DOI:10.13476/j.cnki.nsbdqk.2020.0026
安婷莉,韩昕雪琦,高学睿,等.虚拟水理论发展及应用前景综述[J].南水北调与水利科技(中英文),2020,18(2):44-61. AN T L,HAN X X Q,GAO X R,et al. A review of the development and application prospect of virtual water theory[J]. South-to-North Water Transfers and Water Science & Technology,2020,18(2):44-61.(in Chinese)

虚拟水理论发展及应用前景综述

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摘要:自20世纪末虚拟水的概念提出以来,其基本理论、核算方法及案例研究在国内外得到了蓬勃发展,逐步建立了包含虚拟水含量、虚拟水贸易、虚拟水流动、虚拟水平衡、水足迹等概念的经济社会水资源管理理论框架,成为研究水资源在经济社会中循环演变的重要方法。系统地对虚拟水的概念及特点进行了解析,梳理了虚拟水理论的产生和发展历程,详细阐述了当前虚拟水研究进展,并对虚拟水理论在水资源管理中的应用前景进行了分析,提出了将其应用于农业水资源管理中的三大科学设想,为虚拟水理论的研究与应用提供参考。

关键词:虚拟水;水足迹;水资源管理;应用前景

中图分类号:TV214 文献标志码:A 开放科学(资源服务)标识码(OSID):

随着人类文明的进步和经济社会的发展,日益增长的水资源需求、不断恶化的水环境以及不合理的水资源利用方式加剧了水资源危机,也逐渐深化了人们对水资源演变规律的认识,催生了新的水资源管理理念。20世纪末期,伴随区域间贸易规模不断发展,地区间商品流通伴生的虚拟水贸易量不断增加[1]。在此背景下,传统的单纯考虑实体水资源的水管理理念表现出较大的局限性,虚拟水的概念由此而产生,为水资源管理与供需安全战略提出了新思路,成为水资源研究的热点[2-3]。2002年荷兰学者Hoekstra[4]对虚拟水概念进一步拓展,提出了水足迹理论,为水资源评价体系提供了一个多维度的指标,能够对水资源的利用途径(利用、消耗和净化水污染)进行系统评价,丰富了传统水资源评价体系的内涵和外延,能够更好地刻画社会经济发展对水资源的需求和占用情况,成为虚拟水研究领域的重要分支[5]。总的来看,虚拟水理论更加真实地反映了人类社会水资源的耗用和资源流动情况,揭示了水资源作用于经济社会的价值效用本质,是一种新的水资源观[6]。本文主要介绍了虚拟水理论的发展及其应用前景。首先,解析了虚拟水的概念及内涵,回顾了虚拟水理论的产生及发展历程,在此基础上详细阐述了当前虚拟水的研究进展,最后介绍了虚拟水在水资源管理中的应用前景并提出了虚拟水应用于农业水资源管理的三大科学设想。

1 虚拟水概念

虚拟水是指生产产品或服务过程中所消耗的全部水资源数量,即凝结在产品或服务中的水资源量,最初是以农产品为主要研究对象提出的。随后,虚拟水概念被进一步扩展和完善,适用对象从农产品变为更广泛的产品和服务,逐步建立了包含虚拟水含量、虚拟水贸易、虚拟水流动、虚拟水平衡、水足迹等概念的经济社会水资源管理理论框架[7-9]。虚拟水不是真

收稿日期:2019-08-26 修回日期:2019-12-20 网络出版时间:2020-01-13
网络出版地址:http://kns.cnki.net/kcms/detail/13.1334.tv.20200111.1501.002.html
基金项目:国家重点研发计划(2018YFF0215702);重庆市教委科技研究项目(KJ1600533);中国水利水电科学研究院流域水循环模拟与调控国家重点实验室开放研究基金(IWHR-SKL-201601;IWHR-SKL-201712)
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实意义上的实物资源，而是以“虚拟”的形式包含在产品中的“看不见”的水资源，虚拟水流动的本质是水资源通过经济系统转换进入商品，其价值随之在社会生产—贸易—消费系统中流转的过程，虚拟水是水资源在国民经济系统中的价值表现形式。虚拟水概念的特点在于：首先，它将水与产品特别是农产品生产联系起来，强调农产品生产所消耗的水资源不仅包括地表水和地下水（蓝水），还包括土壤水（绿水）；其次，虚拟水内嵌于商品通过贸易实现水资源在国家或地区间的交换，相当于在消费端对内嵌于商品中的水资源进行了二次分配。虚拟水概念的引入对水资源合理配置、水资源承载能力、水资源高效利用的研究具有重要意义，突破了水资源研究围绕“实体水”本身展开的观念束缚，提出了水资源被生产活动利用后并没有消失，而是以虚拟形态内嵌于商品或服务中通过贸易、消费体现其价值的观点，建立了水资源系统与社会经济系统研究的桥梁，拓宽了水资源研究的领域。

水足迹是虚拟水研究的重要发展，是一个基于消耗的用水指标，指生产人类社会所需的商品或服务所消耗的水资源量。区别于传统的取用水指标，一种产品的水足迹不仅包括消费者或生产者的直接用水，也包括间接用水。根据水源不同，水足迹可以分为蓝水足迹（生产所耗的地表水和地下水量）、绿水足迹（生产所耗降水量）和灰水足迹（稀释生产产生的污水所需水量）[10-11]。其中，蓝水足迹和绿水足迹又可统称为水稀缺足迹（生产所消耗的水资源总量）；灰水足迹可称为水污染足迹，按照污染类型还可细分水富营养化足迹等。与传统的“取用水量”指标相比，水足迹理论有以下特点：(1)水足迹从水源角度区分了生产活动所消耗水资源的类型，更加完整清晰地刻画水资源的取用消耗；(2)水足迹从时间和空间上明确了不同用途对水资源的占用量，它们能满足水资源可持续性和公平用水及其分配的要求，并且可为区域环境评估、用水对经济社会的影响评价奠定基础。水足迹概念将人们的生产、消费活动与水资源的消耗和污染联系起来，让人们意识到水资源的总体消耗和污染最终是与生产、消费产品的类型和数量密不可分的，同时，水足迹作为和人们生产、消费有关的用水指标，能够清晰地刻画区域消费水足迹的结构及来源，揭示区域的水资源系统状态和社会经济发展对外部资源的依赖程度，为水安全战略研究提供了重要基础[12-13]。

从概念的本质上来看，生产水足迹是实体水到虚拟水转化过程的效率表达，用来衡量商品生产过程中对水资源的利用效率；虚拟水流动是商品中蕴含的水资源价值以虚拟的形式在社会经济系统中运移，衡量的是水资源价值的流动通量；消费水足迹是指消费端人们对水资源价值消费量的表达指标，衡量的是经济社会对水资源的需求强度；虚拟水和水足迹是对水资源的价值形成、价值转移和价值消费全过程的表达手段。

2　虚拟水理论发展

2.1　虚拟水理论发展历程

从20世纪80年代以色列经济学家“嵌入水”的思想初现至今，虚拟水的研究经历了30年左右的发展，其发展历程根据虚拟水理论的研究进展可以划分为四个阶段（表1）。

表1　虚拟水理论发展历程

发展阶段	研究进展	阶段特征
萌芽阶段（1993年以前）	20世纪80年代，与虚拟水含义相似的概念开始出现，例如Haddadin引入的“外生水”，Tony Allan使用的“嵌入水”以及Mc Calla使用的“水、粮食、贸易结合体”均表达了与虚拟水相似的含义[14]。	虚拟水概念雏形初现。
初步发展阶段（1993－2001年）	1993年Tony Allan[15]提出虚拟水概念并以中东水资源短缺的长期解决方案为例阐述了虚拟水理论的应用，自此虚拟水概念逐渐被接受，相关研究也相继展开[16-17]，虚拟水贸易等含义逐步形成，拓宽了水资源的认知范畴，丰富了水问题解决手段。	虚拟水概念正式提出，并得到初步发展。
快速发展阶段（2002－2015年）	2002年Hoekstra提出水足迹的理论推动了虚拟水量化领域的研究进程[4]，成为虚拟水研究的热点。虚拟水贸易格局、伴生效应、体现的比较优势等相关研究不断深入[18-22]，逐步形成虚拟水量化、虚拟水贸易格局解析及伴生影响评价等方法体系[23-25]。	虚拟水理论引起广泛的关注，并得到快速发展，其理论方法体系不断成熟。
进一步发展阶段（2016年至今）	实体水－虚拟水“二维三元”耦合流动等理论的提出推动了将虚拟水融入水资源管理体系的研究进程[6,26-27]。相关学者开始探索通过虚拟水手段调控水资源、解决水问题的方法[28-30]。	虚拟水理论与研究进一步发展，开始了从虚拟水角度解决水资源问题的尝试，将传统的水资源管理模式进一步拓展。

2.2　虚拟水理论研究进展

虚拟水理论的研究经历的四个发展阶段，成为了刻画社会经济发展中水循环演变规律的重要方法，并且开始逐步融入水文水循环体系，成为解决水

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问题的手段。目前关于虚拟水的研究进展可以分为以下三个方面。

(1)虚拟水流量、流向、贸易格局核算及其伴生效应评价、驱动机制分析。

虚拟水流动、虚拟水贸易的概念是虚拟水理论的核心,国家或地区间的虚拟水贸易可以缓解因地区间水资源时空分布不均或者水资源生产率低下而造成的水资源短缺,解决因此而引发的地区冲突,实现社会经济发展的水资源和粮食供应安全。由于虚拟水最初是用于衡量农产品所需的水资源量,同时农业又是水资源的第一大用户,许多学者对农产品的虚拟水进行了研究。结果表明全球农业用水中有13%以虚拟水形式在国家、地区间流动,粮食进口能够有效降低区域水资源消耗,具有节水效益,因此通过虚拟水贸易可以实现对水资源的优化配置[31-32]。然而,也有研究表明部分区域间农产品的虚拟水流动方向与水资源禀赋相反,这与土地、人力等资源比较优势以及产业、贸易结构相关[33-34],因此基于虚拟水贸易的优化配置要考虑多种因素的影响。随着研究的深入,相关学者运用投入产出、全生命周期评价(LCA)等方法对高耗水行业、区域全行业虚拟水流动格局及伴生效应展开了研究,能源、化工、纺织业、旅游业等行业的生产消费伴生的虚拟水流动格局及带来的社会、经济、生态效应引起广泛关注[35-38]。虚拟水贸易驱动机制的分析结果表明,影响区域虚拟水贸易的主要因素有经济、人口、用水强度和产业结构,经济和人口的增长会显著引起虚拟水流动量的增加,而产业结构和水资源的可获得性不仅影响各国的生产能力,而且影响贸易产品的种类[39-41]。

(2)产品、区域水足迹评价及区域水足迹可持续性分析。

水足迹通过研究个人、家庭、部门、某行业、城市到整个国家生产或者消费中包含的虚拟水数量,从生产者和消费者的角度研究用水。水足迹评价体系可以刻画在生产或消费过程中不同种类的用水,并且可以明确水足迹产生的时间、地点以及具体的水源种类,是多维的水资源研究指标。水足迹的计算方法可分为自下而上和自上而下两种。自下向上法是以生产树法为代表通过对系统中各工序的水足迹进行核算得到系统水足迹的方法,能够详细刻画各生产环节用水特征。Wang Wei 等人利用 AquaCrop 模型计算的2000—2014年我国小麦水足迹的变化探讨了节水灌溉普及率对我国小麦生产水足迹的影响采用就是典型的自下而上的方法[42]。此外,自下而上的水足迹计算方法还有基于统计数据、遥感以及蒸散发模型等方法[35-37]。自上向下的方法一般基于消费平衡理论,其结果能够反映研究虚拟水在不同部门间的流转以及区域对外部水资源的依赖程度。基于投入产出模型的单区域或多区域水资源投入产出法是自上而下法的典型代表[43]。虚拟水转移的便捷性使区域无需运输实体水就能依赖其他区域水资源,并且随着贸易规模的不断扩大,各区域外部水资源的依赖性将会不断增加[44-45]。因此,区域水足迹可持续性分析成为水足迹研究的另一焦点,研究者通过对区域生产水足迹与消费水足迹的分析,对区域的水足迹构成进行深入讨论,分析区域的水资源自给率、水资源进口依赖程度,根据水资源匮乏程度分析识别影响区域水资源可持续性问题的根源[46]。

(3)实体水—虚拟水耦合流动规律及区域水资源安全调控。

掌握虚拟水流动规律,对虚拟水流动路径进行刻画,将虚拟水理论融入水资源管理体系,使虚拟水成为能够有效调控水资源保障区域水安全的重要工具是当前虚拟水研究的另一热点。吴普特等[6,26]提出的实体水—虚拟水耦合流动理论基本框架和量化方法,为进一步解析实体水和虚拟水循环、转化、流动作用机制、建立全过程量化方法提供了基本思路。这是对自然—经济—社会复杂系统中水文过程的认识开展的重要探索。Zhao Xu 等人表示我国当前的实体水和虚拟水流在缓解受水区的水压力方面并没有起到主要作用,但却加剧了水输出地区的水压力[47]。因此,如何通过优化调控实体水和虚拟水的流动格局来缓解区域水资源压力对水资源管理具有重要意义。为了给国家或区域的水资源决策提供支撑,国内外对如何将虚拟水理论应用于水资源管理开展了许多研究,更多地开始关注水资源系统与社会系统、经济系统的复杂耦合关系。Tony Allan 指出,人类生存所需要的水资源中,直接饮用获取的占10%,其余90%则是通过农副产品的食用而获得,这部分水资源恰恰是可以通过农副产品贸易来获得的,存在较大的调整空间[48]。Dennis 对虚拟水战略在保障粮食安全和实现其他国家层面目标时的作用进行了分析,并从经济角度阐述了虚拟水资源实践的相对优势[49]。Ye Quanliang 等人开发了考虑经济效益和环境影响的实体水—虚拟水统筹配置模型对北京地区的水资源供给模式进行了探索,得出虚拟水贸易是北京满足农业需求的主要水源,而工业和环境对水资源的消耗主要通过实体水的形式,再生水是其主要水源[50]。Wang Zongzhi 等人从水资源经济价值的角度在线性优化模型中加入机会成本

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对粮食贸易进行了优化，得出了调整我国粮食虚拟水贸易的相关结论和启示[51]。

3 虚拟水理论应用前景

从水资源的学科发展来看，虚拟水理论对水资源利用规律独特的阐释力推动了水资源管理领域制度及体系的不断创新，为区域水资源的高效管理和战略储备提供了一种新选择，受到了多学科领域学者以及专家的高度关注[52-54]。同时，虚拟水理论的产生以及不断的拓展完善推进了虚拟水贸易格局等领域的研究进程，为评价区域水资源承载情况、确定水资源分配方案及由此衍生出的技术改革和产业结构调整提供了重要依据，也为国家水资源战略及贸易体系的不断优化提供了坚实的理论基础[55-56]。基于此，本文介绍了虚拟水理论在水资源管理中的应用前景，并根据农业水资源管理现状，提出了虚拟水理念应用于农业用水管理中的三大科学设想。

3.1 虚拟水理论在水资源管理中的应用前景

虚拟水"流动"的便捷性使商品贸易成为缓解区域水资源短缺的一种经济、可行的方法[30]。基于此，虚拟水战略被提出，即贫水的国家或地区可以集中有限水资源在低耗水高附加值的产业上获得财富后通过从富水国家或地区购买水密集型产品来保障水资源安全的战略。然而，虚拟水战略能否及如何被应用至今仍是学界不断探讨的热点。不可否认的是，基于可持续发展、比较优势等理论合理评价一个国家或区域的水足迹消耗及虚拟水贸易结构是识别区域发展水资源问题关键、根源的有力手段。因此，建立起从社会效益、经济效益、生态效益等多维度合理评价调控区域产业结构进而以此影响虚拟水贸易格局的方法体系，结合输入区与输出区间的虚拟水生态补偿制度，为国家或区域制定合理发展规划、产业规模布局，使虚拟水贸易真正落地，将是虚拟水理论在水资源管理中应用的重要进展。

随着生产力的提高，人类活动对水文水循环系统影响程度的不断加深，当前的水循环已经进入实体水－虚拟水"二维三元"耦合流动阶段[6]。从实体水与虚拟水统筹管理的视角来看，水资源利用的最终目的即是满足人类社会对商品和服务的需求，这些商品和服务可以通过实体水在本地进行生产获得，也可以通过商品贸易以虚拟水战略的途径来获得。在此背景下，水资源管理可以通过建立起实体水－虚拟水统筹的水安全保障模式，综合利用节水、实体水调运、虚拟水贸易以及产业结构调整等措施保障区域水安全，制定水足迹控制标准，从生命周期角度提升全产业链用水效率，扩大区域具有水足迹比较优势的产品生产规模，统筹实体水与虚拟水管理，实现区域全口径水资源的可持续利用。

3.2 虚拟水理念应用于农业用水管理的科学设想

农业的水资源利用量占全国用水量的60%左右，是我国用水最多的部门，在水资源利用中占绝对的主导地位。同时，虚拟水的研究始于农产品，现阶段学者开展了许多农业领域的研究，并取得了丰硕成果[57-59]。因此，本文从农业领域着手，结合上述虚拟水在水资源管理中的应用前景，提出虚拟水理念应用于农业用水管理中的三大设想。

(1)制定农业生产水足迹控制标准。

虽然农业水资源利用效率评价在指标的概念发展上取得了丰硕的成果，但是传统水资源利用评价主要以蓝水作为指标，忽略了绿水资源对于农业粮食安全的重要作用[60]，且没有考虑对水环境的影响[61]。农业水足迹控制标准指对于每一种作物，根据不同地区和同一地区不同农田生产单位产品水足迹的差异，建立一个分级基准，并以此作为农业生产活动时对水资源利用效率的控制红线。对生产者来说，低于最低用水效率控制红线意味着造成了对水资源的浪费，需通过各种惩罚措施督促生产者提高技术从而提升用水效率；高于最高用水效率控制标准，可以通过奖励激励的手段来进一步巩固这种生产方式，并推广相应的生产技术。此标准还可具体将水足迹划分为水稀缺足迹和水污染足迹分别进行评价，充分发挥水足迹概念特性并结合宏观政策影响力推动农业节水工作进程。不同用水过程中的基准水足迹可以作为农民和企业节水努力的目标，也可以为政府向不同用户分配取水许可时提供参考。不同领域内的行业协会可以制定自己的区域或全球尺度的水足迹基准值，同时，政府也可以在这方面采取举措，包括制定法规或立法，并淘汰落后的用水技术。

(2)建立农业生产虚拟水补偿制度。

传统水资源利用评价指标多局限于生产活动本身，而忽略了社会消费活动对水资源利用与消耗的影响[62]。伴随着市场经济的不断发展，农业、工业、生活和生态所需要的水资源量越来越大，且不同行业效益差距较大，农业在市场竞争中的弱势地位逐渐凸显。虚拟水补偿是指农产品流入区对农产品输出区进行的补偿[63]。由于农产品是水资源密集型产品，粮食的区域间调运不仅伴随着巨大的虚拟水流动，还对区域环境造成了影响。"北粮南运"加剧了北方地区资源环境压力，也阻碍了粮食输出区的经济

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发展,加大了南北方经济发展水平的差距。应充分认识到粮食贸易背后的资源不合理配置问题,统筹实体水—虚拟水管理,建立区域间农业虚拟水补偿制度。虚拟水输入地因虚拟水输入可以缓解输入地的社会经济发展的水资源压力或者置换出水资源用于其他产业的生产,其社会经济系统的收益增量按照一定分配方法在输出区和输入地之间进行分配,达到一种合作博弈的纳什均衡状态。在这种合作下,不仅虚拟水输入地社会经济的水资源安全得到保障,而且虚拟水输出地可以从粮食贸易中获得利益,系统收益增量相当于资源补偿以维持或恢复生态环境。

(3)实施区域实体水—虚拟水统筹管理。

全球 76% 的虚拟水流动源于粮食贸易,基于水资源利用效率逆差,合理的虚拟水流动格局可以节水[64]。然而,我国的粮食"北水南调"虚拟工程每年"浪费"约 93 亿 m^3 蓝水资源,印度每年由北部的旁遮普等缺水地区流向东部水资源更丰富的比哈尔等地区的水资源规模也高达 220 亿 m^3[65]。因此,实施区域实体水—虚拟水统筹管理,从全口径水资源视角下进行水资源规划十分重要。如前所述,实体水—虚拟水统筹的水安全是指保障社会经济发展对全口径水资源的需求。对于农业领域,在一个区域实施实体水—虚拟水统筹的水资源管理模式,需要从系统的角度看待问题,评估区域食物需求及生产能力,统筹实体水与虚拟水资源,综合利用节水、实体水调运、虚拟水贸易等措施,保障区域的农业生产的水安全以及区域社会经济发展的食物安全,维持区域可持续发展。

4 总结

20 世纪 90 年代虚拟水概念提出以来,其基本理论、核算方法及案例研究在国内外得到了蓬勃发展,水足迹概念的提出更是丰富了虚拟水的理论研究,成为虚拟水研究的重要分支。本研究系统地对虚拟水的概念和特点进行了解析,指出虚拟水的本质是水资源在国民经济系统中的价值表现形式,虚拟水和水足迹是对水资源的价值形成、价值转移和价值消费全过程的表达手段。虚拟水的研究经历了虚拟水概念雏形初现的萌芽阶段、虚拟水概念正式形成的初步发展阶段、以水足迹为代表的量化评价方法形成的快速发展阶段和逐步融入水资源管理体系的进一步发展阶段四个时期。当前的主要研究内容围绕以下三方面开展:(1)虚拟水流量、流向、贸易格局核算及其伴生效应、驱动机制分析;(2)产品、区域水足迹评价及区域水足迹可持续性分析;(3)实体水—虚拟水耦合流动规律及区域水资源安全调控。虽然虚拟水"流动"的便捷性使商品贸易成为缓解区域水资源短缺的一种经济、可行的方法,虚拟水研究也取得了丰硕的成果,但如何将其应用于水资源管理还是目前研究的难点,目前国内外研究开始探索将虚拟水理论应用于现有水资源管理体系的方式方法,使之成为支撑产业结构调整、虚拟水贸易战略和节水政策等管理实践的重要依据,着力构建实体水—虚拟水耦合流动的社会水循环理论体系,深入剖析其耦合流动的驱动机制,并利用此规律探索能够实现现代环境在区域水资源高效利用和可持续调控的方法,通过实体水—虚拟水统筹的广义节水和联合配置保障水资源系统的安全稳定运行。

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·译文·

DOI:10.13476/j.cnki.nsbdqk.2020.0026

A review of the development and application prospect of virtual water theory

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Abstract: Since the end of the twentieth century, the concept of virtual water is raised, the basic theory, calculation methods and case studies both at home and abroad has been booming, containing virtual water content has been established gradually, virtual water trade, virtual water flow, water balance, water footprint and other economic and social management of water resources of the concept of theoretical framework, become the important method of water cycle in the economic and social evolution. Systematically in this paper on the concept and characteristics of virtual water analysis, the emergence and development of the theory of virtual water, expounds the current research progress of virtual water and virtual water theory, analyzes the application prospect in water resources management, put forward the applied to the three scientific idea of agricultural water resources management, to provide the reference to the research of virtual water theory and application.

Key words: virtual water; water footprint; water resources management; application prospect

With the progress of human civilization and the development of economy and society, the increasing demand for water resources, the deteriorating water environment and the unreasonable use of water resources have aggravated the water resources crisis, gradually deepened people's understanding of the law of water resources evolution, and spawned a new concept of water resources management. At the end of the 20th century, with the continuous development of inter-regional trade scale, the volume of virtual water trade associated with inter-regional commodity circulation keeps increasing[1]. In this context, the traditional concept of water management that only considers physical water resources shows great limitations, and the concept of virtual water is thus generated, which puts forward new ideas for water resources management and security strategy of supply and demand, and has become a hot topic of water resources research[2-3]. In 2002, Dutch scholar Hoekstra further expanded the concept of virtual water and proposed the water footprint theory, which

Received: 2019-08-26 **Take back**: 2019-12-20 **Online publishing**: 2020-01-13
Online publishing address: http://kns.cnki.net/kcms/detail/13.1334.tv.20200111.1501.002.html
Funds: National key Research and Development Program of China (2018YFF0215702); Scientific and Technological Research Program of Chongqing Municipal Education Commission (KJ1600533); Open Research Fund of State Key Laboratory of Watershed Water Cycle Simulation and Regulation, China Academy of Water Resources and Hydropower Research (IWHR-SKL-201601; IWHR-SKL-201712)
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provided a multidimensional index for the water resources evaluation system[4]. Water footprint can systematically evaluate the utilization approaches of water resources (utilization, consumption and purification of water pollution), enrich the connotation and denotation of the traditional water resources evaluation system, better depict the demand and occupation of water resources for social and economic development, and become an important branch in the field of virtual water research[5]. In general, the virtual water theory more truly reflects the consumption and flow of water resources in human society, reveals the nature of the value utility of water resources on economic society, and is a new concept of water resources[6]. This paper mainly introduces the development and application prospect of virtual water theory. Firstly, the concept and connotation of virtual water are analyzed, and the generation and development of virtual water theory are reviewed. Then, the research progress of virtual water is described in detail. Finally, this paper introduces the application prospect of virtual water in water resources management and puts forward three scientific assumptions about the application of virtual water in agricultural water resources management.

1 Virtual water concept

Virtual water refers to the total amount of water resources consumed during the production of a product or service, that is, the amount of water resources condensed in the product or service. This concept was first put forward in agricultural products as the main research object, and then the concept of virtual water was further extension and improvement of the applicable objects from agricultural products to a wider range of products and services, gradually established a contain virtual water content, virtual water trade, virtual water flow, water balance, water footprint and other economic and social management of water resources of the concept of theoretical framework[7-9]. Virtual water is not a real material resource, but an " invisible" water resource contained in the product in a" virtual" form. The essence of virtual water flow is the process that water resources are converted into commodities through the economic system, and its value is transferred in the social production-trade-consumption system. Virtual water is the manifestation of the value of water resources in the national economic system. The characteristics of the concept of virtual water are as follows: first, it relates water to the production of products, especially agricultural products. It emphasizes that the water resources consumed by the production of agricultural products include not only surface water and groundwater (blue water), but also soil water (green water). Secondly, virtual water embedded in commodities can realize the exchange of water resources between countries or regions through trade, which is equivalent to the secondary distribution of water resources embedded in commodities at the consumption end. The introduction of the concept of virtual water is of great significance to the research on rational allocation of water resources, carrying capacity of water resources and efficient utilization of water resources. It puts forward the idea that water resources do not disappear after being used by production activities, but are embedded in goods or services in a virtual form to reflect their value through trade and consumption. This has established the bridge of water resources system and social and economic system research, and widened the field of water resources research.

Water footprint is an important development of virtual water research. It is a consumption-based water index, referring to the amount of water consumed to produce goods or services required by human society. Different from the traditional water consumption index, water footprint includes not only the direct use of water by consumers or producers, but also the indirect use of water. According to different water sources, water footprint can be divided into blue water footprint (the amount of surface water and groundwater consumed by production), green water footprint (the amount of precipitation consumed by production), and gray water footprint (the amount of water needed to dilute the wastewater produced by production)[10-11]. Blue water footprint and green water footprint can also be collectively called water scarcity footprint (the total amount of water consumed by production).

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Gray water footprint can be called water pollution footprint, according to the type of pollution can also be subdivided into water eutrophication footprint. Compared with the traditional water consumption index, the water footprint theory has the following characteristics: (1) water footprint distinguishes the types of water resources consumed by production activities from the perspective of water sources, which can more completely and clearly describe the use and consumption of water resources; (2) water footprint clarifies the occupancy of water resources by different uses in time and space, which can lay the foundation for regional environmental assessment and evaluation of the impact of water use on the economy and society. The concept of water footprint connects production and consumption activities with the consumption and pollution of water resources, making people realize that the total consumption and pollution of water resources are ultimately inseparable from the types and quantities of products produced and consumed. At the same time, water footprint, as a water consumption indicator related to people′s production and consumption, can reveal water resource dependence or crisis state by combining water footprint with available water resources, providing an important basis for the study of water security strategy[12-13].

From the essence of the concept, production water footprint is the efficiency expression of the transformation process from physical water to virtual water, which is used to measure the utilization efficiency of water resources in the process of commodity production. Virtual water flow is the migration of water resource value in commodities in the social and economic system in a virtual form and measures the flow of water resource value. Consumption water footprint refers to the index of people′s consumption of water resources, which measures the intensity of economic and social demand for water resources. Virtual water and water footprint are the means to realize the value formation, value transfer and value consumption of water resources.

2 Virtual water theory development

2.1 Development course of virtual water theory

Since the initial emergence of the idea of embedded water by Israeli economists in the 1980s, the research on virtual water has experienced about 30 years of development, which can be divided into four stages according to the research progress of virtual water theory (Tab. 1).

Tab. 1 The development course of virtual water theory

Development Stage	Research Progress	Phase characteristics
Budding Stage (1993 years ago)	In the 1980s, concepts similar to the meaning of virtual water began to emerge, such as external water introduced by Haddadin, embedded water used by Tony Allan and water, food and trade combination used by Mc Calla all expressed the meaning similar to virtual water[14].	The prototype of the virtual water concept began to emerge.
Preliminary Development Stage(1993-2001)	In 1993, Tony Allan proposed the concept of virtual water and illustrated the application of virtual water theory by taking the long-term solution of water shortage in the Middle East as an example[15]. Since then, the concept of virtual water has been gradually accepted and relevant studies have been carried out[16-17]. The meaning of virtual water trade is gradually formed, which broadens the cognitive scope of water resources and enriches the solutions to water problems.	The concept of virtual water was formally proposed and has been developed initially.
Rapid Development Stage (2002-2015)	In 2002, Hoekstra proposed the theory of water footprint, which promoted the research process of virtual water quantification and became the focus of virtual water research[4]. Studies on virtual water trade pattern, associated effect, embodiment of comparative advantage and other relevant aspects have been continuously deepened[18-22]. A system of methods such as virtual water quantification, virtual water trade pattern analysis and associated impact assessment has been gradually formed[23-25]	Virtual water theory has attracted widespread attention and has been rapidly developed, and its theoretical method system has continued to mature.
Further development stage (2016 to present)	Further development stage(2016 to present) The theory of " two-dimensional and ternary" coupled flow of physical water and virtual water has promoted the research process of integrating virtual water into the water resource management system[6,26,27]. Related scholars have begun to explore ways to regulate water resources and solve water problems through virtual water methods[28-30].	The theory and research of virtual water have been further developed. Attempts have been made to solve the problem of water resources from the perspective of virtual water, and the traditional water resource management model has been further expanded.

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2.2 Research progress of virtual water theory

The study of virtual water theory has gone through four stages of development, which has become an important method to describe the evolution law of water cycle in social and economic development. The research progress of virtual water can be divided into the following three aspects.

(1) Virtual water flow, flow direction, trade pattern accounting and associated effect evaluation, driving mechanism analysis.

The concepts of virtual water flow and virtual water trade are the core of virtual water theory. Virtual water trade between countries or regions can alleviate the shortage of water resources caused by the uneven spatial and temporal distribution of water resources among regions or the low productivity of water resources, resolve regional conflicts caused by it, and achieve water and food security for socioeconomic development. Since virtual water was originally used to measure the amount of water resources required for agricultural products, and agriculture is the largest user of water resources, many scholars have studied virtual water for agricultural products. The results show that 13% of the global agricultural water flows between countries and regions in the form of virtual water. Food imports can effectively reduce the consumption of regional water resources and have water-saving benefits. Therefore, the optimal allocation of water resources can be realized through virtual water trade[31-32]. However, studies have also shown that the virtual water flow direction of agricultural products between some regions is opposite to water resource endowment, which is related to the comparative advantages of land, human and other resources, as well as the industrial and trade structure[33-34]. Therefore, the optimal allocation based on virtual water trade should consider the influence of various factors. With the deepening of research, related scholars have used water resources input-output model, life cycle assessment (LCA) and other methods to conduct research on virtual water flow patterns and associated effects in high water consuming industries and regional entire industries. The virtual water flow pattern associated with production and consumption in energy, chemical, textile and tourism industries and its social, economic and ecological effects have attracted wide attention[35-38]. The analysis results of the driving mechanism of virtual water trade show that the main factors influencing regional virtual water trade are economy, population, water intensity and industrial structure. The growth of economy and population will significantly cause the increase of virtual water flow momentum, while the industrial structure and availability of water resources not only affect the production capacity of countries, but also affect the types of traded products[39-41].

(2) Product, regional water footprint evaluation and regional water footprint sustainability analysis.

Water footprint studies water use from the producer and consumer perspectives by studying the amount of virtual water contained in the production or consumption of individuals, households, sectors, industries, cities and entire countries. Water footprint evaluation system can describe different types of water used in the process of production or consumption, and can specify the time, place and specific type of water source of water footprint, which is a multidimensional indicator of water resources research. The calculation methods of water footprint can be divided into bottom-up and top-down. The bottom-up method, represented by the production tree method, calculates the water footprint of each process in the system to obtain the water footprint of the system, which can describe the water characteristics of each production link in detail. Wang Wei et al[42]. used the AquaCrop model to calculate the changes of China's wheat water footprint from 2000 to 2014 to explore the impact of the penetration rate of water-saving irrigation on China's wheat production water footprint using a typical bottom-up approach. In addition, bottom-up calculation methods for water footprints are based on statistical data, remote sensing, and evapotranspiration models[35-37]. The top-down approach is generally based on the consumption balance theory, and the results can reflect the flow of virtual water between different sectors and the dependence

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of regions on external water resources. The water resources input-output model of single-region or multi-region is a typical representative of the top-down method[43]. The convenience of virtual water transfer enables regions to rely on other regional water resources without the need to transport physical water. As the scale of trade continues to expand, the dependence on external water resources of each region will continue to increase[44-45]. Therefore, regional water footprint sustainability analysis has become another focus of water footprint research. Through the analysis of the water footprint of regional production and consumption, the researchers conducted in-depth discussions on the composition of the water footprint of the region, analyzed the regional water resource self-sufficiency rate and water resource import dependence, and identified the root causes affecting the sustainability of regional water resources based on the analysis of water resource scarcity[46].

(3) Physical water-virtual water coupling flow law and regional water resources security regulation.

To grasp the law of virtual water flow, to describe the virtual water flow path, to integrate the virtual water theory into the water resources management system, and to make virtual water become an important tool to effectively regulate water resources and guarantee regional water security is another hot spot of current virtual water research. Wu pute et al.[6,26] proposed the basic framework and quantitative method of physical virtual water coupled flow theory, which provided a basic idea for further analyzing the circulation, transformation, flow action mechanism of solid water and virtual water and establishing a whole-process quantitative method. This is an important exploration of the understanding of hydrological processes in complex systems of nature, economy and society. Zhao Xu et al. Indicated that the current physical water and virtual water flow in China has not played a major role in alleviating the water pressure in the water receiving area, but it has aggravated the water pressure in the water export area[47]. Therefore, how to alleviate regional water resource pressure by optimizing and regulating the flow pattern of physical water and virtual water is of great significance to water resource management. In order to provide support for national or regional water resources decision-making, many researches have been carried out at home and abroad on how to apply virtual water theory to water resources management. More studies have begun to focus on the complex coupling relationship between water resources system, social system and economic system. Tony Allan pointed out that among the water resources needed by human survival, 10% is obtained from direct drinking, while the other 90% is obtained from the consumption of agricultural and sideline products. This part of water resources can be obtained through trade in agricultural and sideline products. So there is much room for adjustment[48]. Dennis analyzed the role of virtual water strategy in ensuring food security and achieving goals at the level of other countries, and elaborated the comparative advantages of virtual water practices from an economic perspective[49]. Ye Quanliang et al. developed a physical water-virtual water pooling model considering economic benefits and environmental impacts to explore the water supply model in Beijing. It is concluded that virtual water trade is the main water source for Beijing to meet agricultural needs, while industrial and environmental consumption of water resources is mainly in the form of physical water, and recycled water is the main water source[50]. From the perspective of the economic value of water resources, Wang Zongzhi et al. added opportunity cost into the linear optimization model to optimize food trade, and drew relevant conclusions and enlightenment on adjusting China's food virtual water trade[51].

3 Application prospect of virtual water theory

From the perspective of the development of water resources, the unique explanatory power of virtual water theory on the law of water resources utilization has promoted the continuous innovation of the system and system in the field of water resources management. This provides a new option for efficient management and strategic reserve of

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regional water resources, which has been highly concerned by scholars and experts in multi-disciplinary fields[52-54]. At the same time, the emergence of the virtual water theory and the continuous expansion and improvement of the virtual water trade pattern and other areas of the research process. It provides an important basis for the evaluation of regional water resources carrying capacity, the determination of water resources distribution plan and the technical reform and industrial structure adjustment derived from it, as well as a solid theoretical basis for the continuous optimization of national water resources strategy and trade system[55-56]. Based on this, this paper introduces the application prospect of virtual water theory in water resources management, and puts forward three scientific assumptions of applying virtual water theory to agricultural water resources management according to the current situation of agricultural water resources management.

3.1 Application prospect of virtual water theory in water resources management

The convenience of virtual water flow makes commodity trade an economic and feasible method to alleviate regional water shortage[30]. Based on this, the virtual water strategy is proposed, that is, water-poor countries or regions can concentrate limited water resources to obtain wealth in low-consumption and high-value-added industries and then guarantee water resource security by purchasing water-intensive products from water-rich countries or regions. However, whether and how virtual water strategy can be applied is still a hot topic in academic circles. It is undeniable that rational evaluation of water footprint consumption and virtual water trade structure of a country or region based on the theories of sustainable development and comparative advantage is a powerful means to identify the key and root causes of regional water resources development. Therefore, it is very important to establish a method system to rationally evaluate and regulate regional industrial structure from social benefits, economic benefits, ecological benefits and other dimensions and then influence the pattern of virtual water trade. Combining the virtual water ecological compensation system of the input area and the output area, formulating a reasonable development plan and industrial scale layout for the country or region, and making the virtual water trade truly implemented, will be an important advance in the application of virtual water theory in water resources management.

With the improvement of productivity, the influence of human activities on hydrologic and water circulation system is deepening. The current water cycle has entered the " two-dimension three-element" coupling flow stage of physical water and virtual water[6]. From the perspective of integrated management of physical water and virtual water, the ultimate goal of water resources utilization is to meet the demand of human society for commodities and services. These goods and services can be obtained locally through physical water production or through virtual water strategy through commodity trade. In this context, water resources management can establish the water security guarantee mode of integrating physical water with virtual water, and ensure regional water security through comprehensive utilization of water-saving, physical water transportation, virtual water trade and industrial structure adjustment. Develop standards for water footprint control, improve the water resource utilization efficiency of the whole industrial chain from the perspective of life cycle, expand the scale of product production with comparative advantage of water footprint in the region, coordinate the management of physical water and virtual water, and realize the sustainable use of regional full-caliber water resources.

3.2 Scientific assumption of the application of virtual water concept in agricultural water management

Agricultural water resources use accounts for about 60% of the country's water consumption. It is the sector that uses the most water in our country and occupies an absolute dominant position in water resources use. At the same time, the research on virtual water began with agricultural products. At this stage, scholars have carried out research in many agricultural fields and achieved fruitful re-

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sults[57-59]. Therefore, this article starts from the agricultural field and combines the above-mentioned application prospects of virtual water in water resources management, and proposes three major ideas for the application of virtual water concepts in agricultural water management:

(1) Formulate the water footprint control standards for agricultural production.

Although the evaluation of agricultural water resources utilization efficiency has made fruitful achievements in the concept development of indicators, the traditional evaluation of water resources utilization mainly takes blue water as the indicator, ignoring the important role of green water resources in agricultural food security[60] and without considering the impact on the water environment[61]. Agricultural water footprint control standard refers to the establishment of a hierarchical benchmark for each crop according to the difference of water footprint of different farmland production units in different regions and the same region, which is used as the control red line for water utilization efficiency in agricultural production activities. For producers, lower than the red line of minimum water efficiency control means waste of water resources, so various punitive measures should be taken to urge producers to improve technology to improve water efficiency. Above the maximum water use efficiency control standards, incentives can be used to further consolidate this mode of production and promote the corresponding production technology. In addition, water footprint can be divided into water scarcity footprint and water pollution footprint for evaluation, giving full play to the conceptual characteristics of water footprint and combining the influence of macro policies to promote the process of agricultural water-saving. The benchmark water footprint in different water use processes can be used as a target for farmers and businesses in their efforts to save water, and can also be used as a reference for governments in allocating water access permits to different users. Trade associations in different fields can set their own regional or global water footprint benchmarks. At the same time, the government can also take measures in this regard, including the enactment of regulations or legislation, and the elimination of outdated water technology.

(2) Establish a virtual water compensation system for agricultural production.

Traditional water resource utilization evaluation indexes are mostly limited to production activities themselves, while ignoring the impact of social consumption activities on water resource utilization and consumption[62]. With the continuous development of market economy, more and more water resources are needed for agriculture, industry, life and ecology, and the benefit gap between different industries is large, so the weak position of agriculture in market competition gradually becomes prominent. Virtual water compensation refers to the compensation made by the inflow zone of agricultural products to the output zone of agricultural products[63]. As agricultural products are water-intensive products, the inter-regional transport of grain is not only accompanied by huge virtual water flow, but also has an impact on the regional environment. The food north-south Water Transfer Project aggravates the pressure on resources and environment in the northern region, hinders the economic development of the grain export region and widens the gap between the economic development levels in the South and the North. It is necessary to fully recognize the unreasonable allocation of resources behind food trade, coordinate the management of physical water and virtual water, and establish the system of interregional compensation for agricultural virtual water. Virtual water input fields for virtual water input can alleviate the pressure of the input fields of the social and economic development of water resources or replacement water is used in the production of the other industry, its social and economic system of revenue increment method according to certain allocation between the output and input fields distribution, to achieve a Nash equilibrium of cooperative game. Under this kind of cooperation, not only the social and economic water resources security of the virtual water importing place is guaranteed, but also the virtual water exporting place can gain benefits

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from food trade, and the increment of system benefits is equivalent to resource compensation to maintain or restore the ecological environment.

(3) Implement the integrated management of physical water and virtual water in the region.

Globally, 76% of virtual water flows are derived from food trade. Based on the deficit of water resource utilization efficiency, a reasonable virtual water flow pattern can save water[64]. However, the virtual project of " north to south water diversion" for grain in China wastes about 9. 3 billion m3 of blue water resources every year, and the annual water resources in India from the water-scarce areas such as Punjab in the north to the more water-rich areas such as Bihar in the east are up to 22 billion m^3[56]. Therefore, it is very important to implement the integrated management of regional physical water and virtual water and carry out water resources planning from the perspective of full-caliber water resources. As mentioned above, the water security of physical water-virtual water pooling refers to the demand of full caliber water resources for social and economic development. For the agricultural field, implementing a water resource management model of integrated physical water-virtual water in a region requires a systematic perspective, assessing regional food demand and production capacity, coordinating physical water and virtual water resources, and comprehensively using water-saving and physical resources. Measures such as water transfer and virtual water trade ensure the water security of agricultural production in the region and the food security of regional socio-economic development, and maintain sustainable regional development.

4 Conclusion

Since the concept of virtual water was put forward in the 1990s, its basic theory, accounting methods and case studies have been developed vigorously at home and abroad. The concept of water footprint enriches the theoretical research of virtual water and becomes an important branch of virtual water research. This paper systematically analyzes the concept and characteristics of virtual water, and points out that the essence of virtual water is the expression form of the value of water resources in the national economic system, and virtual water and water footprint are the expression means of the whole process of the formation, transfer and consumption of the value of water resources. The research of virtual water has gone through four stages: the building stage where the concept of the virtual water concept is emerging, the preliminary development stage where the virtual water concept is formally formed, the rapid development stage formed by the quantitative evaluation method represented by water footprint, and the further development stage of integration into the water resources management system. At present, the main research contents focus on three aspects: ① virtual water flow, flow direction, trade pattern accounting and associated effect evaluation, driving mechanism analysis; ② product, regional water footprint evaluation and regional water footprint sustainability analysis; ③ physical water-virtual water coupling flow law and regional water resources security regulation. Although the convenience of virtual water flow makes commodity trade an economic and feasible method to alleviate regional water shortage. The research on virtual water has also made great achievements, but how to apply it to water resources management is still a difficult problem. At present, researchers begin to explore ways and methods to apply the virtual water theory to the existing water resources management system, making it an important basis to support the management practices such as industrial structure adjustment, virtual water trade strategy and water-saving policy. Strive to build physical water - virtual water flow coupling system of social water cycle theory, analyze the coupling flow driving mechanism, and use the law to modern environment in regional water resources utilization and sustainable control, the method of generalized water through the entity physical water - virtual water as a whole and joint configuration to ensure safe and stable operation of the water resources system.

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