第 21 卷 第 4 期　南水北调与水利科技（中英文）　Vol. 21 No. 4
2023 年 8 月　South-to-North Water Transfers and Water Science & Technology　Aug. 2023

智协飞，田云涛，陈昌春，等. 干旱传播研究进展与展望Ⅰ：干旱传播含义、特征、类型与研究方法[J]. 南水北调与水利科技（中英文），2023，21（4）：625-653. ZHI X F，TIAN Y T，CHEN C C，et al. Drought propagation：Progress and prospect Ⅰ：The meaning，characteristics，types，and research methods of drought propagation[J]. South-to-North Water Transfers and Water Science & Technology，2023，21（4）：625-653.（in Chinese）

干旱传播研究进展与展望Ⅰ

——干旱传播含义、特征、类型与研究方法

智协飞[1,2]，田云涛[1,2]，陈昌春[3]，张余庆[4]

（1. 南京信息工程大学 气象灾害预报预警与评估协同创新中心/气象灾害教育部重点实验室，南京 210044；
2. 天气在线气象应用研究所，江苏 无锡 214000；3. 南京信息工程大学 地理科学学院，南京 210044；
4. 淮阴师范学院 城市与环境学院，江苏 淮安 223000）

摘要：在回顾干旱传播概念和内涵的基础上，明确提出干旱传播全环节的详细定义，阐述干旱传播的累积、衰减、滞后及延长特征，并重点就累积性与滞后性提炼了有关进展。按干旱传播环节、干旱传播时空特征两种方法划分干旱传播的类型，从线性回归、对数函数、小波分析、Copula 函数、因果分析、贝叶斯网络和随机森林 7 个方面、从单一水文模型模拟和多个模型集合模拟两大方面，分别归纳统计方法、水文模拟方法在干旱传播研究领域的应用。

关键词：干旱传播；定义；特征；类型；方法；进展

中图分类号：P343　　**文献标志码：**A　　**DOI：**10.13476/j.cnki.nsbdqk.2023.0064

干旱，由于世界各地水文气象变量和社会经济因素的差异，以及水需求的随机性，迄今尚无公认且精确的定义[1]。1992 年，世界气象组织将干旱定义为“长期缺乏或明显缺乏降水”或“一段异常干燥的天气，其持续时间足以导致降水不足，从而导致严重的水文失衡”[2]。1994 年，《联合国防治干旱和荒漠化公约》[3-4]称：“‘干旱’是指当降水量显著低于正常记录水平时出现的自然现象，造成严重的水文失衡，对土地资源生产系统产生不利影响”。干旱一般分为 4 种类型：气象干旱、农业干旱、水文干旱和社会经济干旱[5]。其中：气象干旱主要是长期降水短缺导致的干旱；水文干旱表现为径流减少以及地下水位下降；农业干旱一般指土壤含水量长期不足导致作物减产甚至死亡；社会经济干旱表现为上述 3 种干旱类型对社会与经济造成严重影响（如生活用水、农业用水和工业用水等）。

气象干旱的发生与存在会导致水资源缺乏，相应地对生态、农业生产和社会经济发展等造成明显的影响。例如，2022 年 7 月至 11 月上半月，长江流域降水异常偏少、极端高温天气持续，中旱以上日数为 77 天，为有完整实测资料以来最严重的气象水文干旱，极端高温干旱对相关地区农业生产、人畜饮水、电力供应、生态环境等造成严重影响。旱情峰值时，四川、重庆、湖北、湖南、江西等 12 省（自治区、直辖市）3 978 万人受灾，701.4 万人因旱情需生活救助，农作物受灾面积 427 万 hm^2，直接经济损失 408.5 亿元[6]。

近年来，研究不同类型干旱之间的传递过程及特征的新概念——干旱传播，受到了国内外学者的注意，并取得了不少成果。简单来说，干旱传播主要指从气象干旱到农业干旱以及水文干旱间的传播过程。干旱传播已逐渐成为国内外干旱领域的前沿和热点之一[7-8]。干旱传播研究尚处于一个起步探索阶段，其理论基础与研究方法还有待完善。比如干旱传播概念界定不够全面及特征描述不清、研究思路与框架单一、干旱传播机制与规律仍不清

收稿日期：2022-05-10　　**修回日期：**2023-05-10　　**网络出版时间：**2023-07-10
网络出版地址：https://link.cnki.net/urlid/13.1430.tv.20230707.1602.004
基金项目：国家重点研发计划重点专项项目（2017YFC1502000）
作者简介：智协飞（1965—），男，江苏盐城人，教授，博士，主要从事数值天气预报、短期气候预测研究。E-mail：zhi@nuist.edu.cn

楚等诸多方面[9]。在气候变暖的背景下，我国干旱发生频次、持续时间和严重程度等指标呈明显增加趋势[10-11]。因此，明确干旱传播概念、探究干旱传播过程及特征、提炼与归纳干旱传播研究方法，有助于深入理解干旱传播机制，从而可为强化旱情监测预报、提高综合抗旱能力、改善水资源管理等提供理论依据[12-13]。

1　干旱传播的由来、含义、特征及类型

1.1　干旱传播的由来

1999 年，美国麻省理工学院的 Eltahir 等[14] 最早将“传播(propagation)”一词及动态的“droughts propagate”用于表述气象干旱演变为水文干旱的过程，以刻画长期降水短缺造成水循环异常，及其导致土壤含水量降低和地下水位下降的现象[15-16]。2001 年，Marani 等[17] 提及了“droughts that propagate”。2001 年，Stahl[18] 绘制了“水文循环中‘干旱的传播’(propagation of drought)流程图”。2003 年，Peters 等[19-20] 使用“干旱的传播”研究了干旱从地下水补给到排泄的传播以及含水层特征对干旱的影响、干旱在半干旱和亚湿润气候条件下的地下水传播。2003 年底，Peters[21] 首次明确提出“drought propagation(干旱传播)”这一表述，并对英国 Pang 流域与西班牙 Upper-Guadiana 流域的地下水干旱传播做了系统的研究[22]。她一并指出，已有地下水干旱传播研究中“Eltahir 等的 1999 年论文是最有价值的”。2006 年，Van Lanen[23] 采用“干旱传播”作为标题，探讨水循环过程中的干旱传播，研究了不同气候区(西班牙和荷兰)的地下水补给对干旱传播的影响。

1.2　干旱传播的含义

干旱传播，大体可以理解为异常气象、水文特征等，渐次传播导致不同类型干旱传递或传播的过程。与“传播”字面上比较直白与容易理解有关，不少研究中直接使用，一般未显性地强调明确的“干旱传播”定义。然而，其实际且主要的含义从产生到后来基本上是稳定的，即 Eltahir 等的 1999 年文章中所指的气象干旱演变为农业干旱(一般以土壤水分表征)及水文干旱的传递过程[14, 24] 或简化形式“气象干旱到水文干旱”[25]。Peters 针对“干旱”缺少确切而普遍的定义[1]，2003 年在其博士论文中特别用了一个小节“4.2 Definition of drought events”进行界定[21]，但未提及“干旱传播”的定义问题。总之，上述早期研究中缺乏“干旱传播”的专门与明确的定义。

后来一些近似定义的显性概括或表述，包括 2010 年 Tallaksen 等[26] 用括号备注的“气象干旱到水文干旱”、2012 年 Van Loon 等[27] 使用“所谓的干旱传播(气象干旱到水文干旱)”、2017 年 Apurv 等[28] 的转述性概括“气象干旱到水文干旱的转化”等。可视为接近明确定义的表述，是 2013 年 Van Loon[16] 归纳已有研究并指出的“干旱传播表示干旱信号在水文循环的陆地部分转移时的变化”以及他自己对干旱传播一语的严格限定——“异常气象条件向水文干旱的转换”。Li 等[29] 把 Van Loon 的观点转述为“干旱传播是指在整个水文循环的陆地部分，干旱信号从异常气象条件向水文干旱的变化。”2018 年，Wu 等[30] 基于“气象干旱至水文干旱”对干旱传播所涉及的历时、量级和峰值强度等具体指标进行了定义。2020 年，Bhardwaj 等[31] 称“干旱传播是指干旱期(水分)缺乏的加强及期末的恢复”。2022 年，有综述文章[32] 称“通过相互关联的陆地水文循环(即土壤、地表水和地下水系统)，异常水文气候变量得以发展(如降水不足、大气蒸发需求(AED)增强或蒸散增加)的概念通常被称为干旱传播”，并指出干旱传播也表示干旱信号在水和能量循环的多个过程中的转换。2022 年，Fuentes[33] 粗略地称“干旱传播可以定义为不同子系统中干旱反应的延迟”。

鉴于“干旱传播”迄今比较缺少明确且面向全环节的直接“定义”，为便于国内外学术交流，本文作者建议在“干旱传播是指在整个水文循环的陆地部分中，干旱信号从异常气象条件向水文干旱的变化”等的基础上，将干旱传播定义为“干旱传播是指在整个水文循环的陆地部分，干旱信号从异常气象条件向农业干旱(含土壤水分干旱)、水文干旱、生态干旱、社会经济干旱等的转移与传播。”

干旱传播在中文文献中也被译作“干旱传递”[34-37]，含义与“干旱传播”相同，只是“干旱传播”当前更为通用。有文章[38] 将“drought transmission”作为“干旱传播”的同义语使用，或使用“transmission”(此词在英文中有“传输、传递”之意)表示“(干旱)传播”[39-40]。“干旱传播”与水文学研究中常用的“水文响应”在含义上有同有异。“水文响应”一般指地理环境变化引起的水文变化或水文响应[41-43]，不局限于以气象干旱作为自变量。其中研究气象干旱的水文响应的著述，多与干旱传播有关。

关于“drought propagation”当前并存的两种汉译——“干旱传播”与“干旱传递”，结合《全球变化

背景下多尺度干旱过程及预测研究进展》等文[44-45]作者的表述及相关文献等，笔者征求了干旱传播研究者王文、黄生志、吴杰峰等的意见，共同认为“干旱传递”比“干旱传播”更适合表达不同类型干旱在时间上前后环节的转移与传递过程。相比之下，“干旱传播”更适合用于表达同一干旱类型在空间上的迁移与扩散过程，比如气象干旱、水文干旱各自在空间的传播。为保持行文风格的一致，本文主要使用“干旱传播”对中外干旱传播、干旱传递研究成果一并进行回顾与展望。

1.3　干旱传播的特征

从现有文献及研究[9,12,27]看，干旱传播主要包括以下 4 个特征：

累积。多次气象干旱累积发展成持续时间更长的农业、水文干旱。

衰减。在气象干旱初期，流域水储量较大时会对农业、水文干旱的发展有一定的抑制作用。

滞后。不同类型干旱之间的传播存在时间上的滞后。

延长。气象干旱传播为持续时间更长的农业、水文干旱。

累积和延长往往受到气候因素和地表因素的共同控制；滞后和衰减主要受地表及流域因素，如水文调节作用等的控制。下面就累积性与滞后性两项的研究情况举一些例子。

关于累积性，Sattar 等[46]用干旱传播响应率来衡量水文干旱对气象干旱的响应程度，用一定时间内水文干旱事件数量与气象干旱数量的比值来表示。Guo 等[47]考虑到多个气象干旱传播为一个水文干旱的可能，提出了一种“修正干旱传播率”（触发水文干旱的气象干旱次数与气象干旱总次数的比值），认为比值越大，证明农业、水文干旱对于气象干旱的响应越强。

关于滞后性，主要集中于对滞后时间的研究，包括气象干旱和农业、水文干旱之间不同时段或者不同阶段（如发生、发展、持续、峰值和结束）之间的滞后时间[32,48-49]。滞后时间可以通过不同类型不同时间尺度干旱表征量（如气象、农业和水文变量序列或相关的干旱指数）的相关性得出[50-51]，或是借助游程理论识别不同类型的干旱事件，将所识别的不同类型干旱事件进行对应和匹配，得出相应的滞后时间[52]。滞后时间越短，表明干旱传播的响应速度越快。对于特定干旱传播类型（如气象干旱传播至水文干旱）可以通过相应干旱类型的频次、持续时间和严重程度等进行综合表征[53]。

1.4　干旱传播的类型

干旱传播的类型可以根据不同指标进行分类，比如按传播环节和按传播时空特征等分类。

1.4.1　按干旱传播环节分类

干旱传播的环节，现有研究文章多为“气象干旱到农业干旱的传播”与“气象干旱到水文干旱的传播”。《气候变化下的干旱传播综述研究：特征、方法、过程、控制因素》[32]分为“至农业干旱的传播、至水文干旱的传播、至环境干旱的传播”。张强等[45]指出，在大气降水累计亏缺的前提下就必然会出现气象干旱，然后会经历气象干旱→农业干旱→水文干旱→生态干旱→社会经济干旱这样一个链条式传递过程，农业干旱、水文干旱、生态干旱和社会经济干旱的内部发展进程中也存在明显的传递过程。本文试按全环节归纳为以下 4 类：

至农业干旱（土壤干旱）的传播。此项指气象干旱传播至农业干旱（土壤干旱）。农业干旱往往用土壤水分亏损或干旱表征，可视作狭义的农业干旱。土壤水分之外表征农业干旱的叶片特征与作物长势、产量等的农业干旱表现，可视作广义的农业干旱，或可归入“生态干旱”范畴，比如，安雪丽等[54]就“土壤相对湿度（RSM）与标准化植被指数（SVI）、站点农气灾情数据及产量数据的关系，探究了土壤相对湿度对东北地区农业干旱的监测能力”，其中的有关指标均可视作农业干旱的范畴。

至水文干旱的传播。此项指气象干旱传播至水文干旱。它可细分为：至地表径流的传播；至地下水的传播。

至生态干旱的传播。此项指气象干旱经农业干旱或水文干旱传播到生态干旱。生态干旱，亦有学者称为“环境干旱”。Crausbay 等[55-56]认为，为了应对 21 世纪的干旱风险，需要定义新的干旱类型，将生态干旱定义为“一种间歇性的供水不足，并导致生态系统超过其脆弱性阈值，影响生态系统服务，并在自然和/或人类系统中触发反馈”。

至社会经济干旱的传播。此项指气象干旱经农业干旱或水文干旱及生态干旱传播至社会经济干旱。相比而言，经济干旱比较容易度量，社会干旱有时不易度量，细分“经济干旱、社会干旱”并进行相应的干旱传播研究是有益的，即：至经济干旱的传播；至社会干旱的传播。

1.4.2　依时空特性分类

干旱传播可以根据时间维与空间维区分为时序干旱传播、空间干旱传播。此种分类比较简略，意在强调不同类型干旱转换的时空特征。

时序干旱传播。时序干旱传播主要是基于时间轴探讨不同干旱传播类型间的转移与传播，近年来出现了大量研究成果。这也是干旱传播研究的主流领域。比如，Ho 等[57] 把“最大水文干旱区对最大气象干旱区的响应时间”作为“(干旱)时间迁移(传播时间)值，并认为次月尺度的估计值适用于对骤发干旱的详细分析。

空间干旱传播。空间干旱传播是基于空间角度(如传播方向、距离和范围等参数)由一地向另一地的传播。以空间干旱传播作为明确研究内容的成果目前较少，但在逐步增加之中[24,57-59]。值得指出的是，与时序干旱传播相比，空间干旱传播侧重表示同一类型干旱在空间的移动与传播，但也可以用于研究不同干旱类型之间的时空传递关系。

现有的空间干旱传播，主要指同类型干旱在空间上的传播，尤以气象干旱传播的研究居多。地表水干旱传播到地下水干旱，尽管同是水文干旱，但仍存在两小类(即地表水干旱、地下水干旱)在时间与空间的传播。气象干旱或水文干旱的单旱种空间传播，虽然此前不少文献并未显性地使用“干旱传播”表述，但可视作空间干旱传播的研究成果。有多篇文章使用“drought migration”表达与探讨空间范围的干旱迁移[60]。如，1999 年马宗晋等[61] 探讨了亚非地区地震和干旱向东定向迁移的机制，英文标题中使用了“migration of earthquakes and droughts”。2001 年，Hu 等[62] 在英文文章中采用“干旱迁移(drought migration)”研究了我国东部和美国西部百年尺度旱涝变化的南移。

2　干旱传播的研究方法

干旱传播的研究方法涉及诸多研究内容，包括干旱的识别、干旱指数的选取等。限于篇幅，本文对干旱指数的详情不多作介绍。

关于干旱传播研究方法的分类，Zhang 等[32] 分为统计方法、水文模型，并将统计方法再分为相关性分析、游程理论、响应函数。Wu 等[63] 从传播阈值计算的角度分为游程理论法、相关性分析法、非线性响应法。本文结合现有分类方法，采用统计方法和水文模拟方法两大类，将统计方法分为相关性分析、游程理论、统计模型，将水文模拟方法分为单一水文模型模拟、多个模型集合模拟，对干旱传播研究中所用方法进行归纳与介绍。

2.1　统计方法

统计方法中，包括相关性分析、游程理论、回归模型、Copula 函数、小波分析、因果分析、神经网络和随机森林及其他机器学习算法、智能算法等，在干旱传播研究中逐渐得到了比较多的应用。本小节按相关性分析、游程理论、统计模型分别归纳与介绍干旱传播研究中的主要统计方法。

2.1.1　相关性分析

相关性分析在干旱传播滞后性及传播时间上有广泛的应用。此外，相关性分析也是回归模型、小波分析等其他统计模型分析的前期工作。气象干旱至农业、水文干旱的传播及相关性分析，在当前研究中比较集中。以下就相关性分析在干旱传播领域的应用情况进行阐述：

Lorenzo-lacruz 等[64] 利用皮尔逊相关系数确定与标准化河川径流指数 (SSI) 相关性最好的标准化降水指数(SPI)的时间尺度，作为水文干旱对累积降水亏缺的响应时间。韩会明等[65] 在赣江流域气象干旱至水文干旱的传播研究中，分别计算 1~24 个月尺度的 SPEI(标准化降水蒸散指数)、SPI 与标准化径流指数(SRI)之间的 Pearson 相关系数，将 SPEI-i、SPI-i 与 SRI-1 之间相关性最强时刻作为对应的传播时间尺度 i。Zhao 等[66] 发现，我国南方湘江流域的 SPEI 和 SRI 之间有很强的相关性，2 个月尺度的 Pearson 相关性最强，旱季的相关性比雨季更强。相恺政等[50] 以海河流域为例发现气象干旱向农业干旱的传播时间存在季节性差异，夏季和秋季较短，春季和冬季较长。Zhou 等[67] 发现在珠江流域的 5 个子区域气象干旱向水文干旱传播时间为 2~6 个月。Zhang 等[68] 通过研究长江、黄河流域气象、农业、水文干旱之间的相关性，发现气象干旱与农业干旱相关性更强，夏季和秋季的气象干旱向农业干旱传播时间短于冬季和春季，长江流域的传播时间比黄河流域更长。

2.1.2　游程理论

在干旱传播研究中，干旱事件的识别往往需要先行。游程理论 (run theory) 及相关的阈值分析，在干旱的识别、判别方面具有重要作用。根据游程理论，如果某一周期干旱事件的干旱指数值低于阈值

水平，则认为游程为负游程，干旱事件发生[69-70]。具体来说，假设给定值X来截取一个随时间变化的离散系列X_t，当X_t在一个或多个时段内连续大于X时出现正游程；而当X_t连续小于X时则出现负游程。在干旱研究中，把负游程的长度称作干旱历时即干旱开始至结束时间的长度；负游程的总量称为干旱烈度，也称干旱的严重程度，即干旱历时内所有小于截断水平值的累积之和[71]。

阈值分析是旱涝灾害研究中的重要手段，也是游程理论识别干旱的关键指标。阈值法可分绝对阈值（固定阈值、恒定阈值）与相对阈值（可变阈值）。绝对阈值是指选取某一固定值作为极端事件中极值的阈值。相对阈值，当前国际上使用比较广泛的方法有两类：一是分位数法（注：多用百分位）[72]；二是基于极值理论的参数估计算法，包括广义极值分布 (GEV)、广义帕累托分布 (GPD) 等方法[73]。Heudorfer 等[74] 按恒定阈值与变量阈值两种分类法对德国不同阈值水平的干旱传播分析方法进行了比较，认为其在不同情形下各有其优缺点，需要仔细权衡。

确定阈值后，通过游程理论可以提取不同类型干旱事件的发生时间、结束时间、持续时间和强度等特征，可以确定不同类型干旱事件之间的时间差即滞后时间[57,75]。下面按绝对阈值法与相对阈值法分别归纳其在干旱传播领域中的应用：

绝对阈值法。绝对阈值是固定不变的，由于其计算简便，在干旱传播中的应用广泛。恒定阈值法更适合于在人类社会消费的水可利用性（河流或含水层）的背景下对干旱进行表征，因为无论一年中的时期或季节如何，缺水都可以定义为干旱。如 Yevjevich 等[69] 基于游程理论将帕默尔干旱指数（PDSI）小于 0 作为干旱。Wang 等[76] 设定固定阈值-1 提取了淮河流域的气象干旱（SPI）和水文干旱（SRI）事件。Wu 等[30] 选择固定阈值（TL）为 0 作为不同国家（中国、美国、德国）的水文站判定干旱事件开始或者结束的标准，当干旱指数低于（或大于）0 时，河流流量已恢复到干燥（或潮湿）状态。

相对阈值法。相对（可变）阈值是一段时间内干旱表征量基于概率分布的百分位临界值[72]，选择不同的百分位会直接影响干旱特征[12]。相对阈值法考虑了一年中不同时期或季节水的可用性，非常适合于对气象和水文干旱特征进行统计比较[28,77]。干旱序列百分位的计算，有按降水量从小到大的顺序与从大到小的逆序两种方法。所谓降水逆序百分位法，是将降水最小量（即最干旱）的数据作为 1，其他依次为 2、3 等，与一般百分位的计算方法相同。有文章[78] 对安徽省 4 个地区的降水量从大到小排序，并按保证率计算百分位，以第> 70%~≤80%、> 80%~≤90% 和> 90% 百分位降水量分别作为偏旱、旱和大旱的指标。

一般的干旱研究中，相对阈值多用降水的顺序百分位。干旱传播分析中，顺序、逆序兼而有之。有文献介绍，常用的相对阈值包括 70%、80%、90%[72,79]。如 Van Loon 等[77] 基于 80 百分位数的月阈值研究了干旱传播的季节性特征。Apurv 等[28] 称“大多数先前的研究都在干旱研究中使用了第 5 至第 30 百分位的阈值水平”，并使用每月第 25 个百分位数作为定义干旱的阈值，研究了全球不同气候区 10 个地点的气候特征在水文干旱传播中的作用。Wang 等[76] 发现淮河流域 16 个子流域气象干旱向水文干旱的传播时间为 1~47 d。Wu 等[63] 对东江流域的 3 个子流域的气象-水文干旱传播阈值进行了多时间尺度的评估，认为水文干旱的时间尺度越长，PT（propagation threshold）就越大，反之亦然。

Wang 等[80] 使用经过 GEV 拟合的 3 个月时间尺度的 SPEI 数据，指出我国从 1961 年到 2018 年干旱事件的严重程度、持续时间和频率都有明显的加剧趋势。Nadarajah[81] 使用 GPD 拟合了美国内布拉斯加州的干旱序列，认为拟合结果有一定的合理性。廖显薇[82] 基于 Copula 函数研究了松花江流域水文干旱对气象干旱的响应后认为，GEV 和 GPD 能较多地拟合流域多尺度径流序列。

2.1.3　统计模型

在相关性分析与游程分析的基础上，可通过线性和非线性方法构建回归模型等统计模型，拟合不同类型干旱表征量或干旱特征之间的关系，进而探究干旱传播的统计特点与规律。一元线性、多元线性、对数函数、小波分析、Copula 函数、贝叶斯网络、随机森林等统计方法与模型已应用于干旱传播研究。统计模型在干旱传播领域的应用，大体归纳如下：

线性回归。线性回归是干旱研究中很常用的方法。华悦[83] 通过建立水文-气象干旱特征变量间的一元线性关系函数，并将其与非线性函数进行比较，发现水文-气象及农业-气象干旱响应函数分别对于中长历时、中高强度、中等历时和强度的模拟效果更好，且非线性函数比线性函数更适合于描述其响应关系。Ma 等[84] 使用多元线性回归研究了不同季

节干旱传播的特征与关键强迫因素的联系,指出传播时间取决于相应时间尺度的 SPI 和 SRI 之间的最大相关系数。Li 等[85]为了解释滦河流域的干旱传播模式以确定可能的驱动因素,使用多元回归模型建立了农业、水文干旱与驱动因素之间的关系,并认为这些关系可以很好地解释了“①仅存在气象干旱;②气象干旱发展成农业与水文干旱;③未形成气象干旱但形成农业与水文干旱”这 3 种干旱特征或传播过程。

对数函数。吴杰峰等[86]以东南沿海晋江流域为例,以 y 为水文干旱历时或烈度,x 为气象干旱历时或烈度,发现用对数函数模型确定的气象干旱和水文干旱的响应关系是合理的。华悦[83]建立了嫩江干流下游 3 个水文站的干旱传播函数关系,指出 3 个站的气象干旱和水文干旱历时拟合效果最好的均为对数函数分布,并称与 Wu[87]的研究结果一致,但发现嫩江下游 3 个站的气象干旱和水文干旱烈度响应关系与以往的研究结果不同,更符合幂函数分布。王志霞等[88]在对喀什河流域干旱传播的研究中发现,基于三参数的对数函数模型可以很好地表征气象干旱与水文干旱的响应关系。王飞[89]以地表径流数据为基础研究了黄河流域的水文干旱演变特征,认为水文干旱历时和强度的最优边缘分布函数大多为对数逻辑分布 Log-L 和广义极值分布 GEV。

小波分析。Ding 等[90]采用小波分析方法,按气候带将中国分成 8 个亚区,对 1902 年至 2014 年气象、水文这两种类型的干旱进行了研究,结果表明,干旱环境比潮湿环境具有较弱的传播关系。这两种类型的干旱之间的关系夏季和秋季比春季和冬季更为密切。Li 等[91]应用交叉小波分析和空间自相关方法研究了长江流域农业干旱的传播过程,发现从气象干旱到水文干旱的传播速度快于农业干旱。石朋等[92]分析了黄河源区气象干旱与水文干旱的关联性后指出:交叉小波变换和小波相干分析表明,SPI-9 和 SRI-1 在不同周期尺度表现出显著的正相关关系;黄河源区气象干旱向水文干旱的传播时间为 9 月,SPI-9 序列可用于水文干旱监测。

Copula 函数。Zhu 等[93]通过基于 Copula 的概率模型,利用全球土地数据同化系统(GLDAS)模拟得出的 SPEI 和 SMI(标准化土壤水分指数)的时间序列,指出前期土壤水分条件影响干旱传播的概率,这种影响对中国北部、俄罗斯、美国中西部、加拿大和澳大利亚尤为显著。顾磊等[13]基于水文模型和 Copula 函数定量评估了我国 135 个流域水文干旱对气象干旱响应的敏感性,发现其受到气候变暖影响不大,未来北方地区气象干旱和水文干旱同时发生的概率将会小幅度增加。Xu 等[94]使用 Copula 模型对我国不同地区的传播概率进行了量化,发现气象干旱与农业干旱之间的相关性最强和最弱分别出现在夏季和冬季,而传播时间从夏季的 1 至 2 个月增加到次年春季的 2 至 7 个月。在空间上,潮湿地区的气象干旱与农业干旱之间的相关性和传播敏感性高于其他气候区。Wang 等[95]在对 1961 年至 2015 年黄河流域的水文干旱传播研究中,通过拟合具有最优分布函数的月径流数据来计算 SSI,使用具有最高拟合优度(GOF)的 Copula 函数研究干旱重现期,并认为 Frank copula 是 YRB(黄河流域) 中拟合效果最好的 Copula 函数。

因果分析。因果分析也称归因分析。Shi 等[96] 2022 年在《干旱传播的新视角:因果关系》中指出,在水文气象学领域,因果关系分析在模型模拟中蓬勃发展,但在分析观测结果时仍然很少。他们利用基于单纯观测数据的收敛交叉映射(CCM),为干旱传播(即因果关系)提供了一个新的视角。与以往研究结果相比,因果关系分析在干旱传播研究中的有效性得到了验证。尤其是在检测干旱传播方向上,因果关系分析比相关性分析更有效。Zhai 等[97]归纳指出,对于干旱这种受降水、温度、风速和土壤湿度等多种因素影响的极端气候现象来说,全球范围内干旱变化的检测和归因有着很大的不确定性。任立良等[98]对渭河流域咸阳和华县两水文站径流变化进行了归因分析,发现人类活动是引起 1991 年以来渭河流域径流量衰减的主要因素,其中社会发展和农业生产的水需求增长是引起径流下降的主要原因。

贝叶斯网络。Jehanzaib 等[99]等采用贝叶斯网络模型(BNM)计算了不同类型气象干旱至水文干旱的传播似然度。Shin 等[100]根据韩国 54 个气象站的数据等,计算 Palmer 水文干旱指数,使用包含动态贝叶斯网络开发的模型(BNDF_DP)预测干旱传播概率,认为 BNDF_DP 是一种很有前途的概率干旱预测工具。刘永强等[101]以黄土高原沁河流域为例,将贝叶斯网络的不确定性环境下的概率分析与 Copula 函数的多元干旱分析相结合,发现气象干旱到不同等级水文干旱的传播阈值随着水文干旱等级提升而增加,且在传播过程中气象干旱的强度有

所削弱。

随机森林。随机森林是一种机器学习方法，具有学习过程快速、运算速度快、稳定性好、预测精度高等优点。Jiang 等[102]指出，有 11 种机器学习的分类方法可用于干旱传播的评估，并使用混合式机器学习 Copula 方法估计了西北地区气象干旱到生态干旱的传播概率。郭佳[103]采用多项遥感指数及土壤因子作为自变量，综合气象干旱指数(CI)为目标变量，构建了基于随机森林的遥感干旱监测模型，发现模型的训练集结果与 CI 的相关系数分别达到了 0.96 以上，测试集达到了 0.74 以上。刘永佳等[104]基于气象和下垫面因子对动态传播阈值进行了随机森林回归分析，认为回归模型的模拟精度达到了较满意的结果且泛化能力较强，能够用于反映流域的气象干旱到水文干旱的传播阈值的量化评估。

2.2　水文模拟方法

水文模拟是研究干旱传播的有效工具之一，它往往可以直接或间接地表征及模拟水文循环过程中干旱传播中的物理量特征。水文模拟方法，基于水量平衡等原理，通过水文模型模拟有关变量，如产流量、土壤含水量、蒸发量等。水文模拟，根据时空尺度大小，一般可分为大尺度模拟与区域模拟。根据用于模拟的个数多少，可分为单一模型模拟与多模型集合模拟。下面从单一水文模型模拟与多模型集合模拟两个方面归纳其在干旱传播上的应用。

2.2.1　单一水文模型模拟

采用单独水文模型模拟水文循环中有关变量，这是水文学研究中常用的做法。水文模拟方法可以用于分析区域尺度的干旱传播过程[49]，如 Van Lanen[23]基于 SIMGRO 模型以西班牙和荷兰为例，发现气象干旱通过地下水系统向非饱和带的传播通常会导致程度较轻的水文干旱。现有的干旱传播研究中，用于水文模拟的模型主要有 SWAT(soil and water assessment tool)模型与 VIC(variable infiltration capacity)模型等。

SWAT 模型。李昱等[105]基于 SWAT 模型发现未来气候变化情景下，干旱在从气象到水文的传播过程中有所加剧。Veettil 等[106]基于 SWAT 水文模型和分类及回归树(CART)算法量化了气候、流域等因素对美国萨凡纳河流域水文干旱持续时间和严重程度的潜在影响。我国西北部的内陆盆地寒冷和干旱地区的水文观测往往太短或缺失，使得监测干旱变得困难，Liang 等[107]使用 SWAT 模型模拟水文变量，建立了一个多变量(气象-农业-水文)综合干旱指数(MAHDI)，发现其在表征气象干旱至农业和水文干旱的季节性滞后时间上有良好的表现。

VIC 模型。Bhardwaj 等[31]使用 VIC 模型模拟水文变量，并结合观测值，分别估计了印度 18 个主要流域的气象、农业和水文干旱间的干旱传播时间。朱烨[108]利用 VIC 模拟的结果，系统分析了黄河流域 16 个流域特性因子与水文干旱 5 个特征的相关性，发现基流指数 BFI 与水文干旱特征的相关性最高，高程次之。流域调节在干旱传播过程中起着不可忽视的作用，特别是对于短时间尺度。Lin 等[59]以我国华南的西江流域为例，用 VIC 模型产生的日径流量表示水文干旱，通过线性及非线性函数建立了干旱变量、地理位置和滞后时间的干旱传播规律。最后，将传播规律应用于 2021 至 2050 年的水文干旱预测。

2.2.2　多个模型集合模拟

干旱传播研究中，气候模式与水文模型的集合应用已很普遍。多模型模拟对单一模型进行集合处理，能够充分利用各单一模型在建模中的优势，可有效地提高模型精度，具有良好的前景。下面就多个气候模式及多个水文模型集合模拟分别进行介绍：

多个气候模式。2013 年，Van Loon[16]在其博士论文《论干旱传播》中指出：“对气候和集水区特征相似的小而均匀的地区进行干旱传播研究，可以选择在该区域中表现最好的大规模模型。但对于大陆或全球范围的干旱研究，其中的条件和模型结果千差万别，无法做出这样的选择，最好的解决方案是使用多模型集合”。

Zhang 等[32]指出，利用具有不同温室气体排放情景或社会经济发展情景的气候模型对未来气候进行模拟，如耦合模型相互比较项目第 5 阶段(CMIP5)和第 6 阶段(CMIP6)的模拟，已较多地被应用于评估气候变化对干旱传播的影响。Jehanzaib 等[109]利用多个气候模式模拟的未来气候情景研究干旱传播后发现：在 RCP 4.5 情景下，极端状态的气象干旱导致中度和重度水文干旱的平均传播概率分别增加了 13% 和 2%；在 RCP 8.5 情景下，极端状态的气象干旱导致中度和重度水文干旱的平均传播概率分别增加了 1.5% 和 84%。

多个水文模型。Van Loon 等[25]在《基于大尺度水文模型的集合平均值评估干旱传播》一文中指出，

水文学中多用单个模型进行水文模拟。然而，近年来发现，无论是在水文学一般研究还是在枯水径流研究中，大尺度模型的多模型集合都比大多数单独参与的模型更接近观测结果。关于“多个气候模式+多个水文模型”，顾磊等[13]基于站点、栅格观测资料和 CMIP5 的 19 个气候模式输出数据，采用新安江等 4 个水文模型模拟了我国 135 个流域的历史时期(1961—2005 年)和未来时期(2011—2055 年，2056—2100 年)的水文过程，指出了气象干旱至水文干旱的潜在风险传播特性。

3　结 论

本文阐述了干旱传播的由来、从干旱类型演变的全环节对干旱传播进行了明确的界定，并剖析了干旱传播的特征，划分了干旱传播类型，并总结了干旱传播中的各种研究方法。主要结论如下：

对干旱传播的由来、含义、特征进行了细致的梳理、提炼与归纳，特别是纠正了英文“drought propagation”出处上的模糊之处，并针对缺少“干旱传播”具体而全面定义的情形提出了笔者的定义。在征求多位专家意见的基础上指出“水文传递”一词更适合于表征不同类型干旱的传播过程。

按干旱传播环节、传播时空特征两个方面划分了干旱传播类型，特别是按干旱环节进行了全环节且颇为细致的分类，并强调了区分农业干旱与土壤干旱、区分社会干旱与经济干旱的必要性。

在干旱传播研究方法上，按照统计方法和水文模拟方法进行了层次清晰的分类，将统计方法分为线性回归、对数函数、小波分析、Copula 函数、因果分析、贝叶斯网络、随机森林 7 种方法，将水文模拟方法分为单一水文模型模拟、多个模型集合模拟，并进行了细致的阐述。在气候模式与水文模型的衔接或耦合方式上，重点就多个气候模式、多个水文模型及结合方面进行了提炼与回顾，并指出多模型结合有更强的代表性，具有良好的应用前景。

致谢　感谢河海大学王文教授、西安理工大学黄生志教授、南京信息工程大学吴杰峰教授对本文提供的建设性意见与修改。

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• 译文 •

Progress and prospects in drought propagation research part I: Meaning, characteristics, types, and research methods

ZHI Xiefei[1,2], TIAN Yuntao[1,2], CHEN Changchun[3], ZHANG Yuqing[4]

（1. *Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters* (*CIC-FEMD*)*/Key Laboratory of Meteorological Disaster*, *Ministry of Education* (*KLME*), *Nanjing University of Information Science and Technology*, *Nanjing* 210044, *China*；2. *Weather Online Institute of Meteorological Applications*, *Wuxi* 214000, *China*；3. *School of Geographical Sciences*, *Nanjing University of Information Science and Technology*, *Nanjing* 210044, *China*；4. *School of Urban and Environmental Sciences*, *Huaiyin Normal University*, *Huai'an* 223000, *China*）

Abstract: Based on the review of the concept and connotation of drought propagation, a detailed definition of the entire process of drought propagation is provided and the accumulation, attenuation, lagging, and lengthening characteristics of drought propagation are expanded on. Progress in the aspects of accumulation and lag is emphasized. Drought propagation is classified into different types based on the process and spatiotemporal characteristics. The statistical methods, including linear regression, logarithmic function, wavelet analysis, Copula function, causal analysis, Bayesian network, and random forest, as well as hydrological simulation methods, including single hydrological model simulation and multiple model ensemble simulation, are summarized and discussed regarding their applications in drought propagation research.

Key words: drought propagation; definition; characteristics; type; method; progress

Chinese Library Classification No. : P343 **Document Code:** A

Drought, due to the differences in hydro-meteorological variables and socio-economic factors worldwide, as well as the stochastic nature of water demand, lacks a universally accepted and precise definition [1]. In 1992, the World Meteorological Organization defined drought as a period of extended precipitation deficiency or an unusual dry weather condition that is long enough to cause a serious hydrological imbalance [2]. In 1994, the *United Nations Convention to Combat Desertification* (UNCCD) referred to drought as a natural phenomenon arising when precipitation is significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems [3–4]. Drought can generally be classified into four types: meteorological drought, agricultural drought, hydrological drought, and socio-economic drought [5]. Specifically, meteorological drought is primarily caused by a long-term lack of precipitation; hydrological drought is characterized by reduced runoff and declining groundwater levels; agricultural drought refers to long-term soil moisture deficit leading to crop failure or death; socio-economic drought involves serious impacts on society and the economy due to the three aforementioned types of droughts (e.g., water supply for domestic, agricultural, and industrial purposes).

The occurrence and existence of meteorological drought can lead to water scarcity, resulting in significant impacts on ecology, agricultural production, and socioeconomic development. For instance, from July to mid-November 2022, the Yangtze River basin experienced significantly reduced precipitation and prolonged extreme high temperatures, leading to a meteorological and hydrological drought, which was the most severe since complete observational records began. The extreme heat and drought had a serious impact on agriculture, domestic water supply, power generation, and ecological environments in the affected regions. At its peak, the drought affected 39.78 million

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Received: 2022-05-10 **Revised:** 2023-05-10

Online publishing address: http//:

Fund: Research Project of National Key Research and Development Program(2017YFC1502000)

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

people in 12 provinces (autonomous regions and municipalities), with 7.014 million people requiring life assistance due to the drought; the affected cropland area was 4.27 million hectares, and the direct economic losses reached 40.85 billion yuan [6].

In recent years, the concept of drought propagation, which explores the transmission process and characteristics among different types of droughts, has attracted attention from scholars both in China and abroad, leading to many achievements in this field. In simple terms, drought propagation mainly refers to the process of meteorological drought transforming into agricultural drought and then into hydrological drought. Drought propagation has gradually become a frontier and hotspot in the field of drought research [7–8]. However, drought propagation research is still in its infancy, and its theoretical foundation and research methods need to be further improved. For example, there are some deficiencies in the comprehensive definition and characterization of drought propagation. The research approaches and frameworks are relatively limited, and the mechanisms and laws of drought propagation remain unclear [9]. Against the backdrop of global warming, China's drought frequency, duration, and severity have shown a clear increasing trend [10–11]. Therefore, clarifying the concept of drought propagation, exploring the process and characteristics of drought propagation, and summarizing research methods in drought propagation are essential for better understanding the mechanisms behind drought propagation. This, in turn, can provide a theoretical basis for strengthening drought monitoring and forecasting, enhancing comprehensive drought resistance capabilities, and improving water resource management [12–13].

1 Origin, meaning, characteristics, and types of drought propagation

1.1 Origin of drought propagation

In 1999, Eltahir et al.[14] from the Massachusetts Institute of Technology (MIT) were the first to use the term “propagation” and the dynamic process of “droughts propagate” to describe the transformation of meteorological drought into hydrological drought . This was used to depict the phenomenon of long-term precipitation deficiency causing anomalies in the water cycle, leading to decreased soil moisture and declining groundwater levels [15–16]. In 2001, Marani et al.[17] mentioned “droughts that propagate” . In the same year, Stahl[18] created a flowchart of “the propagation of drought in the hydrological cycle” . In 2003, Peters et al. [19–20] studied “drought propagation” from groundwater recharge to discharge and the impact of aquifer characteristics on drought, as well as the underground water propagation in semi-arid and sub-humid climatic conditions. Towards the end of 2003, Peters explicitly proposed the term “drought propagation” and conducted systematic studies on groundwater drought propagation in the Pang River basin of the UK and the Upper Guadiana basin in Spain [21–22]. She also mentioned that the 1999 paper by Eltahir et al. was the most valuable among existing research on groundwater drought propagation. In 2006, Van Lanen[23] used “drought propagation” as a title to explore the propagation of drought in the water cycle, studying the impact of groundwater recharge in different climatic regions (Spain and the Netherlands) on drought propagation .

The occurrence and existence of meteorological drought can lead to water scarcity, resulting in significant impacts on ecology, agricultural production, and socioeconomic development. For instance, from July to mid-November 2022, the Yangtze River basin experienced significantly reduced precipitation and prolonged extreme high temperatures, leading to a meteorological and hydrological drought, which was the most severe since complete observational records began. The extreme heat and drought had a serious impact on agriculture, domestic water supply, power generation, and ecological environments in the affected regions. At its peak, the drought affected 39.78 million people in 12 provinces (autonomous regions and municipalities), with 7.014 million people requiring life assistance due to the drought; the affected cropland area was 4.27 million hectares, and the direct economic losses reached 40.85 billion yuan [6].

1.2 Meaning of drought propagation

Drought propagation can generally be understood as the gradual transmission of abnormal meteorological and hydrological characteristics, leading to the transmission and propagation of different types of droughts. The term "propagation" is used directly in many studies without explicitly emphasizing a clear definition of "drought propagation". However, its primary meaning, from its inception until now, has been relatively stable, specifically referring to the process described in Eltahir's 1999 paper, which is the transformation of meteorological drought into agricultural drought (usually represented by soil moisture) and then into hydrological drought [14, 24], or simply "from meteorological drought to hydrological drought" [25]. Peters addressed the lack of a precise and widely accepted definition of "drought" [1] in her doctoral thesis in 2003 and specifically defined it in a section titled "4.2 Definition of drought events" [21], but she did not mention the issue of defining "drought propagation". In short, early studies lacked a specific and explicit definition of "drought propagation".

Some subsequent explicit generalizations or expressions that are close to definitions include the use of parentheses by Tallaksen et al.[26]in 2010, indicating "from meteorological drought to hydrological drought" , the use of "so-called drought propagation (from meteorological drought to hydrological drought)" by Van Loon et al. [27]in 2012, and the paraphrased generalization by Apurv et al.[28] in 2017, referring to the transition from meteorological drought to hydrological drought. A more definitive statement was made by Van Loon[16] in 2013, who summarized existing researches and specified that drought propagation refers to changes in drought signals during the transfer of drought from exceptional meteorological conditions to hydrological drought in the land part of the hydrological cycle. Li et al. [29] rephrased Van Loon's viewpoint as "drought propagation refers to changes in drought signals from exceptional meteorological conditions to hydrological drought in the land part of the hydrological cycle." In 2018, Wu et al. [30] defined specific indicators related to drought propagation, such as duration, magnitude, and peak intensity, based on "from meteorological drought to hydrological drought." In 2020, Bhardwaj et al. [31] defined drought propagation as the strengthening and recovery of water scarcity during the drought period. In 2022, a review[32] article stated that the concept of drought propagation usually refers to the development of anomalous hydroclimate variables (such as insufficient precipitation, enhanced atmospheric evaporative demand, or increased evapotranspiration) through interconnected land hydrological cycles (i.e., soil, surface water, and groundwater systems) and that drought propagation implies the transformation of drought signals in multiple processes of water and energy cycles . In the same year, Fuentes[33]roughly referred to drought propagation as the delay of drought responses in different subsystems .

Given that "drought propagation" still lacks a direct and comprehensive definition, for the convenience of academic exchange both domestically and internationally, we propose to base the definition of drought propagation on "drought propagation refers to the transmission and propagation of drought signals from exceptional meteorological conditions to agricultural drought (including soil moisture drought), hydrological drought, ecological drought, socio-economic drought, etc., in the land part of the hydrological cycle."

In Chinese literature, "drought propagation" is sometimes translated as "drought transmission" [34–37], which has the same meaning, but "drought propagation" is currently more commonly used. Some articles use "drought transmission" as a synonym for "drought propagation" or use "transmission" (which means "transfer" or "propagation" in English) to represent "(drought) propagation" [38–40]. The meaning of "drought propagation" and the commonly used hydrological term "hydrological response" are similar in some aspects but differ in others. "Hydrological response" generally refers to hydrological changes or responses caused by geographical environmental changes [41–43], not limited to meteorological drought as the independent variable. However, many studies on hydrological responses to meteorological drought are related to drought propagation.

Regarding the two existing Chinese translations of “drought propagation” and “drought transmission”, combined with the expressions of scholars in the articles *A review on multi-scale drought processes and prediction under global change* [44–45] and related literature, we sought the opinions of drought propagation researchers WANG Wen, HUANG Shengzhi, and WU Jiefeng. They collectively believe that “drought transmission” is more suitable for expressing the transfer and transmission process of different types of droughts in different stages. In contrast, “drought propagation” is more suitable for expressing the migration and diffusion process of the same type of drought in space, such as the propagation of meteorological drought and hydrological drought in their respective spatial domains. To maintain consistency in writing style, this article mainly uses “drought propagation” to review and look ahead at research achievements related to drought propagation and transmission both domestically and internationally.

1.3 Characteristics of drought propagation

Drought propagation exhibits four main characteristics based on existing literature and researches:

Accumulation: It involves the cumulative development of multiple meteorological droughts, resulting in longer-lasting agricultural and hydrological droughts.

Attenuation: In the early stages of meteorological drought, when basin water storage is relatively abundant, it can inhibit the development of agricultural and hydrological droughts to a certain extent.

Lagging: There is a time lag in the propagation of different types of droughts.

Lengthening: Meteorological drought propagation leads to longer durations of agricultural and hydrological droughts.

Accumulation and extension are often influenced by both climate and surface factors. In addition, lagging and attenuation are mainly influenced by surface and basin factors, such as hydrological regulation. For example, Sattar et al. [46] used drought propagation response rate to measure the response of hydrological drought to meteorological drought, expressed as the ratio of the number of hydrological drought events to the total number of meteorological drought events within a certain time period. Guo et al. [47] proposed a “modified drought propagation rate” that considers the possibility of multiple meteorological droughts leading to one hydrological drought, where it is the ratio of the number of meteorological drought events triggering hydrological droughts to the total number of meteorological drought events. A higher ratio indicates a stronger response of agricultural and hydrological droughts to meteorological drought.

Regarding lagging, research mainly focuses on the time lag between meteorological and agricultural/hydrological droughts during different periods or stages (e.g., occurrence, development, duration, peak, and end) [32, 48–49]. Lagging time can be determined through the correlation of different types and time-scale drought indicators (e.g., meteorological, agricultural, and hydrological variables or relevant drought indices) [50–51], or by the run theory to identify different types of drought events and match them to obtain the corresponding lagging time [52]. A shorter lagging time indicates a faster response to drought propagation. For specific types of drought propagation (e.g., meteorological drought propagating to hydrological drought), comprehensive characterization can be achieved through the frequency, duration, and severity of the corresponding drought types [53].

1.4 Types of drought propagation

Drought propagation can be classified based on different indicators, such as propagation stages and spatiotemporal characteristics.

1.4.1 Classification based on drought propagation stages

Existing research articles on drought propagation mainly focus on “propagation from meteorological drought to agricultural drought” and “propagation from meteorological drought to hydrological drought”. A Review of *Drought Propagation under Climate Change*: *Characteristics*, *Methods*, *Processes*, *and*

Controlling Factors [32] further categorizes it into "propagation to agricultural drought, propagation to hydrological drought, and propagation to environmental drought". Zhang et al. [45] pointed out that under the premise of cumulative deficit in atmospheric precipitation, meteorological drought is bound to occur, followed by a chain-like transmission process of meteorological drought → agricultural drought → hydrological drought → ecological drought → socio-economic drought. There is also an evident propagation process in the internal development of agricultural drought, hydrological drought, ecological drought, and socio-economic drought. This article attempts to summarize them into the following four categories:

Propagation to agricultural drought (soil drought): This category refers to the propagation from meteorological drought to agricultural drought (soil drought). Agricultural drought is often characterized by soil moisture deficit and can be considered a narrow agricultural drought. In addition to soil moisture, broader indicators such as leaf characteristics and crop growth and yield can be used to represent agricultural drought, which can be categorized as ecological drought. For instance, An et al. [54] investigated the monitoring capability of relative soil moisture (RSM) for agricultural drought in Northeast China using the relationship among RSM, standardized vegetation index (SVI), agricultural meteorological disaster data, and yield data, all of which fall into the category of agricultural drought.

Propagation to hydrological drought: This category refers to the propagation from meteorological drought to hydrological drought. It can be further divided into propagation to surface runoff and propagation to groundwater.

Propagation to ecological drought: This category refers to the propagation from meteorological drought through agricultural drought or hydrological drought to ecological drought. Ecological drought is also referred to as "environmental drought". Crausbay et al. [55–56] defined ecological drought as an "intermittent water supply shortage that causes ecosystems to exceed their vulnerability threshold, affecting ecosystem services and triggering feedbacks in natural and/or human systems".

Propagation to socio-economic drought: This category refers to the propagation from meteorological drought through agricultural drought or hydrological drought and ecological drought to socio-economic drought. Economic drought is relatively easy to measure, while socio-economic drought may be more challenging to quantify. It is beneficial to further classify and study economic drought and socio-economic drought separately, such as propagation to economic drought and propagation to socio-economic drought.

1.4.2 Classification based on spatiotemporal characteristics

Based on spatiotemporal characteristics, drought propagation can be classified into two types: temporal drought propagation and spatial drought propagation. This classification is concise and emphasizes the spatiotemporal features of different types of drought transitions.

Temporal drought propagation: Temporal drought propagation mainly explores the transfer and propagation of different drought types along the time axis. In recent years, numerous research achievements have emerged in this field, making it the mainstream area of drought propagation studies. For example, Ho et al. [57] used the "time lag (propagation time) value between the maximum hydrological drought area and the maximum meteorological drought area" and considered that estimates at a sub-monthly scale are suitable for detailed analysis of sudden drought events.

Spatial drought propagation: Spatial drought propagation involves propagation from one location to another based on spatial aspects such as propagation direction, distance, and range. While there are fewer research outcomes explicitly focusing on spatial drought propagation, this area is gradually increasing [24, 57–59]. It is worth noting that compared to temporal drought propagation, spatial drought propagation focuses on representing the movement and propagation of the same type of drought in space but can also be used to study the spatiotemporal transmission relationships between different drought types.

Existing research on spatial drought propagation primarily refers to the propagation of the same type of drought in space, especially in the context of meteorological drought propagation. For instance, the propagation of surface water drought to groundwater drought, although both are hydrological droughts, still involves the spatiotemporal propagation of two subcategories (surface water drought and groundwater drought). Studies on the spatial propagation of meteorological droughts or hydrological droughts, although some of them might not explicitly use the term "drought propagation" in previous literature, can be considered as research outcomes of spatial drought propagation. Several articles used the term "drought migration" to express and explore the spatial movement of droughts [60]. For example, in 1999, Ma et al. [61] investigated the mechanism of eastward migration of earthquakes and droughts in Asia and Africa, using the term "migration of earthquakes and droughts" in the English title. In 2001, Hu et al. [62] used "drought migration" in their English article to study the southward migration of centennial-scale droughts and floods in eastern China and the western United States.

2 Research methods for drought propagation

The study of drought propagation involves various research aspects, including drought identification and selection of drought indices. Due to space limitations, this article will not delve into the details of drought indices.

Regarding the classification of research methods for drought propagation, Zhang et al.[32]categorized them into statistical methods and hydrological models, with statistical methods further divided into correlation analysis, run theory, and response functions. Wu et al. [63] classified them from the perspective of propagation threshold calculation into run theory, correlation analysis, and non-linear response method. we adopt the classification based on existing methods, dividing them into two main categories: statistical methods and hydrological simulation methods. Within the statistical methods, we further subdivide them into correlation analysis, run theory, and statistical models, while within the hydrological simulation methods, we distinguish them between single hydrological model simulation and ensemble simulation of multiple models, summarizing and introducing the methods used in drought propagation research.

2.1 Statistical methods

In statistical methods, correlation analysis, run theory, regression models, Copula functions, wavelet analysis, causal analysis, neural networks, random forests, other machine learning algorithms, and intelligent algorithms have gradually gained significant applications in drought propagation research. This section will separately summarize and introduce the main statistical methods used in drought propagation research: correlation analysis, run theory, and statistical models.

2.1.1 Correlation analysis

Correlation analysis has been widely applied in studying the lag and propagation time of drought propagation. Additionally, it serves as a preliminary analysis for other statistical models such as regression analysis and wavelet analysis. The research on the propagation and correlation analysis from meteorological drought to agricultural and hydrological droughts is relatively concentrated in current studies. The following elaborates on the application of correlation analysis in drought propagation research:

Lorenzo-lacruz et al. [64] used Pearson correlation coefficients to determine the time scale of the standardized precipitation index (SPI) with the best correlation to the standardized streamflow index (SSI), which was then considered as the response time of hydrological drought to cumulative precipitation deficit. Han et al. [65] conducted a study on the propagation from meteorological drought to hydrological drought in the Gan River basin, calculating the Pearson correlation coefficients among 1- to 24-month scale standardized precipitation evapotranspiration index (SPEI), SPI, and standardized runoff index (SRI). They identified the time scale i with the strongest correlation among SPEI-i, SPI-i, and SRI-1 as the corresponding propagation time scale. Zhao et al. [66] found a strong correlation between SPEI and SRI in the Xiangjiang River basin in southern China, with a 2-month scale showing the strongest Pearson correlation, and the correlation was stronger in the dry season than in the rainy season. Xiang et al. [50], using the Haihe River basin as an example, found seasonal differences in the propagation time from meteorological drought to agricultural drought, with shorter time scales in summer and autumn and longer time scales in spring and winter. Zhou et al. [67] found that the propagation time from meteorological drought to hydrological drought in the Pearl River basin ranged from two to six months across five sub-regions. Zhang et al. [68], by studying the correlations among meteorological, agricultural, and hydrological droughts in the Yangtze River and Yellow River basins, discovered a stronger correlation between meteorological drought and agricultural drought, with shorter propagation times in summer and autumn compared to winter and spring. The propagation time in the Yangtze River basin was longer than that in the Yellow River basin.

2.1.2 Run theory

In drought propagation research, the identification of drought events often requires prior analysis. Run theory and related threshold analysis play a crucial role in drought identification and discrimination. According to run theory, if the value of a drought index is below a certain threshold level for a specific period, it is considered a negative run, indicating the occurrence of a drought event [69–70]. Specifically, given a value X, a discrete series X_t varying with time is analyzed. When X_t is continuously greater than X for one or more time periods, a positive run occurs. On the other hand, when X_t is continuously lower than X, a negative run occurs. In drought research, the length of negative runs is referred to as drought duration, representing the time from the start to the end of a drought event. The total magnitude of negative runs is called drought severity, reflecting the severity of the drought, i.e., the accumulation of values below the cutoff level [71].

Threshold analysis is an important approach in drought and flood research and a key indicator for identifying drought using run theory. Threshold methods can be classified into absolute thresholds (fixed thresholds or constant thresholds) and relative thresholds (variable thresholds). Absolute thresholds refer to a fixed value used as the threshold for extreme events. In contrast, relative thresholds, which are more widely used internationally, fall into two main categories: quantile-based methods (often using percentiles) [72] and parameter estimation algorithms based on extreme value theory, including the generalized extreme value (GEV) distribution and the generalized Pareto distribution (GPD) [73]. Heudorfer et al. [74] compared different threshold levels' methods for drought propagation analysis in Germany using both constant and variable thresholds, suggesting that each has its advantages and disadvantages under different circumstances, requiring careful consideration.

Once the thresholds are determined, run theory can be used to extract features of different types of drought events, such as their occurrence time, end time, duration, and intensity. It also helps identify the time lag between different types of drought events [57, 75]. Below, we summarize the application of absolute and relative threshold methods in drought propagation research:

Absolute threshold method: Absolute thresholds are fixed and unchanging. Due to their simple calculation, they are widely used in drought propagation analysis. The constant threshold method is more suitable for characterizing drought under the background of available water consumption in human society (rivers or aquifers), as water shortage can be defined as drought regardless of the time or season of the year. For example, Yevjevich [69] used run theory to define drought as Palmer drought severity index (PDSI) values below 0. Wang et al. [76] used a fixed threshold of −1 to extract meteorological (SPI) and hydrological (SRI) drought events in the Huaihe River basin. Wu et al. [30] set a fixed threshold (TL) of 0 as the criterion for determining the start or end of drought events in different countries (China, the United States, and Germany) at hydrological stations. When the drought index is lower than (or greater than) 0, the river flow has returned to a dry (or wet) state.

Relative threshold method: The relative (variable) threshold is the percentile threshold based on the probability distribution of drought characteristics within a certain period [72], and different percentiles directly influence drought characteristics [12]. The relative threshold method takes into account the availability of water during different periods or seasons throughout the year, making it very suitable for comparing meteorological and hydrological drought characteristics statistically [28, 77]. There are two methods for calculating drought sequence percentiles based on precipitation: the ascending order method and the descending order method. The so-called descending order percentile method takes the smallest amount of precipitation (i.e., the most severe drought) as 1, and the others as 2, 3, and so on, following the general percentile calculation method. A previous article [78] sorted precipitation data from four areas in Anhui Province from largest to smallest and calculated percentiles based on confidence levels, with percentiles of >70%– ≤80%, >80%– ≤ 90%, and >90% used as indicators of mild drought, moderate drought, and severe drought, respectively.

In general drought research, relative thresholds are commonly used based on precipitation percentiles. In drought propagation analysis, both ascending and descending order methods are used. Commonly used relative threshold levels include 70%, 80%, and 90% [72, 79]. For instance, Van Loon et al. [77] studied the seasonal characteristics of drought propagation based on the 80th percentile threshold. Apurv et al. [28] stated that “most previous studies used threshold levels from the 5th to 30th percentiles in drought research” and used the 25th percentile of each month as the threshold to study the role of climate characteristics in hydrological drought propagation in ten locations across different climatic regions globally. Wang et al. [76] found that the propagation time of meteorological drought to hydrological drought in 16 sub-basins of the Huaihe River basin ranged from one to 47 days. Wu et al. [63] assessed the meteorological-hydrological drought propagation threshold in three sub-basins of the Dongjiang River basin at multiple time scales and concluded that a larger time scale of hydrological drought indicated greater propagation threshold (PT), and vice versa.

Wang et al. [80] used GEV-fitted 3-month SPEI data to indicate that the severity, duration, and frequency of drought events in China exhibited a noticeable increasing trend from 1961 to 2018. Nadarajah [81] fitted drought sequences in Nebraska, USA, using GPD and found the fitting results to be reasonably valid. Liao [82] studied the response of hydrological drought to meteorological drought in the Songhua River basin using the Copula function and concluded that GEV and GPD were capable of fitting multi-scale runoff sequences in the basin.

2.1.3 Statistical models

Based on correlation analysis and run analysis, statistical models such as linear and nonlinear methods can be constructed, including regression models, to fit the relationship between different drought indices or drought characteristics, thereby exploring the statistical characteristics and patterns of drought propagation. Various statistical methods and models, such as univariate linear regression, multivariate linear regression, logarithmic functions, wavelet analysis, Copula functions, Bayesian networks, and random forests, have been applied in drought propagation studies. The applications of statistical models in drought propagation can be summarized as follows:

Linear regression: Linear regression is commonly used in drought research. Hua [83] established univariate linear relationships between hydro-meteorological drought characteristic variables and compared them with nonlinear functions, finding that the nonlinear functions were more suitable for describing the response relationships for hydro-meteorological and agricultural-meteorological droughts with medium and long durations, medium-high intensities, and medium durations and intensities, respectively. Ma et al. [84] used multivariate linear regression to study the characteristics of different seasonal drought propagation and their key forcing factors, concluding that the propagation time depended on the maximum correlation coefficient between the corresponding time scales of SPI and SRI. Li et al. [85] established multivariate regression models to explore the relationships between agricultural, hydrological droughts, and driving factors in the Luanhe River basin, suggesting that these relationships could well explain the three drought features or propagation processes: existence of only meteorological drought, development of agricultural and hydrological drought from meteorological drought, and formation of agricultural and hydrological drought without meteorological drought.

Logarithmic functions: Wu et al. [86], using the example of the Jinjiang River basin in the southeast coastal region of China, found that the response relationship between meteorological and hydrological droughts determined by the logarithmic function model was reasonable. Hua [83] established drought propagation function relationships at three hydrological stations in the downstream of the Nenjiang River, and the best-fitting distributions for both meteorological and hydrological drought durations were found to be the logarithmic functions, consistent with the results of Wu et al. [87], but the intensity response relationships were different from previous studies and better fit for the power function distribution. Wang et al. [88] found that the logarithmic function model with three parameters could well characterize the response relationship between meteorological and hydrological drought in the Kashgar River basin. Wang [89] studied the evolution characteristics of hydrological drought in the Yellow River basin based on surface runoff data and found that the optimal marginal distribution functions for hydrological drought duration and intensity were mostly Log-L and GEV distributions, respectively.

Wavelet analysis: Ding et al. [90] used wavelet analysis to study meteorological and hydrological droughts in eight sub-regions of China divided by climatic zones from 1902 to 2014. Their results indicated that the propagation relationship between droughts was weaker in dry environments than in wet environments, and the relationship between the two types of droughts was more closely related in summer and autumn than in spring and winter. Li et al. [91] applied cross-wavelet analysis and spatial autocorrelation methods to study the propagation process of agricultural drought in the Yangtze River basin, finding that the propagation from meteorological drought to hydrological drought was faster than that to agricultural drought. Shi et al. [92] analyzed the correlation between meteorological drought and hydrological drought in the source region of the Yellow River and showed that cross-wavelet transform and wavelet coherence analysis indicated a significant positive correlation between SPI-9 and SRI-1 at different periodic scales; the propagation time from meteorological drought to hydrological drought was September, and the SPI-9 sequence could be used for hydrological drought monitoring.

Copula functions: Zhu et al. [93], using a Copula-based probabilistic model and time series of SPEI and standardized soil moisture index (SMI) obtained from the global land data assimilation system (GLDAS) simulation, found that antecedent soil moisture conditions influenced the probability of drought propagation, which was particularly significant for northern China, Russia, the central and western United States, Canada, and Australia. Guo et al. [13] quantitatively assessed the sensitivity of hydrological drought to meteorological drought in 135 basins in China using a hydrological model and Copula function, concluding that it would be less affected by climate warming, and the probability of simultaneous occurrence of meteorological and hydrological drought in the northern regions would increase slightly in the future. Xu et al. [94] quantified the propagation probabilities in different regions of China using the Copula model, and they found that the strongest and weakest correlations between meteorological and agricultural drought occurred in summer and winter, respectively, and the propagation time increased from one to two months in summer to two to seven months in the following spring.

In terms of spatial distribution, the correlation and propagation sensitivity between meteorological drought and agricultural drought were higher in humid regions than in other climatic zones. Wang et al. [95], in their study of hydrological drought propagation in the Yellow River basin from 1961 to 2015, calculated the streamflow severity index (SSI) by fitting the monthly streamflow data with the optimal distribution function and used the Copula function with the highest goodness-of-fit (GOF) to study drought recurrence periods, concluding that the Frank copula function yielded the best fitting results in the Yellow River basin.

Causal analysis: Causal analysis, also known as attribution analysis, has shown vigorous development in model simulation in the field of hydro-meteorology but remains limited in analyzing observed results. Shi et al. [96], in their paper *A New Perspective on Drought Propagation: Causal Relations*, published in 2022, pointed out that causal relationship analysis, based on convergent cross-mapping (CCM) using purely observational data, provided a new perspective on drought propagation (i.e., causal relations). The effectiveness of causal relationship analysis in drought propagation studies has been validated, especially for detecting the direction of drought propagation, where it outperforms correlation analysis. Zhai et al. [97] summarized that for extreme climate phenomena like drought, which is influenced by various factors such as precipitation, temperature, wind speed, and soil moisture, global-scale detection and attribution of drought changes have considerable uncertainty. Ren et al. [98] conducted an attribution analysis of runoff changes at two hydrological stations in the Weihe River basin in Xianyang and Huaxian, finding that human activities were the main factors causing the decline in runoff in the Weihe River basin since 1991, among which the increased water demand due to social development and agricultural production was the main cause of the runoff reduction.

Bayesian networks: Jehanzaib et al. [99] used the Bayesian network model (BNM) to calculate the likelihood of drought propagation from different types of meteorological drought to hydrological drought. Shin et al. [100], based on data from 54 meteorological stations in Republic of Korea, calculated the Palmer hydrological drought index and used a model developed with dynamic Bayesian networks (BNDF_DP) to predict the probability of drought propagation, suggesting that BNDF_DP is a promising probabilistic drought prediction tool. Liu et al. [101], taking the Qinhe River basin on the Loess Plateau as an example, combined the probability analysis under the uncertainty of the Bayesian network with the multivariate drought analysis of the Copula function, finding that the propagation threshold from meteorological drought to different levels of hydrological drought increased with the level of hydrological drought, and the intensity of meteorological drought weakened during the propagation process.

Random forests: Random forests are a machine learning method known for their fast learning process, quick computation speed, good stability, and high prediction accuracy. Jiang et al. [102] indicated that 11 machine learning classification methods could be used for evaluating drought propagation and used a hybrid machine learning Copula method to estimate the probability of meteorological drought to ecological drought propagation in the northwest region. Guo [103] constructed a remote sensing drought monitoring model based on random forests, using multiple remote sensing indices and soil factors as independent variables and the comprehensive meteorological drought index (CI) as the target variable. The results of the training set and test set achieved correlation coefficients with CI of above 0.96 and above 0.74, respectively. Liu et al. [104] conducted a random forest regression analysis of dynamic propagation thresholds based on meteorological and underlying surface factors, finding that the regression model achieved satisfactory results and had strong generalization ability, suitable for quantitatively evaluating the propagation thresholds of meteorological drought to hydrological drought in the basin.

2.2 Hydrological simulation methods

Hydrological simulation is an effective tool for studying drought propagation, as it can directly or indirectly represent and simulate the physical characteristics of hydrological processes involved in drought propagation. Hydrological simulation methods, based on principles such as water balance, simulate relevant variables such as runoff, soil moisture, and evaporation through hydrological models. Hydrological simulations can be classified into large-scale simulations and regional simulations based on the size of the spatial and temporal scales. Additionally, they can be categorized as single-model simulations and ensemble simulations based on the number of models used. The following sections summarize their applications in drought propagation.

2.2.1 Single hydrological model simulation

Using individual hydrological models to simulate hydrological cycle variables is a common practice in hydrology research. Hydrological simulation methods can be applied to analyze regional-scale drought propagation processes [49]. For example, Van Lanen [23] used the SIMGRO model to study drought propagation in Spain and the Netherlands and found that meteorological drought propagating through the groundwater system to the unsaturated zone usually resulted in relatively mild hydrological droughts. Among existing drought propagation studies, common models used for hydrological simulation include the soil and water assessment tool (SWAT) model and the variable infiltration capacity (VIC) model.

SWAT model: Li et al. [105], based on the SWAT model, found that droughts are likely to intensify in the future under climate change scenarios during the propagation process from meteorological to hydrological drought. Veettil et al. [106], using the SWAT hydrological model and the classification and regression tree (CART) algorithm, quantified the potential impacts of climate, watershed, and other factors on the duration and severity of hydrological drought in the Savannah River basin in the United States. In arid and cold regions of northwestern China, hydrological observations are often too short or lacking, making drought monitoring challenging. Liang et al. [107] used the SWAT model to simulate hydrological variables and developed a multivariate agricultural-hydrological drought index (MAHDI) that performed well in characterizing the seasonal lag times from meteorological drought to agricultural and hydrological droughts.

VIC model: Bhardwaj et al. [31] used the VIC model to simulate hydrological variables and estimated the propagation time among meteorological, agricultural, and hydrological droughts in 18 major river basins in India in combination with observations. Zhu [108], using VIC simulation results, systematically analyzed the correlation between 16 basin characteristic factors of the Yellow River basin and five hydrological drought characteristics, finding that the base flow index (BFI) had the highest correlation with hydrological drought characteristics, followed by elevation. Basin regulation plays a significant role in the drought propagation process, especially at short time scales. Lin et al. [59], using the VIC model to generate daily runoff data for the Xijiang River basin in southern China, established drought propagation patterns based on drought variables, geographical locations, and lag time using linear and nonlinear functions. Finally, they applied these propagation patterns to predict hydrological drought from 2021 to 2050.

2.2.2 Ensemble simulation of multiple models

In drought propagation research, the application of ensemble climate models and hydrological models has become common. Ensemble simulation involves using multiple models to collectively represent the processes, taking advantage of the strengths of individual models, thereby effectively improving model accuracy with promising prospects. Below, we introduce the ensemble simulations using multiple climate models and multiple hydrological models separately:

Multiple climate models: Zhang et al. [32] pointed out that future climate can be simulated using climate models with different greenhouse gas emission scenarios or socio-economic development scenarios, such as those from the coupled model intercomparison project phase 5 (CMIP5) and phase 6 (CMIP6). These simulations have been widely used to assess the impacts of climate change on drought propagation. Jehanzaib et al. [109], using multiple climate models to simulate future climate scenarios, found that: under the RCP 4.5 scenario, extreme meteorological droughts resulted in an average increase of 13% and 2% in the propagation probability of moderate and severe hydrological droughts, respectively. ;under the RCP 8.5 scenario, extreme meteorological droughts caused an average increase of 1.5% and 84% in the propagation probability of moderate and severe hydrological droughts, respectively.

Multiple hydrological models. Van Loon et al. [25] pointed out in the paper *Assessment of Drought Propagation Based on Large-Scale Hydrological Models* that in hydrology, single models are commonly used for hydrological simulation. However, in recent years, it has been found that ensemble simulations using multiple large-scale hydrological models are closer to observed results, whether in general hydrological studies or studies on low flow discharge. Regarding “multiple climate models + multiple hydrological models” , Gu et al. [13], based on data from sites, gridded observations, and outputs from 19 climate models of CMIP5, employed four hydrological models, including Xin'anjiang model, to simulate the hydrological processes in 135 watersheds in China for historical periods (1961-2005) and future periods (2011-2055 and 2056-2100), and indicated the potential risk propagation characteristics from meteorological drought to hydrological drought.

3 Conclusion

This article expounds on the origin and explicit definition of drought propagation, including its evolution from different types of droughts and analyzes the characteristics of drought propagation. It classifies the types of drought propagation and summarizes various research methods applied to drought propagation. The main conclusions are as follows:

A meticulous analysis and extraction were conducted on the origin, meaning, and characteristics of drought propagation. In particular, the ambiguity of the term “drought propagation” in English literature was corrected, and the author's definition of “hydrological transmission” was proposed, which is more suitable for representing the propagation process of different types of droughts.

Drought propagation was classified based on the aspects of propagation stages and spatiotemporal characteristics. The classification was detailed and comprehensive, with an emphasis on distinguishing between agricultural drought and soil drought, as well as between social drought and economic drought.

In terms of research methods for drought propagation, a clear hierarchical classification was presented, dividing statistical methods into seven categories: linear regression, logarithmic function, wavelet analysis, Copula function, causal analysis, Bayesian networks, and random forests. Hydrological simulation methods were classified into single hydrological model simulation and ensemble simulation of multiple models. Detailed explanations were provided. In the connection or coupling between climate models and hydrological models, emphasis was placed on the extraction and review of multiple climate models, multiple hydrological models, and their combinations, pointing out the stronger representativeness and promising prospects of multi-model ensembles.

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