Collective Versus Household Iron Removal from Groundwater at Villages in Lithuania

Linas Kliučininkas, Viktoras Račys, Inga Radžiūnienė and Dalia Jankūnaitė

Abstract The Water Framework Directive (WFD) provides a framework to integrate high environmental standards for water quality and sustainable water resource management. Hydro-geological conditions typical for southwest part of Lithuania determine high concentrations of iron in the groundwater. Untreated groundwater is commonly used for every day needs by local inhabitants living in a villages (water consumption <100 m^3/day). Seasonal measurements indicated high variations of total iron concentrations in groundwater. The detected annual concentration of total iron in the water wells was 3.3 mg/L. The concentrations of total iron in the tap water were some 40 % lower compared to those in the groundwater. Iron removal from the ground drinking water yields advantages with the comfort of consumers; however, it entails environmental impacts and additional costs. A comparative analysis of collective and individual household iron removal systems for the selected village has been performed to estimate possible environmental impacts and costs. For assessment of costs and environmental impacts, authors applied input–output analysis. The chosen technique for collective iron removal was non-reagent method implying oxidation of contaminants in the drinking water and their containment in the filters. For individual households, reverse osmosis filtration method was selected. The environmental benefits of using central iron removal system result in formation of almost 70 % less of solid waste, 13 % less of wastewater, and 97 % less consumption of electric energy compared to the individual iron removal facility at each household. Estimated overall cost, including purchase, installation, and operational costs, for central iron removal system is 390 Euro/year per household, the respective cost for individual household iron removal facility—1,335 Euro/year. The analysis revealed that central iron removal system has advantages in comparison with iron removal facilities at each individual household.

Keywords Iron · Groundwater · Central and household iron removal

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L. Kliučininkas (✉) · V. Račys · I. Radžiūnienė · D. Jankūnaitė
Department of Environmental Technology, Kaunas University of Technology, Kaunas, Lithuania
e-mail: linas.kliucininkas@ktu.lt

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1 Introduction

Mismanagement of groundwater may result in a cycle of unsustainable socioeconomic development—including risk of poverty, social distress, energy, and food security. Lack of good quality drinking water also limits processing of agricultural production, creation, and development of small businesses, as well as attraction of investments. To ensure the sustainable management of groundwater resources for domestic use, authors provide input–output analysis approach regarding selected village in Lithuania. The analysis covers innovative assessment of environmental impacts and cost of iron removal from groundwater.

During the last 40–50 years, groundwater use for drinking purposes has increased in many countries, especially in the developing countries and countries in transition (Shah 2005). However, considerable differences in the availability and quality of groundwater result in varying overall use of groundwater in individual countries. Groundwater part in a general balance of drinking water supply exceeds 70 % in Austria, Armenia, Belarus, Belgium, Hungary, Georgia, Denmark, Lithuania, Switzerland, and Germany. In most of these countries, groundwater is the primary source for water supply in rural areas (Zekster and Everett 2004). Since groundwater often needs some kind of pretreatment, local communities express willingness to have a possibility to use good quality drinking water. Surveys show that people living in those areas are prepared to pay for improved drinking water quality (Genius et al. 2008). In order to offer cost-efficient water pretreatment technologies, thorough analysis of possible alternatives of drinking water preparation systems is required (Lindhe et al. 2011).

Lithuania is one of the characteristic countries, generally using groundwater for drinking water needs. Iron removal from groundwater in cities and towns is no longer a matter of great concern in urban Lithuania, whereas rural areas face problems with drinking water quality. The quality of water is often the issue in small settlements. Residents of villages (with a drinking water consumption <100 m^3/day) often extract water from the water wells, most of which are physically and technologically outdated and do not meet consumers' needs. Since for the time of the study Lithuania has an economy in transition, it was relevant to estimate the environmental impacts and costs of drinking water preparation.

2 The EU Water Resource Management

The Water Framework Directive (WFD, 2000/60/EC), providing a framework to integrate high environmental standards for water quality and sustainable water resource management, is a new approach to environmental policymaking from a European perspective. The main purpose is to improve the quality of all types of water bodies across the EU. Different instruments are used to obtain the objective, involving different level of organization—from public participation to national or European goals. The integration of water policy with other EU directives and sector policies as well as with spatial planning is also emphasized. WFD for the first time at European level provides a framework for integrated management of groundwater and surface water. The components of the WFD dealing with groundwater cover a number of different steps for achieving good quantitative and chemical status of groundwater by 2015.

The Drinking Water Directive (DWD, 98/83/EC) concerns the quality of water intended for human consumption. Its objective is to protect human health from adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean. It sets standards at EU level for the most common substances (so-called parameters) that can be found in drinking water. According to the DWD, a total of 48 microbiological and chemical and indicator parameters must be monitored and tested regularly.

3 Characterization of Iron-rich Groundwater for Public Supply Purposes

The basic parameters that characterize and predetermine iron concentrations in the groundwater are pH and oxidation reduction potential (ORP) (Diliunas et al. 2006). Iron removal process is more effective in low-acidity environments (Bong-Yeon 2005) with high oxidation potential (Tekerlekopoulou et al. 2006). Water temperature and intensive aeration have no significant effect on iron removal process. The presence of ammonium is undesirable because it causes taste and odor problems, reduces disinfection possibilities, and also undergoes oxidation process, converting to nitrate (Katsoyiannis et al. 2008). Waters, containing high concentrations of chlorides, stimulate formation of iron corrosion products—green rusts (green-blue iron hydroxide compounds formed under reduction and weakly acid or weakly alkaline conditions as intermediate phases in the formation of FE oxides—goethite, lepidocrocite, magnetite). Water salinity can also influence iron release to the groundwater (Pezzetta et al. 2011). If water is containing organic substances, iron practically does not form the flocks or particles suitable for filtration or sedimentation. This problem is caused by the presence of stable iron colloids or iron complex compounds with dissolved organic substances (Serikov et al. 2009).

The DWD sets 200 μg/L (98/83/EC) concentration as the threshold limit value for iron in drinking water, and the same level is set as the Specific Limit Value (SLV) in the national Hygiene Norm of Lithuania (HN 24:2003). Use of untreated water, containing high concentrations of iron, has no significant effect on human health. However, the reddish-brown color of water can cause discomfort when taking a bath, it can stain clothing, and it requires additional detergents for washing. It also has negative effect on the sanitary wear, mainly caused by the corrosion of metal components. If water containing high concentration of iron is used, negative impact on the environment is caused by use of chemical products for the daily living needs (comparatively more detergents, bleach, sanitary cleaning, and dish washing chemicals are needed to perform daily cleaning procedures); it also raises consumption of energy (in order to obtain the desired water quality, additional procedures of water boiling, laundry, etc., are used). If bottled drinking water is purchased, it results in additional amount of plastic waste. In summary, the possible additional costs of untreated water use are faster sanitary wear and additional electric energy consumption.

4 Methods for Iron Removal from Groundwater

Iron removal from groundwater is based on oxidation of soluble ferrous compounds to insoluble ones. Katsoyiannis and Zouboulis (2004) and Katsoyiannis et al. (2008) denoted that oxidation methods for iron removal can be divided into physical (without using chemical reagents), chemical (chemical reagent based), and biological. Generally, physical methods involve aeration–filtration technology and are advantageous for small- and medium-size applications. Other methods used for iron removal from drinking water are as follows: ion exchange (Vaaramaa and Lehto 2003); use of activated carbon or other adsorbing materials (Munter et al. 2005; Das et al. 2007); adsorption based on electro-coagulation processes (Vasudevan et al. 2009); oxidation–microfiltration systems (Ellis et al. 2000); subsurface treatment, involving aerated water injection into aquifer (van Halem et al. 2010); and other. Biological iron removal methods utilize microorganisms as oxidation catalysts (Munter et al. 2005).

In this study, for collective removal of iron from groundwater, authors selected the non-reagent method. This method was selected as the most economically feasible and effective iron removal technology, as the water met the following requirements: Iron concentration is below 3 mg/l, pH is less than 6, and permanganate index is below 7 mgO_2/L. The method implies oxidation of contaminants in the drinking water and their containment in the filters. The contaminants are removed by washing the filter. Filters are washed successively with water from the towers. It is proposed to install two parallel lines of filtering devices. This will reduce the instantaneous flow rate required for washing and will guarantee good operation of the system. The maximal capacity of the system for iron removal in the selected settlement—9.0 m^3/h. For iron removal from groundwater at the individual household, the reverse osmosis filtration method was selected. This method is widely used for removal of many types of large molecules and ions from groundwater. It is the reliable and effective technology for drinking water preparation. Since it is fully automated, the technology is not requiring the complex process control and is often chosen by the individual consumers.

The aim of this study was to analyze iron concentrations and related processes in the groundwater and tap water of the selected village, as well as to estimate collective versus individual household iron removal systems in respect to environmental impacts and costs. The estimates of cost for housing-related activities were based on current cost of living in Lithuania.

5 Methods and Materials

5.1 Study Area

Detailed studies of iron concentrations in the groundwater and tap water, as well as other water properties, were analyzed at Barzdai village, which is located 22 km southeast from the district municipality center Sakiai, Lithuania (Fig. 1). The 1,280 residents of the village use drinking water from upper cretaceous aquifer. The extracted water is directed to water tower and provided (without treatment) to local residents. Currently, there are three drinking water wells in Barzdai, two of them belong to the community of the village.

Hydro-geological conditions typical for southwest part of Lithuania determine high concentrations of iron in the groundwater. Chemistry of fresh groundwater is determined by rock composition. Water inflow from overlaying Quaternary intermorainic aquifers causes higher iron content (1–3 mg/L) in the groundwater. The distribution of iron concentrations is weakly related to the horizontal flow of groundwater; the uplift of more mineralized water from deeper aquifers via hydrogeological "windows" and tectonic faults is observed. The most important factor determining the iron content is the CO_2 regime, affected significantly by the conditions of inflow from deeper aquifers.

The closed groundwater system belongs to lower cretaceous aquifer, which is rich in ammonium compounds and organic matter. In the upper cretaceous aquifer, increased concentrations of ammonium, chlorides, and iron are recorded. Iron occurs in groundwater under reduction conditions (i.e., where dissolved oxygen is lacking and carbon dioxide content is high). Soluble form of iron (Fe^{2+}) is typically chemically bound with organic matter.

Fig. 1 Šakiai district municipality

6 Groundwater and Tap Water Measurements

Seasonal concentrations of total iron as well as ammonium nitrogen, chlorides, which potentially have effect on iron levels in the groundwater or influence efficiency of iron removal process, were performed from March 2010 to February 2011. In addition, measurements of iron concentrations in the untreated tap water at different distances from the groundwater wells as well as measurements of pH, temperature, permanganate index (PI), and ORP were performed. The campaign involved in situ measurements as well as chemical analyses at the laboratories of Department of Environmental Engineering, Kaunas University of Technology. Triplicate samples were taken from drinking water wells and tap water. Sampling was carried out in accordance to the ISO 5667-5:2006 and ISO 5667-11:2009 standards. Concentrations of total iron, ammonium nitrogen, and chlorides were measured in conformity with the respective ISO 6332:1988, ISO 7150-1:1984, and ISO 9297:1998 standards; PI was determined in accordance with the ISO 8467-1993 standard. Multimeter WTW pH/Cond 340i/SET was used to determine temperature, pH, and ORP (WTW pH Electrode SenTix ORP). In order to assess deterioration/improvement of water quality in the water supply systems, additional analysis of tap water in the selected households was performed. The selected households were situated in 400–500 m, 500–600 m, and 600–800 m distances from the water well ID 34932.

7 Assessment of Alternative Iron Removal Systems

In order to estimate environmental impacts and costs of collective versus individual household iron removal, authors applied input–output analysis. The estimation of costs involved purchase, installation, and operational costs. Iron removal facilities were assessed with respect to commercial prices offered by local providers. The estimation of environmental impacts involved demand of filter load material and electric power consumption as input parameters, respectively, the CO_2 equivalent emissions; amounts of non-hazardous waste and discharges of wastewater were estimated as output parameters (see Fig. 4).

8 Results and Discussion

8.1 Water Quality Assessment

The results of chemical analysis showed that iron concentrations in all samples significantly exceeded the Specific Limit Value ($SLV_{Fe} = 0.2$ mg/L) (see Fig. 2). The average total iron concentration in the well ID 34932 has exceeded SLV_{Fe} by the factor of 20, and 29 in the well ID 26047, respective concentrations in the well

ID 38890 outreached SLV_{Fe} by the factor of 9. The highest concentration of total iron was observed in the well ID 26047 during summer measurement campaign and reached 6.89 mg/L.

Concentrations of ammonium nitrogen in the samples taken in the summer and the autumn sampling periods have not exceeded the Specific Limit Value ($SLV_{NH_4-N} = 0.5\,mg/L$); however, average concentrations of ammonium nitrogen during the spring and the winter sampling campaigns in wells ID 34932 and ID 26047 exceeded the SLV_{NH_4-N} by 60 %, respectively, and in well ID 38890, average concentration was higher by factor 2 compared to SLV_{NH_4-N} (Fig. 2). The highest concentration of ammonium nitrogen was observed in the well ID 26047 during winter and reached 1.97 mg/L value.

Because of presence of ammonium in the groundwater, the required amount of oxygen during iron removal process would be higher. Ammonium forms the nitrates; therefore, it's presence in the water should be taken into account during the technological project preparation phase (Katsoyiannis et al. 2008).

Concentrations of chlorides showed high variation between the seasons and the wells (Fig. 2). The highest concentration (333.1 mg/L) was observed in the well ID 26047 during summer, and this was the only case when the Specific Limit Value (SLV_{Cl} = 250.0 mg/L) of chlorides was exceeded. The presence of chlorides in the groundwater is caused by the intrusion of these compounds into the groundwater from the Lower Cretaceous aquifer layer.

The water temperature in the wells analyzed varied from 7.5 to 11.0 °C. The pH values ranged from 7.3 to 9.5 (SLV_{pH} = 6.5–9.5); the highest values were observed during the summer sampling campaign and varied from 9.0 to 9.5. The high water pH values indicate faster oxidation of bivalent iron and manganese ions.

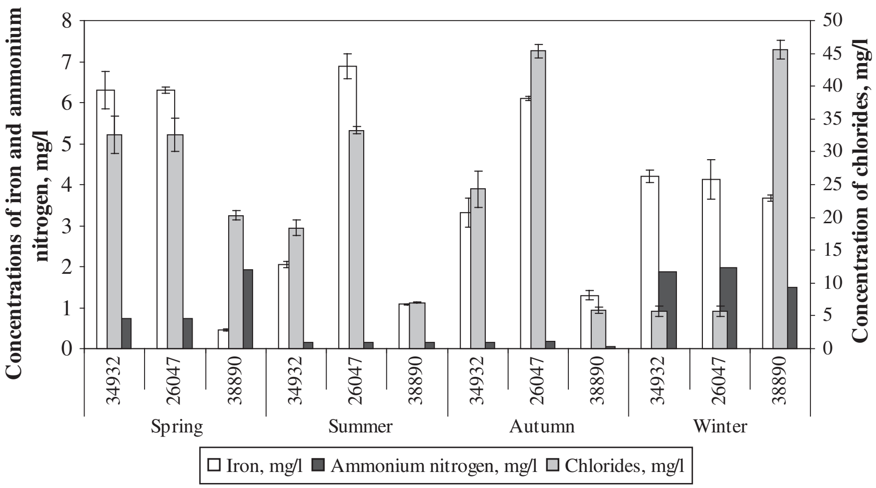

Fig. 2 Concentrations of iron, ammonium nitrogen, and chlorides in the groundwater, mg/L

The ORP of the groundwater usually varies between −480 and 550 mV. In our case, ORP measurements showed negative values and ranged from −250 to −80 mV. The ORP values confirm the reductive conditions in the groundwater. These conditions are usually caused by reducing agents, such as ammonium and bivalent iron.

The PI indicates water contamination by oxidizing organic and inorganic matters, and at the same, it is an important indicator of iron removal process. Each sampling campaign was followed by PI measurements. The PI values ranged from 0.5 to 2.1 mg/L O_2 and did not exceed the Specific Limit Value (SLV_{PI} = 5.0 mg/L O_2). Low PI values indicate that iron compounds in the water are of inorganic origin and their oxidation is easier.

In order to assess deterioration/improvement of water quality in the water supply systems, analysis of tap water in the selected households was performed. Observed iron and ammonium nitrogen concentrations in the tap water are presented in the Fig. 3.

In general, it could be stated that the observed iron concentrations in the tap water were lower than those in the water wells by some 40 %. The explanations of this phenomenon could be that the bivalent iron ions are oxidized and precipitated in the pipes of the water supply system. Sedimentation of iron oxide in the pipelines reduces water flow and creates conditions for biofilm formation. This also could increase microbiological contamination of drinking water. Ammonium nitrogen concentrations in the tap water were slightly lower compared to those measured in the water wells. This could be explained by the specific conditions of

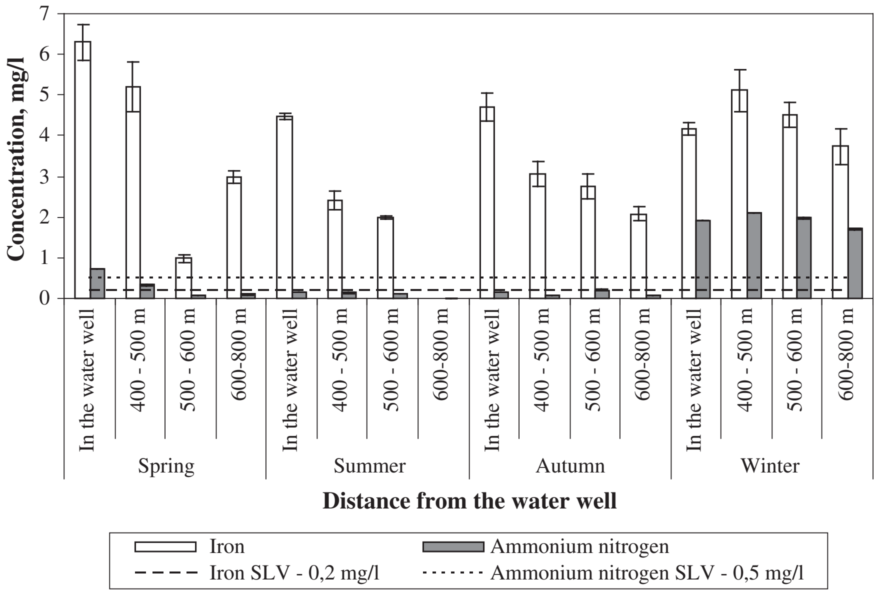

Fig. 3 Concentrations of total iron and ammonium nitrogen in the tap water, mg/L

water stagnation in the pipelines. The analysis revealed that decrease of iron and ammonium nitrogen concentrations receding from the water well is more rapid in warm period, while during cold period the concentrations decline less.

9 Estimation of Environmental Impacts and Costs

The total requirement of drinking water for the analyzed village is 16,790 m^3/year. In addition, 1.1 m^3 of water is used in filter backwashing process. The flowchart of input–output analysis for estimation of environmental impacts and costs of water preparation is presented in the Fig. 4. The input–output analysis of groundwater pretreatment included evaluation of incoming material and energy flows as well as assessment of energy use and waste generated during the drinking water preparation procedure.

It was assumed that reverse osmosis filters will be suitable option for water preparation at each individual household (see Fig. 4). If water would be treated individually at each household, it would require 8,150.0 kWh of electric energy per year. Regular filter regeneration is performed by backwashing, and used filter medium makes 5,477.6 kg of non-hazardous waste yearly. Wastewater (1,116.3 m^3) after backwash is discharged directly into the surface water body.

The purchase and installation cost of iron removal filter for an individual household is 1,280 Euro, respectively, and yearly operational cost makes up 54.84 Euro.

For central iron removal system, the non-reagent technology, which implies oxidation of contaminants and their containment in the filters, was analyzed.

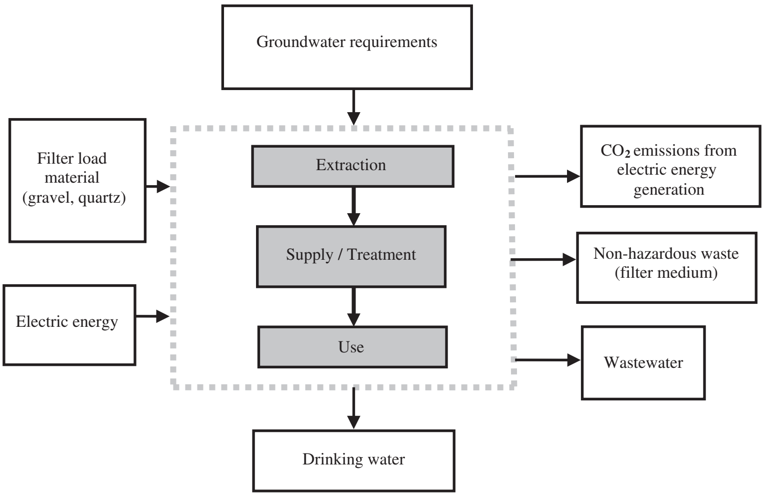

Fig. 4 Flowchart of input–output analysis

Table 1 Annual environmental impacts of alternative iron removal systems estimated for one household

	Input parameters		Output parameters		
	Amount of filter load material, m^3	Electric energy, kWh	Equivalent CO_2 emissions, kg[a]	Non-hazardous waste, kg	Wastewater, m^3
Individual household iron removal system	2.1	8150.0	4295.4	5477.6	1116.3
Collective iron removal system	0.6	263.4	138.8	1590.2	964.0

[a]www.defra.gov.uk/environment/climatechange/uk/individual/pdf/actonco2-calc-methodology.pdf

The total yearly electric energy requirement, estimated for one household, will be 263.4 kWh, respectively, and the CO_2 equivalent emissions will make 138.8 CO_2/kWh. Removal of contaminants by washing the filter will amount in 1,590.2 kg of non-hazardous waste (gravel, quartz) and 964.0 m^3 of wastewater (see Table 1).

The purchase and installation cost of collective ground drinking water quality conditioning system with automated iron removal filters and pumping station for the selected village is 29,000.00 Euro. Annual operational cost, including electric power consumption and water loses, makes 1,136.00 Euro.

10 Conclusion

The results of chemical analysis showed that total iron concentrations in all water wells significantly exceeded the Specific Limit Value ($SLV_{Fe} = 0.2$ mg/L). The indicated average total iron concentrations were 3.3 mg/L. The observed iron concentrations in the tap water were lower by 60 % compared to those in the water wells. The explanations of this phenomenon could be that the bivalent iron ions are oxidized and precipitated in the pipes. Physical–chemical analysis of the other ground drinking water properties (ammonium nitrogen, chlorides, ORP, pH, PI) revealed that the water wells prevail reductive conditions and iron compounds have inorganic origin resulting in faster oxidation of bivalent iron and manganese ions.

The environmental benefits of using collective iron removal system result in formation of almost 70 % less of solid waste and 13 % less of wastewater, and it consumes 97 % less of electric energy compared to the individual iron removal facility at each household. Of course, benefits would be different between the households which use untreated water or purchase drinking bottled water; however, it was not in the scope of this study.

Central iron removal systems for small settlements have evident benefits with reduction of costs. Estimated overall cost, including installation and operational costs, for collective iron removal system make up 1,335 Euro/year per household, and the respective cost for individual household iron removal facility is 390 Euro/year.

The analysis showed that central iron removal system is more beneficial compared to individual household iron removal system. The simplified approach used in this study provides expeditious assessment results and could serve as a model for sustainable groundwater use in small-/medium-scale villages facing high concentrations of iron.

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Authors Biography

Linas Kliučininkas, Viktoras Račys, Inga Radžiūnienė and Dalia Jankūnaitė Authors of the paper represent the Department of Environmental Technology at Kaunas University of Technology, Lithuania. The research group has an extensive record of publications on different aspects of environmental science. A special interest is paid on water supply as well as wastewater treatment issues. The major part of publications is of an applied character and has an interdisciplinary nature. During last decade, the group has initiated and participated in a number of national and international programs and projects supporting environmental and sustainability studies and research in the Baltic Sea Region.