AQUA
Water Infrastructure, Ecosystems and Society

AQUA — Water Infrastructure, Ecosystems and Society Vol 72 No 7, 1309 doi: 10.2166/aqua.2023.288

Waste load allocation by integrated GMS modeling and economic evaluation for nitrate reduction in Varamin aquifer

MohammadAmin Souri[a], Shervin Jamshidi[a,*] and Hamid Kardan Moghaddam[b]
[a] Department of Civil Engineering, University of Isfahan, Isfahan, Iran
[b] Department of Environment, Water Research Institute, Ministry of Energy, Tehran, Iran
*Corresponding author. E-mail: sh.jamshidi@eng.ui.ac.ir

SJ, 0000-0003-3067-1529; HKM, 0000-0003-4018-4388

ABSTRACT

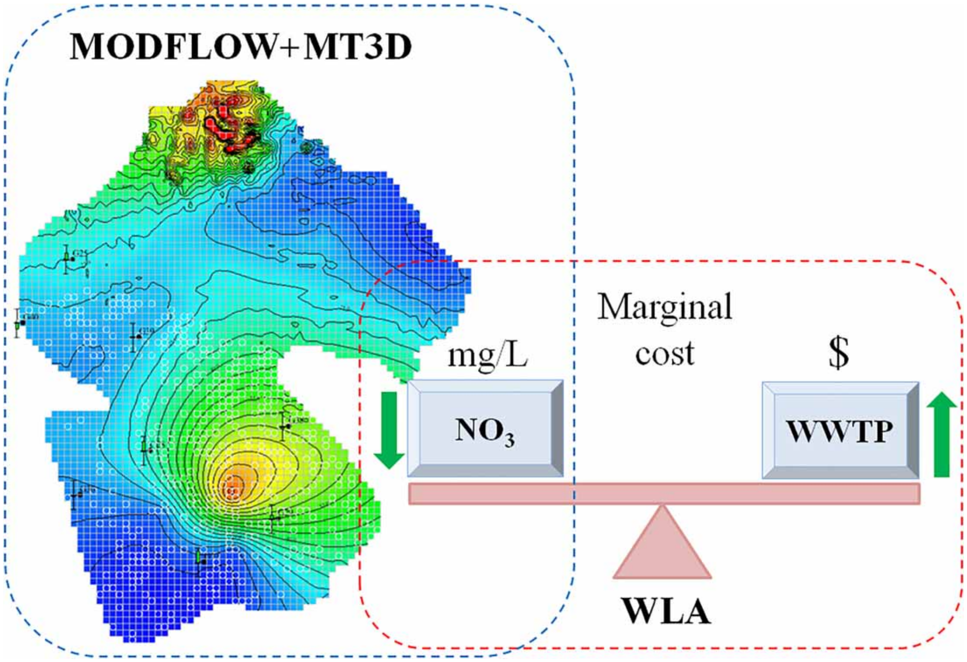
Groundwater is a dependable freshwater resource in arid and semi-arid areas where its quality management is essential. However, untreated wastewater is a risk to safe water supply from aquifers. Wastewater treatment plants (WWTPs) can reduce pollutants, but their impact on groundwater quality versus their operating costs requires case studies. This research uses the two modules of the groundwater modeling system (GMS) to simulate the Varamin Plain, south-eastern Tehran, Iran. The MODFLOW and MT3D were used for groundwater quantity and quality modeling, respectively. Through these modules, the effectiveness of two WWTPs (Pakdasht and Varamin) in six waste load allocation (WLA) scenarios was compared based on nitrate reduction in 3-year and 10-year periods. The construction and operating costs of each WLA scenario were also calculated. The best WLA is a scenario with the lowest marginal cost. Therefore, constructing Varamin WWTP with 25% nitrogen removal was the selected option. Here, the average nitrate concentration in the aquifer is reduced from 28.4 mg/L (±4.1) to less than 25 mg/L (±2.4) with an annual marginal cost of 8 M$.L/mg. It implies that constructing more WWTPs or tertiary units for nitrate removal is not recommended as they do not add significant nitrate abatement in groundwater regarding the related costs.

Key words: economic valuation, groundwater modeling, tertiary treatment, waste load allocation (WLA), water quality management

HIGHLIGHTS

- Varamin aquifer is modeled by combined MODFLOW and MT3D modules.
- Impacts of six WLA scenarios were compared in 3- and 10-year periods.
- Optimal WLA is a scenario with the least annual marginal cost (8 M$.L/mg).
- A costly tertiary unit is not necessarily a sustainable option for WLA.
- The aquifer is gradually reactive to nitrate removal for more than a decade.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Groundwater management with competing users is a challenge in arid and semi-arid areas (Darbandsari *et al.* 2020). Its quality is also vulnerable to wastewater and leaching from domestic, industrial, and agricultural activities (Wada *et al.* 2021). In particular, nutrient puts groundwater resources at risk and has secondary impacts on health and the economy (Kariman *et al.* 2018; Golian *et al.* 2021). Recent research indicates increased global concerns about nitrate leaching into the groundwater. Water extraction and wastewater discharges can affect its concentration in an aquifer (Shahraki *et al.* 2020). Water with excessive nitrate concentration can cause serious health problems for livestock and humans (Lorenz *et al.* 2014; Najafi Alamdarlo *et al.* 2016). Methemoglobinemia in infants and cancer risk are some examples (Gardner *et al.* 2020; Liu *et al.* 2022). Nitrate concentration in soil and aquifer increases in areas with a high level of agricultural activity using fertilizers and manure (Imani *et al.* 2015, 2017). Nitrogenous fertilizers are heavily invested in the fields by farmers to maintain adequate production and increase yields (Jamshidi *et al.* 2020; Jamshidi & Naderi 2023). The excess nitrate leaches into groundwater and causes contamination problems (Martínez *et al.* 2020). In contrast to natural attenuation processes (Akbarzadeh *et al.* 2015), engineered systems, such as a wastewater treatment plant (WWTP), can significantly reduce nitrate pollution (Jamshidi & Niksokhan 2016). Thus, recent research efforts have focused on understanding the pathways of nitrate (NO_3) generation and contamination in groundwater and developing eco-friendly approaches to remove NO_3 from groundwater (Huno *et al.* 2018). Marshall *et al.* (2019) examined the spatiotemporal variability of wastewater parameters, including nitrate and their transport in groundwater. They could estimate the impacts of WWTP on groundwater pollution transport over time (Marshall *et al.* 2019).

NO_3 is traceable and manageable through waste load allocation (WLA) policies (Menció *et al.* 2016; Alfarrah & Walraevens 2018). To predict NO_3 contamination in groundwater, a nitrate-based transport model was recently used to estimate four WLA scenarios. In every scenario, NO_3 concentration was influenced by discharged pollution loads. Its concentration decreased in all scenarios during the 20-year prediction period, while none of the scenarios could reduce it below the standard level (Karlović *et al.* 2022). Depending on the specific aquifer conditions, the types of contaminants, and related costs, each WLA scenario may control or reduce some pollution loads (Benjakul 2010; Matiatos *et al.* 2019). It is recommended to select the best-performing WLA systematically by evaluating its effectiveness or potential in water quality improvement (Samadi-Darafshani *et al.* 2021). Since pollution removal is set at a desired level in WLAs, the related cost of attaining that purity level increases as treatment improves (Jamshidi *et al.* 2014; Englande *et al.* 2015). Identifying appropriate strategies and financing for wastewater infrastructure under WLA is often challenging for decision-makers (van Afferden *et al.* 2015). Therefore, groundwater quality management by constructing WWTP requires a two-faceted economic-functional analysis. This should be implemented by an integrated simulation tool to estimate the fate and transport of pollutants and track the sensitivity of receiving aquifer to different emissions. For this purpose, numerical models are valuable tools in understanding groundwater systems and estimating their qualitative status under various WLA scenarios (Foster *et al.* 2021). Groundwater resources modeling poses challenges in understanding influential parameters and achieving proper model calibration, crucial for accurate results, and effective water resource management (Eini *et al.* 2020; Jafari *et al.* 2021). To solve WLA problems, it is necessary to understand the quality response of receiving water bodies to each scenario. Groundwater simulation is commonly carried out by two GMS software modules. The MODFLOW and MT3D modules are used for water quantity and quality modeling, respectively (Raetz 2022). For example, a new simulation-optimization method in a watershed has been devised to solve problems associated with multiple pollutants (Sadak *et al.* 2020). Multipollutant loads were allocated according to the locations of their sources using an optimization formula. However, groundwater systems may take a decade or more to respond to this strategy.

This study aims to compare the impacts of constructing two WWTPs (Pakdasht and Varamin) with different nitrate removal efficiencies on groundwater quality. This study uses aquifer flow simulation by MODFLOW, followed by contaminant fate and transport modeling by MT3D. These modules predict NO_3 concentration in groundwater in different WLA scenarios during 3-year (T3) and 10-year (T10) periods. Here, WWTPs have different nitrate removal efficiencies with total abatement costs. Thus, on the basis of a numerical model, this research evaluates the effectiveness of WWTPs in remediating groundwater quality and considers related costs. By these means, the optimal WLA strategy is recommended in the study area. Accordingly, this study has two notable innovations in the field. Firstly, the research employs a combined qualitative and quantitative modeling for WLA in groundwater. This approach ensures a holistic understanding of the nitrogen reduction in aquifers by different wastewater treatments. Secondly, by incorporating multiple scenarios, the study provides a cost-effective analysis that enhances our understanding of potential management strategies. The question 'is it necessary to upgrade both WWTPs with tertiary units?' is answered by introducing the marginal cost (MC), as a decisive index, in the applied methodology.

2. MATERIALS AND METHODS

2.1. Methodology

This study follows a three-step methodology (Figure 1). At first, the aquifer was simulated by focusing on nitrate concentration. Six WLA scenarios were then testified to compare WWTPs' impacts on groundwater quality improvement. These two steps can provide a framework for evaluating the most cost-effective WLA policy in the final step.

2.2. Study area

This study examines the impacts of WWTPs on the Varamin Plain, located in the south-eastern part of Tehran province, Iran. This plain is between the latitudes of 35.39°N and 35.07°N and the longitudes of 51.26°E and 51.55°E and covers approximately 957 km^2 area. Excessive water demands and unsustainable groundwater extraction in the Varamin aquifer have caused declining water levels, resulting in land subsidence and reduced groundwater table (Nayyeri *et al.* 2021). This plain supplies the agricultural and drinking water of two counties, Pakdasht and Varamin. Droughts in recent decades have made wastewater recharge an attractive option. It could partially compensate for water quantity for agriculture, whereas deteriorated water quality (Noghreyan *et al.* 2022). Here, untreated wastewater of Pakdasht and Varamin are the primary point sources (Ministry of power 2013; Nouri *et al.* 2020). It is planned to construct and operate two WWTPs for these two counties. WW1 locates in 35°24′0″N, 51°53′0″E (Varamin) and the WW2 blueprint is 35°28′0″N, 51°48′0″E (Pakdasht). WW1 and WW2 receive sewage from about 284,000 and 351,000 persons, respectively. Accordingly, this study seeks a cost-effective and environmentally sound WLA to answer the following question: which WWTP, WW1 or WW2, should be prioritized regarding groundwater quality variations and total costs?

2.3. Simulation and calibration

GMS software (version 10.1) was used to simulate the Varamin aquifer. MODFLOW and MT3DMs were the modules that simulated groundwater level and quality, respectively. Since the study area is quite large, it has been divided into six zones based on land use and available observation wells having water quality data. This zoning could provide an elaborate

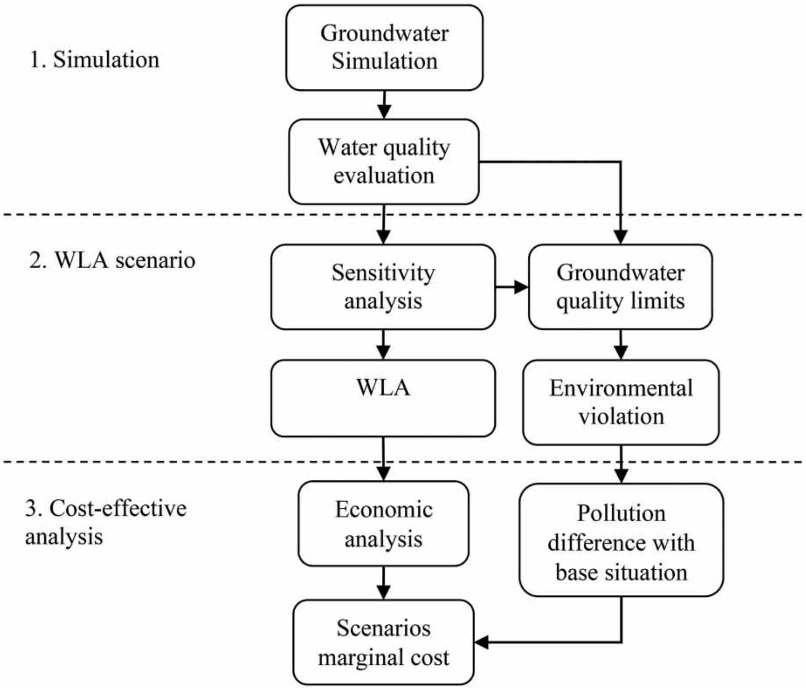


Figure 1 | Methodology steps of this study.

framework for demonstrating the sensitivity of groundwater to the WLA scenario in short term (3 years) and long term (10 years). For simulation, the study area was gridded by 250,000 m^2 squares. The locations of observation wells, their temporal variations on water levels, and aquifer recharge were initially determined based on available data. Furthermore, qualitative information, such as NO_3 concentrations and discharges from emission sources, were assigned to the nodes (Ministry of Energy 2013).

Calibration was carried out on available data from September 2009–March 2012 (1,002 days). T0 corresponds to autumn 2011 when the model is calibrated, T3 represents the conditions 3 years after simulation (2011–2014), and T10 represents groundwater quality for each WLA scenario 10 years after the simulation ends (2011–2021). Figure 2 summarizes the average groundwater depth in 42 piezometric wells. R-square and the root mean square errors (RMSE) for the average simulated groundwater depth and observed data (2009–2011) are 0.81 and 0.46, respectively. The concentration of NO_3 collected from observation wells with the collection time period (monthly) is expressed in Table 1.

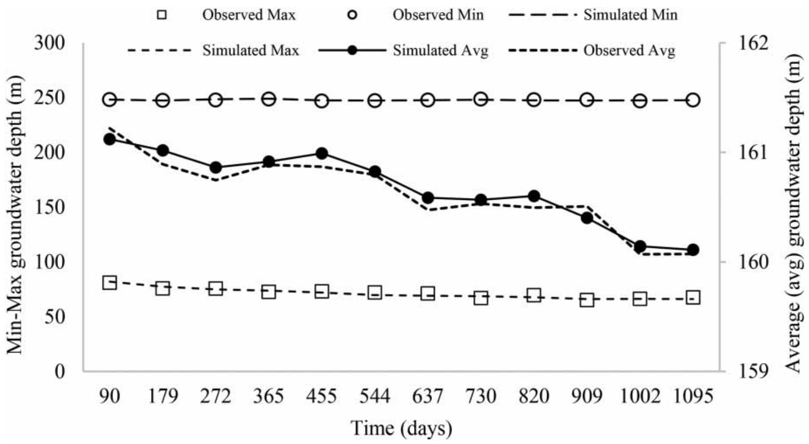


Figure 2 | Maximum, minimum and average observed and simulated groundwater depth (m).

Table 1 | NO_3 concentration in observation wells with time periods (Sep 2009-Mar. 2012)

	NO_3 concentration in observation wells (mg/L)							
Time	G25	G28	G29	G36	G37	G38	G39	G40
2009-09	24.5	29.9	31.2	25.6	24.8	63.9	23.6	26.1
2009-12	24.8	28.7	31.4	25.6	24.9	66.1	21.6	26.1
2010-03	25.1	24.2	31.3	25.5	25.0	63.2	19.6	26.0
2010-06	25.4	19.7	30.9	25.5	25.1	57.4	17.7	25.9
2010-09	25.6	19.3	30.4	25.5	25.2	53.6	17.2	25.8
2010-12	25.9	20.0	30.0	25.4	25.5	52.4	17.5	25.8
2011-03	26.1	18.0	29.6	25.3	25.8	49.6	17.0	25.7
2011-06	26.4	15.6	29.0	25.2	26.1	45.5	15.8	25.6
2011-09	26.7	16.2	28.4	25.2	26.6	42.8	15.6	25.6
2011-12	27.0	17.8	28.0	25.1	27.2	42.4	16.2	25.5
2012-03	27.3	16.5	27.6	25.0	27.7	41.3	15.7	25.4

2.4. WLA scenarios

The effectiveness of six WLA scenarios on aquifer quality was investigated and compared through the calibrated model. Table 2 illustrates the specifications of these WLA scenarios. Differences in WLAs are basically in the locations of WWTPs (WW1 and WW2), the zoning of treated wastewater recharge, and their NO_3 removal efficiency (25 and 50%). S0 depicts the basic status of the simulated aquifer in the study area without any projected WLA.

In each WLA scenario (S1–S6), the abated nitrogen (N) was assigned to the target residential region as equivalent to reduced NO_3 concentration (%). It is necessary as Pakdasht and Varamin counties have no WWTPs and the untreated wastewater is conventionally discharged to the aquifer. N mitigation in S1–S6 means that NO_3 concentration in treated wastewater is decreased via constructing and operating WWTPs prior to any discharge or infiltration to the groundwater. The outcomes of all WLA scenarios were then analyzed and evaluated in both the objective area as well as the study area observation wells.

It should be added that WLA scenarios were individually defined in the calibrated model and NO_3 concentration at eight observation wells was obtained by GMS outputs. The impact of each scenario on pollution abatement is estimated using the average T3 and T10 concentrations from all observation wells. Following that WLA scenarios were qualitatively ordered based on their effectiveness on groundwater quality. In this case, the most environmentally favorable WLA is the one with the lowest average NO_3 concentration in the entire plain based on NO_3 concentration at both T3 and T10. Nevertheless, a viable WLA scenario needs economic analysis as well.

2.5. Economic analysis

Total cost (TC) is required for conducting economic analysis for WLAs. For WWTPs, TC attributes to their construction and operation costs in their lifetime. In WLA scenarios, it can be defined according to the required biochemical oxidation demand

Table 2 | Definition of WLA scenario in this study

Scenario	Description
S0	Basic scenario
S1	WW2 with 25% N removal and aquifer recharge
S2	WW2 with 50% N removal and aquifer recharge
S3	WW1 with 25% N removal and aquifer recharge
S4	WW1 with 50% N removal and aquifer recharge
S5	S1 + S3
S6	S2 + S4

(BOD) and N removal efficiencies in WWTPs as Equation (1) (Jamshidi & Niksokhan 2016)

$$C_W = T \times Q \tag{1}$$

where C_W is the annual capital and operation costs (million\$/yr), Q is the annual average wastewater inflow (m^3/s), and T is the annual capital and operating cost of WWTPs per unit volume (million\$/m^3) which is calculated by Equation (2)

$$T = T_{\mathrm{BOD}} + T_{\mathrm{NO_3}} \tag{2}$$

Here, T_{BOD} and T_{NO3} are the costs of reducing BOD and NO_3 pollutants, respectively (M\$/m^3). They depend on the required efficiency as calculated by Equations (3) and (4), respectively.

$$T_{\mathrm{BOD}} = 1.7X^2 + 0.9X + 0.11 \tag{3}$$

X denotes BOD concentration abatement in WWTP that ranges between 0 and 1. In this study, BOD concentration reduction for all WWTPs is assumed as 0.9, meaning that WWTPs should at least remove 90% of the BOD concentration of wastewater in any scenario. However, it is noteworthy that BOD is only used for cost evaluations and is not included in water quality assessment in simulation and WLA.

$$T_{\mathrm{NO_3}} = -2.8Z^3 + 4.1Z^2 - 0.3Z \tag{4}$$

where Z represents the NO_3 removal efficiency of WWTPs and it ranges between 0 and 1. For example, in S1 with 25% N removal, Z equals 0.25.

The average MC of WLAs is an economic index that can be calculated using Equation (5).

$$\mathrm{MC}_W = \frac{C_W}{R} \tag{5}$$

where MC_W is the annual average marginal cost of each WLA scenario (M\$.L/mg), R is the abated nitrate concentration of the aquifer of each WLA in comparison with S0 (mg/L), and C_W is defined earlier.

3. RESULTS

3.1. Simulation results

Simulation results show that the average groundwater level at T0 is 852 m and the average nitrate concentration in the aquifer is 28.4 mg/L. The latter varies between 17.7 mg/L and 57.4 mg/L in the whole plain (Figure 3). It is clear that the distribution of contaminants is not uniform across the plain, with relatively high NO_3 concentrations in the northern and central-south parts of the plain.

Figure 4 illustrates the average, minimum, and maximum of NO_3 concentration in observation wells during T3 and T10 for all WLA scenarios. Comparatively, S6 has the lowest nitrate concentration in both periods. Nonetheless, the optimal WLA policy is a strategy that fulfills the lowest pollutant concentration with the least cost. In S0, NO_3 concentration decreases during T10 as a matter of aquifer recharge with treated wastewater without nitrate removal in WWTPs. The difference between S6 and S0 in T3 and T10 indicates how much nitrate reduction in WWTPs is effective on groundwater in the mid term and long term.

Figure 5 illustrates NO_3 removal efficiency (%) of different WLAs in the aquifer for both T3 and T10. It shows that S6 has the highest NO_3 reduction in groundwater in both periods. The average abated NO_3 of S6 in T3 and for T10 are 4.3% (±2.1) and 11.7% (±2.9), respectively. On the contrary, the least effective WLAs on NO_3 removal in T3 and T10 are S1 and S3 with 0.3% (±0.4) and 3.3% (±1.7), respectively. It means that constructing WW1 and WW2 with 50%N removal is more effective than constructing just one WWTP. However, economic evaluation analysis is also required to compare the cost-effectiveness of these WLAs.

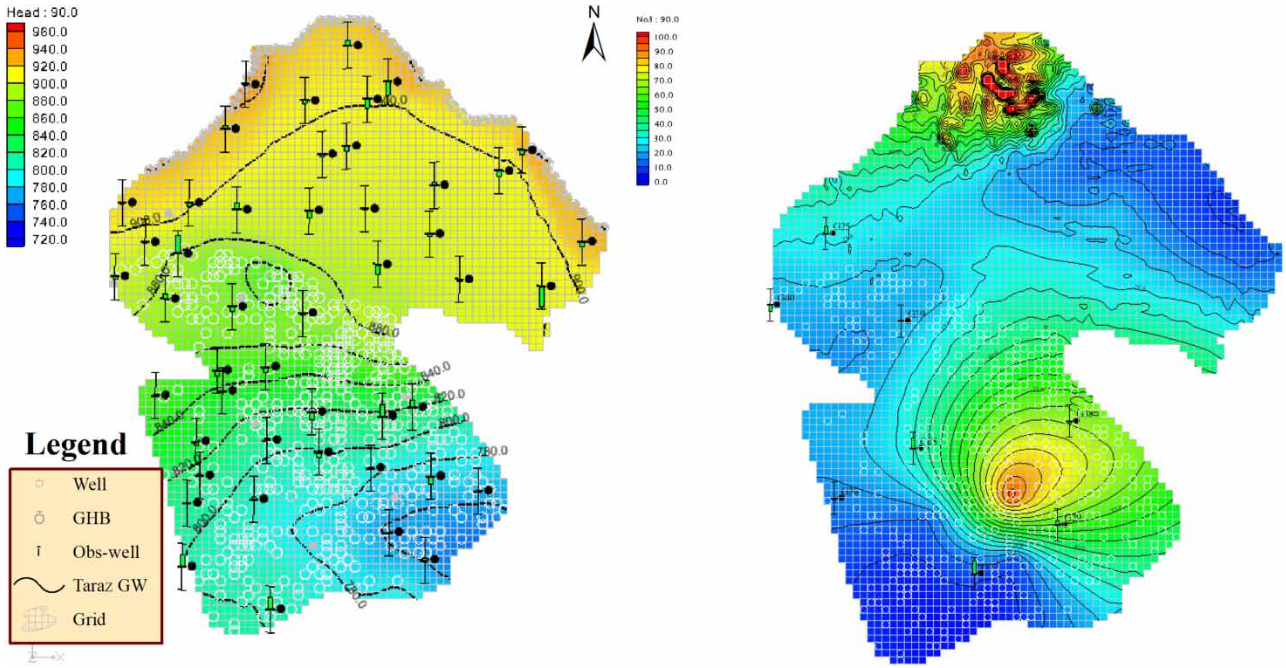


Figure 3 | Groundwater level (Left) and simulated NO_3 concentration (Right) at T0.

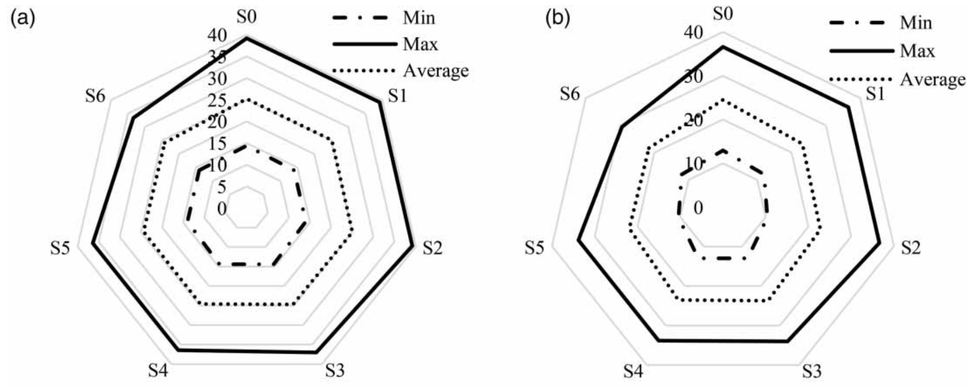


Figure 4 | The average with minimum and maximum concentrations of NO_3 (mg/L) in aquifer at T3 (a) and T10 (b) for all WLA scenarios (S0-S6).

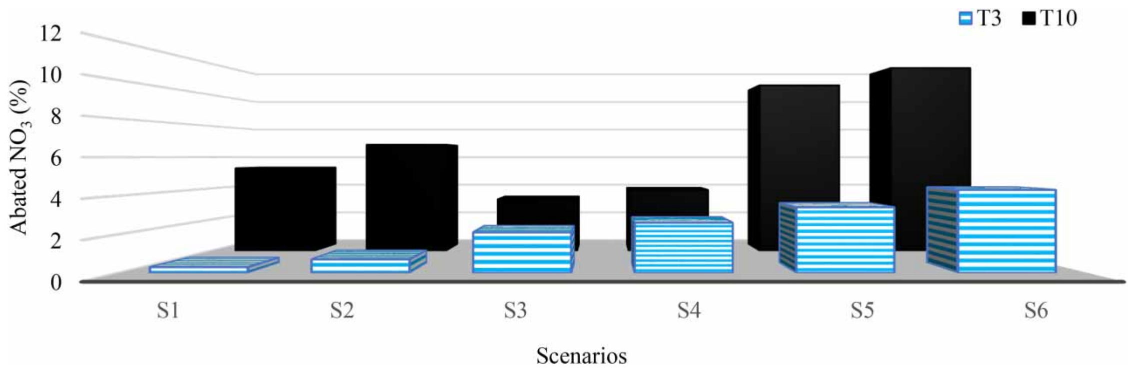


Figure 5 | Pollution reduction of WLAs (%) in the aquifer in T3 and T10.

3.2. Economic evaluation

Figure 6 illustrates MC and TC required for switching from S0 to each WLA in the logarithmic scale. The MC for T10 is determined by the average impact of each scenario on groundwater quality. The least cost option is S3 (38.3 M$/yr), whereas the most costly strategy is S6 (99.6 M$/yr). Due to the accumulated cost of building WWTPs, it is obvious that WLAs with two WWTPs (S5 and S6) have relatively higher costs than other scenarios (S1–S4). As shown in Figure 6, annual NO_3 removal MC ranges between 8 (S3) and 14.6 M$.L/mg (S6). It means that annually 8 million US$ is required in S3 for 1 mg/L nitrate abatement from the Varamin aquifer for 10 years. Hence, S3 is the best cost-effective scenario because it has the highest economic return for stakeholders and has the least MC and TC.

4. DISCUSSION

In this research, we conducted a comprehensive assessment of various WLA scenarios and their implications for long-term groundwater quality and economic considerations. Our study was based on the NO_3 parameter recommended by Nzama *et al.* (2021), as it is considered a critical groundwater pollutant that can be managed through land-use changes and WWTPs (Nzama *et al.* 2021). The effectiveness of these practices was verified through simulations using MODFLOW and MT3DMs, recognized as efficient groundwater modeling techniques (Raetz 2022).

Our investigation on the Varamin Plain showed that the simultaneous implementation of two WWTPs presents relatively higher pollution abatement compared to WLA policies involving a single WWTP. However, their pollution abatement is not significant in groundwater in the short term, and therefore, implementing both WWTPs is not recommended considering the related costs. Interestingly, this finding aligns with the results of Wada *et al.* (2021), where a single WWTP had a more significant impact on groundwater quality. Our results also contradict the findings of Adebowale *et al.* (2019), with the notion that constructing multiple WWTPs yields greater efficiency, particularly in the areas surrounding the WWTPs, within a shorter time period (Adebowale *et al.* 2019).

In a recent study by Saadatpour *et al.* (2019), it was concluded that WWTPs can improve the water quality index, and increasing the investment cost leads to greater quality improvements. However, there is a specific limit beyond which the water quality index cannot be further improved, regardless of the cost incurred or equity sacrificed (Saadatpour *et al.* 2019). In our current study, we also found that increasing the cost of WWTPs results in greater quality improvements. However, once specific limits are reached, more investment would be futile.

It has also become evident that pollution concentration limits set by regulatory bodies must consider a combination of pollution objectives and stakeholder demands to ensure the development of user-friendly applications. By doing so, water quality violations can be minimized for up to 20 years (Dinar & Quinn 2022). Moreover, previous studies have highlighted the practicality of pollution removal in WWTPs (Jamshidi & Niksokhan 2016) within the context of WLA. These factors, coupled

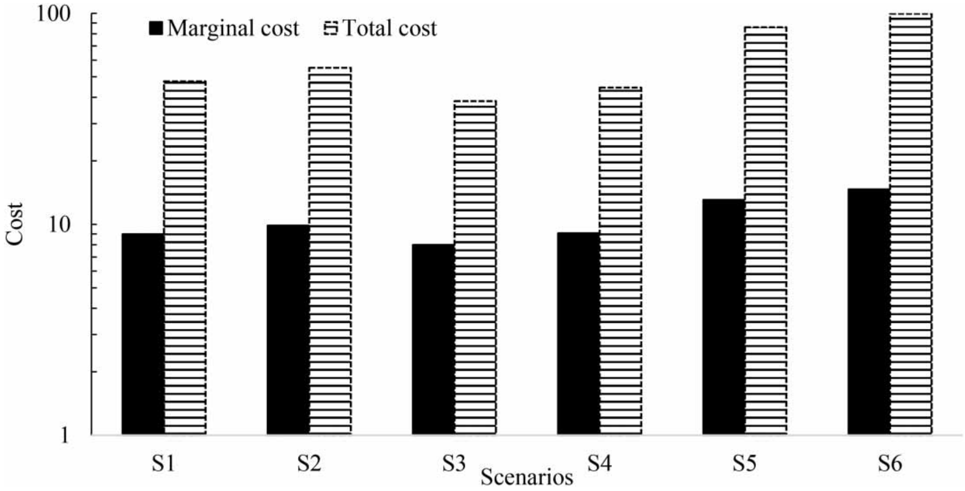


Figure 6 | Required total cost (M$/yr) and the annual marginal cost (M$.L/mg) for one unit pollutant reduction in each WLA scenario in logarithmic scale.

with our latest research findings, underscore the importance of integrating economic objectives and practical considerations to establish sustainable groundwater quality management strategies.

5. CONCLUSION

This study used GMS modules to simulate the impacts of 6 WLA scenarios on NO_3 reduction in two time periods (T3 and T10). Results showed that GMS is a reliable and practical tool for groundwater simulation prior to WLA analysis. The MODFLOW and MT3D modules can be used for quantity and quality modeling, respectively. According to the results, WWTPs in the study area would not be considerably effective on NO_3 abatement in less than 10 years. Here, constructing two WWTPs (WW1 and WW2) is the most leading WLA for groundwater quality enhancement. However, it requires considerable costs. In addition, improving aquifer quality is not linear to the number of constructed WWTPs. Thus, this study recommended calculating the marginal costs, as an efficiency index, for referring to the optimal WLA. By this approach, S3 (WW1 with 25%N removal), S1 (WW2 with 25%N removal), and S4 (WW1 with 50%N removal) are prioritized as cost-effective WLAs.

AUTHORS' CONTRIBUTIONS

M.A.S. led the investigation, prepared the methodology, did software analysis, validated, analyzed, did data curation, visualized, and wrote the original draft. S.J. conceptualized the study, prepared the methodology, did analysis, supervised, did project administration, and wrote (reviewed and edited) the article. H.K.M. collected resources, did software analysis, validated, and visualized the study.

FUNDING

Iran Water Resource Management Co. under contract No. S.07.1401 with the University of Isfahan partially contributed to the funding of this research.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adebowale, T., Surapaneni, A., Faulkner, D., McCance, W., Wang, S. & Currell, M. 2019 Delineation of contaminant sources and denitrification using isotopes of nitrate near a wastewater treatment plant in peri-urban settings. *Science of The Total Environment* **651**, 2701–2711. https://doi.org/10.1016/j.scitotenv.2018.10.146.

Akbarzadeh, A., Jamshidi, S. & Vakhshouri, M. 2015 Nutrient uptake rate and removal efficiency of vetiveria zizanioides in contaminated waters. *Pollution* **1** (1), 1–8.

Alfarrah, N. & Walraevens, K. 2018 Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. *Water* **10** (2), 143. https://doi.org/10.3390/w10020143.

Benjakul, R. 2010 *Simulating Dioxane Transport in A Heterogeneous Glacial Aquifer System (Washtenaw County, Michigan) Using Publicly Available Models and Data*. Michigan Technological University. https://doi.org/10.37099/mtu.dc.etds/313.

Darbandsari, P., Kerachian, R., Malakpour-Estalaki, S. & Khorasani, H. 2020 An agent-based conflict resolution model for urban water resources management. *Sustainable Cities and Society* **57**, 102112. https://doi.org/10.1016/j.scs.2020.102112.

Dinar, A. & Quinn, N. W. T. 2022 Developing a decision support system for regional agricultural nonpoint salinity pollution management: application to the San Joaquin River, California. *Water* **14** (15), 2384. https://doi.org/10.3390/w14152384.

Eini, M. R., Javadi, S., Delavar, M., Gassman, P. W. & Jarihani, B. 2020 Development of alternative SWAT-based models for simulating water budget components and streamflow for a karstic-influenced watershed. *CATENA* **195**, 104801. https://doi.org/10.1016/j.catena.2020.104801.

Englande, A. J., Krenkel, P. & Shamas, J. 2015 Wastewater treatment & water reclamation. *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.09508-7.

Foster, L. K., White, J. T., Leaf, A. T., Houston, N. A. & Teague, A. 2021 Risk-based decision-support groundwater modeling for the lower San Antonio River Basin. *Groundwater*. **59** (4), 581–596. Texas, USA.

Gardner, S. G., Levison, J., Parker, B. L. & Martin, R. C. 2020 Groundwater nitrate in three distinct hydrogeologic and land-use settings in southwestern Ontario, Canada. *Hydrogeology Journal* **28** (5), 1891–1908. https://doi.org/10.1007/s10040-020-02156-4.

Golian, M., Saffarzadeh, A., Katibeh, H., Mahdad, M., Saadat, H., Khazaei, M., Sametzadeh, E., Ahmadi, A., Sharifi Teshnizi, E., Samadi Darafshani, M. & Dashti Barmaki, M. 2021 Consequences of groundwater overexploitation on land subsidence in Fars Province of Iran and its mitigation management programme. *Water and Environment Journal* **35** (3), 975–985. https://doi.org/10.1111/wej.12688.

Huno, S. K. M., Rene, E. R., van Hullebusch, E. D. & Annachhatre, A. P. 2018 Nitrate removal from groundwater: a review of natural and engineered processes. *Journal of Water Supply: Research and Technology-Aqua* **67** (8), 885–902. https://doi.org/10.2166/aqua.2018.194.

Imani, S., Delavar, M. & Niksokhan, M. H. 2016 Periodical effects of land uses on water quality of Zrebar Lake, Iranian. *Journal of Geology* **9** (36), 1–10.

Imani, S., Delavar, M. & Niksokhan, M. H. 2017 Simulation and assessment of management practices for reduction of nutrients discharge to the zrebar lake using swat model. *Iran-Water Resources Research* **13** (1), 69–87.

Jafari, T., Kiem, A. S., Javadi, S., Nakamura, T. & Nishida, K. 2021 Fully integrated numerical simulation of surface water-groundwater interactions using SWAT-MODFLOW with an improved calibration tool. *Journal of Hydrology: Regional Studies* **35**, 100822. https://doi.org/10.1016/j.ejrh.2021.100822.

Jamshidi, S. & Naderi, A. 2023 A quantitative approach on environment-food nexus: integrated modeling and indices for cumulative impact assessment of farm management practices. *PeerJ* **11**, e14816. https://doi.org/10.7717/peerj.14816.

Jamshidi, S. & Niksokhan, M. H. 2016 Multiple pollutant discharge permit markets, a challenge for wastewater treatment plants. *Journal of Environmental Planning and Management* **59** (8), 1438–1455. https://doi.org/10.1080/09640568.2015.1077106.

Jamshidi, S., Niksokhan, M. H. & Ardestani, M. 2014 Surface water quality management using an integrated discharge permit and the reclaimed water market. *Water Science and Technology* **70** (5), 917–924. https://doi.org/10.2166/wst.2014.314.

Jamshidi, S., Imani, S. & Delavar, M. 2020 Impact assessment of best management practices (BMPs) on the water footprint of agricultural productions. *International Journal of Environmental Research* **14** (6), 641–652. https://doi.org/10.1007/s41742-020-00285-y.

Kariman, A. S., Salimi, L. & Jamshidi, S. 2018 Determining the economic value of surface water quality improvements to trout farmers. *Journal of Water Supply: Research and Technology – Aqua* **67** (2), 192–201. https://doi.org/10.2166/aqua.2017.229.

Karlović, I., Posavec, K., Larva, O. & Marković, T. 2022 Numerical groundwater flow and nitrate transport assessment in alluvial aquifer of Varaždin region, NW Croatia. *Journal of Hydrology: Regional Studies* **41**, 101084. https://doi.org/10.1016/j.ejrh.2022.101084.

Liu, R., Xia, L., Liu, M., Gao, Z., Feng, J., You, H., Qu, W., Xing, T., Wang, J. & Zhao, Y. 2022 Influence of the carbon source concentration on the nitrate removal rate in groundwater. *Environmental Technology* **43** (22), 3355–3365. https://doi.org/10.1080/09593330.2021.1921053.

Lorenz, K., Iwanyshyn, M., Olson, B., Kalischk, A. & Pentland, J. 2014 *Livestock Manure Impacts on Groundwater Quality in Alberta*.

Marshall, R. E., Levison, J., McBean, E. A. & Parker, B. 2019 Wastewater impacts on groundwater at a fractured sedimentary bedrock site in Ontario, Canada: implications for First Nations' source-water protection. *Hydrogeology Journal* **27** (8), 2739–2753. https://doi.org/10.1007/s10040-019-02019-7.

Martínez, R., Vela, N., el Aatik, A., Murray, E., Roche, P. & Navarro, J. M. 2020 On the use of an IoT integrated system for water quality monitoring and management in wastewater treatment plants. *Water* **12** (4), 1096. https://doi.org/10.3390/w12041096.

Matiatos, I., Varouchakis, E. A. & Papadopoulou, M. P. 2019 Performance evaluation of multiple groundwater flow and nitrate mass transport numerical models. *Environmental Modeling & Assessment* **24** (6), 659–675. https://doi.org/10.1007/s10666-019-9653-7.

Menció, A., Mas-Pla, J., Otero, N., Regàs, O., Boy-Roura, M., Puig, R., Bach, J., Domènech, C., Zamorano, M., Brusi, D. & Folch, A. 2016 Nitrate pollution of groundwater; all right…, but nothing else? *Science of The Total Environment* **539**, 241–251. https://doi.org/10.1016/J.SCITOTENV.2015.08.151.

Ministry of power. 2013 *Report on the Flow of Water Sources in the Study Area of Varamin*.

Najafi Alamdarlo, H., Ahmadian, M. & Khalilian, S. 2016 Groundwater management at varamin plain: the consideration of stochastic and environmental fffects. *International Journal of Environmental Research* **10** (1), 21–30. https://doi.org/10.22059/ijer.2016.56884.

Nayyeri, M., Hosseini, S. A., Javadi, S. & Sharafati, A. 2021 Spatial differentiation characteristics of groundwater stress index and its relation to land use and subsidence in the Varamin Plain, Iran. *Natural Resources Research* **30** (1), 339–357. https://doi.org/10.1007/s11053-020-09758-5.

Noghreyan, A., Samani, J. M. & Mazaheri, M. 2022 Comparison of the SINTACS aquifer vulnerability model to nitrate with three-dimensional numerical model (case study of varamin plain aquifer). *Iranian Journal of Soil and Water Research* **53** (1), 15–31. https://doi.org/10.22059/ijswr.2022.323930.668975.

Nouri, B., Nouri, H., Zehtabian, G., Ehsani, A., Khosravi, H. & Azarninvand, H. 2020 Estimation of virtual water and water requirement of desert margin vegetation using satellite images (a case study: varamin plain). *Journal of Water and Soil Science* **23** (04), 113–127. https://doi.org/10.47176/jwss.23.4.24304.

Nzama, S. M., Kanyerere, T. O. B. & Mapoma, H. W. T. 2021 Using groundwater quality index and concentration duration curves for classification and protection of groundwater resources: relevance of groundwater quality of reserve determination, South Africa. *Sustainable Water Resources Management* **7** (3), 31. https://doi.org/10.1007/s40899-021-00503-1.

Raetz, A. 2022 *Simulating Groundwater Pollutant Transport for Remediation Design, Antrim County, Michigan*. Michigan Technological University. https://doi.org/10.37099/mtu.dc.etdr/1384.

Saadatpour, M., Afshar, A. & Khoshkam, H. 2019 Multi-objective multi-pollutant waste load allocation model for rivers using coupled archived simulated annealing algorithm with QUAL2Kw. *Journal of Hydroinformatics* **21** (3), 397–410. https://doi.org/10.2166/hydro.2019.056.

Sadak, D., Ayvaz, M. T. & Elçi, A. 2020 Allocation of unequally-weighted wastewater discharge loads using a simulation-optimization approach. *Journal of Hydrology* **589**, 125158. https://doi.org/10.1016/j.jhydrol.2020.125158.

Samadi-Darafshani, M., Safavi, H. R., Golmohammadi, M. H. & Rezaei, F. 2021 Assessment of the management scenarios for groundwater quality remediation of a nitrate-contaminated aquifer. *Environmental Monitoring and Assessment* **193** (4). https://doi.org/10.1007/s10661-021-08978-3.

Shahraki, Z. M., Mao, X., Waugh, S., Lotfikatouli, S., Walker, H. W., Gobler, C. & Wanlass, J. 2020 Potential release of legacy nitrogen from soil surrounding onsite wastewater leaching pools. *Water Research* **169**, 115241. https://doi.org/10.1016/j.watres.2019.115241.

van Afferden, M., Cardona, J. A., Lee, M.-Y., Subah, A. & Müller, R. A. 2015 A new approach to implementing decentralized wastewater treatment concepts. *Water Science and Technology* **72** (11), 1923–1930. https://doi.org/10.2166/wst.2015.393.

Wada, C. A., Burnett Id, K. M., Okuhata, B. K., Delevaux, J. M. S., Dulai, H., El-Kadi, A. I., Gibson, V., Smith, C. & Bremer, L. L. 2021 Identifying wastewater management tradeoffs: costs, nearshore water quality, and implications for marine coastal ecosystems in Kona, Hawai'i. https://doi.org/10.1371/journal.pone.0257125.

First received 13 April 2023; accepted in revised form 15 June 2023. Available online 24 June 2023