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REVIEW ARTICLE

Nitrates in Turkish waters: sources, mechanisms, impacts, and mitigation

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Abstract

Intensive technological developments, rapid population growth and urbanization, and excessive use of nitrogen fertilizers have caused water resources to be contaminated substantially by nitrates in Turkey. The accumulated information should be evaluated to draw a nationwide attention to the problem. The aim of this review article was to highlight the importance of nitrate (NO_3) contamination and to discuss the measures to be taken to mitigate the contamination across the nation. Agriculture, especially chemical fertilizers used in irrigated agriculture, was the most important source of NO_3 in groundwater. Also, the industrial and domestic discharges substantially contributed to NO_3 in both groundwater and surface waters in many cases. The most severe and widespread groundwater (e.g., 344 mg NO_3 L^{-1} in İzmir, 476 mg L^{-1} in Afyon, 477 mg L^{-1} in Antalya, and 948.0 mg L^{-1} in Konya) and surface water contaminations (e.g., 293.8 mg NO_3 L^{-1} in İzmir, 63.3 mg L^{-1} in Eskişehir, 89.8 mg L^{-1} in Edirne, and 90.6 mg L^{-1} in Sakarya) occurred in the regions where intensive agriculture, industrial development, and rapid urbanization were clustered. Well-established irrigation and fertilizer management plans are critical for reducing fertilizer-related NO_3 contaminations in the irrigated agriculture. Special attention should be given to the regions where industrially and domestically contaminated running water bodies are in contact with groundwater. Discharge of wastewaters to the streams, creeks, rivers, and lakes should be prevented. Well-designed studies are needed to evaluate potential health effects, including the risk of cancer, of NO_3 in drinking water.

Keywords Domestic discharges · Drinking water · Groundwater · Industrial discharges · Irrigation · Nitrogen fertilizers · Surface water

Introduction

Anthropogenic nitrate (NO_3) contamination is a global problem causing negative impacts on surface and groundwater systems (Zhang et al. 2015: Kazakis et al. 2020; Carstensen et al. 2020; Abascal et al. 2022; Singh et al. 2022). Nitrate pollution is a serious problem in both surface and groundwaters in China (Zhang et al. 2015, 2021), across the EU (Grizzetti et al. 2021), and India, South Korea, and the USA (Singh et al. 2022). It has been reported that many aquifers have exhibited values exceeding the maximum permissible concentration of NO_3 in drinking water (50 mg L^{-1}) across Asia, Africa, the USA, South America, and Europe (Abascal et al. 2022). Ground and surface waters can be enriched with NO_3 originating from various sources such as agricultural nitrogen fertilizers, industrial wastewater discharges, domestic discharges from sewage, septic systems, animal feedlots, natural soil organic matter, and atmospheric nitrogen deposition (Kazakis et al. 2020). Agriculture is generally the principal cause of anthropogenic NO_3 pollution in aquatic systems. However, in many cases, domestic or industrial wastewaters, atmospheric depositions, and animal farming wastes are important causes of NO_3 contamination in water systems (Liu et al. 2019; Paredes et al. 2020).

The maximum limit for NO_3 concentration in the drinking water is 50 mg L^{-1} in the Turkish legislation (Elçi and Polat 2011; Ağca et al. 2014; Kurunc et al. 2016). Those waters can cause many health problems including blue baby syndrome (methemoglobinemia) in infants (Ekmekci 2005),

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gastrointestinal illness, multiple digestive tract impairments, indigestion and inflammation of stomach, gastroenteritis, abdominal pain, diarrhea, and blood in urine faces (Topcuoğlu 2017). The International Agency for Research on Cancer (IARC) classified NO_3 and nitrite as probable human carcinogens when ingested under conditions that result in endogenous nitrosation (Quist et al. 2018; Buller et al. 2021). Nitrate itself is generally considered harmless at the low concentrations. However, its toxicity increases greatly when bacteria commonly found in the upper gastrointestinal tract reduce it to nitrite (Gulis et al. 2002; Quist et al. 2018; Buller et al. 2021). Nitrite can undergo nitrosation reactions in the gastrointestinal tract and bladder with amines and amides to give rise to N-nitroso compounds, which are some of the most potent known carcinogens that can induce cancers in a variety of organs, including the stomach, colon, bladder, lymphatics, and hematopoietic system (Gulis et al. 2002). When ingested under conditions favorable to endogenous nitrosation, NO_3 and nitrite are classified as probable human carcinogens (Quist et al. 2018).

Literature shows inconsistency in results on the association between NO_3 in drinking water and stomach cancer incidence, resulting in a disagreement among scientists over the interpretation of evidence on the issue (Powlson et al. 2008). Most early epidemiologic studies of cancer were ecologic studies of stomach cancer mortality that used exposure estimates concurrent with the time of death. Results were mixed, with some studies showing positive associations, many showing no association, and a few showing inverse associations (Ward et al. 2018). In a recent study (Buller et al. 2021), it was concluded that in the drinking water analysis, no association between mean NO_3 concentrations and any of the digestive system cancers was found, and that no association between any cancer and years with exposure to average NO_3 as a continuous variable was the case. De Roos et al. (2003) concluded that any increased risk of colon cancer associated with NO_3 in public water supplies might occur only among susceptible subpopulations in Iowa. On the other hand, Buller et al. (2021) reported that a small hospital-based case–control study in India observed a positive association between drinking water NO_3 and stomach cancer at relatively higher median drinking water NO_3 levels and that a population-based case–control study in Japan observed a positive association between drinking water NO_3 and stomach cancer mortality. Ghaffari et al. (2019) reported contradictory results on NO_3 concentration in drinking water and the incidence of gastric cancer across Iran. In another review, Picetti et al. (2022) concluded that they identified an association of NO_3 in drinking water with gastric cancer but with no other cancer site and that there exists a paucity of robust studies from settings with high levels of NO_3 pollution in drinking water. Ward et al. (2018) informed that with follow-up through 2010, the risk of ovarian cancer remained increased among women in the highest quartile of average NO_3 in public water supplies (PWS). Ovarian cancer risk among private well users was also elevated compared to the lowest PWS NO_3 quartile. Considering all studies to date, the strongest evidence for a relationship between drinking water NO_3 ingestion and adverse health outcomes (besides methemoglobinemia) is for colorectal cancer, thyroid disease, and neural tube defects. Thus, the evidence continues to accumulate that higher NO_3 intake is a risk factor for exposed people (Ward et al. 2018).

Multiple actions have been taken worldwide to reduce and prevent the negative impacts of NO_3 contamination on humans and the environment (Harrison et al. 2019; Paredes et al. 2020). World Health Organization (WHO) and various other governing bodies of different nations have specified NO_3 concentration limits in drinking water (Singh et al. 2022). The World Health Organization has set an upper limit of 50 mg NO_3 L^{-1} for drinking water (Zhang et al. 2015). In the USA, Environmental Protection Agency (EPA) has established an upper limit of 45 mg L^{-1} for nitrates in drinking waters (Azzellino et al. 2019; Cui et al. 2020). The Water Framework Directive of the EU (2000/60/EC) requires that NO_3 levels in waters within the EU should not exceed 50 mg L^{-1} NO_3 (Paredes et al. 2020). The supply of high-quality drinking water constitutes the Sustainable Development Goal (SDG) 6 by 2030 established by United Nations General Assembly in 2015 (Abascal et al. 2022). The World Health Organization and the Food and Agriculture Organization (FAO) of the United Nations have established quality standards for drinking and irrigation water (Abascal et al. 2022).

The key step to effectively control NO_3 contamination is to identify the factors affecting groundwater NO_3 level (Zhang et al. 2015). A thorough understanding of attenuation mechanisms and tracing NO_3 contamination sources are central to mitigating NO_3 contamination of water resources (Kazakis et al. 2020). Optimizing the amount of fertilizer N, time of application, source modification, and proper coordination with soil and water management are important measures for reducing NO_3 leaching in agricultural systems (Singh and Craswell 2021). However, the efficiency of those measures may be highly site- and case-specific. For example, the controlled-release nitrogen fertilizers primarily slow the release of nutrients, improving fertilizer use efficiency and reducing NO_3 leaching, while their use may not be proper on arid lands since the nutrients cannot be effectively released when water is limited, resulting in reduced crop yields (Cui et al. 2020). Singh and Craswell (2021) reported that improvement in water management had the largest effect on reducing NO_3 leaching from nitrogen fertilizers applied to agroecosystems, followed by improved fertilizer management and improvement in fertilizer technologies. Structural adjustments in agriculture based on different crops and crop rotations show promise for reducing NO_3 leaching losses (Singh and Craswell 2021). The application of some green and less polluting methods can also reduce NO_3 leaching. For example, adding biochar or planting natural vegetation can reduce the NO_3 leaching without affecting the yield and quality of the fruits. These measures have relatively little pollution to the environment and may provide good examples for the sustainable development of agriculture (Cui et al. 2020).

The removal of NO_3 from drinking water is challenging (Cui et al. 2020). Various techniques are used to remove NO_3 from contaminated waters. Free water surface, constructed wetlands, denitrifying bioreactors, controlled drainage, saturated buffer zones, and integrated buffer zones are widely used for removing NO_3 from the NO_3-enriched waters (Carstensen et al. 2020). Also, other techniques such as reverse osmosis, chemical denitrification, biological denitrification, ion exchange, electrodialysis, and adsorption have been used for decades to decrease NO_3 concentrations in contaminated waters. However, the byproducts from these technologies have some limitations in their use (Singh et al. 2022).

Considerable literature exists on agricultural practices that can be used to control water pollution. However, concerns have been raised over their adoption, which is hampered by factors including the time and effort required. Knowledge and its communication are among the most limiting factors for farmers to adopt alternative management practices. Farmers require evidence of the environmental impact and costs of interventions and the trade-offs of different interventions (Evans et al. 2019). Stakeholder network analysis by Musacchio et al. (2020) showed that the governance framework did not support knowledge dissemination and changes in farmers' attitudes, hindering water quality improvements, and they commented that the local governance scale has a key role in enhancing ND dissemination. Choosing the most appropriate and avoiding incompatible mitigation measures require collaboration between the different actors in the region for aligning the interests of all stakeholders (Carstensen et al. 2020).

Approximately 88 million people live on 780,400 km^2 in Turkey. Nearly one-third of the nation's total area is cultivable, and approximately one-third of the cultivable area is proper for irrigation (Yetis et al. 2013). Agriculture is the most important sector in the Turkish economy in terms of employment, and agricultural production is highly diversified (Yetis et al. 2013). The soils show high diversity due to large differences in plant cover, parent material, topography, and climate characteristics (Yetis et al. 2013). The extreme geoclimatic diversity of the country (Iyigun et al. 2013) allows the production of a wide range of livestock and crops (Yetis et al. 2013). Twenty-two agro-ecological zones have been identified across the nation (Yetis et al. 2013).

The total water potential of Turkey is 234 billion m^3, and its gross potential of water available per capita per year is 1600 m^3 as of 2010 (Baba and Tayfur 2011). The annual potential surface water is 193 billion m^3, and potential groundwater resources are 14 billion m^3. The total usable potential of the annual surface and groundwater resources of Turkey is 112 billion m^3 (Baba and Tayfur 2011). Agriculture, which consumes approximately 70% of the total amount (Ustaoglu et al. 2020), is the largest water consumer sector in Turkey (Cakmak and Apaydin 2010). The General Directorate of State Hydraulic Works (DSI in Turkish acronym) is responsible for the planning, design, construction, and operation of national hydraulic structures (Arslan 2009).

Intensive and uncontrolled use of nitrogen fertilizers combined with improperly and excessively used irrigation water resulted in severe NO_3 contaminations in many regions across the nation. The most severe NO_3 contamination of water resources occurred in densely populated areas where irrigated agriculture, rapid urbanization, and heavy industry meet. Besides, agriculture, domestic solid wastes and wastewater discharges are important sources of NO_3 contamination in many localities, even in highly remote areas. For example, Güler et al. (2017) reported that an aquifer in a seasonally inhabited headwater area in Aladağlar (a mountainous region in Adana) was contaminated by NO_3 via domestic waste discharges through cesspits during the summer season when the population sharply increases.

Cui et al. (2020) concluded that NO_3 contamination of water resources still remains a hot topic as evidenced by increasing number of articles between 2000 and 2019. The objectives of this review article were as follows: (1) to synthesize/reanalyze published data on NO_3 contamination in Turkish waters to draw nationwide attention to the problem, (2) to discuss the measures to be taken to mitigate NO_3 contamination and propose potential methods and tools to save waters from further contamination. We believe that this literature review has the potential to motivate similar reviews in other nations and regions across the world.

Methods

The key words: *nitrates, point source, Turkey* (52,200 results); *nitrates, nonpoint source, Turkey* (6750 results); *nitrates, groundwater, Turkey* (28,400 results); *nitrates, surface water, Turkey* (19,500 results); *nitrates, drinking water, Turkey* (30,800 results); *agriculture, nitrate contamination, water, Turkey* (33,200 results); *nitrates, industry, Turkey* (37,200 results); and *nitrates, domestic, Turkey* (27,100 results) were used in Google Scholar to find the relevant literature on the sources and mechanisms of NO_3 contamination of groundwater, surface water, and drinking water in Turkey. The peer-reviewed sources published between 1995 and 2022 were included in the literature search. Also, a second literature search was conducted using the following key words: *nitrate, drinking water, cancer* (92,000 results) and *nitrate, drinking water, human health* (472,000 results) to evaluate the most relevant peer-reviewed sources on the relation between drinking water NO_3 content and human health. No time period was specified in the second literature search. In total, over 700 peer-reviewed scientific papers were examined, and 165 of them were cited in this paper.

Based on the information obtained from the above literature search, this paper was organized as follows: Firstly, the spatial distribution of NO_3 concentrations in groundwater and surface waters was mapped by GIS. In mapping, the coordinates of the majority of the sites were used as they have been reported in the corresponding publications, while the sites of which coordinates have not been given were addressed by approximate coordinates. Secondly, the contribution (in percent) of each of the agricultural, domestic, and industrial sectors solely and/or in combination to NO_3 contamination (C_i) was calculated by Eq. (1).

$$C_i(\%) = \frac{N\left(C_i\right)}{N_t} x100 \tag{1}$$

where C_i is the sector of which percent contribution is calculated (e.g., agriculture (A)), $N(C_i)$ is the number of contamination cases for which the sector C_i is responsible, and N_t is the total number of NO_3 contamination cases, which is calculated by Eq. (2):

$$N_t = (A + I + D + (A + I) + (A + D) + (D + I) + (A + I + D) + NS) \tag{2}$$

where A is the number of NO_3 contamination cases caused solely by agricultural, D by domestic, and I by industrial source. In many cases, multitudes of sectors are responsible for the contamination. For example, $A+D$ represents the cases for which both agricultural and domestic, $A+I$ agricultural and industrial, and $D+I$ domestic and industrial sources are responsible. The last term $A+I+D$ represents cases caused by a combination of all three sectors. The term NS represents the number of cases for which the contamination source is not specified in the published paper. The values calculated by Eq. (1) were graphed. Thirdly, spatial distribution, sources, and mechanisms of the NO_3 contamination were discussed extensively. Special attention was given to the regions (hot spots) where NO_3 contamination is alarming. Fourthly, inter-annual and seasonal differences in NO_3 contamination were discussed. Fifthly, NO_3 contamination in drinking and potential drinking waters was discussed, and their likely health impacts were noted. And sixthly, the likely future trends in NO_3 contamination in Turkish waters were stated and potential measures to be taken for mitigating NO_3 contamination were discussed.

Spatial variation of nitrate contamination in waters

Figure 1 a and b depict the spatial distribution of NO_3 concentration in groundwater and surface waters, respectively. Details are given in Appendices A and B, respectively. Diffused contaminants from agricultural areas, leakages from waste disposal sites, and wastewater discharges from residential and industrial areas were the main sources of anthropogenic NO_3 contamination in the Turkish waters. Agriculture has been the main source of NO_3 contamination in the majority of groundwaters (Fig. 2a and Appendix A) and surface waters (Fig. 2b and Appendix B) in Turkey. Excessively used nitrogen fertilizers combined with improperly used irrigation water (e.g., surface irrigation, furrow irrigation, etc.) have caused groundwater to be contaminated seriously in many regions (Fig. 1a and Appendix A). Agriculture is solely responsible for the 45% of total contamination cases in groundwater (Fig. 2a), and it has significantly contributed to NO_3 contamination in surface waters, as well (Fig. 2b and Appendix B). In some areas where irrigated agriculture coincided with uncontrolled industrial development and rapid population growth, the surface and groundwater were drastically contaminated by NO_3. Figure 2b shows that approximately 25% of surface water contamination cases have resulted from the combination of domestic and industrial discharges and agriculture; this ratio was approximately 14% for cases of groundwater contamination (Fig. 2a).

Nitrate concentration in uncontaminated surface waters rarely exceeds 5 mg NO_3 L^{-1} and is generally less than 1.0 mg NO_3 L^{-1}. However, it may exceed 100 mg NO_3 L^{-1} in some heavily contaminated surface waters (Kaçaroğlu and Günay 1997). Figure 1b shows that the NO_3 concentration in surface waters is highly spatially variable in Turkey. As a result, numerous hotspots (hot regions) of NO_3 contamination have been noticed across the nation. There are numerous reasons behind the emergence of those hotspots. The negative impact of surface activities concentrated in karstic and alluvial regions on groundwater and surface water systems is noticeable. In particular, aquifers have been drastically contaminated with NO_3 in those karstic and alluvial regions where contaminated surface water systems are in contact with aquifers or vice versa. The severe NO_3 contamination in those hotspots and their surrounding areas has a potential to cause considerably high environmental and social hazards.

Figure 1 shows that one of the major hotspots is located in İzmir metropolitan area and its surroundings. "Dry Summer Subtropical Semihumid Coastal Aegean climate" is typical in the region (Iyigun et al. 2013). The altitude ranges from 0 (sea level) to 1483 m (Fig. 1c). The topography in the region

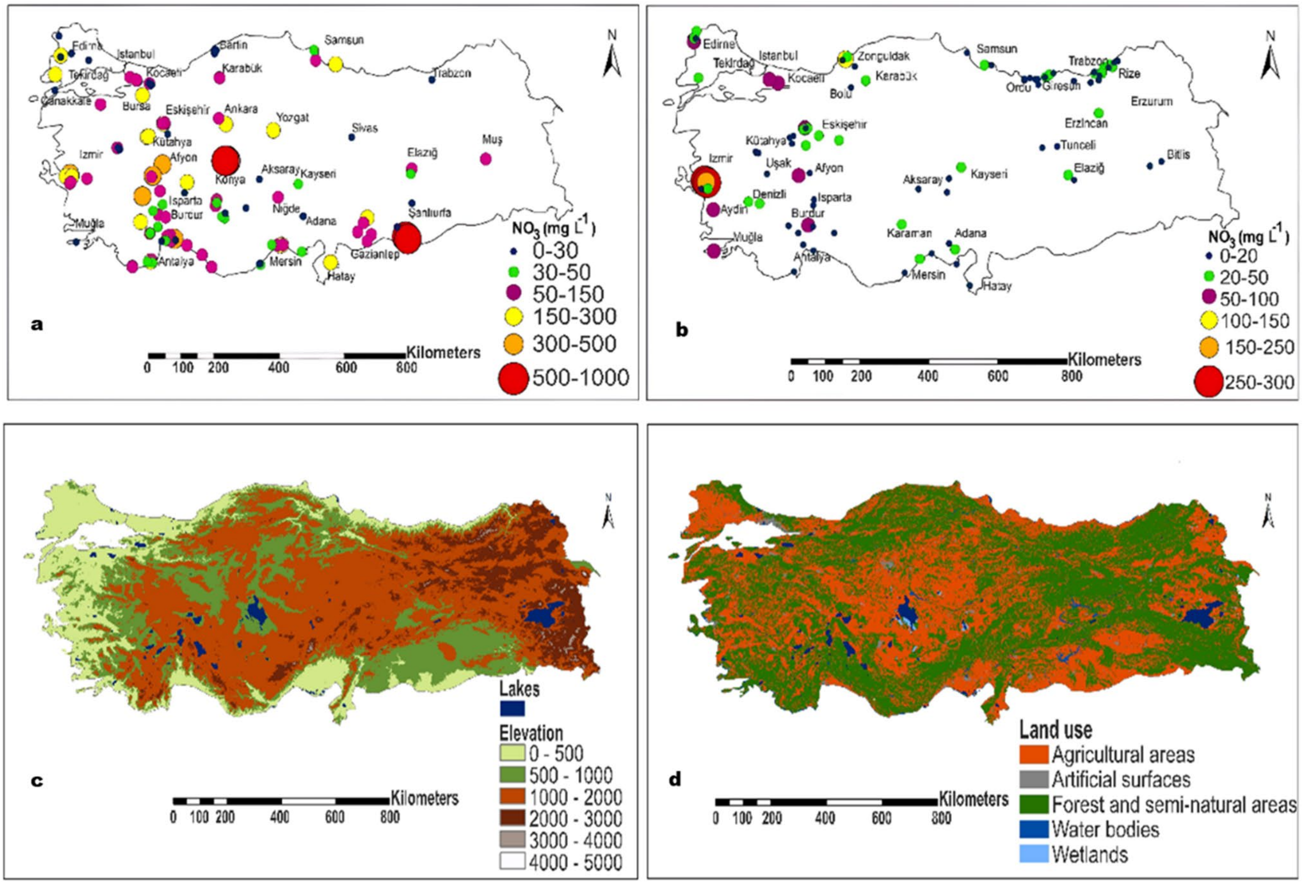

Fig. 1 Spatial distribution of nitrate concentration in groundwater (**a**) in surface waters (b9 across Turkey. **c** and **d** Distribution of topography and land use, respectively

is characterized by highly fertile plains surrounded by hills with different topographic features. The plains and foothills are the common landforms subjected to intensive irrigated agriculture (Fig. 1 c and d) and uncontrolled urbanization and development of industrial facilities. Anthropogenic features such as sanitary landfills, sewage lagoons, surface mines, drainage ditches, dumps, and floodways are common in the region. Substantial acreage of the fertile agricultural land has been converted to organized industrial zones and/or residential lots in the region due to the rapidly growing population and economic activities (Simsek et al. 2008).

The Mountain Nif Karstic Aquifer System is the principal water source of the city of İzmir (Elçi and Polat 2011), the third largest metropolis by population (4 and a half million by 2021) in Turkey. Mountain Nif Aquifer recharges the below Bornova, Kemalpaşa, and Torbalı plains, the areas where intensive agricultural and industrial activities are taking place (Elçi and Polat 2011). Tahtalı Dam reservoir meets 30% of the total water consumed in the metropolis (Elçi and Polat 2011). There are four principal aquifers supplying water to the metropolis and its environs. All of those aquifers are supported by Mountain Nif (Simsek et al. 2008). Also, there are several springs that originate from the Mountain Nif aquifers. The discharge rate of those springs is highly dependent on their origin and spatial orientation in the Mountain Nif (Simsek et al. 2008). The discharge regime of the springs is highly affected by the precipitation regime and differences in the amount of water taken from the below aquifers by local people. Simsek et al. (2008) concluded that water from Mountain Nif has high quality. However, its water quality gradually deteriorates by natural and anthropogenic factors as it moves toward the lowlands. The greatest NO_3 concentration was reported in a spring in a densely populated area probably due to domestic discharges (Simsek et al. 2008). Also, the highest NO_3 concentration coincided with Neocene Series formations in the region (Simsek et al. 2008).

Karstic aquifers in the region are potential water resources that can meet a significant portion of groundwater demand (Simsek et al. 2008). However, these aquifer systems are highly vulnerable to land surface-originated contamination due to rapid transport and limited attenuation of contaminants (Elçi and Polat 2011). Elçi and Polat (2011) reported some local NO_3 contamination hotspots of groundwater in and around Izmir metropolitan area, noting that sewage leakages,

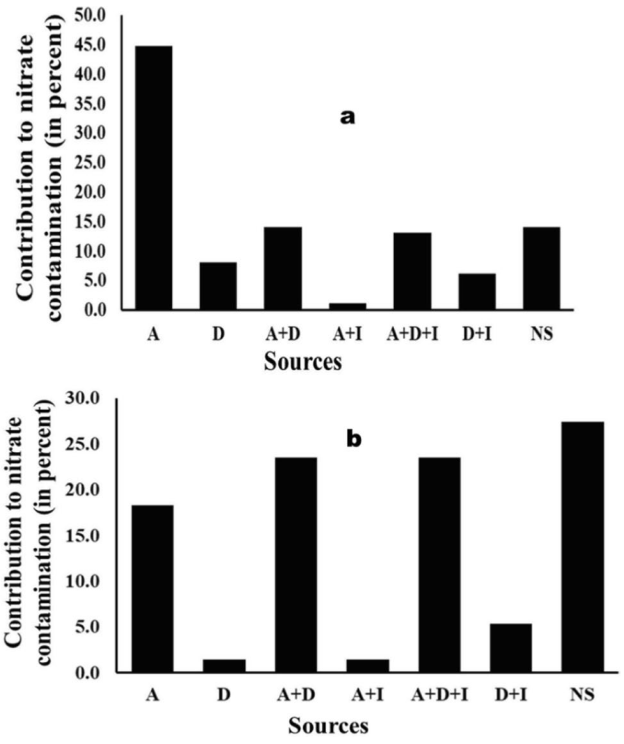

Fig. 2 Sectoral contributions (in percent) to nitrate contamination in groundwater (**a**) and surface waters (**b**) across Turkey. A, agriculture; D, domestic; I, industry; A + D, both of agriculture and domestic; A + I, both of agriculture and industry; D + I, both of domestic and industry; and A + D + I, agriculture, domestic and industry altogether; NS, not specified in the source literature. See the text for calculations

wastewater discharges, leakages from consolidated industrial sites, and NO_3 leached from agricultural areas were the common sources of NO_3 in their study wells. Aksoy and Scheytt (2007) showed that NO_3 concentrations in the majority of the wells in Torbalı, one of the major vegetable growing areas in the region, were greater than 50 mg NO_3 L^{-1}, legislated as the upper limit for drinking waters by WHO, EU, and Turkey. They attributed those high groundwater NO_3 concentrations to intensive agriculture combined with large-scale industrial activities and domestic discharges.

Figure 1a, b shows that the region including Kütahya, Eskişehir, and Ankara provinces is another chief hotspot of NO_3 contamination. "Dry-subhumid/Semiarid Continental Central Anatolia climate" (Iyigun et al. 2013) prevails in the region. The region is experiencing a rapid population growth, intensified agriculture, and intense industrial activities (Berhe et al. 2017. The topography of the region is dominated by wide plains (fluvial, lacustrine, alluvial flat, stream terrace, etc.) surrounded by hills and highlands (Fig. 1c). The land cover is mostly crop cover on the flat to slightly sloping landscapes (plains, depression, valley floors, etc.), woody plants, and grasslands on the highlands with varying slopes. Kütahya and Eskişehir and Ankara are major metropolises where intensive irrigated agriculture, heavy industry, and rapid population growth are clustered.

The surface and groundwater contamination with NO_3 is a serious problem in the basin. Porsuk River is the most important running water body in the basin, supplying potable and irrigation water to Küthaya and Eskişehir. Agricultural, industrial, and residential discharges to the natural drainage system of Porsuk River resulted in a severe NO_3 contamination (Berhe et al. 2017). Albek (2003) showed that the Porsuk River was contaminated heavily by industrial wastewaters and domestic discharges in Kütahya. Kaçaroğlu and Günay (1997) reported a NO_3 concentration of 63.3 mg NO_3 L^{-1} in the Porsuk River due to municipal and industrial wastewaters from Kütahya downstream. Also, industrial and municipal wastewater disposal to Porsuk River along its path from Kütahya to Eskişehir is one of the principal sources of the surface and groundwater contamination by NO_3 in the region of Eskişehir (Kaçaroğlu and Günay 1997; Albek 2003; Yuce et al. 2006; Arslan 2009). In addition, agricultural and industrial activities in Eskişehir Plain substantially contribute to NO_3 contamination in the Porsuk River (Yuce et al. 2006).

Eskişehir region is one of the rapidly developing areas where demand for groundwater is increasing hugely by agricultural, industrial, and domestic use (Kaçaroğlu and Günay 1997; Yuce et al. 2006). Irrigated agriculture is carried out, and fertilizers are applied intensively in the plains across Eskişehir and Kütahya. The groundwater is extracted by wells (boreholes) drilled in the alluvium of the Eskişehir Plain to meet municipal, industrial, and agricultural water requirements to a large extent (Kaçaroğlu and Günay 1997). Agricultural activities in the Eskişehir region are considerably intense; approximately 60% of the cultivated lands in the plain are irrigated, allowing a range of field and horticultural crops to be grown intensively (Yuce et al. 2006). Depending on the crop type, 30–120 kg ha^{-1} nitrogen fertilizers are applied in agriculture across the region of Eskişehir (Kaçaroğlu and Günay 1997). Extremely high NO_3 contamination incidents have been reported in the region (Fig. 1a, b and Appendices 1 and 2). The authors noted that leaching of NO_3 from fertilizers, especially during irrigation, and leakages from overloaded sewage networks were the principal sources of elevated NO_3 in groundwater. In another study, Kaçaroğlu and Günay (1997) reported that NO_3 concentration in 34.2% of 51 groundwater samples was over 45 mg L^{-1} in the region. Significant amounts of pollutants infiltrate from the Porsuk River to groundwater in the region of Eskişehir (Kaçaroğlu and Günay 1997; Albek 2003). Also, a significant number of septic tanks throughout the city directly contaminate groundwater in the alluvium aquifer beneath the city (Kaçaroğlu and Günay 1997).

A noticeable hotspot is located in Central South Anatolia and Mediterranean region, comprising provinces of Afyon, Isparta, Burdur, and Antalya (Fig. 1a). The altitude ranges from 0 m in Antalya to 2328 m in Burdur (Fig. 1c). The topography is comprised of very diverse landscapes (plains, valley side alluviums, slope alluviums, delta plains, lake plains, lacustrine deposits, badlands, breaklands, dissected plateaus, foothills, mountains, piedmonts, plateaus, pediments, valley-floor remnants, interior valley, etc.). Also, karsts (cockpit karsts, fluviokarsts, cone karsts, sinkhole karsts, collapse sinkholes, thermokarsts, tower karstic marine terrace karsts, karst valleys, thermokarst depressions, etc.), delta plains, lake plains, and canyonlands are common in the region. Irrigated agriculture is mainly practiced in the plains, valley sides, foothills, and some of the plateaus where irrigation water is available. The highlands, mountains, and sloping hills are mainly used as grassland, woodland, and forest. Barelands (badlands) are noticeable in some highly eroded sites across the region. The basins in which agriculture, urban residence, and industrial activities are clustered (e.g., Sandıklı basin, plains in Afyonkarahisar, Burdur, Isparta, Burdur, and Antalya) are the most significantly impacted areas by NO_3 contamination. "Subhumid Mid-Western Anatolia climate" prevails in Afyon, Isparta, Burdur, and "West Coast Mediterranean climate" in Antalya (Fig. 1a) (Iyigun et al. 2013).

Agricultural activities, especially nitrogen fertilizers and domestic and industrial discharges, are the major NO_3 contamination sources in the region (Appendices A and B). Aksever (2019) reported that NO_3 concentrations in 2 of 10 springs in the Emirdağ Region of Afyonkarahisar Province exceeded the 50 mg NO_3 L^{-1} threshold for drinking waters and noted that the high NO_3 in those springs would be related to intensive agriculture in the vicinity of their sampling locations.

The Sandıklı Basin, one of the major agricultural production areas in the inner Aegean Region, locates within this hot spot (within Afyon Province) (Fig. 1). Intensive agriculture, practiced on the porous aquifer, was reported as the key source of NO_3 in the groundwater (Aksever et al. 2015a). Seventy percent of cultivated land is irrigated, and potato cultivation is the most important cause of NO_3 contamination in the irrigated localities (Aksever et al. 2015a). Also, animal wastes have a considerable contribution to the groundwater NO_3 contamination in the basin. Groundwater in the basin is widely used for drinking, domestic, and irrigation purposes (Davraz et al. 2016). A large geothermal field is located in the middle of the Sandıklı Basin. The geothermal water from the field is used for different purposes such as balneotherapy, heating, and thermal tourism. The contact of those thermal waters with the below cold water further deteriorates the quality of the aquifer (Davraz et al. 2016).

Intensive agricultural applications have resulted in severe NO_3 contaminations of groundwater across Afyon. Karaman et al. (2017) reported a value of 487.0 mg L^{-1} of NO_3 concentration in groundwater in Acıgöl Basin (Afyon) and noted that nitrogen fertilizers were the principal source of NO_3 contamination in the groundwater across the region. Özdemir et al. (2007) noted that NO_3 concentrations in 78 of 100 well-water samples exceeded the 50 mg L^{-1} threshold limit and concluded that nitrogen fertilizers and irrigation water were the primary causes of NO_3 contamination in the groundwater. Also, Akarçay, formed by the confluence of Aksu and Acıçay streams, is the most important creek in the Afyonkarahisar region; its water is used for many purposes including drinking (Kivrak and Uygun 2012). Kivrak and Uygun (2012) reported a value of 14.49 mg NO_3 L^{-1} (Appendix B) and noted that the water quality of Akarçay was gradually decreasing downstream as it passed through a number of residential sites, localities of hot springs, and farmlands.

Water resources have been contaminated via NO_3 across Burdur province (Varol and Davraz 2015). For example, groundwater in the Tefenni Plain has been degraded seriously by nitrogen fertilizers and by discharges from livestock production facilities (Varol and Davraz 2015). There are several springs, which are in connection with the Tefenni Plain groundwater discharges to Burdur Lake. Similarly, Davraz and Özdemir (2014) observed a considerably high NO_3 contamination in the aquifers under Çelikli Plain, one of the major agricultural production areas in Burdur, due principally to nitrogen fertilizers used in agriculture. They noted that approximately 20% of groundwater samples had NO_3 concentration greater than the safety limit of 50 mg L^{-1} set by WHO (Ward et al. 2018).

Isparta Plain is an important groundwater basin. Karagüzel and Irlayici (1998) reported that NO_3 concentration in groundwater in the plain ranged from 0.55 to 48.34 mg L^{-1} and that two-thirds of the aquifer in the Isparta Plain was contaminated by NO_3. Those researchers noted that sewage waters in the city canals and waste storage sites were the principal polluters, noting that seepage from the Isparta Creek, which passes through waste storage sites, was significantly contributing to the NO_3 contamination of the groundwater.

Surface water contamination was identified as the major problem in the Lake District (located in Burdur and Isparta provinces, Fig. 1a), which comprises Beyşehir, Eğirdir, Burdur, and Akşehir lakes (Şener et al. 2013). The authors noted that improperly stored solid wastes of Senirkent and Uluborlu townships (located in Isparta province) had a significant contribution to NO_3 contamination in the Lake Eğirdir Region. Solid wastes cause serious environmental concern as there is no controlled landfill site in the basin, and uncontrolled dump areas are located in highly permeable limestone and alluvium units (Şener et al. 2013). The leachates from the dump sites mix in the surface water systems or infiltrate into the soil, eventually reaching groundwater (Şener et al. 2013). Agriculture was another important source of elevated NO_3 in groundwater and in the Lake's water (Şener et al. 2013). Şener et al. (2013) emphasized that irrigated horticulture (apple, cherry, and other fruits) combined with excessively used fertilizers, farmyard manure, and pesticides threatened the quality of the lake's water.

Antalya region is the most intensive greenhouse cultivation region of Turkey (Fig. 1 a and d). Groundwater and surface waters across the Antalya region are vastly contaminated with NO_3 (Fig. 1 and appendices A and B) as reported by numerous studies. The NO_3 concentration in groundwater and surface water resources are highly spatially variable across Antalya as shown in Fig. 1 and appendices A and B. Agriculture (especially nitrogen fertilizers) and industrial and residential waste waters (to a lesser extent) are the common sources of NO_3 contamination in those water resources. Very high NO_3 concentrations have been reported for groundwater and surface water across the region (appendices A and B). For example, Kaplan et al. (1999) reported 164.9 mg NO_3 L^{-1} in aquifers in Kumluca (Appendix A), one of the most intensive greenhouse cultivation districts, noting that the highly permeable vadose zone combined with intensively used fertilizers and excessively and improperly used irrigation water resulted in a severe groundwater contamination. Topcuoğlu (2017) studied NO_3 contamination of groundwater in 10 major greenhouse production districts across Antalya and reported that the NO_3 concentration in groundwater ranged from 29.7 to 144.2 mg L^{-1} with a mean of 65.2 mg L^{-1}. The author concluded that the high NO_3 content in groundwater was the main threat to public health in those areas. In another study, conducted in Kaş, which is an intensive greenhouse production district of Antalya, NO_3 concentration ranged from 47.00 to 100 mg L^{-1} and exceeded 50 mg L^{-1} threshold in 9 of 10 groundwater samples.

The Serik Plain is one of the major intensive agricultural areas in Antalya province. Groundwater in the plain is contaminated vastly by NO_3 as evidenced by extremely high NO_3 concentrations reported for groundwater (Appendix A) (Kurunc et al. 2011, 2016). The NO_3 concentration in the groundwater showed a considerably high spatial variability depending on crop type, soil texture, and groundwater depth; greater concentrations occurred in localities with higher water tables, greater soil sand content, and irrigated cotton and wheat (Kurunc et al. 2011). Kurunc et al. (2011) further noted that combined with heavy surface and furrow irrigation, low water holding capacity and well-drained sandy soils would be the principal reasons for high NO_3 concentrations in some localities across the plain.

The Mediterranean coastal region encompassing Mersin, Tarsus, Adana, and Hatay (Fig. 1) is the most intensively cultivated region in Turkey, and it is quite advanced in terms of industry. Adana (the fourth largest metropolis with over three million population), Mersin, and Hatay are the participial cities in the region. The region is one of the most densely populated regions in Turkey. "Eastern Mediterranean climate", characterized by mild and rainy winters and dry and hot summers, prevails in the region (Iyigun et al. 2013). Lands with flat to slightly sloping topography, extending 50–100 km inwards from the Mediterranean Sea, prevail in the region. Due to proper soil and climatic conditions and provision of irrigation facilities, irrigated agriculture has been made intensively for a long time in the region, and this resulted in a heavy pollution of water resources by agro-chemicals including NO_3. The altitude varies between 0 and 200 m in areas under intensive irrigated agriculture.

Intensive irrigated agriculture and industry combined with a rapid urbanization have resulted in groundwater, and surface water systems have been contaminated substantially across Mersin. Figure 1 indicates a substantial NO_3 contamination of groundwater and surface waters to a lesser extent across the Mersin region, and appendices A and B show that the agriculture is the chief sector, responsible for the contamination. Industrial nitrogen fertilizers are the main causes of elevated NO_3 concentrations in groundwater in the region. For example, Güler (2009) noted that intensively used nitrogen fertilizers caused an excessive NO_3 contamination in Karaduvar Site in Mersin region, and they stressed that the people living on this site depended on water derived from the underlying aquifer for agricultural, industrial, drinking, and domestic uses. On the other hand, the author concluded that the NO_3 concentration decreased drastically in fuel-contaminated sites of the aquifer due likely to that NO_3 was utilized as an electron acceptor by fuel-degrading microorganisms in contaminated sites. In other studies, substantially high NO_3 contamination cases have been reported for alluvial aquifers across Mersin region due to agricultural activities combined with industrial and domestic discharges (Demirel and Külege 2005) (Fig. 1a and Appendix A). The authors noted that the Berdan River, which was highly contaminated by wastewater discharges on a number of sites along its flow, had a negative impact on the aquifer below as it is in hydraulic contact with the aquifer. In another study, Güler et al. (2013) reported a maximum value of 201 mg L^{-1} for NO_3 concentration in a coastal plain in Tarsus (located within Mersin Province), resulting mainly from nitrogen fertilizers and irrigation water used in agriculture, besides domestic and industrial discharges. They noted that NO_3 concentration was greater than 45 mg L^{-1} in 10 of 214 wells.

Serious agriculture-related NO_3 contamination of water resources has been reported in Çukurova Plain (Adana) (Zeybek and Gür 2009). Ibrikci et al. (2012) noted that excessively used irrigation water combined with heavily used nitrogen fertilizer resulted in a considerable contamination of NO_3 in shallow groundwater systems across Adana (Fig. 1a). Also, irrigation return flow was reported as an important source of NO_3 contamination in shallow groundwater systems in Seyhan Plain of Adana (Ibrikci et al. 2015).

Amik Plain (Hatay) is one of the most significant agricultural production areas in Turkey (Ağca et al. 2014). Groundwater in the plain is used for various purposes including drinking by local people. A study by Ağca et al. (2014) showed that the groundwater in the plain has been contaminated severely by NO_3 (Appendix A) due to nitrogen fertilizers used in the cultivation of numerous different crops. The authors noted that the concentration of NO_3 was highly spatially variable and that 12 of 96 wells had NO_3 concentration greater than 50 mg L^{-1}, legislated by WHO, EU, and Turkish Standards.

The region comprising Gaziantep and Şanlıurfa, two major metropolitan cities in South Eastern Turkey (Fig. 1), shows groundwater NO_3 contamination to a considerable extent resulting from intensive agricultural activities and uncontrolled domestic discharges (Appendix A). "Dry Summer Subtropical Semihumid/Semiarid Continental Mediterranean climate" prevails in the region according to Iyigun et al. (2013). The topography in the region is characterized by plains (lake plains, alluvial plains, delta plains, flood plains, etc.) surrounded by hills, mountains, and karstic landscapes. Miscellaneous landforms such as volcanic fields, shield volcanos, badlands, break lands, dissected plateaus, pediments, and valley-floor remnants are also noticeable in the region. The region has been experiencing a rapid economic development in the last 30 years. Irrigated and dryland agriculture are practiced to a considerable extent in the region, especially in flat to slightly to moderately sloping landscapes. Besides intensive agriculture, animal husbandry is made to a significant extent in the region.

Turkey has developed several integrated water resources projects. Southeastern Anatolian Development Project (GAP in Turkish acronym) is the most important one of those projects. The GAP comprises 22 dams and hydroelectric power plants and large irrigation networks across the GAP Region (Yesilnacar et al. 2008; Yesilnacar et al. 2008). Harran Plain, one of the major agricultural development areas within the GAP project, has been undergoing large-scale land use changes due to a rapidly growing population resulting from rapid industrial, agricultural, and commercial development. Yesilnacar et al. (2008) reported that NO_3 concentration across the plain ranged from 1.30 to 806.00 mg L^{-1} with a mean of 164.00 mg L^{-1} (Appendix 1), indicating a severe contamination of the aquifers in the plain. These authors concluded that fertilizers and accompanying irrigation water were the chief factors causing the NO_3 contamination in the plain. They also noted that the NO_3 concentration of groundwater was highly spatially variable depending on the spatial variability of NO_3 sources and soils across the plain.

The Konya Basin in the Central Anatolia is highly affected by groundwater contamination of NO_3 (Fig. 1a). The basin is highly developed in agricultural, industrial, and urbanization aspect. The basin is under the influence of "Dry-subhumid/Semiarid Continental Central Anatolia climate" (Iyigun et al. 2013). The topography in the basin is characterized by vast plains where dryland and irrigated agriculture are practiced. Altitude ranges from approximately 1000 to 1800 m (Fig. 1c). The basin has been named Nation's Wheat Warehouse. Groundwater is the most important source of water supply due to the insufficiency of surface water in this typical semiarid region. However, as a result of rapid development, the groundwater has been exploited intensively and excessively for agricultural, industrial, and demographic use (Bozdag 2016). The range of agricultural crops, including sugar beet, sunflower, wheat, barley, corn, lentils, beans, tomatoes, potatoes, chickpeas, alfalfa, oats, and melons, is widely grown in the region. Many of those crops depend on groundwater for irrigation (Bozdag 2015, 2016). Intensive agriculture combined with rapidly developed industry and fast population growth has resulted in a vast NO_3 contamination of water resources across the basin (Appendix A and Fig. 1) in recent decades (Varol 2021). For example, an excessive NO_3 contamination occurred in groundwater in Cihanbeyli and Akşehir sub-basins (within Konya Province) (Bozdağ and Göçmez 2013; Varol 2021) (Appendix A and Fig. 1) where groundwater is the major water resource for drinking, agricultural, and industrial uses.

Konya metropolis with over 1 and half million population has been growing rapidly, and accordingly, the need for water is increasing (Nas and Berktay 2010). The metropolis heavily depends on groundwater. The water consumption in the city has increased drastically in recent decades. For example, the amount of water consumed almost doubled from 1998 to 2005 (Nas and Berktay 2010). Also, NO_3 contamination of groundwater increased significantly. Nas and Berktay (2010) showed that NO_3 concentration in groundwater in the metropolitan area ranged from 3.0 to 110.0 mg L^{-1} and that the groundwater contamination by NO_3 showed a considerable spatial variability depending on the land use type. More severe groundwater NO_3 contamination occurred in residential areas, at cemeteries, and in city parks compared to those on industrial sites.

Kocaeli-Sakarya basin (Fig. 1) is one of the most industrialized and economically developed regions in Turkey. The region is located in Northwestern Anatolia where agriculture is one of the most important economic sectors. "Mid-latitude Humid Temperate Coastal Black Sea climate" prevails in the basin (Iyigun et al. 2013). The topography is characterized by fertile plains surrounded by hills and various types of landscapes (foothills, piedmonts, basin floors, stream terraces, etc.). The altitude ranges from 0 to 700 m (Fig. 1c). Proper climate, soils, and topographical conditions allow the farmers to grow a range of field and horticultural crops.

Fast and uncontrolled industrialization and irregular sprawl of residential areas have caused a large-scale NO_3 contamination of waters in the Kocaeli-Sakarya Basin (Fig. 1). Also, the uncontrolled industrialization triggered pollution of Dil Stream, a principal water body in the region. Yolcubal et al. (2016) reported that Dil Stream, contaminated by industrial discharges, sewages, and leachates from wild landfills, had a drastic negative impact on groundwater quality. Industrial structures in the region are generally gathered at the exit of the Dil Stream that empties into the Gulf of Kocaeli. Therefore, inefficiently operating wastewater plants of factories, domestic wastewater discharges from residential areas, and leachates from landfills create a serious surface water contamination in both Dil Stream and Gulf of İzmit (Kocaeli) besides in groundwater in the alluvial aquifer extending along Dil Streambed. Also, in this region, aquifers in İznik (located in Bursa Province) have been substantially contaminated by domestic and industrial solid and liquid wastes disposed of by old marble queries (Simsek et al. 2011) (Fig. 1 and Appendix A). Nitrogen emissions from the heavily industrialized sites in the basin would be an important source of the NO_3 reaching to surface and groundwater via precipitation. Okay et al. (2002) reported a NO_3 concentration of 90.61 mg NO_3 L^{-1} in precipitation water in Kaynarca Township of Sakarya (near Kocaeli).

Turkish Thrace region (Edirne, Kırklareli, Tekirdağ provinces, and part of Çanakkale and İstanbul provinces) (Fig. 1) is one of the most densely populated regions in Turkey. Plains (flood-plains, alluvial plains, delta plains) and shore complexes are the prevalent landscapes in the region. Also, wetlands (everglades, swamps, floodplain playas) are other important landforms in the region. The region is under the control of "Semihumid Western Marmara Transition climate" according to Iyigun et al. (2013). The altitude ranges from 0 to 500 m (Fig. 1c), and irrigated agriculture is predominantly practiced in the region.

Drastically increased industrialization, urbanization, and agricultural production activities have created pressures on the water resources in the region (Özler and Aydın 2008). Özler and Aydın (2008) reported a maximum value of 180.0 and a mean of 52.0 mg L^{-1} for 40 well samples, caused by various sources such as nitrogen fertilizers, organic wastes, irrigation water return, septic tanks, pits, lagoons, and storage ponds across West Thrace Region (Appendix A and Fig. 1). The authors noted that NO_3 concentration in 11 of 40 well-samples were greater than 50 mg L^{-1}. Ozkahya and Camur-Elipek (2016) reported that NO_3 concentration ranged from 0.76 to 180.2 mg L^{-1} across Edirne Province (Edirne center, Lalapaşa, Suloğlu, Havsa, Uzunköpru, Meriç, İpsala, Keşan, and Enez districts) and that NO_3 concentration in 65% of the wells exceeded 50 mg L^{-1}. The authors emphasized that agriculture was the principal source of the NO_3 contamination in the region. Similarly, Arkoç (2016) reported severe NO_3 contamination of groundwater across East Trace due to the use of nitrogen fertilizers.

The water quality of the Meriç River, the longest fluvial ecosystem in the Balkans, decreases substantially, especially after it merges with the Ergene River (Tokatlı et al. 2020). Divrik et al. (2020) reported that NO_3 concentration ranged from 3.40 to 89.7 mg L^{-1} in Meriç River. Meriç Delta is among the richest aquatic habitats in the world (Tokatlı 2018a, 2018b). This very important ecosystem has been contaminated substantially by NO_3 from agricultural, industrial, and domestic sources. Intensive paddy cultivation and industrial activities are considered the main contamination factors degrading the ecosystem in this basin (Tokatlı 2018a, 2018b). Over 95% of the Meriç Basin in Turkish Thrace is proper for agriculture. Rice, sugar beet, sunflower, corn, and many vegetables and fruits are grown in the basin. Ergene River, one of the principal tributaries of the Meriç River, has been contaminated severely by intensive agriculture, rapidly growing urbanization, and industrialization (Tokatlı et al. 2020). Wastes from residential areas and consolidated industrial sites and drainage water from agricultural sites are the main sources of contamination in the Ergene River (Tokatlı et al. 2020 and references therein).

Rize-Trabzon-Giresun basin is located in Northeastern Turkey (Fig. 1b). The area comprising Rize and Eastern Trabzon is the only tea production area in Turkey, and the area comprising the rest of Trabzon and Giresun is the major nuts production area. The topography in the region is characterized by landscapes of hills, mountain ranges, valley-side alluviums, slope alluviums, foothills, dissected plateaus, alluvial plain remnants, fan collars, etc. "East Coast Black Sea climate", which is characterized by mild rainy winters and warm rainy summers, prevails in the region (Iyigun et al. 2013).

Figure 1b shows a significant contamination of NO_3 in streams across Rize province, caused by nitrogen fertilizers used in tea cultivation (Kuştul et al. 2020). Similarly, nitrogen fertilizers used in nut cultivation resulted in surface waters being highly contaminated with NO_3 in Trabzon and Giresun. Aydin et al. (2021) showed that maximum values for NO_3 concentration on all seven study streams in Giresun were greater than 20 mg L^{-1} caused by nitrogen fertilizers leached from nut orchards and discharges from residential areas. Also, a considerable amount of NO_3 is contributed by domestic discharges to NO_3 contamination in streams across the region.

Temporal variation of nitrate contamination of Turkish waters

Results of many studies showed that inter-seasonal (differences in NO_3 concentration between wet and dry seasons) and/or interannual (differences in the NO_3 concentrations between years) variability in NO_3 concentrations in waters were significant. Seasonal differences in agricultural and industrial activities, climate factors such as precipitation seasonality, seasonal and annual differences in amount of precipitation, and differences in evapotranspiration are the main factors affecting the temporal variability of NO_3 contamination of water resources.

Nitrate contamination severity of water resources generally varied between wet and dry seasons as reported by many studies. In general, greater concentrations have occurred in dry seasons compared to those in wet seasons. For example, Güler (2009) reported that far greater NO_3 concentrations occurred in October (dry season) than in April (wet season) in coastal aquifers in Karaburun (Mersin), and Kurunc et al. (2016) reported that NO_3 concentration in groundwater in Serik Plain showed a substantial variability between the dry and the wet seasons. The geostatistical analysis of Kurunc et al. (2016) showed that the spatial structures of the groundwater NO_3 concentration were highly different between the dry and wet seasons.

Similarly to those in irrigated Mediterranean Region, considerable seasonal variability was observed in NO_3 contamination of groundwater in semi-arid Central Anatolia. Kaçaroğlu and Günay (1997) reported significant seasonal variations in groundwater in Eskişehir and its ambiance, which they attributed to differences in (1) recharge conditions of groundwater, (2) concentration of contamination resources, (3) meteorological conditions, (4) groundwater level, (5) amount of groundwater abstracted from the wells, and (6) agricultural activities. Davraz and Özdemir (2014) observed a noticeable seasonal variation in NO_3 concentration in groundwater between the wet and the dry season in Çeltikçi Plain (Burdur); the NO_3 concentration ranged from 0.23 to 26.15 mg L^{-1} in the wet season and from 1.81 to 106.24 mg L^{-1} in the dry season.

Some mixed results have been reported on the seasonality of NO_3 contamination severity in water resources in Turkey. Elçi and Polat (2011) reported that NO_3 concentration was increasing in some of their observation wells from the wet (April) to the dry (September) season, while it was decreasing in some other wells, and Aksever et al. (2015a) reported that, in general, greater NO_3 concentrations were measured in a groundwater in dry seasons than wet seasons. However, they also noted that a continuous percolation from dairy farms caused NO_3 concentrations to be greater during the wet seasons than the dry seasons in some sites. Ibrikci et al. (2012) reported that the monthly distribution of NO_3 concentrations in 107 shallow wells highly varied due to differences in rainfall pattern, irrigation water use, and crop vigor. They noted that February was the high season and October was the low season with respect to NO_3 concentration in groundwater. They further noted that monthly mean NO_3 loads in drainage waters were highly influential on monthly NO_3 concentrations in groundwater.

Nitrate concentration in many water resources showed high year-by-year variability as well as seasonal variability. For example, Demirel and Külege (2005) showed that NO_3 concentrations were increasing dramatically across three consecutive sampling dates in some sampling wells in Mersin, and Ibrikci et al. (2012) showed that the NO_3 contamination of the groundwater significantly varied between 2007 and 2008 due to differences in the amount of precipitation. In another study, NO_3 concentration in groundwater wells in the city of Konya and its environment increased drastically from 1998 to 2001 (Davraz and Özdemir 2014). Demirel and Külege (2005) reported a substantially high interannual variability in NO_3 content in groundwater across some townships in Mersin due to differences in precipitation and rate and amount of agricultural, industrial, and domestic discharges. Kurunc et al. (2016) reported greater NO_3 concentrations in groundwater across the Serik plain of Antalya (Southern Turkey) in 2009 than in 2010, which they attributed to greater annual precipitation and lower mean temperature in 2009 compared to in 2010.

Nitrate contamination in surface water systems showed a high seasonal variability similar to in groundwater. Differences in domestic discharges, climate factors, and season-specific agricultural activities were the principal factors behind the seasonal variability in NO_3 contamination severity. Elçi and Polat (2011) reported maximum values of NO_3 concentrations of 293.8 and 240.9 mg L^{-1} for spring waters in Izmir in April 2006 and September 2006, respectively. Nitrate concentrations reported for surface waters in Hasanağa Stream Basin in Edirne were highly different between 2019 and 2020 (Tokatlı 2021), and those reported at nine points along Porsuk River (Kutahya and Eskişehir), a main watercourse in the Eskişehir Plain, ranged from 1.50 to 63.3 mg NO_3 L^{-1} during the period from July 1986 to August 1988 (Kaçaroğlu and Günay 1997). Nitrate concentration in Berdan River (Mersin) showed a considerably high variation between 2001 and 2002 depending on the variation in industrial and domestic discharges and differences in rainfall. Similarly, Yolcubal et al. (2016) reported a substantially high seasonal variability in NO_3 concentration in Dil Stream (Kocaeli), which is heavily contaminated by industrial and domestic wastewater. Celiker et al. (2014) reported that temporal values of NO_3 concentration varied from 3.82 to 42.48 mg L^{-1} in Munzur Stream (Tunceli) between March

2008 and October 2008. The concentration of NO_3 in Meriç River showed a high seasonal variability; the highest mean and maximum values occurred in winter and the lowest in summer (Divrik et al. 2020). Similarly, NO_3 concentration maxima in Kadıköy and Karademir freshwater lakes (located in Turkish Thrace) showed an important seasonal variability (Divrik et al. 2020).

Nitrogen fertilizers are solely responsible for seasonal variability in NO_3 contamination of water systems in many cases. For example, Kuştul et al. (2020) reported that the maximum NO_3 concentration in some fountains used as drinking water in villages across Rize (Fig. 1b) was greater in August than in April. The authors concluded that nitrogen fertilizers used in tea cultivation were the main source of NO_3 contamination.

Nitrates in drinking waters

High NO_3 concentration is one of the main health concerns in drinking water, as it seriously threatens human health (Ward et al. 2018; Ghaffari et al. 2019). The presence of NO_3 concentrations greater than 5 mg L^{-1} in waters may indicate unsanitary conditions (Kaçaroğlu and Günay 1997). Quality of drinking water has been rated based on NO_3 concentrations: NO_3 concentrations < 5.0 mg L^{-1} very good quality; between 5.0 and 10.0 mg L^{-1}, good quality; between 10.0 and 20.0 mg L^{-1}, medium quality; and > 20 mg NO_3 L^{-1}, poor quality (Akbal et al. 2011; Kavurmaci 2016; Kavurmaci and Üstün 2016; Aksever and Büyükşahin 2017).

In many regions, massive groundwater resources, which are extremely important in terms of drinking, irrigation and domestic use for large populations have been damaged seriously by NO_3 as reported by the number of studies conducted across the nation (Kaplan et al. 1999; Çelik 2002; Yuce et al. 2006; Özdemir et al. 2007; Elhatip and Kömür 2008; Elhatip et al. 2008; Arman et al. 2009; Davraz and Özdemir 2014; Varol and Davraz 2015; Davraz et al. 2016; Elipek et al. 2017; Karaman et al. 2017; Güner et al. 2018; Avci et al. 2018; Ersoy and Karaca 2019; Mimiroğlu et al. 2020; Varol 2021, and many others). In many cases, the concentrations reported were greater than the maximum limit of 50 mg L^{-1} set by WHO and EU and accepted in Turkey for drinking waters. For example, Varol (2021) reported maximum values of 232.5 mg L^{-1} in Akşehir of Konya Province and noted that 25% of 31 well-water samples exceeded the maximum limit of 50 mg L^{-1}. Diffused contaminants from agricultural areas, leakages from waste disposal sites, and wastewater discharges from residential and industrial areas have been reported as the principal sources of contamination. Similarly to groundwater, water from streams, springs, lakes, and rivers is widely used for drinking by local people across Turkey. Studies (e.g., Çelik et al. 2013; Şener et al. 2013; Aksever et al. 2015b; Aksever 2019; Kuştul et al. 2020) reported that numerous water resources have been exposed to NO_3 contamination (Fig. 1b and Appendix B). Besides agricultural, domestic, and industrial discharges significantly contributed to NO_3 in surface waters (Fig. 2b).

Some water sources are fairly clean in terms of NO_3. For example, Turnasuyu Stream was excellent in water quality, including NO_3 content (Ustaoglu et al. 2020a, 2020b). Similarly, Çetindağ (2005) reported fairly low values for NO_3 concentration in Karasu Spring (Muş, Eastern Turkey) (Appendix B) and Gültekin et al. (2013) reported little evidence of NO_3 enrichment in streams and lakes in Solaklı Basin of Trabzon (Appendix B). On the other hand, studies showed that NO_3 contamination can be a potential threat to the people living even in sparsely populated rural areas, which are fairly free from industry and intensive agriculture. For example, there is no heavy industrial or intensive agricultural activity in Tunceli where water resources are abundant due to plenty of rain and heavy snowfall in mountains. However, a study by Demir and Ergin (2013) showed that NO_3 concentration in 21 drinking water samples, collected from the city center and 6 townships, ranged from 0.28 to 16.22, indicating potential health risk of NO_3 to the disadvantaged people as the majority of the people living on those locations drink tap water. Similarly, Celiker et al. (2014) showed that NO_3 concentration in Stream Munzur (Tunceli) ranged from 3.82 to 43.48 mg L^{-1}, indicating a significant NO_3 enrichment.

Tap water is widely used for drinking across Turkey. There are a limited number of studies in Turkey on NO_3 in tap water. Özdemir et al. (2007) showed that 48 of 100 tap water samples collected from residences on townships in Afyon had NO_3 concentration over 45 mg NO_3 L^{-1}, which is an upper limit set by Environmental Protection Agency (EPA). Nitrate concentration ranged from 1.69 to 44.90 mg L^{-1} in towns and in cities in Çankırı Province (Çaylak and Tokar 2012) (Table 1). Demir and Ergin (2013) emphasized that NO_3 concentrations greater than 10 mg L^{-1} would be harmful to the infants, referring that 10 mg L^{-1} of NO_3 concentration has been recommended in some countries like Italy as the upper limit for the water destined to infants.

Increased tap water contamination resulted in a considerable increase in the demand for natural and fruity mineral waters in Turkey (Cemek et al. 2007). The Maximum NO_3 contamination legislated by EPA to protect infants from blue baby syndrome is 10 mg L^{-1} (Davraz et al. 2016), while Güler (2007) reported that NO_3 concentrations in bottled natural spring waters ranged from 0.05 to 19.20 mg L^{-1} and in bottled natural mineral waters from 0 (undetected) to 20 mg L^{-1} (Table 1). A long-time consumption of those bottled mineral water brands and their fruit flavored products with NO_3 concentration greater than 10 mg L^{-1} may result in health problems in infants, pregnant women, and other

Table 1 Nitrate concentrations in drinking waters across Turkey

Location	n	NO_3 concentration (mg L^{-1})			CV (%)	Type	Source of contamination	Reference
		Minimum	**Maximum**	**Mean**				
Burdur (Ağlasun)	12	2.70	8.69	5.15	31.26	Spring water	Agriculture	Aksever et al. (2016)
Turkey (overall)	146	0.05	**19.40**[b]	4.50	95.56	Natural spring water[a]	Not specified	Güler (2007)
	24	UD	**20.00**	4.82	130.71	Natural mineral water[a]		
	12	UD	7.92	1.70	123.53	Drinking water[a]		
	5	1.00	4.84	1.77	96.05	Processed drinking water[a]		
Isparta	20	0.20	8.83	2.93	81.23	Tap water	Not specified	Varol and Davraz et al. (2016)
Turkey (overall)	20	2.13	**17.40**	5.12		Plain water[a]	Not specified	Gümüş et al. (2021)
Turkey (overall)	29	1.26	**17.00**			Fruit-flavored water[a]		
Turkey (overall)	63	1.02	7.50	3.09	49.51	Fruity mineral water[a]	Not specified	Cemek et al. (2007)
	77	1.09	**13.20**	3.99	61.65	Natural mineral water[a]		
Edirne (İpsala)	23	0.42	**19.30**	4.93	90.87	Well water[a]	Agriculture	Tokatlı (2014)
Edirne (İpsala)	23	0.42	**19.30**	4.93	98.99	Drill fountains	Agriculture	Tokatlı (2014)
Edirne (Center)	10	0.90	11.50	5.54	58.30	Well water	Agriculture	Tokatlı et al. (2020)
Edirne (Keşan)	15	UD	5.50	2.53	72.33	Well water	Agriculture	Tokatlı (2018a, 2018b)
Edirne (Uzunköprü)	12	0.30	5.50	2.05	94.63			
Çankırı (Center)	8	3.56	**44.90**	**15.62**	44.68	Tap water	Not specified	Çaylak and Tokar (2012)
Çankırı (Atkaracalar)	3	1.86	**23.21**	23.21	8.07	Tap water		
Çankırı (Çerkeş)	4	4.44	**12.10**	7.80	3.78	Tap water		
Çankırı (Eldivan)	2	1.03	1.69			Tap water		
Çankırı (Ilgaz)	2	3.91	5.16			Tap water		
Çankırı (Kızılırmak)	4	1.30	**35.40**	24.93	66.61	Tap water		
Çankırı (Korgun)	4	2.00	9.30	5.67	67.20	Tap water		
Çankırı (Kurşunlu)	7	2.50	**14.20**	5.96	82.21	Tap water		
Çankırı (Orta)	6	0.70	5.57	3.11	63.03	Tap water		
Çankırı (Şabanözü)	4	1.42	**14.80**	8.57	63.94	Tap water		
Çankırı (Yapraklı)	5	1.30	**13.00**	8.99	59.07	Tap water		
Rize (some villages)	12	5.84	**49.66**	20.34	65.49	Fountain water	Agriculture	Kuştul et al. (2020)
Tunceli (City tap water)	21	0.28	**16.22**	4.78	85.75	Spring water	Domestic discharges, agriculture	Demir and Ergin (2013)

[a]Bottled water, [b]concentrations greater than 10 mg L^{-1} are typed in bold, conveniently

disadvantaged groups (Ward et al. 2018; Ghaffari et al. 2019).

Mitigating nitrate contamination in Turkish waters

This study has shown that the NO_3 contamination is the case almost all waters across the nation and that it has reached to serious levels in many economically important regions. Nitrate contamination mechanisms, severity, and sources are quite variable spatially and temporally. The severity of negative impact of the NO_3 contamination sources depends on the type, variety, and intensity of the human activities in the water exposed areas. Once contaminated, the aquifers may remain unclean for decades, and even satisfactory measures are taken to reduce NO_3 contamination (Kurunc et al. 2011; Singh and Craswell 2021). Necessary steps should be taken for a more sustainable and effective use of water resources and protecting them for future generations (Güler et al. 2013).

Vulnerability of groundwater to NO_3 contamination should be considered in planning and designing irrigation projects. There are many natural factors affecting the vulnerability of an aquifer to NO_3 contamination. For example, aquifer characteristics such as depth and type of the aquifer (confined, unconfined), thickness and conductivity of the vadose zone, and the net recharge of the aquifer are principal determinants of its vulnerability to NO_3 contamination in many cases

(Kurunc et al. 2016). In sloping landscapes, low slope localities have a greater potential to transport of contaminants vertically (Aksever et al. 2015b). Also, fate of nitrogen fertilizers in soil is affected by various soil factors such as water flow rate, water holding capacity, bulk density, thickness, structure, and porosity. Coarse-textured soils are prune to contaminants to pass more rapidly through the vadose zone compared to fine-textured soils (Aksever et al. 2015b).

Nitrogen fertilizers used in irrigated agriculture poses a considerable risk to the water resources (Kurunc et al. 2011). Measures to reduce leaching losses of fertilizer N from agricultural soils to control water pollution problems mainly have focused on amount of fertilizer N, time of application, source modification, and proper coordination with soil and water management (Singh and Craswell 2021). Many studies showed that excessively used nitrogen fertilizers combined with improperly used irrigation water are the principal reasons for high NO_3 concentration in groundwater in many of intensively cultivated areas. Therefore, soil and water management in agricultural areas have a critical importance to reduce NO_3 in water resources. Ibrikci et al. (2015) stressed that well-established irrigation and management plans are crucial for reducing the fertilizer-related NO_3 contamination risk in Mediterranean irrigated crops. Optimization of nitrogen fertilization, irrigation scheduling, and increased irrigation efficiency were critical measures to reduce NO_3 transport to groundwater (Ibrikci et al. 2015). Shaffer et al. (1995) reported that switching from furrow to sprinkler irrigation resulted in a 95% decrease in NO_3 leached and 84% in nitrogen fertilizer input in a sandy loam soil. The authors attributed those decreases in NO_3 leaching to a more uniformly and better controlled application of irrigation water, which increased nitrogen use efficiency and decreased volume of water percolated beyond the root zone. Similarly, Kurunc et al. (2011) suggested shifting the surface irrigation system to sprinkler irrigation to reduce NO_3 leaching at hotspots mainly associated to irrigated wheat and cotton cultivation localities in Serik Plain of Antalya. Rate of fertilizers, animal manures, and irrigation water should be applied site-specifically in the areas prone to NO_3 leaching to avoid further contamination and to decrease current levels of NO_3 contamination in groundwater and surface water systems. Limited water application and split applications of nitrogen fertilizers can reduce amount of NO_3 moving beyond the root zone (Ersahin 2001; Kurunc et al. 2016). Irrigation return flows have been recognized as one of the fertilizer-related NO_3 contamination sources in Adana (Southern Turkey) (Ibrikci et al. 2015); the authors concluded that irrigation scheduling and increased irrigation efficiency reduced NO_3 exports to drainage water. Treating drainage water before it enters streams holds a high potential for reducing nitrogen and phosphorus losses from agricultural areas (Carstensen et al. 2020).

Application of crop rotation can help mitigate NO_3 contamination in water resources. Studies showed that, in general, NO_3 contamination is greatest under vegetable, orchards, potato, and cotton cultivation. Changing cropping pattern and including nitrogen scavenging plants (especially deep-rooted ones) in the cropping pattern can be considered to reduce NO_3 leaching beyond the root zone. For example, a deep-rooted crop may follow a shallow-rooted one to utilize NO_3 ready to leach in deeper soil depths (Pasten-Zapata et al. 2014). Randall et al. (1997) reported NO_3 concentrations in drainage waters from corn and soybean fields 35 times greater than those from alfalfa and perennial grasses. Producing crops with high fertilizer and irrigation water demand should be avoided, especially in areas with shallow groundwater and rapid soil water percolation. For example, Aksever et al. (2015a) concluded that potato cultivation should be avoided in areas where groundwater depth is less than 2.0 m to reduce NO_3 contamination of groundwater in Sandıklı Basin (located in Afyon Province). Also, the use of fertilizers should be regulated based on the fertilizers need of crops as determined by soil analyses. Enhanced efficiency fertilizers like polymer coated fertilizers, nitrification inhibitors, urease inhibitors, and double inhibitors (nitrification and urease inhibitors combined) have been developed to improve fertilizer N use efficiency and reduce losses of N from the soil–plant system. Studies showed that the enhanced efficiency fertilizers play a significant role by minimizing fertilizer mismanagement (Singh and Craswell 2021). Strategies like structural adjustments in agriculture in terms of changes in land use patterns based on different crops and crop rotations, the use of biochar, and distributing N inputs across locations to maximize production show promise for reducing leaching loss of NO_3. In many cases, combination of targeted mitigation measures may be more cost-effective rather than a single option for reducing the NO_3 loading to aquatic ecosystems (Carstensen et al. 2020).

Coastal zones are highly vulnerable to NO_3 contamination since they are under influence of both of marine and terrestrial environments (Güler et al. 2013). Rapidly increasing population accompanied by increased housing and infrastructure development and intensified economic activities such as agriculture, aquaculture, trade, tourism, and transport poses a significant risk of environmental pollution on those coastal zones (Güler et al. 2013). Güler et al. (2013) showed that chemicals released from agricultural, domestic, and industrial sources resulted in a severe NO_3 contamination in a coastal plain and noted that NO_3 concentrations in groundwater were strongly correlated with land-use types like open-field farms, citrus orchards, industrial complexes, and residential areas. The authors stressed that the most severe contamination sites occurred on the citrus cultivation sites where wild irrigation is combined with excessive nitrogen fertilizers use.

Discharges from local residences and public entities resulted in NO_3 contamination of water resources in many regions (Karagüzel and Irlayici 1998; Çetindağ 2005; Bayram et al. 2013). In many cases, leakages from open storage of farmyard manure can be an important source of NO_3 contamination in nearby surface water and groundwater. The farmyard manure should be stored properly to avoid its impact on surrounding water resources.

Studies showed that karstic and alluvial systems are the main aquifer materials around the world, supplying drinking and irrigation water for communities. Karstic aquifers provide favorable conditions for groundwater recharge. However, karst aquifers have complex and unique geological and hydrogeological characteristics, which make them extremely vulnerable to the contaminants from surface. The high permeability of carbonate rocks arises principally from enlargement of joints and bedding plane partings. The continuous groundwater circulation results in formation of primary pathways, which leads to a rapid transport of dissolved chemicals to groundwater. Contaminants from karstic surfaces can reach to groundwater within a short time, which makes those aquifers quite vulnerable to those contaminants (Simsek et al. 2008).

Karstic aquifers are quite common in Turkey, especially in Aegean, Mediterranean, and Southeastern Anatolian regions. The Antalya Basin located in the Western Taurus Karst Belt is an important area; large volumes of groundwater discharge from the intensively karstic Taurus Mountains and flow through the Travertine Plateau to the Mediterranean Sea (Ekmekci 2005). The Kırkgöz Springs discharge from several outlets with a combined flow of 10-60 m^3 s^1. The springs are the major source of all other springs on the Antalya Travertine Plateau and Travertine Deposits. However, the future of those extremely important water resources is threatened via investments by local people and public institutions. There are a number of poljes, which are highly negatively affected by those activities. Also, the use of features such as poljes and sinkholes as solid waste/sewage disposal stores often causes extensive groundwater contamination of NO_3 (Elhatip 1997; Baba and Tayfur 2011). Field studies showed that some municipalities near Pamukkale Region (one of the most important karstic regions located in Southwestern Turkey) were disposing of their solid waste, sewage water, and sewage disposal to highly developed karstic features such as sinkholes in the upstream area of the thermal karst springs (Elhatip 1997). Results from Ekmekci (2005) showed that surface water and groundwater in the Kestel Polje and Kırkgözler Springs were highly contaminated by pesticides and NO_3 originated in agricultural areas. Davraz et al. (2009) emphasized that approximately 4 m^3 s-^{1} of drinking water resources were not being used due to NO_3 contamination in Antalya. Therefore, those karstic regions comprising features such as dolines, shallow holes, and sinkholes should be protected from waste disposal (Simsek et al. 2011). Local people and government entities in the region should be alerted to the significance of the problem, and measures should be taken to save those indispensable water resources.

Uncontrolled and excessively used groundwater has resulted in sharp decreases in groundwater level in some regions such as in the Konya Closed-Basin. Groundwater use of local people and government entities should be regulated more strictly in the areas where groundwater is the only water source for the local economy. Large withdrawals from wells and recharge from irrigation applications can considerably increase groundwater velocity and vertical flow components, potentially affecting NO_3 transport in those aquifers (Aksever et al. 2015a).

Wetlands are an important source of biodiversity and large-scale ecological balance. A slight increase in NO_3 level in wetlands may disturb their delicate ecosystem. This study showed that NO_3 contamination is evident in several wetlands in Turkey. Also, water from some of those wetlands is used carelessly by local people and legal entities. For example, Gala Lake (declared as a “National Park” in 2005) provides dwelling for many bird species migrating between Europe and Africa, and Siğirci Lake is a significant fishing area; both of them are located on Meriç Delta (Turkish Thrace) (Tokatlı 2018a, 2018b). Water from those lakes is used for irrigation in paddy fields, and then drainage water from those fields is discharged back to the lakes (Tokatlı 2018a, 2018b), degrading the lakes’ ecosystems. Technical and legal measures should be taken to protect those and similar delicate ecosystems from degradation.

Nitrate is the stable form of dissolved nitrogen in strongly oxidizing groundwater; it moves in groundwater with no transformation and a little or no retardation due to its anionic form (Kaçaroğlu and Günay 1997); it is transported along with water percolating to aquifers via subsurface drainage systems (Varol and Davraz 2010). In general, increased precipitation has been inversely related to the concentration of NO_3 in groundwater, due possibly to the dilution effect of rainwater in wetter seasons (Varol and Davraz 2010). Varol and Davraz (2010) suggested that NO_3 measurements should be made in high NO_3-load conditions to obtain reasonable results of NO_3 contamination of groundwater. Seasonality of NO_3 concentration in drinking waters should be considered in monitoring their contamination status.

Understanding the response of NO_3 leaching from agricultural fields to local field scale management as well as broader environmental drivers such as climate and soil can be helpful in reducing the contribution of fertilizer nitrogen to pollution of freshwater bodies (Singh and Craswell 2021). Information on water and nitrogen balance can provide an effective basis for optimizing fertilization strategies. The computer models can effectively balance the water and nitrogen in agricultural systems, and they can reasonably predict the nitrogen fertilizer demand and NO_3 leaching, providing effective guidance for the rational use of nitrogen fertilizers (Cui et al. 2020). Modelling contaminant pathways and processes can provide insights and facilitate scenario development. Decision support systems linking models of nitrogen dynamics in soil–plant system, NO_3 leaching, plant growth, and modern diagnostic tools for estimating fertilizer nitrogen requirement of different crops can generate required fertilizer management scenarios (Singh and Craswell 2021). Climate change is expected to cause more intense and frequent precipitation events and prolonged summer droughts in the future (Christensen et al. 2013). Global climatic change may alter the pattern of NO_3 concentrations in waters (Singh and Craswell 2021). Water quality modelling can be used to identify hotspots and trends for different climate change scenarios (Singh and Craswell 2021).

In some cases, the treatment of NO_3-contaminated soil and water is the only option to reduce the associated health hazards (Singh et al. 2022). Various techniques such as reverse osmosis, chemical denitrification, biological denitrification, ion exchange, electrodialysis, and adsorption have been used currently. However, the byproducts from these technologies have some limitations (Singh et al. 2022). The use of greener and novel routes such as employing different nanocomposites, halloysite nanotubes, and nanorods to remove NO_3 may improve the NO_3 removal efficiencies. The development in the field of nanoscience and its techniques may overcome the limitations of nanomaterials. Immobilization of these nanocomposites or nanotubes on a membrane overtakes the limitation of recycling and separating from the water. Sensing techniques seem to be more suitable and reliable for the quantitative and qualitative estimation of NO_3 ions from soil and water. Also, the consumption pattern of nitrogen fertilizers at the region or country level provides the first-hand information on the possibility of NO_3 contamination in water bodies (Singh and Craswell 2021). Future research is needed to develop sophisticated techniques that remove NO_3 from the environment and senses its presence above permissible limits (Singh et al. 2022). Different sources of NO_3 contamination in ground and surface water can be estimated using different techniques such as NO_3 isotopic composition, co-contaminants, water tracers, and other specialized techniques (Singh et al. 2022).

The scientifically proven mitigation measures may not find favor with farmers and agribusinesses due to a lack of steadfast decisions based on sound economics (Singh and Craswell 2021). Choosing the most appropriate and avoiding incompatible mitigation measures requires collaboration between the different actors in the catchment to align the interests of all stakeholders (Carstensen et al. 2020). Management-oriented decision support systems should be developed to formulate best practices for achieving optimum production and minimal NO_3 leaching (Musacchio et al. 2020). Musacchio et al. (2020) suggested that adaptive governance is required to deal with the uncertainty, the speed of environmental changes, and potential modifications to regulations.

Potential health effects of NO_3 in drinking water, including the risk of cancer, have been a subject of scientific research for decades as reported by the number of studies (e.g., Quist et al. 2018; Ward et al. 2018; Ghaffari et al. 2019; Buller et al. 2021). A number of well-designed studies have been conducted to evaluate the health effect of drinking water NO_3 across the world as reported by many review articles like Ward et al. (2018) and Picetti et al. (2022). Studies of colorectal cancer, thyroid disease, and central nervous system birth defects showed consistent associations with water NO_3 ingestion. To our knowledge, no such studies have been conducted on the potential health effects of NO_3 in drinking water in Turkey, to date. Research is needed on this topic to draw firm conclusions on the risk of drinking water NO_3 ingestion. Future health studies should prioritize populations with high exposure to NO_3 from their drinking water (e.g., people living in the areas where surface and groundwater are heavily contaminated due to high uncontrolled residential and industrial discharges and diffuse contaminants from intensive agricultural sites are clustered). Mineral water bottles are labeled with information on the content of some anions, while many of those labels provide no information on NO_3 that might be present in the water (Gümüş et al. 2021). Therefore, the NO_3 concentration of those mineral water brands should be specified on their labels.

Actions taken under the implementation of nitrate directive (91/676/EEC) in Turkey

The nitrates Directive (ND) (91/676/EEC) of the European Union (EU) aims to reduce water contamination caused by nitrates from agricultural sources and to prevent further such contamination (Yetis et al. 2013; Musacchio et al. 2020). The Directive requires member states to monitor the effectiveness of the measures implemented to reduce NO_3 contamination (Yetis et al. 2013). The "Regulation on the Protection of Water Against Nitrate Contamination of Agricultural Origin," which was prepared in accordance with the Directive on improving water quality in the harmonization process of Turkey's candidacy to the European Union, was published in the Official Gazette on February 18, 2004. The regulation was later revised and published in the Official Gazette dated 23 July 2016 and numbered 29779.

Studies to monitor NO_3 contamination of agricultural origin in waters have started in Turkey within the framework of the Regulation, which envisages identification of contaminated or threatened waters, recognition of NO_3-sensitive areas, determination of sustainable agricultural practices, creation of agricultural action plans, and establishment of a monitoring network and reporting system. Within the scope of “Implementation of the Nitrate Directive Project (NDP),” a monitoring network including 4752 points (2451 surface and 2301 groundwater) was established, a web-based NO_3 information system (NİBİS in the Turkish acronym) was developed, 20 mobile laboratories were established, 10 NO_3 contamination monitoring and inspection tools were purchased, and a team working on NO_3 contamination was formed on the provincial basis. In this context, water quality monitoring studies have been carried out in surface and underground waters throughout the country, NO_3 analyses have been conducted in 61 provinces, and the data obtained have been entered into the NİBİS.

Data accumulated in NİBİS show that NO_3 contamination in both surface and groundwater gradually increased from 2008 to 2021. This is clearly shown in the series of the nationwide surface maps exhibiting the spatial pattern of NO_3 contamination severity of surface and groundwater. The spatial patterns of those maps are highly similar to those shown in Fig. 1a, b. Therefore, information reviewed in this study may be used along with data accumulated in NİBİS to better envisage spatial and temporal patterns in NO_3 contamination of Turkish waters.

Within the scope of NDP, a series of measures has been considered to reduce NO_3 contamination originating from agriculture. However, considering the diversity, impact, and spatial distribution of NO_3 contamination sources in Turkey (see Fig. 2a, b), it is obvious that the measures taken within the scope of NDP will be insufficient to adequately reduce NO_3 contamination in waters throughout the country, especially in those regions where non-agricultural sources significantly contribute to the NO_3 contamination. Also, reducing NO_3 contamination originating from industry and residential areas is extremely important in many of those previously mentioned hot spots, where industrially and domestically contaminated running water bodies are in contact with groundwater.

Despite the ND being issued almost 30 years ago, groundwater NO_3 contamination is still a serious threat to ecosystems and human health across the EU (Musacchio et al. 2020). After almost three decades, there is no significant reduction in groundwater NO_3 contamination, and agriculture still remains the main source of NO_3 pollution in Europe. About half of the European monitoring stations show no significant change in nitrates, and 26.6% of them present increasing trends, suggesting that efforts are still required to restore groundwater quality (Musacchio et al. 2020). Recently, it was observed that failure in groundwater management is often the result of an inadequate governance configuration, rather than the lack of knowledge related to aquifer vulnerability or hydrogeological dynamics. The concept of governance refers to “the range of political, social, economic and administrative systems that are in place to regulate development and management of water resources and provisions of water services at different levels of society” (Musacchio et al. 2020). Musacchio et al. (2020) noted that dissimilar to management, governance includes the complexity of the regulatory processes that result from the interaction between the different actors who help define the legal framework and then implement the environmental policy and its tools. Therefore, governance is an ongoing process in which multiple actors on different scales, with multiple purposes and priorities, interact more or less directly through formal and informal relationships (Musacchio et al. 2020). Stakeholder network analysis (Musacchio et al. 2020) revealed that the governance framework should support knowledge dissemination and changes in farmers' attitudes to successfully improving water quality.

Conclusions

The accumulated literature has shown that the water resources across Turkey have been contaminated vastly by NO_3 from numerous sources. Agriculture, especially nitrogen fertilizers, has been the chief source of NO_3 contamination in waters, especially in groundwater. The most notable contaminations have been reported in the regions (hotspots/hot regions) where intensive agriculture, rapid urbanization, and intensive industrial development intercept. In many cases, severely contaminated surface water bodies are in contact with groundwater, exacerbating the groundwater contamination.

Strategies should be developed to reduce the extent of contamination for avoiding its hazard to the environment and society. In this context, it is crucial to develop a strategic action plan, in which all the factors of NO_3 contamination of water resources are considered and evaluated holistically. Educational material and environmental guidelines may be developed for creating public awareness of the severity and importance of the problem. Nitrate vulnerability maps of the nation should be prepared for managers and end users to avoid further degradation of water resources. Well-established fertilizer and irrigation water management plans are crucial for reducing fertilizer- and irrigation-related NO_3 contamination. Nitrate concentrations in drinking waters should be monitored to ensure their safety. Maximum concentration for NO_3 concentration should be limited to 10 mg L^{-1} in bottled drinking water for the safety of disadvantaged groups such as infants, pregnant women, and elders with stomach problem. The nitrate concentration of bottled drinking waters should be provided on their labels. Also, considering that tap water is intensively drunk by people in Turkey, the legislation on NO_3 concentrations in tap water should be specified for infants and disadvantaged (NO_3 vulnerable) groups. A considerable amount of information has been accumulated on NO_3 in Turkish waters. Data collected by public institutions such as DSI, universities, research institutions, and other establishments should be evaluated by an interdisciplinary scientific team to develop strategies to save water resources against contamination.

Future research priorities include modelling the pathways of NO_3 contamination, harmonization of data collection, and sharing knowledge to incentivize improved agricultural practices. Decision support systems linking outputs of models of nitrogen dynamics in soil–plant system, NO_3 leaching, plant growth, and modern diagnostic tools to estimate fertilizer nitrogen requirement of different crops can generate required fertilizer management scenarios. Also, model outputs should be linked to policy outcomes.

Climate change is predicted to cause more intense and frequent precipitation events and prolonged summer droughts in the future. The effect of potential changes in climate variables on the hydrological processes that will affect NO_3 concentration in surface and groundwater should be evaluated. Changes in rainfall patterns directly or indirectly affect the regional water resources. Research is needed on the design and implementation of novel conservation programs. Management-oriented decision support systems should be developed for optimum production and minimal leaching of nitrogen fertilizers.

A broad range of emerging information technologies provides opportunities for monitoring and managing water pollution by fertilizers and many other aspects of agricultural production. Big data technology promises to provide a basis for capturing, storing, and analyzing current unstructured information on fertilizer application rates and water pollution at the global, national, and watershed levels. Sophisticated machine learning and artificial intelligence technologies and their application to precision farming are expected to make significant contributions to reducing NO_3 leaching in agroecosystems.

Studies need to develop an adaptive governance system, which considers a range of political, social, economic, and administrative systems for regulating and managing water resources and provisions of water services at different levels of society. Novel studies such as social network analysis may be conducted for these aims. The social network analysis considers the mutual relationships between people and water resources and it identifies both the actors affected (directly or indirectly) by the water system and the socio-economic factors hindering the good management practices. Adaptive governance is required to deal with both the uncertainty, and the speed of environmental changes and potential modifications to regulations.

Future health studies should prioritize populations with the exposure to high NO_3 from their drinking water (e.g., people living in the areas where surface and groundwater are heavily contaminated due to high uncontrolled residential and industrial discharges and diffuse contaminants from intensive agricultural sites are clustered). Most adverse health effects related to drinking water NO_3 are likely due to a combination of high NO_3 ingestion and factors that increase endogenous nitrosation. Epidemiologic studies targeting the identification of subgroups with greater potential for endogenous nitrosation should be conducted. New methods for quantifying the nitrate-reducing bacteria in the oral microbiome and characterizing genetic variation in N-nitroso compounds metabolism hold promise for identifying high-risk groups in epidemiologic studies.

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Author contributions Sabit Erşahin had the idea for the article, performed the literature search and data analysis, and drafted and/or critically revised the work. Bayram C. Bilgili performed the literature search and data analysis, prepared the figures, and revised the work.

Declarations

Competing interests The authors declare no competing interests.

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