DOI: 10.13476/j.cnki.nsbdqk.2018.0103
王茜, 郇环, 王红瑞, 等. 再生水利用对土壤和地下水的影响研究综述[J]. 南水北调与水利科技, 2018, 16(4): 104-113. WANG Q, HUAN H, WANG H R, et al. Review about effects of reclaimed water usage on soil and groundwater[J]. South-to-North Water Transfers and Water Science & Technology, 2018, 16(4): 104-113. (in Chinese)

再生水利用对土壤和地下水的影响研究综述

王 茜[1,2], 郇 环[3], 王红瑞[1], 张波涛[1,2]

(1. 北京师范大学 水科学研究院, 北京 100875; 2. 地下水污染控制与修复教育部工程研究中心, 北京 100875; 3. 国家环境保护地下水污染模拟与控制重点实验室 中国环境科学研究院, 北京 100012)

摘要: 由于处理工艺和运行成本的限制, 再生水中仍残留一定数量的污染物, 长期使用必然会对受纳区的土壤和地下水环境产生一定影响。通过文献调研和数据统计, 获得了再生水受纳区土壤和地下水中有机污染物、重金属、营养物质、盐度、pH 值和微生物等的种类和浓度, 并结合环境统计年报、土壤环境和地下水质量标准, 分析和讨论了再生水利用对受纳区土壤和地下水环境的影响。结果表明, 再生水多来自于生活污水, 其受纳区域介质中药物及个人护理品污染和盐度增加对土壤和地下水环境影响较大, 再生水中其他污染物则影响不大。为了提高再生水利用安全性, 应根据受纳区的使用功能, 制定出污染物监测方案、应急预案和管理措施。

关键词: 再生水; 土壤; 地下水; 有机污染物; 重金属; 营养物质; 盐度
中图分类号: X508 文献标志码: A 文章编号: 1672-1683(2018)04-0104-10

Review about effects of reclaimed water usage on soil and groundwater

WANG Qian[1,2], HUAN Huan[3], WANG Hongrui[1], ZHANG Botao[1,2]

(*1. College of Water Sciences, Beijing Normal University, Beijing 100875, China; 2. Engineering Research Center of Groundwater Pollution Control and Remediation, Ministry of Education, Beijing 100875, China; 3. State Environmental Protection Key Laboratory of Simulation and Control of Groundwater Pollution, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*)

Abstract: There are residual contaminants in the reclaimed water due to the limitations of wastewater treatment technology and operating costs. The quality of the soil and groundwater in the reclaimed water usage areas is bound to deteriorate in the long term. In this research, we collected the types and concentrations of contaminants in these areas through literature investigation and data statistics. We analyzed the effects of organic pollutants (polycyclic aromatic hydrocarbons, persistent organic pollutants, pharmaceuticals and personal care products (PPCPs) and endocrine disrupting chemicals), heavy metals, nutrients, salinity, pH, and microbes in reclaimed water on soil and groundwater environment. Since most reclaimed water is from domestic sewage, attention should be paid to the pollution of the PPCPs and salinity. We suggest adopting contaminant monitoring programs, emergency plans, and relevant management measures to ensure the safety of reclaimed water usage.

Key words: reclaimed water; soil; groundwater; organic contaminants; heavy metals; nutrients; salinity

我国人均水资源量仅有 2 300 m^3, 不足世界平均水平的 1/4, 是水资源贫乏的国家之一[1-2], 再生

收稿日期: 2017-10-10 修回日期: 2018-05-02 网络出版时间: 2018-05-17
网络出版地址: http://kns.cnki.net/kcms/detail/13.1334.TV.20180511.1102.002.html
基金项目: 国家自然科学基金(51479003); 中央级公益性科研院所基本科研业务费专项资金项目(2017-9058); 北京市自然科学基金(8164066)
Funds: National Natural Science Foundation of China (51479003); Special Funds for Basic Research and Business Expenses of Central Level Public Welfare Scientific Research Institutions (2017-9058); Beijing Natural Science Foundation (8164066)
作者简介: 王 茜(1994-), 女, 陕西渭南人, 主要从事水污染物控制化学研究。Email: wangqian9401@163.com
通讯作者: 张波涛(1980-), 男, 河南温县人, 副教授, 博士, 主要从事环境分析化学和水污染物控制化学研究。E-mail: zhangbotao@126.com

水利用对缓解水资源短缺，实现水资源可持续发展有重要意义。再生水是指污水经过适当处理后，达到一定的水质指标，满足某种使用要求，可以再次利用的水[3]。再生水的水质指标低于城市饮用水标准，但高于污染水允许排入地面水体的排放标准[4]。它的使用可减少清水的使用量，进而有效解决水资源短缺问题，减少水资源的浪费。再生水已在世界各国得到了广泛利用，主要包括农林利用、城市杂用、景观娱乐利用、工业回用以及河道和地下水补给等[5]。

随着社会经济及城市化进程快速发展，我国城市生活污水排放量日益增加，我国城镇生活污水由2000年的221.0亿t增加到2015年的535.2亿t[2]。美国、日本、澳大利亚等国家某些地区也面临水资源短缺，地下水超采等问题，再生水利用对缓解世界各国水资源短缺，实现水资源可持续发展有重要意义。2016年，全国年再生水利用量为54.02亿m^3。其中，用于景观环境用水32.95亿m^3，占61.0%；工业用水14.95亿m^3，占27.6%；城市非饮用水3.23亿m^3，占6.0%；农林牧业用水2.48亿m^3，占4.6%；地下水补充用水0.41亿m^3，占0.8%[6]。目前，全国共有21个省级行政区出台了再生水利用的相关法规政策，例如：北京市出台了《北京市节约用水办法》、《关于进一步加强污水处理和再生水利用工作的意见》和《加快污水处理和再生水利用设施建设三年行动方案（2013—2015年）》等管理政策。同时，再生水利用相关技术标准不断完善，2002年以来陆续颁布了一系列再生水利用标准，如《再生水水质标准》、《城市污水再生利用分类》、《城市污水再生利用农田灌溉用水水质》等。

同未经处理或简单处理的污水相比，再生水水质大幅度提高，但是由于成本和工艺限制，再生水中仍然存在一定量的有机污染物、重金属、营养物质、盐离子和微生物，其水质特征还与再生水的来源、管网材质以及运输条件等因素有关。再生水的长期使用，可能会对受纳的土壤和地下水环境产生一定影响，造成相应的生态环境风险。根据前期文献调研可知，虽然研究再生水对土壤或地下水影响的文章比较多，但是这些文章的关注点都只集中于单一介质（土壤或地下水）或者集中于再生水中某类污染物研究，缺乏再生水中所有主要污染物在土壤和地下水的检出分析以及对土壤和地下水影响的研究，因此对再生水的利用及管理缺乏基础数据资料和理论依据。

本文通过文献调研和数据统计，获得了再生水受纳区有机污染物（包括多环芳烃、持久性有机污染物、药物及个人护理品、内分泌干扰物）、重金属、营养物质、盐度、pH值和微生物等的种类和浓度，对再生水受纳区土壤和地下水检出浓度进行了分析，并结合环境统计年报、土壤环境和地下水质量标准，分析和讨论了再生水对受纳区土壤和地下水环境的影响。

1　再生水中有机污染物对土壤和地下水的影响

通过对该部分的文献调研，再生水中有机污染物主要通过农业灌溉和城市杂用等利用方式进入土壤和地下水，再生水利用时间为短期利用（1～3个月）与长期利用（4～9年）相结合，对再生水受纳区有机污染物数据统计和分析[7-38]，分别得到了这些区域的土壤（图1）和地下水（图2）中有机污染物浓度的最大值和平均值。从图1和2可以看出，多环芳烃（图1中A1–A8，图2中a1–a6）、持久性有机污染物（图1中B1–B4，图2中b1–b4）、药物及个人护理品（图1中C1–C17，图2中c1–c14）和内分泌干扰物（图1中D1–D6，图2中d1–d6）四类有机污染物在土壤和地下水中均有检出，土壤浓度平均值范围为0.75 ng/kg～332 μg/kg，最大值范围为1.50 ng/kg～399 μg/kg；地下水浓度平均值范围为0.03 ng/L～256 ng/L，最大值范围为0.08 ng/L～563 ng/L。土壤中有机污染物的检出浓度多数高于地下水中的浓度，且药物及个人护理品和内分泌干扰物在土壤和地下水中检出浓度和频率较高。

1.1　再生水中多环芳烃对受纳区土壤和地下水的影响

多环芳烃（Polycyclic Aromatic Hydrocarbons，PAHs）是分子中含有两个以上苯环的碳氢化合物，它主要来源于人类活动，尤其是化石燃料的不完全燃烧[8]。由图1中A1–A8的PAHs浓度数据可以看出，低环PAHs（2–3环）在土壤中的平均浓度在0.75 ng/kg～40.12 μg/kg范围内。检出浓度最大的多环芳烃是萘（399 μg/kg），这是因为该研究区萘在土壤中的含量随季节的差异性变化很大，数据的采集时间是在浓度最高的8月份[7]。虽然多环芳烃在整个土层都有检出，但是表层土壤中检出浓度较高，这是由于PAHs是非极性化合物，有较强的疏水性，在迁移过程中更倾向于吸附在固体介质上[8]。对比地下水不同环数的PAHs浓度可以看出，总体上地下水中低环PAHs（2–3环，a1–a4）的浓度高于高环PAHs（4–5环，a5–a6），这是因为K_{ow}(a1, 1.95×10^3) < K_{ow}(a4, 1.50×10^4) < K_{ow}(a2, 2.80×10^4) ≈ K_{ow}(a3, 2.80×10^4) < K_{ow}(a5,

7.90×10^4) < K_{ow}(a6, 8.00×10^4), 所以低环物质的迁移性相对较强, 可以顺着土壤剖面下渗进入地下水, 再生水持续使用下会形成一定的累积效应, 进一步增加了这些物质在地下水中的浓度。

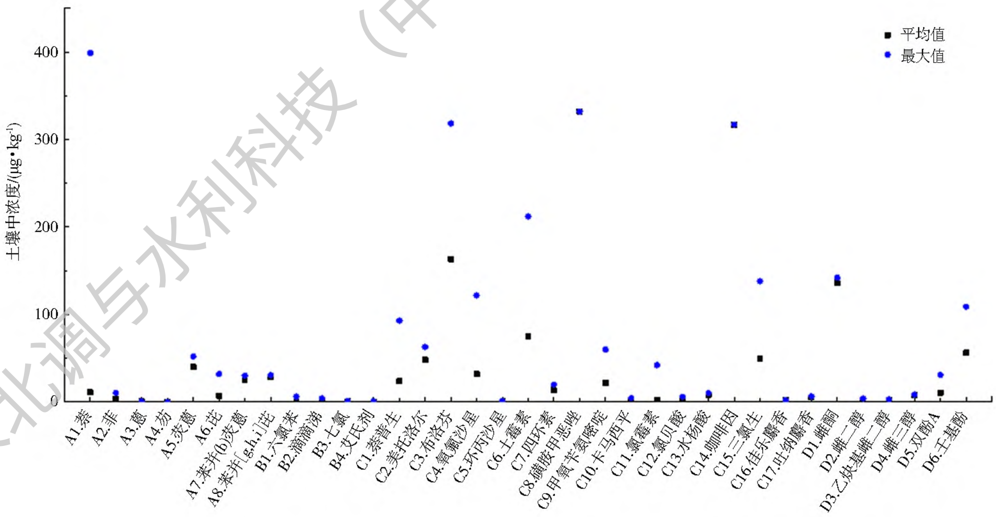

图 1 再生水受纳区土壤中有机污染物的浓度

Fig. 1 The concentration of organic contaminants in soil of reclaimed water usage areas

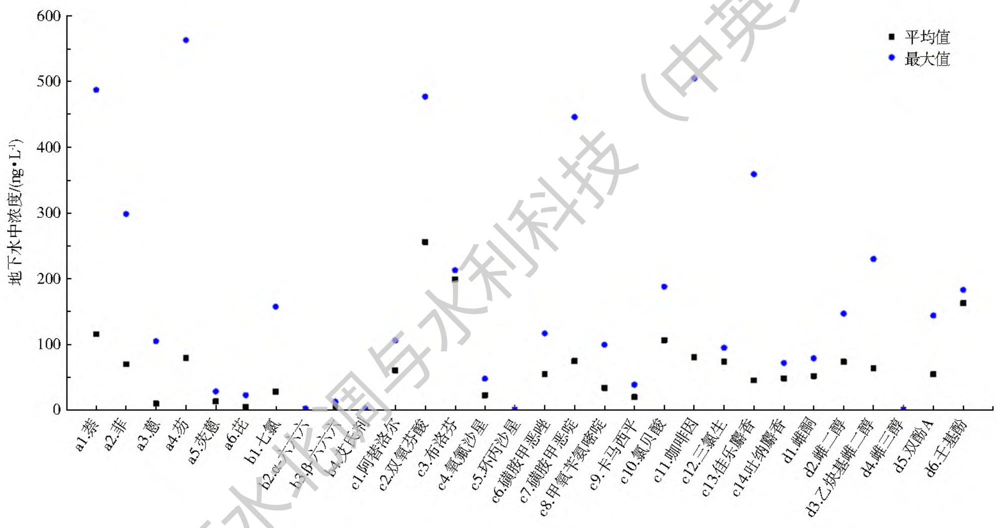

图 2 再生水受纳区地下水中有机污染物的浓度

Fig. 2 The concentration of organic contaminants in groundwater of reclaimed water usage areas

1.2 再生水中持久性有机污染物对受纳区土壤和地下水的影响

持久性有机污染物(Persistent Organic Pollutants, POPs)是指通过各种环境介质能够长距离迁移并能在环境中长时间存留, 进而对人类健康和环境产生严重危害的天然和人工合成的有机污染物[9]。图 1 中 B1-B4 为土壤中检出的四种主要 POPs, 检出浓度都很低, 平均值范围为 0.78 μg/kg~2.81 μg/kg, 最大值范围为 1.13 μg/kg~6.00 μg/kg, 且主要在表层土壤中检出, 这是因为 POPs 大多为疏水性物质, 更容易被土壤中的腐殖质及有机质吸附。图 2 中 b1-b4 为地下水中检出的四种主要 POPs, 七氯的平均值和最大值比较高, 分别为 28.09 ng/L 和 157.45 ng/L, 其余 POPs 浓度较低, 平均值和最大值范围分别为 1.18 ng/L~6.23 ng/L 和 2.25 ng/L~12.90 ng/L, 这是因为该数据所在的点位七氯本底浓度较高, 加上七氯的 K_{ow}(2.6×10^4) 较小, 所以七氯容易从土壤迁移到地下水中[10]。

1.3 再生水中药物及个人护理品对受纳区土壤和地下水的影响

药物及个人护理品(Pharmaceutical and Personal Care Products, PPCPs), 是指为了个人健康和化妆原因以及提高家畜生长和健康而使用的各种化学产品, 包括各种抗生素、激素、药和香料等[11]。如图 1 和 2 所示, PPCPs 在再生水受纳区土壤的浓度平均值在 0.68 μg/kg~318.50 μg/kg 之间, 最大值

达 332 μg/kg；在地下水中的浓度平均值在 0.27 ng/L～256 ng/L 之间，最大值达 505 ng/L。由于生活污水排放量在逐年增加（图 3），因此再生水多数来源于生活污水，而且常规的污水处理工艺一般使用生物法，不能有效去除该类污染物，特别是具有杀菌作用的抗生素和消炎药，所以再生水利用后土壤和地下水中抗生素和消炎药的检出频率和浓度是最高的。由于 PPCPs 大多是亲水性物质，在持续利用的条件下，亲水性的化合物会随着下渗水流从土壤迁移至地下水中。

1.4　再生水中内分泌干扰物对受纳区土壤和地下水的影响

内分泌干扰物（Endocrine Disrupting Chemicals，EDCs）是指环境中存在的能干扰人类或动物内分泌系统诸环节并导致异常效应的物质[12-13]。图 1 中 D1～D6 和图 2 中 d1～d6 分别为再生水受纳区土壤和地下水中检出的主要 EDCs。土壤中雌酮和壬基酚的平均浓度相对较高，分别为 135.90 μg/kg 和 56.20 μg/kg，这和研究地区大量使用该类化合物密切相关。其他 3 种 EDCs 在土壤中的浓度相对较低，在 2.70 μg/kg～10.41 μg/kg 之间。地下水中也检出了较高浓度的壬基酚，平均浓度为 163.00 ng/L，这是由于淋滤和下渗作用，土壤中的壬基酚顺着土壤剖面进入地下水[19]。

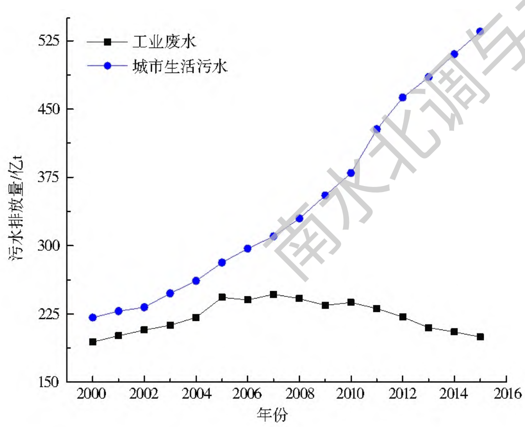

图 3　我国 2000～2015 年城市生活污水和工业废水排放量
Fig.3　The amount of urban household wastewater and industrial sewage from 2000 to 2015 in China

2　再生水中重金属对土壤和地下水的影响

通过对该部分的文献调研，再生水相关研究利用方式主要为农业灌溉，利用时间也是短期利用与长期利用相结合，通过对不同再生水利用区土壤和地下水中重金属浓度的统计分析，结果表明，Pb、Cd、Cr、Hg、As、Cu、Zn、Ni 这八种重金属在土壤和地下水中均有检出[39-64]。土壤中八种重金属浓度平均值范围为 0.18 mg/kg～107.90 mg/kg，最大值范围为 0.50 mg/kg～403.5 mg/kg；地下水中平均值范围为 0.02 μg/L～39.61 μg/L，最大值范围为 0.16 μg/L～140 μg/L。图 4 中八种重金属在土壤中的平均浓度均符合土壤环境质量标准（GB 15618－1995）[65] 二级标准，而 Cd、Cr、Hg、Cu、Zn、Ni 的最大浓度符合三级标准，Zn 的最大值浓度比较高，这是因为 Zn 在该地本底值较高所导致[39]。

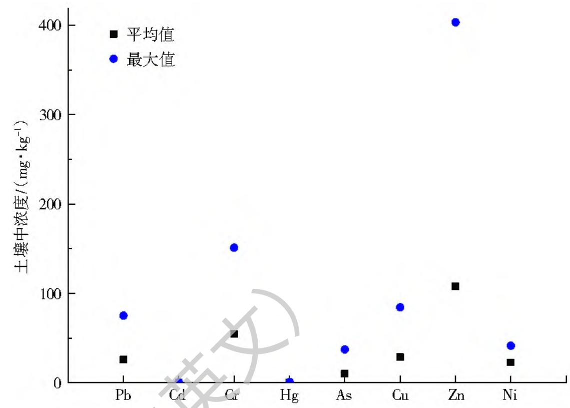

图 4　再生水受纳区土壤中重金属的浓度
Fig.4　The concentration of heavy metals in soil of reclaimed water usage areas

地下水中八种重金属均有检出，浓度平均值范围为 0.02 μg/L～39.61 μg/L（图 5）。这是因为再生水利用输入土壤的重金属离子可顺着土壤剖面迁移至地下水，根据新修订的地下水质量标准（GB/T 14848－2017）[66]，Hg、As、Ni 检出浓度的平均值均略超 II 类水标准，符合 III 类水标准，而 As 和 Ni 的最大检出浓度均超过 III 类水标准，与当地本底值较高和人为活动有关[40,53]。

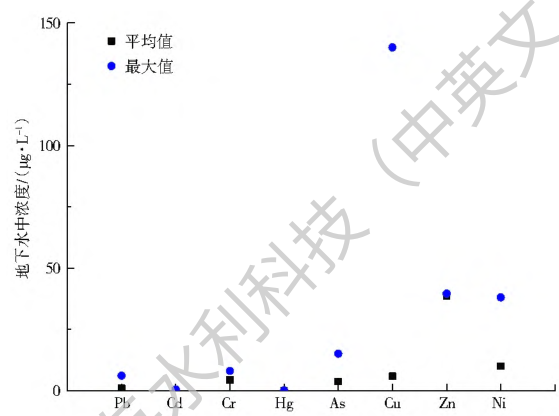

图 5　再生水受纳区地下水中重金属的浓度
Fig.5　The concentration of heavy metals in groundwater of reclaimed water usage areas

近年来，生活污水排放量逐渐增加（图 3），再生水多数来源于生活污水，而生活污水中重金属的含量相对较小，再生水的利用对土壤和地下水重金属浓度改变影响较小。

3 再生水中其他物质或性质对土壤和地下水的影响

3.1 再生水中营养物质对土壤和地下水的影响

营养物质与重金属和有机污染物不同, 当营养物质浓度低时为植物所需营养元素, 但当超过植物所需, 则会造成植物营养元素失衡, 且多余的营养物质会残留在土壤中, 对土壤和地下水造成污染。

乔丽对北京大兴区北野场灌区再生水灌溉进行了研究, 发现再生水灌区土壤中的 N、P 营养物质比其他灌区含量高, N 元素主要在表层 20 cm 处有明显累积, P 元素只在土壤表面稍有累积, 土壤肥力相应升高[67]。还有研究者发现, 再生水中低浓度的磷不会对土壤产生负面影响, 但长时间施用含有磷的再生水会使磷累积在土壤表面, 随径流进入地表水, 促进富营养化[68]。Xu 等人研究表明再生水灌溉可导致 P 含量提高, 但短期内影响不显著[69]。刘昆鹏对再生水灌溉区的研究表明, 与背景值相比, 再生水灌溉土壤中 NH_4^+-N 含量变化不显著, NO_3^--N 含量和 NO_2^--N 含量增加[70]。

当土壤中的硝态氮浓度超过植物需求时, 会渗入地下介质中[71], 而且细菌可将土壤中的 NH_4^+-N 转化为 NO_3^--N, 它们顺着土壤剖面下渗会导致地下水 NO_3^--N 含量超标[72]。尹世洋等人的研究表明, 北京地区再生水受纳区地下水含水层硝酸盐氮浓度的最小值为 0.08 mg/L, 最大值为 11.7 mg/L, 空间变异性较大, 但总体污染较小[72]。由于 P 主要结合在土壤表面, 迁移能力较弱, 因此地下水中几乎没有 P 的累积。

3.2 再生水盐度对土壤和地下水的影响

再生水中一部分盐离子可被植物或者土壤微生物吸收利用, 多余的盐分则会在土壤中累积, 对土壤和地下水造成一定的影响。同时由于蒸发率、浸出率、土壤类型等因素的不同, 盐分累积对土壤和地下水的影响程度也不同。

Chen 等人对北京 7 个园区不同的再生水灌溉历史进行了现场研究, 分析了 20 个土壤属性, 结果表明在再生水灌溉下观察到盐度的积累, 再生水灌溉下两个表层的平均电导率增加了约 20%; 平均钠吸附比在 0~10 cm 层显著上升 40%, 10~20 cm 层增加 70%, 同时观察到总硼含量稍有增加[73]。Qian 等对美国西部 10 个高尔夫球场使用再生水和清水分别灌溉时, 检测出再生水灌溉下的土壤电导率比清水灌溉下高出 187%, 钠吸附比也高出 481%, 4~5 年使用再生水灌溉之后土壤 Na 含量增加 89% 到 95%[74]。这是因为再生水与常规水相比, 一般含有较高浓度的盐离子, 主要是 Na^+ 和 Cl^-, 而传统的废污水处理技术不能去除盐分[75]。再生水盐分对土壤的影响主要表现在对植物生长和对土壤结构的影响。有研究表明再生水利用后, 植物根系中高浓度的盐会导致土壤—水溶液的渗透势能降低, 延缓植物的吸水率, 从而影响植物产量[76]。另外, 生活污水含硼洗涤剂和清洁剂的使用会导致受纳区土壤中硼浓度增加[73]。

再生水利用对地下水的影响大小与地下水渗流区结构有关。Shang 等人在北京市大兴区和通州再生水受纳区观察到了地下水的高电导率, 说明地下水盐度有相应累积, 且由于渗流区结构的不同, 通州地下水污染风险比大兴区高[77]。William 等人研究约旦再生水利用区发现, 由于水分蒸发较大而导致土壤盐分累积, 加上入渗作用, 地下水含水层也观察到了盐分累积[78]。吴文勇等人的研究也表明, 再生水经包气带入渗后, 盐分含量增加[79], 这是因为过量 Na^+ 会与土壤中的 Ca^{2+} 和 Mg^{2+} 发生置换反应, 继续通过下渗、淋滤等作用进入地下水, 导致地下水出现盐化问题。

3.3 再生水 pH 值对土壤和地下水影响

pH 值是反应土壤和地下水酸碱性的指标, 土壤 pH 值发生变化会影响植物营养元素的可用性。研究发现, 再生水灌溉后的绿地土壤样品 pH 值稍有降低, 但是由于土壤的缓冲作用, 再生水对土壤 pH 值影响较小[80-81]。对城市绿化草坪再生水灌溉区的地下水 pH 值检测发现, 相比于自来水灌溉, 再生水灌溉导致地下水的 pH 值略有降低, 降低程度极小, 可忽略不计[82]。因此, 再生水对土壤和地下水的 pH 值影响不大。但是, 再生水中的污染物协同作用对土壤和地下水 pH 值的影响不可忽视, 例如 NO_3^--N 氧化、有机物降解、金属离子价态变化等。

3.4 再生水中微生物对土壤和地下水影响

再生水中残留的微生物, 一方面可以为土壤提供一定的有益菌, 另一方面, 也可以向土壤和地下水引入潜在的病原微生物。Candela 等人对再生水利用区土壤中大肠杆菌群和好氧细菌进行了检测, 发现短期内可在表层土壤中发现大肠杆菌, 但长期检测其已失去活性[83]。Aiello 等人研究发现再生水受纳区土壤表面大肠杆菌和粪便链球菌含量增加, 有一些迁移性较强的病原微生物会从土壤迁移至地

下水,对饮用水安全造成威胁[84]。Birks 检测出了某再生水厂中现场钻孔的地下水中含有军团菌[85]。在 Levantesi 等的研究中,再生水受纳区地下水仅检出几种微生物,但数量很少[86]。因此,再生水利用对土壤和地下水病源微生物的影响较小,可以通过改变污水处理厂的处理工艺和技术,提高出水水质,来相应降低再生水利用中微生物对土壤和地下水的影响。

4　结语

由于再生水主要来自于城市生活污水,药物和个人护理品在土壤和地下水中检出浓度和频率较大,同时再生水会使土壤和地下水盐度增加,这是再生水对土壤和地下水环境的主要影响因素。再生水中重金属、营养物质、pH 和微生物对受纳土壤和地下水环境影响相对较小。

再生水对于缓解水资源短缺有重要作用,特别是我国北方严重缺水地区。再生水利用过程中需注意以下两个方面:首先,应对再生水受纳区进行长期监测,制定相应的保护政策和应急预案;其次,应根据受纳区土壤和地下水的使用功能选择再生水使用方式或者提高再生水水质,尽量减少不利影响。

目前,多数研究的关注点多集中于单一介质(土壤或地下水)或集中于某类污染物质研究,研究的周期也比较短,再生水对受纳区域多种介质中的多种污染物长期复合分析研究,将对再生水的利用及管理提升具有重要意义。

参考文献(References):

[1] 王瑗,盛连喜,李科,等.中国水资源现状分析与可持续发展对策研究[J].水资源与水工程学报,2008,19(3):10-14.(WANG Y,SHENG L X,LI K,et al. Analysis of present situation of water resources and countermeasures for sustainble development in China[J]. Journal of Water Resources & Water Engineering,2008,19(3):10-14.(in Chinese))

[2] 环境保护部. 2000-2015 年环境统计年报[R]. 2000-2015.(Ministry of Environmental Protection of the People's Republic of China. Environmental statistical annual report from 2000-2015[R]. 2000-2015.(in Chinese))

[3] GB/T 30943- 2014,水资源术语[S].(GB/T 30943- 2014, Water resources terminology[S].(in Chinese))

[4] 李昆,魏源送,王健行,等.再生水回用的标准比较与技术经济分析[J].环境科学学报,2014,34(7):1635-1653.(LI K,WEI Y S,WANG J X,et al. Water reclamation: Standards comparison and cost analysis[J]. 2014,34(7):1635-1653.(in Chinese)) DOI:10.13671/j.hjkxxb,2014.0562.

[5] 杨茂刚,赵树旗,王乾勋,等.国外再生水利用进展综述[J].海河水利,2013(4):30-33.(YANG M G,ZHAO S Q,WANG Q X,et al. A summary of progress in reclaimed water utilization and its advancement in foreign countries[J]. Haihe Water Resources,2013(4):30-33.(in Chinese)) DOI:10.3969/j.issn.1004-7328.2013.04.012.

[6] 水利部. 2016 年水资源管理年报[R]. 2016.(The Ministry of Water Resources of the People's Republic of China. Annual Report on Water Resources Management[R]. 2016.(in Chinese))

[7] JIN A,HE J,CHEN S,et al. Distribution and transport of PAHs in soil profiles of different water irrigation areas in Beijing,China[J]. Environmental Science: Processes & Impacts,2014,16(6):1526-1534. DOI:10.1039/c3em00623a

[8] 陈素暖.多环芳烃在不同灌区土壤精细剖面的分布特征研究[D].北京:中国地质大学(北京),2009.(CHEN S N. Distribution characteristics of PAHs in soil profiles of different irrigation areas[D]. Beijing: China University of Geosciences,2009.(in Chinese))

[9] 王春辉,吴绍华,周生路,等.典型土壤持久性有机污染物空间分布特征及环境行为研究进展[J].环境化学,2014,33(11):1828-1840.(WANG C H,WU S H,ZHOU S L,et al. A review on spatial distribution and environmental behavior of typical persistent organic pollutants in soil[J]. Environmental Chemical,2014,33(11):1828-1840.(in Chinese)) DOI:10.7524/j.issn.0254-6108.2014.11.008.

[10] 马文洁,何江涛,金爱芳,等.北京市郊再生水灌区土壤有机氯农药垂向分布特征[J].生态环境学报,2010,19(7):1675-1681.(MA W J,HE J T,JIN A F,et al. Verticle distribution of organochlorine pesticides in reclaimed water irrigation area in Beijing suburbs[J]. Ecology and Environmental Sciences,2010,19(7):1675-1681.(in Chinese)) DOI:10.3969/j.issn.1674-5906.2010.07.028.

[11] DODGEN L K,ZHENG W. Effects of reclaimed water matrix on fate of pharmaceuticals and personal care products in soil[J]. Chemosphere,2016,156:286-293. DOI:10.1016/j.chemosphere.2016.04.109.

[12] SIDHU H S,WILSON P C,O CONNOR G A. Endocrine-Disrupting Compounds in Reclaimed Water and Residential Ponds and Exposure Potential for Dislodgeable Residues in Turf Irrigated With Reclaimed Water[J]. Arch Environ Contam Toxicol,2015,69(1):81-88. DOI 10.1007/s00244-015-0147-6.

[13] LI Z,XIANG X,LI M,et al. Occurrence and risk assessment of pharmaceuticals and personal care products and endocrine disrupting chemicals in reclaimed water and receiving groundwater in China[J]. Ecotoxicology & Environmental Safety,2015,119:74-80. DOI:10.1016/j.ecoenv.2015.04.031.

[14] HERNÁNDEZ M,MAGARZO C,LEMAIRE B. Degradation of emerging contaminants in reclaimed water through soil aquifer treatment(SAT)[J]. Journal of Water Reuse & Desalination,2012,2(3):157-164. DOI:10.2166/wrd.2012.016.

[15] GARCÍASANTIAGO X,GARRIDO J M,LEMA J M,et al. Fate of pharmaceuticals in soil after application of STPs products: Influence of physicochemical properties and modelling

approach[J]. Chemosphere, 2017, 182: 406-415. DOI: 10.1016/j.chemosphere.2017.05.049.

[16] 苏思慧, 何江涛, 杨蕾, 等. 北京东南郊土壤剖面氟喹诺酮类抗生素分布特征[J]. 环境科学, 2014, 35(11): 4257-4266. (SU S H, HE J T, YANG L, et al. Contamination characteristics of fluoroquinolones in different kinds of soil profiles in southeast suburb of Beijing[J]. Environmental Science, 2014, 35(11): 4257-4266. DOI: 10.13227/j.hjkx.2014.11.031 (in Chinese))

[17] 金爱芳. 不同灌溉条件下多环芳烃在包气带中的迁移规律研究[D]. 北京: 中国地质大学(北京), 2010. (JIN A F. The study of migration and transformation of PAHs in soil profiles under different water irrigation[D]. Beijing: China University of Geosciences, 2010. (in Chinese))

[18] MAHJOUB O, ESCANDE A, ROSAIN D, et al. Estrogen-like and dioxin-like organic contaminants in reclaimed wastewater: transfer to irrigated soil and groundwater[J]. Water Science & Technology, 2011, 63(8): 1657-1662. DOI: 10.2166/wst.2011.322.

[19] LI J, FU J, ZHANG H, et al. Spatial and seasonal variations of occurrences and concentrations of endocrine disrupting chemicals in unconfined and confined aquifers recharged by reclaimed water: a field study along the Chaobai River, Beijing[J]. Science of the Total Environment, 2013, 450: 162-168. DOI: 10.1016/j.scitotenv.2013.01.089.

[20] FRIES E, MAHJOUB O, MAHJOUB B, et al. Occurrence of contaminants of emerging concern (CEC) in conventional and non-conventional water resources in Tunisia[J]. Fresenius Environmental Bulletin, 2016, 25(9): 3317-3319.

[21] CORADA-FERNÁNDEZ C, CANDELA L, TORRES-FUENTES N, et al. Effects of extreme rainfall events on the distribution of selected emerging contaminants in surface and groundwater: The Guadalete River basin (SW, Spain)[J]. Science of the Total Environment, 2017, 605: 770-783. DOI: 10.1016/j.scitotenv.2017.06.049.

[22] XU J, CHEN W, WU L, et al. Leachability of some emerging contaminants in reclaimed municipal wastewater-irrigated turf grass fields[J]. Environmental Toxicology & Chemistry, 2009, 28(9): 1842 - 1850. DOI: 10.1897/08-471.1.

[23] 李建忠. 典型内分泌干扰物在土壤中迁移转化规律研究[D]. 北京: 清华大学, 2013. (LI J Z. Study on the migration and transformation of the typical endocrine disrupting chemicals in soil[D]. Beijing: Tsinghua University, 2013. (in Chinese))

[24] 黄德亮, 何江涛, 杨蕾, 等. 某市再生水灌区水土环境中 PPCPs 污染特征分析[J]. 中国环境科学, 2016, 36(9): 2614-2623. (HUANG D L, HE J T, YANG L, et al. Distribution characteristics of pharmaceuticals and personal care products in water and soil environment in reclaimed water irrigation area of a city[J]. China Environmental Science, 2016, 36(9): 2614-2623. (in Chinese)) DOI: 10.3969/j.issn.1000-6923.2016.09.0100

[25] CHEN F, YING G G, KONG L X, et al. Distribution and accumulation of endocrine disrupting chemicals and pharmaceuticals in wastewater irrigated soils in Hebei, China[J]. Environmental Pollution, 2011, 159(6): 1490-1498. DOI: 10.1016/j.envpol.2011.03.016.

[26] KINNEY C A, FURLONG E T, WERNER S L, et al. Presence and distribution of wastewater-derived pharmaceuticals in soil irrigated with reclaimed water[J]. Environmental Toxicology & Chemistry, 2006, 25(2): 317-326. DOI: 10.1897/05-187R.1.

[27] TERNES T A, BONERZ M, HERRMANN N, et al. Irrigation of treated wastewater in Braunschweig, Germany: An option to remove pharmaceuticals and musk fragrances[J]. Chemosphere, 2007, 66(5): 894-904. DOI: 10.1016/j.chemosphere.2006.06.035.

[28] KARNJANAPIBOONWONG A, SUSKI J G, SHAH A A, et al. Occurrence of PPCPs at a wastewater treatment plant and in soil and groundwater at a land application site[J]. Water, Air, & Soil Pollution, 2011, 216(1): 257-273. DOI: 10.1007/s11270-010-0532-8.

[29] CHEN W, XU J, LU S, et al. Fates and transport of PPCPs in soil receiving reclaimed water irrigation[J]. Chemosphere, 2013, 93(10): 2621-2630. DOI: 10.1016/j.chemosphere.2013.09.088.

[30] XU J, WU L S, CHEN W P, et al. Pharmaceuticals and personal care products (PPCPs), and endocrine disrupting compounds (EDCs) in runoff from a potato field irrigated with treated wastewater in southern California[J]. Journal of Health Science, 2009, 55(2): 306-310. DOI: 10.1248/jhs.55.306.

[31] QIN Q, CHEN X, ZHUANG J. The fate and impact of pharmaceuticals and personal care products in agricultural soils irrigated with reclaimed water[J]. Critical Reviews in Environmental Science and Technology, 2015, 45(13): 1379-1408. DOI: 10.1080/10643389.2014.955628.

[32] TEIJON G, CANDELA L, TAMOH K, et al. Occurrence of emerging contaminants, priority substances (2008/105/CE) and heavy metals in treated wastewater and groundwater at Depurbaix facility (Barcelona, Spain)[J]. Science of the Total Environment, 2010, 408(17): 3584-3595. DOI: 10.1016/j.scitotenv.2010.04.041.

[33] 李玮, 何江涛, 马文洁, 等. 北京市东南郊再生水灌区地下水多环芳烃污染风险评估[J]. 农业环境科学学报, 2012, 31(4): 713-720. (LI W, HE J T, MA W J, et al. Groundwater PAHs contamination risk assessment of reclaimed wastewater irrigation area, south-east part of Beijing, China[J]. Journal of Agro-Environment Science, 2012, 31(4): 713-720. (in Chinese))

[34] 吴苗苗. 再生水回灌过程中典型磺胺类抗生素的行为特性研究[D]. 北京: 清华大学, 2015. (WU M M. The behavior of typical sulfanomides in soil by groundwater recharge with reclaimed water[D]. Beijing: Tsinghua University, 2015. (in Chinese))

[35] 姜鲁. 再生水回灌过程中炔雌醇和壬基酚的行为特性研究[D]. 北京: 清华大学, 2012. (JIANG L. The behavior of 17α-ethinyl estradiol and 4-n-nonylphenol in soil by groundwater

recharge with reclaimed water[D]. Beijing: Tsinghua University, 2012. (in Chinese))

[36] 李玮, 何江涛, 刘丽雅, 等. Hydrus-1D软件在地下水污染风险评价中的应用[J]. 中国环境科学, 2013, 33(4): 639-647. (LI W, HE J T, LIU L Y, et al. Application of Hydrus-1D software in groundwater contamination risk assessment. [J]. China Environmental Science, 2013, 33(4): 639-647. (in Chinese)) DOI: 10.3969/j.issn.1000-6923.2013.04.009.

[37] ESTEVEZ E, CABRERA M D C, FERNÁNDEZ-VERA J R, et al. Monitoring priority substances, other organic contaminants and heavy metals in a volcanic aquifer from different sources and hydrological processes[J]. Science of the Total Environment, 2016, 551-552: 186-196. DOI: 10.1016/j.scitotenv.2016.01.177.

[38] YOUNG M H, GREEN R L, CONKLE J L, et al. Field-scale monitoring of pharmaceutical compounds applied to active golf courses by recycled water[J]. Journal of Environmental Quality, 2014, 43(2): 658-670. DOI: 10.2134/jeq2013.07.0299.

[39] 魏益华, 徐应明, 周其文, 等. 再生水灌溉对土壤盐分和重金属累积分布影响的研究[J]. 灌溉排水学报, 2008, 27(3): 5-8. (WEI Y H, XU Y M, ZHOU Q W, et al. Effects of irrigation with reclaimed water on soil salinize-alkalization and heavy metal distribution[J]. Journal of Irrigation and Drainage, 2008, 27(3): 5-8. (in Chinese))

[40] 吴文勇. 再生水灌区地下水防污性能试验及灌溉区划研究[D]. 北京: 中国地质大学(北京), 2009. (WU W Y. Research on groundwater vulnerability experiment of reclaimed wastewater district and irrigation allocation[D]. Beijing: China University of Geosciences, 2009. (in Chinese))

[41] 马闯, 杨军, 雷梅, 等. 北京市再生水灌溉对地下水的重金属污染风险[J]. 地理研究, 2012, 31(12): 2250-2258. (MA C, YANG J, LEI M, et al. Assessing the effect of reclaimed water irrigation on groundwater pollution of heavy metals in Beijing[J]. Geographical Research, 2012, 31(12): 2250-2258. (in Chinese))

[42] 杨军, 陈同斌, 雷梅, 等. 北京市再生水灌溉对土壤、农作物的重金属污染风险[J]. 自然资源学报, 2011, 26(2): 209-217. (YANG J, CHENG T B, LEI M, et al. Assessing the effect of irrigation with reclaimed water: The soil and crop pollution risk of heavy metals[J]. Journal of Natural Resources, 2011, 26(2): 209-217. (in Chinese))

[43] 杨庆娥, 任振江, 张航, 等. 不同水质灌溉对土壤中重金属积累和分布的影响[J]. 灌溉排水学报, 2007, 26(3): 47-48. (YANG Q E, REN Z J, ZHANG H, et al. Affection of the heavy metals accumulation and distribution in soil column under different sewage irrigation[J]. Journal of Irrigation and Drainage, 2007, 26(3): 47-48. (in Chinese)) DOI: 10.3969/j.issn.1672-3317.2007.03.012.

[44] 杨军. 灌溉水中重金属对土壤和农作物的污染风险[D]. 重庆: 西南农业大学, 2005. (YANG J. Pollution risks of heavy metals in irrigated water on soils and crops[D]. Chongqing: Southwest Agricultural University, 2005. (in Chinese))

[45] 徐秀凤. 龙口市再生水灌溉条件下粮食安全研究[D]. 济南: 济南大学, 2012. (XU X F. Study on reclaimed water irrigation security on grain of LongKou city[D]. Jinan: University of Jinan, 2012. (in Chinese))

[46] CHEN W, LU S, JIAO W, et al. Reclaimed water: A safe irrigation water source? [J]. Environmental Development, 2013, 8(1): 74-83.

[47] 巫常林, 黄冠华, 刘洪禄, 等. 再生水短期灌溉对土壤-作物中重金属分布影响的试验研究[J]. 农业工程学报, 2006, 22(7): 91-96. (WU C L, HUANG G H, LIU H L, et al. Experimental investigation on heavy metal distribution in soil-crop system with irrigation of treated sewage effluent[J]. Transactions of the CSAE, 2006, 22(7): 91-96. (in Chinese)) DOI: 10.3321/j.issn:1002-6819.2006.07.019.

[48] MAPANDA F, MANGWAYANA E N. The effects of long-term irrigation using water on heavy metal contents of soils under vegetables[J]. Agriculture Ecosystems & Environment, 2005, 107(2): 151-165. DOI: 10.1016/j.agee.2004.11.005.

[49] 魏益华. 再生水灌溉对蔬菜品质和土壤特性的影响研究[D]. 天津: 中国农业科学院, 2009. (WEI Y H. Effects of irrigation with reclaimed water on the vegetables qualities and soil properties[D]. Tianjin: Chinese Academy of Agricultural Sciences, 2009. (in Chinese))

[50] CORWIN D L, AHMAD H R. Spatio-temporal impacts of dairy lagoon water reuse on soil: heavy metals and salinity [J]. Environmental Science Processes & Impacts, 2015, 17(10): 1731-1748. DOI: 10.1039/c5em00196j.

[51] 张铁军, 宋矗森, 陈莉荣, 等. 再生水灌溉对土壤盐渍化与重金属累积影响研究[J]. 节水灌溉, 2016(12): 72-75. (ZHANG T J, SONG C S, CHEN L R, et al. Effect on reclaimed water irrigation on soil salinization and accumulation of heavy metals [J]. Water Saving Irrigation, 2016(12): 72-75. (in Chinese))

[52] 辛宏杰, 卜庆伟, 王爱琴, 等. 再生水灌溉过程中土壤盐分及重金属运移研究[J]. 灌溉排水学报, 2012, 31(5): 78-81. (XIN H J, BU Q W, WANG A Q, et al. Migration of soil salinize-alkalization and heavy metals in the process of reclaimed water irrigation[J]. Journal of Irrigation and Drainage, 2012, 31(5): 78-81. (in Chinese))

[53] 宝哲. 再生水灌溉土壤—地下水重金属污染特征与风险评价[D]. 北京: 中国地质大学(北京), 2014. BAO Z. Research on pollution risk of heavy metals in soil and groundwater under reclaimed water irrigation[D]. Beijing: China University of Geosciences, 2014. (in Chinese))

[54] 黄冠华. 再生水农业灌溉安全的有关问题研究[J]. 中国农业科技导报, 2007, 9(1): 26-35. (HUANG G H. The safety use of treated waste water for irrigation in agriculture[J]. Review of China Agricultural Science and Technology, 2007, 9(1): 26-35. (in Chinese)) DOI: 10.3969/j.issn.1008-0864.2007.01.005.

[55] 杨军, 郑袁明, 陈同斌, 等. 中水灌溉下重金属在土壤中的垂直迁移及其对地下水的污染风险[J]. 地理研究, 2006, 25(3): 449-456. (YANG J, ZHENG Y M, CHEN T B, et al. Leaching of heavy metals in soil column under irrigation reclaimed water: a simulation experiment[J]. Geographical Research,

2006, 25(3): 449-456. (in Chinese)) DOI: 10.3321/j.issn: 1000-0585.2006.03.010.

[56] YIN S, WU W, LIU H, et al. The impact of river infiltration on the chemistry of shallow groundwater in a reclaimed water irrigation area[J]. Journal of Contaminant Hydrology, 2016, 193: 1-9. DOI: 10.1016/j.jconhyd.2016.08.004.

[57] 赵忠明, 陈卫平, 焦文涛, 等. 再生水灌溉农田土壤镉累积规律模拟研究[J]. 环境科学, 2012, 33(12): 4115-4120. (ZHAO Z M, CHEN W P, JIAO W T, et al. Modeling the Cd Accumulation in Agricultural Soil Irrigated with Reclaimed Water[J]. Environmental Science, 2012, 33(12): 4115-4120. (in Chinese))

[58] HUANG X, WEI X, WEI L, et al. Effect of reclaimed water effluent on bacterial community structure in the Typha angustifolia L. rhizosphere soil of urbanized riverside wetland, China[J]. Journal of Environmental Sciences, 2017, 55(5): 58-68. DOI: 10.1016/j.jes.2016.06.022.

[59] LU S, WANG J, PEI L. Study on the Effects of Irrigation with Reclaimed Water on the Content and Distribution of Heavy Metals in Soil[J]. International Journal of Environmental Research & Public Health, 2016, 13(3): 298-307. DOI: 10.3390/ijerph13030298.

[60] LYU S, CHEN W. Soil quality assessment of urban green space under long-term reclaimed water irrigation[J]. Environmental Science & Pollution Research, 2016, 23(5): 1-11. DOI: 10.1007/s11356-015-5693-y.

[61] 丁光晔, 樊贵盛, 张艳. 山西省汾河再生水灌区土壤重金属污染及分布特征[J]. 灌溉排水学报, 2015, 34(2): 53-55. (DING G Y, FAN G S, ZHANG Y. Pollution and Distribution Characteristic of Heavy Metals in Fenhe River Reclaimed Water Irrigation Area of Shanxi Province[J]. Journal of Irrigation and Drainage, 2015, 34(2): 53-55. DOI: 10.13522/j.cnki.ggps.2015.02.013 (in Chinese))

[62] RAHMAN M M, HAGARE D, MAHESHWARI B, et al. Impacts of Prolonged Drought on Salt Accumulation in the Root Zone Due to Recycled Water Irrigation[J]. Water Air & Soil Pollution, 2015, 226(4): 1-18. DOI: 10.1007/s11270-015-2370-1.

[63] 杜娟, 范瑜, 钱新. 再生水农灌过程中重金属迁移规律研究[J]. 环境污染与防治, 2011, 33(7): 74-77. (DU J, FAN Y, QIAN X. Migration of heavy metals in the process of recycled water irrigation[J]. Environmental Pollution & Control, 2011, 33(7): 74-77. (in Chinese)) DOI: 10.3969/j.issn.1001-3865.2011.07.019.

[64] YOUNIS A, RIAZ A, MUSHTAQ N, et al. Evaluation of the Suitability of Sewage and Recycled Water for Irrigation of Ornamental Plants[J]. Communications in Soil Science & Plant Analysis, 2015, 46(1): 62-79. DOI: 10.1080/00103624.2014.956886.

[65] GB 15618-1995, 土壤环境质量标准[S]. (GB 15618-1995, Environmental Quality Standards for Soils[S]. (in Chinese))

[66] GB/T 14848-1993, 地下水质量标准[S]. (GB/T 14848-1993, Quality Standard for Groundwater[S]. (in Chinese))

[67] 乔丽. 再生水农田灌溉生态效应研究—以灌溉冬小麦为例[D]. 北京: 首都师范大学, 2006. (QIAO L. Study on irrigation ecological effect of reclaimed water farmland- taking irrigation of winter wheat as an example[D]. Beijing: Capital Normal University, 2006. (in Chinese))

[68] ESTEVEZ E, CABRERA M C, FERNANDEZVERA J R, et al. Twenty-five years using reclaimed water to irrigate a golf course in Gran Canaria[J]. Spanish Journal of Agricultural Research, 2010, 8(S2): S95-S101. DOI: 10.5424/sjar/201008S2-1353.

[69] XU J, WU L S, CHANG A C, et al. Impact of long-term reclaimed wastewater irrigation on agricultural soils: a preliminary assessment[J]. Journal of Hazardous Materials, 2010, 183(1): 780-786. DOI: 10.1016/j.jhazmat.2010.07.094.

[70] 刘昆鹏. 再生水灌溉地区氮素在土壤中的运移规律模拟的研究[D]. 北京: 北京工业大学, 2006. (LIU K P. The simulation research on the nitrogen transport rule in the soil under re-use water irrigation[D]. Beijing: Beijing University of Technology, 2006. (in Chinese))

[71] FONSECA, DAHERPIN A F, UWEPAULA, et al. Agricultural use of treated sewage effluents: agronomic and environmental implications and perspectives for Brazil[J]. Scientia Agricola, 2007, 64(2): 194-209. DOI: 10.1590/S0103-90162007000200014.

[72] 尹世洋, 吴文勇, 刘洪禄, 等. 再生水灌区地下水硝态氮空间变异性及污染成因分析[J]. 农业工程学报, 2012, 28(18): 200-207. (YIN S Y, WU W Y, LIU H L, et al. Spatial variability of groundwater nitrate-nitrogen and cause analysis of its pollution for irrigation area with reclaimed water[J]. Transactions of the Chinese Society of Agricultural Engineering, 2012, 28(18): 200-207. (in Chinese)) DOI: 10.3969/j.issn.1002-6819.2012.18.029.

[73] CHEN W, LU S, PAN N, et al. Impact of reclaimed water irrigation on soil health in urban green areas[J]. Chemosphere, 2015, 119(1): 654-661. DOI: 10.1016/j.chemosphere.2014.07.035.

[74] QIAN Y L, MECHAM B. Long-term effects of recycled wastewater irrigation on soil chemical properties on golf course fairways[J]. American Society of Agronomy, 2005, 97(3): 717-721. DOI: 10.2134/agronj2004.0140.

[75] 商放泽, 杨培岭, 任树梅. 再生水灌溉对深层包气带土壤盐分离子的影响[J]. 农业机械学报, 2013, 44(7): 98-106. (SHANG F Z, YANG P L, REN S M. Effects of reclaimed water irrigation on soil salinity in deep vadose zone[J]. Journal of Agricultural Mechanization, 2013, 44(7): 98-106. (in Chinese)) DOI: 10.6041/j.issn.1000-1298.2013.07.018.

[76] 裴亮, 颜明, 陈永莲, 等. 再生水灌溉环境生态效应研究进展[J]. 水资源与水工程学报, 2012, 23(3): 19-25. (PEI L, YAN M, CHEN Y L, et al. Research progress on environmental and ecological effects of reclaimed water irrigation[J]. Journal of Water Resources & Water Engineering, 2012, 23(3): 19-25. (in Chinese))

[77] SHANG F, REN S, YANG P, et al. Modeling the risk of the salt for polluting groundwater irrigation with recycled water

and groundwater using HYDRUS-1D[J]. Water, Air, & Soil Pollution, 2016, 227(6): 1-22. DOI: 10.1007/s11270-016-2875-2.

[78] BAJJALI W, AL-HADIDI K, ISMAIL M M. Water quality and geochemistry evaluation of groundwater upstream and downstream of the Khirbet Al-Samra wastewater treatment plant/Jordan[J]. Applied Water Science, 2017, 7(1): 53-69. DOI: 10.1007/s00382-004-0411-3.

[79] 吴文勇, 刘洪禄, 陈鸿汉, 等. 再生水灌区调蓄工程对地下水盐分的影响[J]. 农业工程学报, 2009, 25(12): 22-25. (WU W Y, LIU H L, CHEN H H, et al. Effect of regulation and storage engineering on groundwater salinity in reclaimed water irrigation district[J]. Transactions of the CSAE, 2009, 25(12): 22-25. (in Chinese)) DOI: 10.3969/j.issn.1002-6819.2009.12.004.

[80] 王祥林. 再生水对土壤理化性质影响的研究[J]. 山东林业科技, 2009, 39(4): 1-4. (WANG X L. Study on the effect of reclaimed water on soil physical and chemical properties[J]. Shandong Forest Science and Technology, 2009, 39(4): 1-4. (in Chinese)) DOI: 10.3969/j.issn.1002-2724.2009.04.001.

[81] KIZILOGLU F M, TURAN M, SAHIN U, et al. Effects of untreated and treated wastewater irrigation on some chemical properties of cauliflower(Brassica olerecea, L. var. botrytis) and red cabbage(Brassica olerecea, L. var. rubra) grown on calcareous soil in Turkey[J]. Agricultural Water Management, 2008, 95(6): 716-724. DOI: 10.1016/j.agwat.2008.01.008.

[82] 王巧环, 陈卫平, 王效科, 等. 城市绿化草坪再生水灌溉对地下水水质影响研究[J]. 环境科学, 2012, 33(12): 4127-4132. (WANG Q H, CHEN W P, WANG X K, et al. Impacts of reclaimed water irrigation of urban lawn on groundwater quality[J]. Environmental Science, 2012, 33(12): 4127-4132. (in Chinese))

[83] CANDELA L, FABREGAT S, JOSA A, et al. Assessment of soil and groundwater impacts by treated urban wastewater reuse. A case study: application in a golf course (Girona, Spain)[J]. Science of the Total Environment, 2007, 374(1): 26-35. DOI: 10.1016/j.scitotenv.2006.12.028.

[84] AIELLO R, CIRELLI G L, CONSOLI S. Effects of reclaimed wastewater irrigation on soil and tomato fruits: A case study in Sicily (Italy)[J]. Agricultural Water Management, 2007, 93(1): 65-72. DOI: 10.1016/j.agwat.2007.06.008.

[85] BIRKS R, COLBOURNE J, HILLS S, et al. Microbiological water quality in a large in-building, water recycling facility[J]. Water Science & Technology, 2004, 50(2): 165-176.

[86] LEVANTESI C, LA MANTIA R, MASCIOPINTO C, et al. Quantification of pathogenic microorganisms and microbial indicators in three wastewater reclamation and managed aquifer recharge facilities in Europe[J]. Science of the Total Environment, 2010, 408(21): 4923-4930. DOI: 10.1016/j.scitotenv.2010.07.042.

(上接第 97 页)

[24] 赵彩霞, 梅旭荣, 居辉, 等. 黄淮海平原各农业亚区潜在蒸散量变化及其对气候要素的敏感性分析[J]. 中国农业气象, 2015, 36(5): 570-577. (ZHAO C X, MEI X R, JU H, et al. Variation in potential evapotranspiration and its sensitivity coefficients to climatic factors in the Huang-Huai-Hai Plain[J]. Chinese Journal of Agrometeorology, 2015, 36(5): 570-577. (in Chinese)) DOI: 10.3969/j.issn.1000-6362.2015.05.006.

[25] 刘宪锋, 潘耀忠, 张锦水, 等. 1960–2011 年西北五省潜在蒸散的时空变化[J]. 应用生态学报, 2013, 24(9): 2564-2570. (LIU X F, PAN Y Z, ZHANG J S, et al. Spatiotemporal variation patterns of potential evapotranspiration in five provinces of North-west China in 1960-2011[J]. Chinese Journal of Applied Ecology, 2013, 24(9): 2564-2570. (in Chinese))

[26] 易浪, 任志远, 崔宇, 等. 陕西省 1961 年– 2011 年气温和降水变化趋势及突变分析[J]. 华中师范大学学报(自然科学版), 2014, 48(4): 592-600. (YI L, REN Z Y, CUI Y, et al. Analysis on the change trends and catastrophe of temperature and percipitation in Shannxi Province from 1961 to 2011[J]. Journal of Center China Normal University (Natural Science Edition), 2014, 48(4): 592-600. (in Chinese)) DOI: 10.3969/j.issn.1000-1190.2014.04.028.

[27] 刘园, 王颖, 杨晓光. 华北平原参考作物蒸散量变化特征及气候影响因素[J]. 生态学报, 2010, 30(4): 5589-5599. (LIU Y, WANG Y, YANG X G. Trends in reference crop evapotranspiration and possible climate factors in the North China Plain[J]. Acta Ecological Sinica, 2010, 30(4): 5589-5599. (in Chinese))

[28] 范建忠, 李登科, 高茂盛. 基于 MOD16 的陕西省蒸散量时空分布特征[J]. 生态环境学报, 2014, 23(9): 1536-1543. (FAN J Z, LI D K, GAO M S. Spatio-temporal variations of evapotranspiration in Shaanxi province using MOD16 products[J]. Ecology and Environmental Sciences, 2014, 23(9): 1536-1543. (in Chinese)) DOI: 10.16258/j.cnki.1674-5906.2014.09.008.

[29] 刘小莽, 郑红星, 刘昌明, 等. 海河流域潜在蒸散发的气候敏感性分析[J]. 资源科学, 2009, 31(9): 1470-1476. (LIU X M, ZHENG H X, LIU C M, et al. Sensitivity of the potential evapotranspiration to key climatic variables in the Haihe River Basin[J]. Resources Science, 2009, 31(9): 1470-1476. (in Chinese)) DOI: doi: 10.3321/j.issn: 1007-7588.2009.09.003.