·专论与综述·

农业灌溉水资源优化配置研究进展

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摘　要：水资源短缺是制约农业可持续发展的关键因素，因此农业灌溉水资源的优化配置对于保障粮食安全和水安全具有重要意义。该研究基于农业灌溉水资源优化配置的主要类型，对单一作物灌溉优化决策、多作物水土资源优化配置和灌溉渠系水资源优化调度 3 个方面的研究进展进行了系统综述。同时指出了当前农业灌溉水资源优化配置中存在的主要问题和未来研究方向，研究认为当前的农业灌溉水资源优化配置应在如下 4 个方面进行完善：1）建立更具生理意义的作物水分-产量-品质模型；2）在气候变化和人类活动的情景下实现农业灌溉水资源的优化配置；3）构建全面考虑水源、渠系、灌区面积、作物配置以及生育阶段的系统性农业灌溉水资源优化配置模型；4）建立以棵间蒸发最小为目标的动态灌溉优化决策模型。研究可为中国的粮食安全和水安全提供理论指导。

关键词：模型；作物；水资源；灌溉优化决策；非充分灌溉；节水调质；渠系

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0　引　言

水资源是促进社会经济可持续发展的关键因素，同时是保障粮食安全和生态健康的重要战略资源。中国是农业大国，农业用水量占总用水量的 60% 以上，其中 90% 的农业用水用于农田灌溉。2023 年中央一号文件[1]指出“统筹推进高效节水灌溉，全方位夯实粮食安全根基”，因此合理配置农业灌溉水资源于保障中国粮食和水安全具有重要意义。

农业灌溉水资源优化配置属于水资源优化配置的重要范畴，是指在整个灌溉季节，如何将可利用的、有限的农业灌溉水资源在时空上进行合理的分配，以达到预先设定的某种目标[2]。国外从 20 世纪 60 年代开始对农业灌溉水资源优化配置进行研究，随着 20 世纪七八十年代数学规划、控制原理和模拟技术等的引入，农业灌溉水资源优化配置的研究得到了迅速发展[3]。20 世纪 90 年代为了解决水资源短缺和水环境问题，传统的以水量为主的优化配置开始向水质、环境效益和水资源可持续利用方向转变[2]。21 世纪以来，数学规划和系统分析新方法的不断涌现为农业灌溉水资源优化配置的研究提供了更强大的技术支持。而中国从 20 世纪 80 年代才开始重视水资源优化配置问题，先后经历了“就水论水配置”“宏观经济配置”“面向生态配置”“广义水资源配置”“跨流域大系统配置”和“量质一体化配置”阶段[4]，随后基于广义耗水量的水资源规划理论被提出[5]，各种相应的农业灌溉水资源优化配置模型也相继被应用。

目前已发表文章多针对作物灌溉制度的优化、作物种植结构、多水源调控、水-能源-粮食协同优化、灌区水资源调控理论与技术和水资源优化配置模型等方面进行综述[6-10]，而关于系统分析农业灌溉水资源优化配置研究现状的研究还较少。因此，本研究依据决策对象对农业灌溉水资源优化配置相关研究进行分类，并对不同分类进行系统性综述，以期为保证中国粮食安全和水安全提供理论依据。

1　农业灌溉水资源优化配置分类

就决策对象而言，目前的农业灌溉水资源优化配置主要可划分为 3 类：单一作物灌溉优化决策、多作物水土资源优化配置和灌溉渠系水资源优化调度[11-12]，具体研究内容、研究目标和研究尺度见表 1。其中，单一作物灌溉优化决策主要包括非充分灌溉下作物的灌水次数、灌水时间、灌水定额和灌溉定额，该部分内容多针对于田间和灌区尺度；多作物水土资源优化配置主要包括灌区内种植结构的优化和水资源优化配置，主要针对区域和灌区尺度；灌溉渠系水资源优化调度主要包括以灌区效益指标最优的渠系水量分配和以灌区水利工程运行管

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理指标最优为目标的渠系水量优化调度，主要针对灌区和渠系尺度。本文将从以上 3 个方面进行综述。

表 1　农业灌溉水资源优化配置的模型分类、研究内容、研究目标和研究尺度

Table 1　Model classification, research content, objectives and scale for optimal allocation of agricultural irrigation water resources

模型分类 Model classification	研究内容 Research content	研究目标 Research objective	研究尺度 Research scale
单一作物灌溉优化决策 Single crop irrigation optimal decision-making	以产量或经济效益最大为目标的灌溉优化决策	作物灌溉制度确定	田间、灌区
	基于水分-产量-品质响应关系的节水调质灌溉优化决策	作物灌溉制度确定	田间、灌区
多作物水土资源优化配置 Multi-crop water and soil resources optimal allocation	农业水土资源的多目标优化	灌区和作物间水量分配、种植结构	灌区
	空间布局优化	作物空间布局	灌区
	水-能源-粮食-生态协同优化	各用水部门水量分配	区域
灌溉渠系水资源优化调度 Canal system water resources optimal operation	灌区效益指标最优	渠系配水	灌区、渠系
	灌区水利工程运行管理指标最优	轮灌组划分、流量控制、闸门启闭	渠系

2　单一作物灌溉优化决策模型

作物灌溉优化决策是多作物水土资源优化配置和灌溉渠系水资源优化调度的基础，其以作物对水分亏缺的一系列适应机制为理论依据，是将一定灌溉水量在作物各生育阶段进行合理分配的多阶段决策过程[13-14]。充分灌溉是以获得高额稳定的单位面积产量为目标，但考虑到气候变化、水价上涨和农业供水不足等问题，充分灌溉在用水管理实践中很难实现。国内外分别从 20 世纪 70 和 80 年代开始提出了非充分灌溉的概念，指有意识地让作物某些生育期受旱以减少灌溉用水量，把节约的水量用于作物需水关键期或其他经济效益更高的地方[15]。众多研究表明虽然水分亏缺会减小作物产量，但适当的水分亏缺可以提高作物品质[16-18]。因此随着水资源短缺等问题的出现，国内外学者提出了一系列的规划模型对可供水量不足条件下的作物灌溉制度进行优化从而对生产实践进行理论指导。

2.1　以产量或经济效益最大为目标的灌溉优化决策

传统的灌溉优化决策追求总产量、效益最佳或限水条件下产量损失最小，其模型是通过一系列数学公式对灌溉制度进行描述和整合，并采用适宜的求解方法寻求最优解，主要包括目标函数、约束条件和求解方法。传统的灌溉优化决策模型常以各生育阶段的灌水量为决策变量[19]，随着研究的深入，其他农艺措施逐渐被考虑到决策过程中，例如播期[20]、种植密度[21]、灌水时间[22] 和施氮量[23] 等。另外传统的灌溉优化决策模型常以土壤含水量、灌水量和耗水量作为约束条件，考虑到作物生长条件和管理措施的不同，越来越多的因素被加入到优化模型的约束条件中。例如，MWIYA 等[24] 在优化江苏省北部玉米灌溉制度时考虑了深层渗漏；LI 等[25] 在优化河套灌区玉米灌溉制度时将生育期末土壤盐分累计量作为约束条件；WU 等[26] 在优化制种玉米的灌溉和施肥制度时约束了氮肥施用量。

建立作物产量与耗水量之间的定量关系是求解最优灌溉制度的基础，常用的模型包括水分生产函数、MODERATO[27]、AquaCrop[24]、CERES[28]、DAISY[29]、EPIC[30]、DSSAT[31]、RZWQM[32] 和 APSIM[20] 等。模型通过输入土壤、气象和农艺等数据对作物生长进行模拟，可以更方便地和气候变化相结合，但模型参数具有空间和物种的变异性，需要通过田间试验对模型参数进行调整。灌溉优化决策过程中必须利用各种优化算法求解问题的最优解，因此优化算法的不断发展和改进在优化过程中起到了至关重要的作用。优化算法在农业灌溉水资源优化配置模型中是通用的，主要包括传统数学规划法、人工智能搜索法、系统学和系统论以及不确定规划法，具体分类见表 2。其中传统数学规划法可以用来描述多个连续时间内决策间的动态关系、多个决策层间的相互影响以及多目标配置等问题[12]。农业灌溉水资源优化配置是个复杂的系统，内部各子系统和要素间关系密切，需要更复杂、高效的优化算法描述这些特征和联系。因此随着计算机技术的发展，人工智能搜索法逐渐被运用到水资源优化配置中。在农业灌溉水资源管理中，存在很多不确定因素例如降雨、径流、蒸发和入渗等，传统的优化方法很难做到有效处理，因此多种不确定规划方法随之产生。

表 2　农业灌溉水资源优化模型的主要求解方法

Table 2　The main solution in the optimization model of agricultural irrigation water resources

求解方法 Solution	简述 Brief description	分类和参考文献 Type and references
传统数学规划 Traditional mathematical programming	计算简单，但处理复杂问题时具有局限性	线性规划[33]、非线性规划[34]、动态规划[35]、多目标规划[36]、分式规划[37]、双层规划[38] 和多层规划[39] 等
人工智能搜索 Artificial intelligence search	运算速度快、稳定，适应性和鲁棒性较强	自由搜索算法[40]、回溯搜索算法[41]、遗传算法[42]、神经网络[43]、蚁群算法[44]、粒子群算法[45]、模拟退火法[46]、鱼群算法[47]、蜂群算法[48] 猫群算法[49] 和天牛群算法[50] 等
系统学和系统论 Systematics and system theory	定量描述各种系统功能，具有逻辑和数学性质	混沌算法[51] 和协同学[52] 等
不确定规划 Uncertain programming	客观地反映水资源配置情况，适用性广泛	区间数学规划（区间目标规划[53]、区间整数规划[54]、区间线性规划[55] 和区间非线性规划[56] 等）、随机数学规划（随机期望值规划[57]、多阶段随机规划[58]、机会约束规划[59] 和随机相关机会约束规划[60] 等）、模糊数学规划（模糊机会约束规划[61]、模糊相关机会约束规划[62]、模糊可能性规划[63]、模糊鲁棒性规划[64] 和模糊弹性规划[65] 等）

除表 2 提到的优化方法外，大系统优化理论也被广泛应用到农业灌溉水资源优化配置中，其可以反映系统内部各子系统、各要素之间的相互作用与联系，例如赵文举等[66] 基于大系统分解协调的思想建立了一种解决多级渠系配水优化编组问题的分解协调模型。作物模型与优化算法的结合使得农业灌溉水资源优化配置模型能更细致地描述作物生长和水分运动过程，从而为生产实践提供有力的理论指导。

2.2　基于水分-产量-品质响应关系的节水调质灌溉优化决策

传统的灌溉优化决策只注重作物产量和经济效益，随着人民生活水平的提高，消费者会更多的关注作物品质。研究表明适当的水分亏缺会促使作物产生一系列的生理化学调控而提高作物品质，因此对于瓜、果和蔬菜等特色经济作物如何建立基于水分-产量-品质响应关系的作物节水调质灌溉优化决策是亟待解决的科学问题[67]。

作物品质主要包括表观品质、口感品质、营养品质、储藏品质、加工品质、播种品质和综合品质等[68-69]。基于水分-产量-品质响应关系的作物节水调质灌溉优化决策研究进展见表 3，目前的研究主要集中在水稻、瓜类、柑橘、番茄、枸杞和制种玉米上。其中制种玉米的种植目的在于为大田玉米提供优质的种源，研究表明其籽粒质量与种子活力呈正相关关系[16]，因此将籽粒质量作为品质指标加入到制种玉米的灌溉优化决策模型中。量化作物品质与耗水量之间的关系是解决节水调质灌溉优化问题的关键，现有的研究常采用的方法主要包括水分生产函数、经验模型和不确定规划法，例如宋歌等[70] 采用区间规划法表征瓜类品质对灌水量的响应值。同时，作物品质是一个综合性状，构建综合品质指标对于优化灌溉制度更具有实际意义，其基本思想是对单一指标进行赋权并采用综合评价法进行量化。常用的单一指标的赋权方法主要包括古林法、Delph 法、层次分析法、熵权法、标准离差法、CRITIC 法和主成分分析法等，综合评价方法有综合指数法、多元统计法、模糊数学法、熵权法、灰色关联法、标准差法以及层次分析法等[68]。品质指标通常采用以下 3 种方式加入到决策模型中：1）采用多目标规划求解产量或经济效益最大同时保证品质最优的灌溉制度[70-73]；2）把多目标规划问题转化为单目标规划问题，例如采用加权系数法赋予产量和品质不同的权重[74-75]、采用优先等级法依次求解[76]、建立品质与经济效益的函数关系[77] 或采用综合评价指标作为目标函数[78]；3）将品质指标作为约束条件加入到模型中，并给某项品质指标一定的约束，从而使产量和品质达到一定程度的平衡[21, 79-81]。决策者可分别通过改变目标函数、增减品质指标权重以及调整约束条件实现特色经济作物的多样化灌溉管理。

表 3　基于水分-产量-品质响应关系的作物节水调质灌溉优化决策研究进展

Table 3　Research progress on crop irrigation optimization decision-making in water-saving and quality-regulating based on the response of water, yield and quality relationship

参考文献 References	作物种类 Crop species	作物模型 Crop model	决策变量 Decision variable	品质指标 Quality index
宋歌等[70]	瓜类	JENSEN 模型	灌水量	–
LIU 等[71]	水稻	经验模型	耗水量、施氮量	稻谷粒质量、长宽比、糙米质量、糙米率、精米质量、直链淀粉、蛋白质、垩白粒率
邓箴[72]	枸杞	JENSEN 模型	灌水量	总糖、粒度、百粒质量
CHEN 等[73]	柑橘	MINHAS 模型、Q-RAO 模型	灌水量	单果质量、色调角、果实含水量、可溶性糖、维生素 C、可滴定酸
陈平[74]	番茄	JENSEN 模型、BLANK 模型	灌水量	亮度、饱和度、红度、单果质量、果形指数、可溶性蛋白、番茄红素、维生素 C、可溶性糖、可溶性固形物、可滴定酸、糖酸比、芳香类物质、果实硬度、含水率
CHEN 等[75]	制种玉米	改进的 JENSEN 和 RAO 模型	灌水量、施氮量	种子活力
宋歌等[70,76-77]	番茄	MINHAS 模型、STEWART 模型、JENSEN 模型	灌水量	可溶性固形物、还原性糖、有机酸、糖酸比、维生素 C、果实硬度、果色指数
马波等[78]	枸杞	经验模型	灌水量	多糖、β-胡萝卜素、黄酮、甜菜碱
WANG 等[79-80]	制种玉米	耗水-开花模型、籽粒质量上下限预测模型	灌水量、父本种植时间及比例	籽粒质量
SHI 等[81]	制种玉米	改进的 AquaCrop 模型、单作物系数法	灌水量、种植密度	种子活力
SHI 等[21]	制种玉米	改进的 RAO 模型、籽粒质量模型	灌水量、种植密度	籽粒质量

3　多作物水土资源优化配置模型

水土资源优化配置是指在一定条件下，为了实现经济、社会和生态效益的协调统一，依据水土资源特性和系统原理，对区域有限水土资源在时空上进行设计和布局，以提高水土资源利用效率和生态系统的相对平衡，从而实现水土资源的可持续利用[82]。当灌区内种植多种作物时，由于不同作物的需水量、对水分的敏感程度以及生育期划分存在着差异，水土资源优化配置直接影响到灌区的经济效益。农业种植结构的优化是农业土地资源优化配置的主要目标，同时是农业灌溉水资源优化配置的重要依据。种植结构的优化可以有效促进农业灌溉水资源的优化配置，提高水资源利用效率，促进农业的可持续发展[2]。种植结构的优化研究从 20 世纪 70 年代开始，经历了由单目标向多目标、结构优化向空间布局优化、只注重粮食产量的提高向水-能源-粮食-生态协同优化方向转变。

3.1　农业水土资源的多目标优化

传统的农业水土资源优化配置的相关研究常将水资源和土地资源分开配置，一种是在种植结构确定的情况下优化农业灌溉水资源[83]，另一种是在灌溉制度确定的情况下优化种植结构[84]。但是水资源和土地资源二者是紧密联系相互制约的，不能简单按照先后顺序分别进行优化配置。单目标优化常以作物总产量或经济效益最大

为目标，但水土资源在规划过程中通常要兼顾经济发展、资源利用和地方政策等多个目标，因此多目标规划模型得到了广泛应用。与单一作物灌溉优化决策不同，多作物水土资源优化配置的多个目标间往往是相互矛盾的，将其转化为单目标优化会造成信息的大量丢失，有很大的局限性[85]。除将灌区经济效益最大作为决策目标外，多目标还常包括总用水量最少[86]、灌溉面积最小[87]、能量消耗最少[88]、水分亏缺程度最小[89-90]、Gini 系数最小[91]、单位面积内水足迹最小[92]、蓝水足迹最小[93]、灰水足迹最小[94]、农业面污染最小[95]、农田植被净碳汇最大[92]、碳吸收总量最大[96]、灌溉水生产力最大[87, 92]、生态效益最大[86, 97]、粮食安全效益最大[97]、单位灌溉面积的作物产量最大[98]和绿水利用率最高[91]等。由于农业灌溉水资源优化配置过程中存在着很多的不确定性，除降雨、径流、蒸发和入渗等因素外，模型中输入的参数、决策变量及其相互关系同样存在着大量不确定性，因此不确定分析常被应用到决策中。考虑到单一的数学规划方法难以适用于广泛的系统性研究，不确定规划法常和其他规划方法、智能算法结合使用。例如张珊等[99]建立了一个多目标模糊可信性优化模型对民勤灌区的种植结构和用水管理进行了调整以获得最大的经济、生态和社会效益；ZHANG 等[100]采用区间线性多目标分式规划模型对泾惠渠灌区水土资源进行优化配置以获得最大的单位水资源经济效益和最小的能量消耗；LI 等[101]运用不精确多目标模糊规划模型对武威市的种植结构进行优化以获得更高的经济效益和水分生产力。

3.2 空间布局优化

作物空间布局主要用于解决作物的种植面积、比例结构和作物面积的空间安排，其变化呈现多尺度和多层次的特征。随着遥感、地理信息系统和全球定位系统等技术以及智能算法和元胞自动机的广泛应用，作物种植面积及空间安排实现了统一配置[6]。作物的种植结构空间优化除需要考虑农田的自然条件，还需要考虑经济、社会和管理水平等因素，因此相较于其他的土地空间优化更为复杂。HAO 等[102]耦合多元遥感信息数据和统计数据建立了基于最小交叉信息熵的种植结构空间布局优化模型，获得了黑河中游玉米和小麦的空间优化布局；HE 等[103]整合了元胞自动机、作物适宜性和作物耗水空间分布模型优化了黑河中游制种玉米、小麦和其他经济作物的空间布局；LIU 等[104]采用 SWAT 和元胞自动机模型以水分生产力、单位水收益和营养水分生产力最大为目标对黑河中上游苜蓿、大麦、油菜、玉米、棉花和小麦的空间布局进行了优化。

3.3 水-能源-粮食-生态协同优化

水、能源和粮食是人类生存和可持续发展的重要资源，正确认识水-能源-粮食三者的纽带关系是实现水土资源高效利用的重要内容。水、能源和粮食是相对独立又紧密联系的耦合互馈系统，该纽带关系通过构建数学模型模拟不同条件下的配水量、能量消耗和经济效益，最终得到最优解[105]。该类研究经历了水、能源和粮食的单一要素，向水-能源、水-粮食和能源-粮食两两关系，再到三者纽带关系的历程。ZUO 等[106]采用 2 型模糊区间规划模型对河南省农业用水、能源、粮食和种植结构进行优化以获得最大经济效益；ZHENG 等[107]建立 2 型模糊区间线性规划模型对河北省种植结构和生物质利用进行协同管理以获得最大净利润。水-能源-粮食协同优化是一个复杂的大系统问题，任何一个要素的失衡都可能会造成严重的生态恶化，影响社会经济的可持续发展，因此水-能源-粮食-生态协同优化管理方案逐渐受到了人们的重视。例如朱兴宇等[108]以地下水均衡量、农业经济效益和生态用水满足度最大为目标建立了基于水-农业-生态协同调控的多水源优化配置模型；ZHANG 等[109]建立了基于协同学和信息熵的水-能源-粮食-生态协同评价模型，并利用 logistic 模型和改进的约束遗传算法建立了水-能源-粮食-生态协同演化模型；常奂宇等[110]于水资源通用配置与模拟软件中添加了粮食生产、能源消耗和层次化需水预测模块，建立了可以实现各子系统关键要素传递和动态互馈模拟的水-能源-粮食-生态协同调控模型。

4 灌溉渠系水资源优化调度模型

渠系配水优化模型的主要目的是为了满足灌区一定的灌水目标，按照一定的规则和方法对各个渠道的灌水次序进行排序，并对输水时间和流量进行调整，从而达到最优结果。科学的渠系配水决策可以减少输配水过程中的渗漏损失和无效弃水，提高灌溉水利用效率。在渠系设计过程中会保证同级渠道或轮灌组的控制面积、配水量与配水时间相近，但是在实际运行过程中受灌溉控制区的种植模式、灌水定额以及灌水方法与技术等因素变化的影响，实际配水量与配水时间往往与设计情况差别较大，因此需要依靠数学模型进行渠系水资源优化调度。灌区渠系输配水优化模型的研究主要分为 2 种，一种是以灌区效益指标最优为目标，另一种是以灌区水利工程运行管理指标最优为目标。

4.1 灌区效益指标最优

该类研究通常模型复杂并且针对性强，同时受到很多因素的影响，例如气候、土壤、种植制度和农产品价格等，并常以灌区作物产量[111]、经济效益[112-113]、灌溉管理部门水费收入[114]和水土资源利用效率[115]等最高为优化目标。由于该类研究涉及到很多不确定因素，不确定规划逐渐被引入到渠系水资源优化模型中，例如 ZHANG 等[116]采用区间多目标规划以最大经济效益为目标对黑河中游 11 个灌区的渠系进行配水优化；GUO 等[115]考虑了黑河中游的渠系调度能力，以经济效益最高为目标建立了基于水-能源-粮食纽带关系的分布式多目标不确定优化模型。GUO 等[117]考虑了河流、渠系、土壤和含水层间的水循环动态过程，建立了以资源节约、经济发展、生态修复、社会保障和环境改善为目的的分布式水-能源-粮食综合管理模型。以灌区效益指标最优为目标的渠系配水优化模型需要参数多且准确衡量参数的难度很大，难以在灌区间推广使用，因此相关研究数量较少。

4.2　灌区水利工程运行管理指标最优

目前的相关研究大多针对两级渠系（干渠和支渠）和三级渠系（干渠、支渠和斗渠），并假定总输水时间或者输水流量为定值，对渠系的运行管理例如轮灌组划分、流量控制和闸门启闭情况等进行优化决策。表 4 列举了以灌区水利工程运行管理指标最优为目标的渠系水资源优化研究进展，从中可以看出该类研究常以渠系运行过程中输漏水损失最小、输水时间最短、水流过渡平稳、各轮灌组持续引水时间差异值最小和灌域缺水量最小等为目标函数进行渠系水资源优化调度。约束条件主要包括渠道配水流量（配水流量和设计流量之比在一定范围内）、配水时间（各级渠道配水开始和结束的时间应在轮期内）、水流平稳过渡（各级渠道过渡过程中流量无大幅波动）、可供水量（渠系总配水流量小于可供水量）、水量（配水流量和时间的乘积）、水量平衡（任意时刻上级渠道配水流量等于各下级渠道配水流量之和）、出水口一次性引水（各出水口闸门只开启一次）和作物需水量（渠系配水流量满足灌域内作物生长需求）等。除表 2 中列举的数学方法外，考虑到闸门启闭情况，0～1 整数规划常被应用到灌区渠系输配水优化模型中。随着信息技术的发展，遥感、地理信息系统和全球定位系统技术逐渐被应用到渠系水资源优化调度中，其不仅可以获取灌区种植结构和渠系分布特点等基础资料，而且可以对灌区信息进行综合分析从而为渠系水资源优化配置提供决策支持[118-119,129-130]。

表 4　以灌区水利工程运行管理指标最优为目标的渠系水资源优化研究进展

Table 4　Research progress on water resources optimization of canal system with the objective of optimizing the operation and management indexes of hydraulic engineering in irrigation districts

参考文献 References	目标函数 Objective	约束条件 Constraints	求解方法 Solution	案例研究 Case study
刘照等[118]	输水时间最短、各轮灌组持续引水时间差异值最小	配水时间、出水口一次性引水、0～1 整数	多目标粒子群算法、蚁群算法	盈科灌区盈科干渠
YANG 等[119]	输水时间最短、渗漏损失最小	可供水量、配水流量、作物需水量、地下水可供水量、灌溉面积、配水时间、非负	排队论、粒子群优化算法	石津灌区
LORD 等[120]	输漏水损失最小	流速、配水流量、水流过渡平稳	蚁群优化算法	Moghan 灌区
吕宏兴等[121]	输水时间最短	配水时间、出水口一次性引水、0～1 整数	0～1 线性整数规划	冯家山灌区北干渠
LIU 等[122]	渗漏损失最小	配水流量、配水时间、作物需水量、水量平衡	粒子群优化算法	冯家山灌区北干渠
PENG 等[123]	水流过渡平稳、渗漏损失最小	配水时间、水量、配水流量、可供水量	遗传算法	高邮灌区南关干渠
韩宇等[124]	水流过渡平稳、渗漏损失最小	配水流量、配水时间、可供水量	回溯搜索算法、多目标粒子群算法、向量评估遗传算法	河套灌区
沈来银等[125]	灌域缺水量最小、渗漏损失最小、水盐条件满足程度最大	配水流量、可供水量、来水流量、灌域缺水比例、水量平衡、水流过渡平稳	非线性规划	河套灌区永济灌域
YAO 等[126]	渗漏损失最小	配水流量、配水时间、水量平衡	遗传算法	华北平原
GUO 等[127]	水流过渡平稳、渗漏损失最小	配水流量、配水时间、可供水量、作物需水量、水量平衡	非线性多层次多目标规划、遗传算法	西干灌区明永分干渠
SUN 等[128]	水流过渡平稳、渗漏损失最小	配水流量、配水时间、可供水量、作物需水量、0～1 整数	回溯搜索算法、向量评估遗传算法	西浚灌区西洞干渠
KANOONI 等[113]	输水量最小、输漏水损失最小、输水时间最短	配水时间、配水流量	遗传算法	Moghan 灌区
田桂林等[50]	渗漏损失最小	配水流量、可供水量、配水时间、0～1 整数	天牛群优化算法	大功灌区西一干渠
赵文举等[66]	渗漏损失最小	配水流量、配水时间、水量、水量平衡	自适应遗传算法	冯家山灌区

5　结论与展望

5.1　结　论

农业灌溉水资源优化配置是减少农业灌溉用水、保证粮食安全和提高水分利用效率的重要措施，优化模型在农业灌溉水资源优化配置中发挥了重要作用。综上所述，农业灌溉水资源优化配置研究不断发展，优化尺度由单一作物的田间尺度逐渐向灌区和区域尺度拓展；优化目标由作物产量和经济效益向作物品质转变，由单纯的经济效益发展到考虑社会、经济及生态的多目标综合效益发展；优化方法由确定性条件向不确定条件转变，由单一的数学规划向模拟技术和智能算法相结合方向发展；优化内容由提高粮食产量向水-能源-粮食-生态协同优化方向转变，由作物的种植面积优化到空间布局优化方向变化，优化水源由静态单一的水量配置向动态多元的水质水量统一调配的方向发展。

5.2　展　望

尽管农业灌溉水资源优化配置的相关研究取得了长足的进步，但仍然有以下问题亟待解决：

1）在单一作物灌溉优化决策方面，众多学者基于非充分灌溉原理对可供水量不足条件下各种作物的灌溉制度进行了优化。随着人民生活水平的提高，作物品质也逐渐得到更多关注，而目前的水分-产量-品质模型大多是基于大量试验数据建立的经验和半经验数学模型例如水分生产函数，当外界环境发生较大变化或水分亏缺超过一定范围时，模拟结果往往会出现较大偏差。因此建立更具有生理意义的作物水分-产量-品质模型对于建立节水调质灌溉优化决策模型具有重要意义。

2）在多作物水土资源优化配置方面，目前已在不确定条件下建立了多层次、多阶段、多目标和多因素的优化模型，为区域和灌区尺度的农业水资源优化提供了可靠方法。然而，气候变化和人类活动对水资源系统与农业生产系统都有重要影响，虽然现有的研究采用了很多的不确定性方法实现了农业灌溉水资源的优化配置，但二者会在多个尺度上改变农业水土资源的利用方式。在

气候变化和人类活动情景下实现多作物水土资源优化配置可以为保障中国粮食安全和水安全提供理论依据。

3）在灌溉渠系水资源优化调度方面，目前国内外学者对配水渠道的优化组合考虑的现实问题越来越全面，在数据获取和处理方面越来越先进，求解结果的可操作性越来越强。虽然现有的渠系水资源优化调度模型已尽量考虑了作物需水量对输配水的影响，但其和单一作物灌溉优化决策以及多作物水土资源优化配置是一个互馈的系统。因此利用大系统理论对水源、渠系、灌区面积、作物配置以及生育阶段内构成的整体进行水资源优化配置可作为下一步研究目标。

4）除此之外，棵间蒸发作为无效耗水占作物全生育期总耗水量的 20%～50%，减少棵间蒸发对于提高农田水分利用效率具有重要意义。而当前各尺度的农业灌溉水资源优化配置模型中极少考虑棵间蒸发这一因素，因此建立以棵间蒸发最小为目标的动态农业灌溉水资源优化配置模型对于制定作物节水高效的灌溉制度具有重要意义。

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Research progress on the optimal allocation of agricultural irrigation water resources

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Abstract: The shortage of water resources is a key factor restricting the sustainable development of agriculture, and the optimal allocation of agricultural irrigation water resources is of great significance to guarantee food and water security. Based on the main types of optimal allocation models of agricultural irrigation water resources, the research progress on single crop irrigation optimal decision-making, multi-crop water and soil resources optimal allocation, and canal system water resources optimal operation were systematically reviewed. In the traditional single crop irrigation optimal decision-making, the maximum crop yield or economic benefit was usually selected as the optimization objective. With the improvement of people’s living standard, consumers pay more attention to crop quality. And the optimal decision-making of water-saving irrigation theory based on the response of water and quality for improving quality of crop has gradually become a research focus. The multi-crop water and soil resources optimal allocation mainly includes the adjustment of crop planting structure and allocation of irrigation water resources in the irrigation district, which has undergone a transformation from single objective to multiple objectives, structural optimization to spatial layout optimization, and only focusing on the improvement of crop yield to the water-energy-food-ecology collaborative optimization. According to the different optimization objectives, the canal system water resources optimal operation is usually divided into two categories. Firstly, the objective is to optimize the benefit indicators of irrigation district, such as crop yield, economic benefits, water fee income of the irrigation management department, and the utilization efficiency of water and soil resources. Secondly, the objective is to optimize the operation and management indexes of hydraulic engineering in irrigation districts, such as the least water loss during the canal operation, water delivery time, differences in the continuous water diversion time of each rotating irrigation group, water shortage, and smooth water flow transition. In addition, the main problems and future research plans in the optimal allocation model of agricultural irrigation water resources were pointed out. The study suggested that the optimal allocation model of irrigation water resources should be improved in the following four aspects: 1) Building more physiological crop water-quality models; 2) Achieving optimal allocation of irrigation water resources under the scenarios of climate change and human activities; 3) Building systematic optimal allocation model of irrigation water resources that fully consider canal systems, irrigation districts, crops, and growth stages; 4) Establishing irrigation optimization decision-making models with the objective of minimum soil evaporation; Overall, this review provides valuable information for domestic researchers.

Keywords: models; crops; water resources; optimization of irrigation decision; deficit irrigation; water saving and quality regulating; canal system