is not simply a one-dimensional transfer between different types of droughts. There is a need for further in-depth research on the three-dimensional spatiotemporal integration of drought propagation. This research can be conducted from various aspects, such as the propagation direction, distance, and impact range and incorporate the temporal and spatial dimensions to provide a more complete depiction and analysis of the process and rules of drought propagation. For different climatic regions, exploring the spatial expression and quantification of drought propagation and constructing the spatial-temporal patterns of different drought types' formation and evolution can be helpful. Virtual reality technology, artificial intelligence, and big data can be used to achieve the visualization of the drought propagation process.

2.3 Research on the driving mechanism of drought propagation

Drought propagation is influenced by climate change, underlying surface characteristics, and human activities. These factors have both direct and indirect effects on drought propagation, and there are feedback mechanisms between these factors. The interactions among them introduce more uncertainties into drought propagation research, and further research is needed to understand the impact and contribution of driving factors to drought propagation. For sudden-onset droughts that have significant socio-economic impacts, their propagation process deserves special attention [50-51]. Revealing the characteristics and mechanisms of drought propagation can promote the development and improvement of meteorological, agricultural, and hydrological drought early warning and forecasting systems, helping to mitigate the adverse effects of drought on agriculture and socio-economic conditions.

2.4 Extension of the drought disaster chain

As drought propagation has a certain lag, after a meteorological drought occurs, it takes some time to propagate into more severe agricultural and hydrological droughts, posing threats to ecosystems and human habitation. Therefore, attention should be paid to the full-process study of the drought disaster chain, particularly focusing on the impact of drought propagation on ecosystems and human living environments. Moreover, research on the drought disaster chain should draw on methods from other disaster chain domains and further explore and reveal the essential laws of drought propagation in the context of interdisciplinary research.

3 Conclusion

This paper systematically reviews the literature on the controlling and influencing factors of drought propagation in terms of climate factors, underlying surface factors, and human activity factors. It categorizes climate factors into precipitation, temperature, wind direction, and atmospheric circulation, underlying surface factors into geological and geomorphological, vegetation, and soil, and human activity factors into land use and changes and water resources development and utilization. While analyzing these factors, it is pointed out that climate and underlying surface factors may show significant spatial and seasonal differences in their impact on drought propagation in different locations and time. Further research on the influencing factors of drought propagation is helpful for understanding the incubation mechanism and revealing the evolution laws of drought propagation.

Additionally, several important aspects that require further exploration in drought propagation research, such as multi-source data fusion, multi-model integration, three-dimensional modeling of drought propagation, and extension of the drought disaster chain, have been discussed with prospects for their application in the field of drought propagation.

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