GEOLOGIJA. 2006. Vol. 56. P. 60–66

Hidrogeologija • Hydrogeology • Гидрогеология

Intensified elimination of iron and other thindispersed compounds from groundwater *in situ* by magnetic activation

Jonas Diliūnas,

Kazimieras Jonaitis,

Arūnas Jurevičius,

Elvyra Rinkevičienė

Diliūnas J., Jonaitis K., Jurevičius A., Rinkevičienė E. Intensified elimination of iron and other thindispersed compounds from groundwater *in situ* by magnetic activation. *Geologija.* Vilnius. 2006. No. 56. P. 60–66. ISSN 1392-110X

The article presents experimental results of the magnetic conditioning of water, aimed at intensifying elimination of iron and other thindispersed compounds from groundwater *in situ*. The experiments were performed in aquifers of Quaternary intertill and alluvial deposits.

Oxidation of bivalent iron ions by atmospheric oxygen and sedimentation of trivalent iron in an aquifer are more efficient when water is conducted through a magnetic water conditioner operating on a principle of a permanent magnet. Groundwater abstraction after aeration and magnetic treatment extends intensive oxidation of iron compounds: their low concentrations last twice or thrice as long as without magnetic water conditioning. Magnetic treatment of water by aeration stabilizes dissolved oxygen in groundwater or the oxygen adsorbed on the rock surface. Magnetic treatment during water aeration and abstraction is an effective method of drinking water quality improvement. This method may considerably reduce the costs of iron elimination *in situ*.

Key words: water quality improvement, magnetic conditioning, iron elimination, aeration, oxidation

Received 07 August 2006, accepted 07 September 2006

Jonas Diliūnas, Arūnas Jurevičius, Institute of Geology and Geography, Department of Groundwater, T. Ševčenkos 13, 03223 Vilnius, Lithuania. E-mail: diliunas@geo.lt
Kazimieras Jonaitis, Kaunas industrial water supply company, Raudondvario pl. 109, 4718 Kaunas, Lithuania. E-mail: vandenys.pr@takas.lt
Elvyra Rinkevičienė, Kaunas University of Technology, Chair of Inorganic Chemistry, Radvilėnų pl. 19, 50254 Kaunas, Lithuania. E-mail: elvyra.rinkeviciene@ktu.lt

INTRODUCTION

Water used for domestic and industrial purposes in Lithuania usually contains elevated concentrations of iron compounds. Efforts are focuses on improving iron elimination technologies. Groundwater quality improvement *in situ* by oxidation is one of the modern technologies and the subject of the present study. Creation of an aeration zone (geochemical barrier) in the aquifer where intensive iron oxidation and sedimentation take place is the main principle of iron and manganese elimination *in situ*. This zone is created by infiltrating clean oxygen-saturated water into the aquifer (Hallberg, Martinell, 1976; Seyfried, Olthoff, 1985; Diliūnas, Sakalauskas, 1996). It is most efficient and saving to use atmospheric oxygen for this purpose. The effectiveness of iron elimination depends on oxygen supply. Aerated water infiltration into the aquifer and clean water abstraction may take place in one or a few wells (inward cyclical scheme) (Fig. 1).

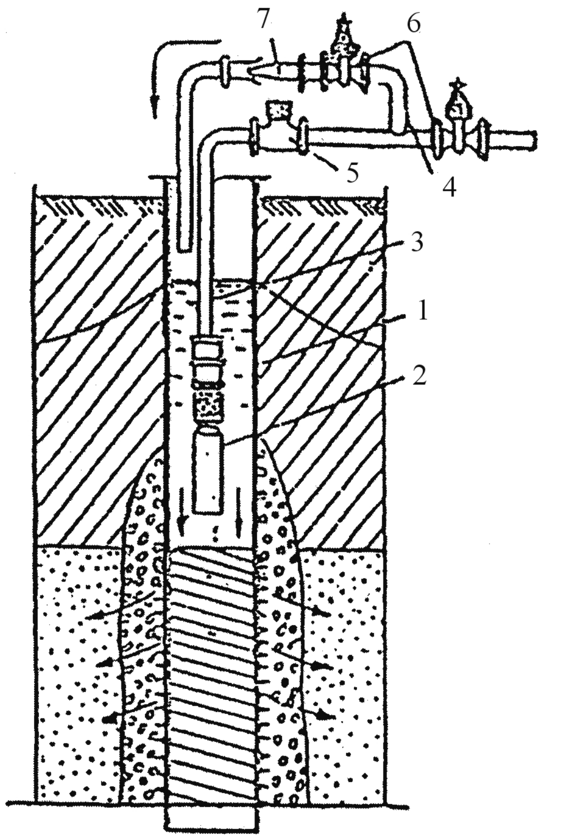

Fig. 1. Scheme of iron elimination from groundwater *in situ*: *1* – well pipes, *2* – pump, *3* – water lifting pipes, *4* – pipes for water infiltration, *5* – water meter, *6* – valves, *7* – ejector

1 pav. Požeminio aeravimo schema naudojant vieną gręžtinį šulinį: *1* – apsauginiai vamzdžiai, *2* – siurblys, *3* – vandens kėlimo vamzdžiai, *4* – infiltracijai tiekiamo vandens vamzdžiai, *5* – vandens skaitliukas, *6* – sklendės, *7* – ežektorius

Different techniques, reagent and non-reagent, stimulating dissolution of oxygen in water and intensifying aquifer aeration can be applied. Magnetic conditioning of water is a new technique. Its effectiveness is evaluated by the results of technological experiments. The main aim of the present work was to evaluate the role of magnetic conditioning processes facilitating elimination of iron from groundwater *in situ*.

Many researchers have investigated the impact of electromagnetic field (EMF) on the stability of dispersed systems. It has been reported that EMF speeds up coagulation of dispersed systems (Navratil, 2000; Lipus et al.; 1994; Busch W., Busch M. A., 1997), reduces the electrokinetic potential of the particles of colloidal iron and aluminum compounds and increases adhesion of solid particles, thus reducing the watering and hydration of particulate material (Shadrin et al., 1993). Integral thermal effects and the concentration of dissolved gas change, oxygen activity in the electromagnetic bidistillate increases, and radicals with a bactericidal effect form (Классен, 1982). Electromagnetic activation of water systems may affect the solubility and crystallization of many compounds (Higashitani et al., 1993). Natural water treatment with permanent magnet reduces the electrokinetic potential of clarified water and coagulant (Rinkevičienė, Mockutė, 2003). EMF reduces formation of fur in thermoelements and water-supply systems (Benson et al., 1993). Magnetic conditioning is most widely used for surface water improvement: softening, coagulation of particulate material and protection of pipes and containers from the formation of a crust of solid carbonaceous sediments. Groundwater aeration *in situ* by magnetic water conditioning has been investigated neither in Lithuania nor in other countries.

METHODS AND DATA

The processes of groundwater quality improvement *in situ* depend on the following main indices: total dissolved solids (TDS), concentration of iron (bi- and trivalent) and manganese, oxygen, carbon dioxide, sulphuretted hydrogen, carbonate hardness, silicon, calcium, nitrogen compounds, sulphates, chlorides, water bicarbonate alkalinity, temperature, the concentration of hydrogen ions (pH), redox potential (Eh), organic matter, humic and fulvic acids, conductivity, and iron bacteria. Researchers still argue about the priority of either biological or chemical factors affecting the oxidation of Fe (II) and Mn (II) *in situ*. The newest theory is based on a postulate that *in situ* supply of groundwater with oxygen in the first stage entails homogeneous direct Fe(II) oxidation in a liquid phase (biogenic factors are presumably the dominant ones) and in the second stage, Fe(II) is adsorbed on the rock surface and heterogeneously oxidized (Крайнов и др., 2004; Плотников, Алексеев, 1990). It was determined that iron elimination processes are most intensive in the oxidation environment with the following typical indices: Eh > 190 mV, pH > 7.5, O_2 > 0.4 mg/l, CO_2 < 50 mg/l. In this environment, the concentration of iron reduces by 80–90% and the vegetation of iron bacteria slows down by 40–50% (Diliūnas, Jurevičius, 1998).

The oxidation reaction $Fe^{2+} \rightarrow Fe^{3+} + \bar{e}$ takes place due to the presence of oxygen in water. The precipitate of iron hydroxide $Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3^0 \rightarrow Fe(OH)_3$ forms as a result of the subsequent process of hydrolysis. These reactions lie at the basis of the principle of iron elimination from water by filtration. Iron hydroxide formed as a result of oxidation during the process of iron elimination from water *in situ* is adsorbed on the rock surface, because a catalytic film which strengthens the adsorptive capacity of rocks develops on iron hydroxide.

EXPERIMENTAL METHODS

Field experiments were carried out in: a) Quaternary intertill aquifer at a depth of 69–86 m; water-bearing deposits were represented by sand; hydraulic conductivity was 10–25 m/d; b) gravel deposits of alluvial aquifer of open type at a depth 23–25 m; hydraulic conductivity is about 50–70 m/d. A scheme of the infiltration–abstraction of aerated water in one well was used. The technological process included four cycles: 1) aerated water infiltration, 2) reaction in the aquifer, 3) well cleaning by pumping, 4) clean groundwater delivery to the water-supply system. An ejector, magnet and measuring devices were installed in the well shaft for water delivery into the well and aeration. The infiltrated water was magnetically treated with a CEPI magnetic conditioner R5/4"DF whose magnetic induction may reach 9000 Gs. Along the mentioned main hydrochemical indices, the following other parameters were determined: particulate material and water color; the concentration and chemical composition of sediments carried away from the wells by groundwater at the beginning of the pumping cycle; the density of magnetic flow.

RESULTS

The natural hydrogeochemical characteristics of groundwater are given in Table.

An almost anaerobic, close to neutral environment prevails in the aquifer. Small concentrations of organic compounds (according to permanganate oxidation) and water alkalinity (>5.0 meq/l) are responsible for a comparatively small concentration of iron. Migration form

Table. **Natural chemical composition of groundwater (average values)**
Lentelė. **Požeminio vandens gamtinė cheminė sudėtis (vidurkinės reikšmės)**

Aquifer, well No	Fe^{2+}	Fe total	Mn total	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	TDS
	mg/l										
Intertill	1.0	1.1	0.04	4.0	9.8	337.0	6.9	1.3	69.8	22.8	459
Alluvial, 7	0.4	0.5	0.40	142	80.5	396.5	119.0	6.3	102.2	237	870
Alluvial, 11	0.1	0.3	0.46	110	83.5	430.0	100.0	6.3	114.2	24.3	868

Aquifer, well No	Total hardness	Alkalinity	Permanganate number	O_2	CO_2	NH_4^+	NO_2^-	NO_3^-	t	pH	Eh	Iron bacteria
	meq/l		mgO_2/l	mg/l					°C		mV	cells/l
Intertill	5.5	5.5	1.8	0.1	66.0	0.32	0	0.01	8.7	7.47	106	362000
Alluvial, 7	7.0	6.5	2.6	1.00	35.4	0.12	0.048	9.4	10,7	6.83	217	599000
Alluvial, 11	5.5	7.0	2.0	0.48	28.4	0.14	0.023	20.9	10.3	7.03	155	599000

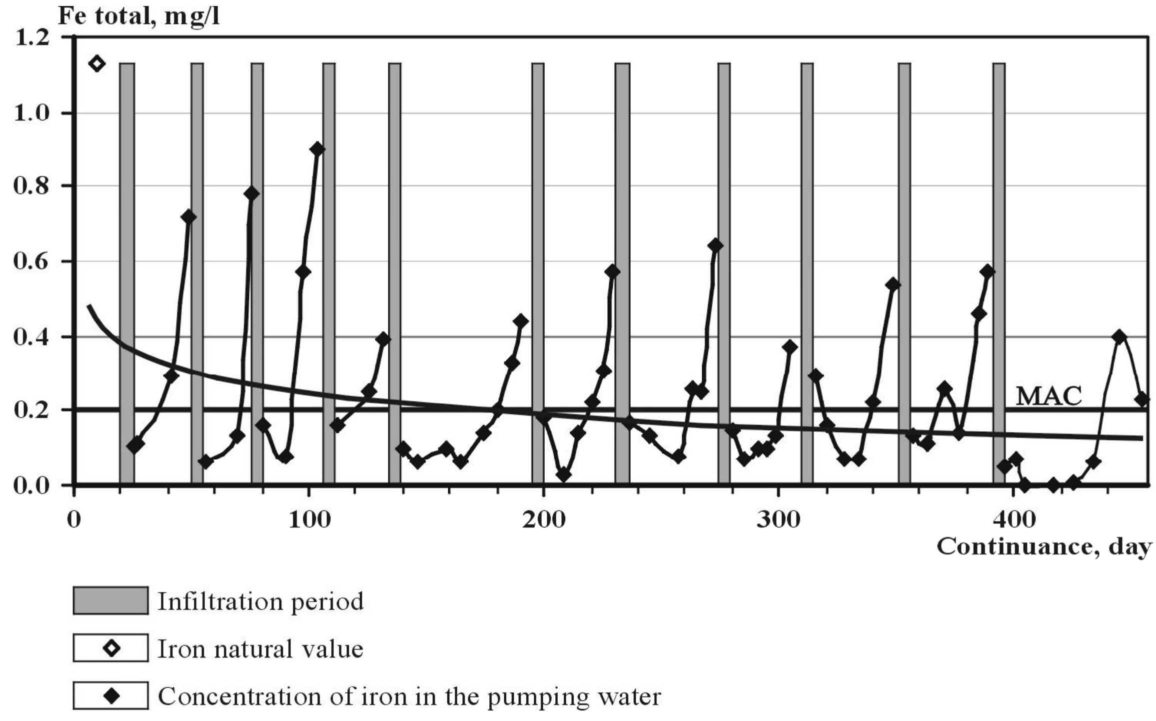

Fig. 2. Cyclical variation of iron concentrations during abstraction of aerated groundwater from a well (MAC – maximum admissible concentration)
2 pav. Geležies koncentracijų cikliškas kitimas siurbiant aeruotą požeminį vandenį iš gręžtinio šulinio (MAC – didžiausia maksimali koncentracija)

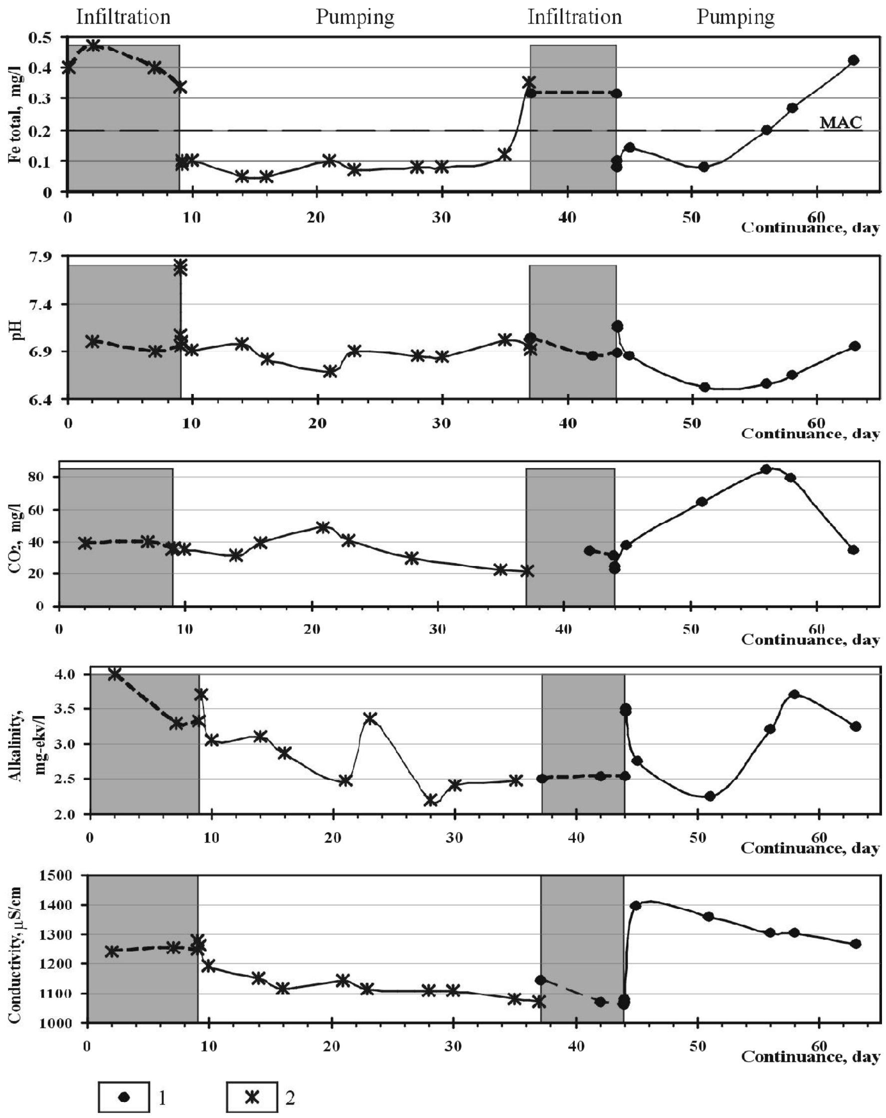

Fig. 3. Dynamics of the main chemical components during abstraction of aerated groundwater (experiments in alluvial aquifer): *1* – infiltration and pumping of aerated water, *2* – infiltration and pumping of aerated and magnetically activated water

3 pav. Svarbiausių cheminių rodiklių kitimas infiltruojant ir siurbiant ežektoriumi aeruotą ir magnetinio lauko paveiktą vandenį (aliuvio vandeningasis sluoksnis): *1* – infiltruojamas ir siurbiamas tik aeruotas vanduo, *2* – infiltruojamas ir siurbiamas aeruotas, magnetiškai aktyvuotas vanduo

of bivalent iron (Fe^{2+}) is prevalent in groundwater. Under the given thermodynamic conditions it may easily oxidize to Fe^{3+} hydroxides (solid phase) and again reduce when oxygen is lacking.

The water infiltrated into the aquifer by an ejector was saturated with oxygen to 3–11 mg/l (6–8 mg/l on the average). The yield of aerated water infiltrated into different wells was 2–9 m^3/h. A typical pattern of iron concentration dynamics in the water of infiltration and abstraction cycles is shown in Fig. 2.

Aquifer saturation with atmospheric oxygen (to the limit of its sorptive capacity) required 2–5 five-day aeration cycles. During these cycles, the hydraulic efficiency coefficient of water treatment (the ratio of pumped and ejected water), i.e. the ratio of clean (W_{cln}) and infiltrated aerated (W_{inf}) water volumes ($a = W_{cln} / W_{inf}$) stabilizes. It increases during the repeated cycles as the saturation of aquifer rocks with oxygen also increases. Effective precipitation of iron compounds starts after some time during which a strong oxidation barrier develops in the zone of saturation with oxygen. Usually, the hydraulic efficiency coefficient varies between 2 and 10. Sometimes, after 15–20 infiltration–abstraction cycles, it may reach 20 and even more.

As a result of long infiltration, the concentration of iron reduces in a dependence close to exponential. The concentration of total iron reduces by 85–87% after 8–10 infiltration cycles. The concentration of oxygen in the aerated water increases the redox potential (Eh) in groundwater to 220–300 mV, i.e. exceeds the natural values by 120–200 mV. The rate of oxygen consumption in the aquifer is comparable with the rate of iron concentration change. Oxidized (trivalent) iron forms dominate in groundwater at the beginning of abstraction cycle. Their concentrations gradually reduce, and 2–5 hours after the beginning of the abstraction cycle Fe^{2+} again becomes prevalent.

Biogenic processes, whose main agents are iron bacteria, affect the oxidation and precipitation of iron compounds. The concentration of iron bacteria in natural groundwater reaches 300–700 thous. cell in one litre of water. Aeration of the water-bearing horizon facilitates their activity. They more intensively accumulate Fe^{2+} in their membranes and cells, oxidize it and secrete hydroxides in the form of precipitate. In highly ferriferous groundwater discharged at the beginning of the abstraction cycle (well cleaning), the number of iron bacteria is 10–100 times as high as in natural groundwater. They are products of oxidation. In water with a small concentration of iron (up to 0.3 mg/l) in the subsequent stages of pumping, the number of iron bacteria is 3–10 times as low as in natural groundwater. In the weakening oxidation environment, the concentration of ferrobacteria again approaches the natural values. Microorganisms of the genus *Siderocapsa* (50–60%) are dominant. They are most susceptible to iron oxidation. Aeration of ground-

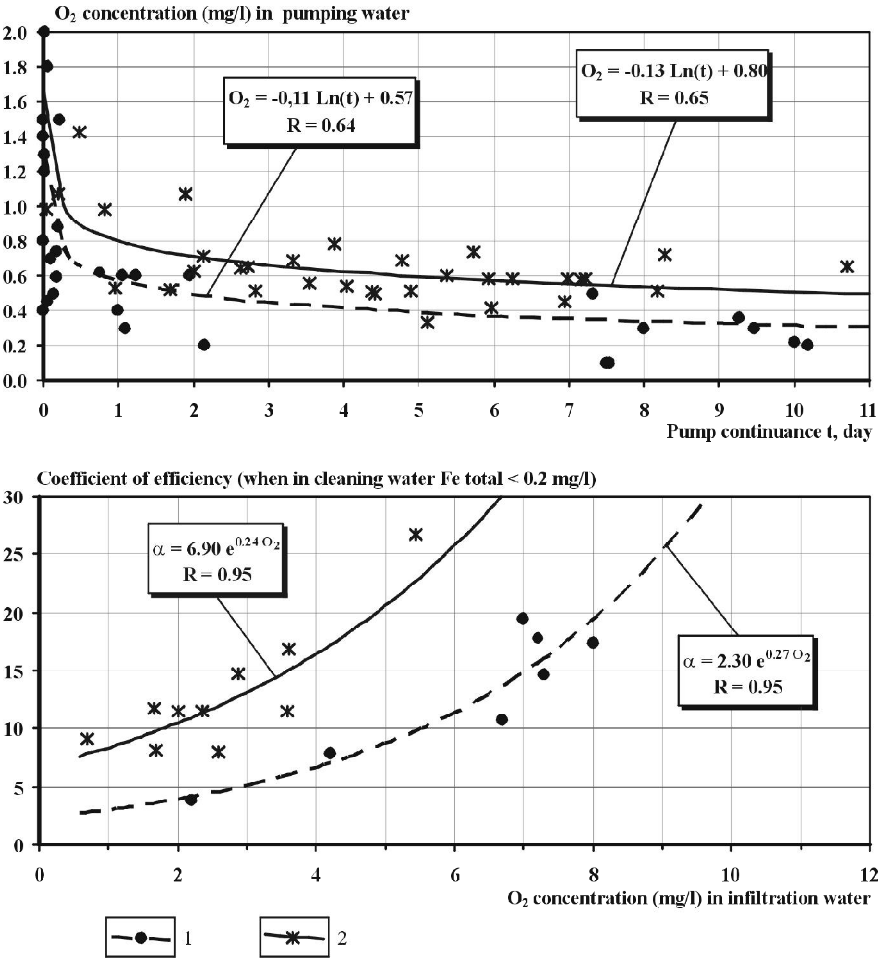

Fig. 4. Variation of oxygen concentration and coefficient of hydraulic efficiency (α) during aeration and magnetic activation of groundwater (experiments at intertill aquifer): *1* – pumping of aerated water, *2* – pumping of aerated and magnetically activated water

4 pav. Požeminio vandens deguonies koncentracijos ir hidraulinio naudingumo koeficiento (α) kaita dėl aeravimo ir magnetinės aktivacijos poveikio (eksperimentai tarpmoreniniame vandeningajame sluoksnyje): *1* – siurbiamas tik aeruotas vanduo, *2* – siurbiamas aeruotas, magnetiškai aktyvuotas vanduo

water increases its alkalinity, pH 7.7–7.8, twice reduces the concentration of free carbon dioxide, and reduces total hardness and concentrations of sulphates and chlorides.

DISCUSSION

Magnetic exposure noticeably affects the physical and chemical properties of water. The dynamics of these changes is demonstrated in Figs. 3 and 4. In the pumped water, after aeration and magnetic conditioning the concentration of dissolved oxygen is considerably higher (about 1.4 times) and intensive oxidation of iron compounds is prolonged: their low concentrations last 2–3 times longer than in water without magnetic conditioning. The high concentration of oxygen remains stable for a considerable time interval (Fig. 4). Presumably, magnetic treatment of aerated water stabilizes the oxygen dissolved in groundwater or adsorbed on the rock surface. The pattern of hydrogen ions after magnetic conditioning is similar: without magnetic conditioning, pH soon reaches the starting (natural) values. In magnetically conditioned water, the low pH values last for a longer time during groundwater abstraction from the aquifer (Fig. 3). The changes of carbon dioxide are especially dynamic (reduction) after saturation of the aquifer with magnetically conditioned water. The reduction of water alkalinity and turbidity are also considerably lower. Magnetic conditioning produces a weaker effect on organic matter (according to permanganate oxidation) and electric conductivity.

It has been determined by hydraulic modelling that the highest effect of magnetic conditioning manifests at the beginning of reaction (after 3–15 min). In the course of time, the concentration of iron(III) ions in the magnetically conditioned water reduces and in a few days equals the values of iron(III) in magnetically unconditioned water. Formation and precipitation of $Fe(OH)_3$ floccules are more intensive in magnetically conditioned water.

The integral effect expressed by the hydraulic efficiency coefficient of iron elimination increases after magnetic conditioning about 2.5 times in comparison with iron elimination rates in aerated but magnetically unconditioned water used for saturation of the water-bearing layer with oxygen (Fig. 4).

CONCLUSIONS

1. Aeration of groundwater *in situ* using saturated with atmospheric oxygen and magnetically conditioned infiltration water entails temporary changes of its chemical and physical properties, such as the concentration of iron, oxygen, carbon dioxide, sulphates and chlorides, hardness, alkalinity, turbidity and other features. The mentioned properties in some way affect the formation and concentrations of iron and other thin-dispersed compounds. The effect is positive in terms of iron elimination and water quality improvement.

2. Oxidation of aerated infiltration water by magnetic conditioning is up to 1.5 times more intensive than

in the magnetically unconditioned water. Intensive oxidation of iron compounds in aerated and magnetically conditioned water lasts considerably longer: low concentrations of iron compounds last 2–3 times longer than in the magnetically unconditioned water. Oxygen concentration in the water-bearing horizon remains stable for a long time.

3. Conditioning of water with a permanent magnet facilitates oxidation of bivalent iron ions with atmospheric oxygen and trivalent iron precipitation *in situ*: the hydraulic efficiency coefficient of iron elimination (i.e. the ratio of the volumes of cleaned and infiltrated water) after magnetic conditioning increases 2.5 times in comparison with the value in the aerated but magnetically unconditioned water.

4. Magnetic conditioning of water during aeration and abstraction is a highly ecological technique of drinking water quality improvement. Its application may considerably reduce the costs of iron elimination *in situ* and drinking water abstraction.

ACKNOWLEDGEMENTS

Special thanks for financial support are due to the Lithuanian State Science and Studies Foundation.

References

1. Benson R. F., Llullosco R., Martin D. F. 2000. Magnetic treatment of solid carbonates, sulphites and phosphates of calcium. *Journal of Environmental Science and Health. Part A. Toxic/Hazardous Substances & Environmental Engineering.* ***35(9).*** 1527–1540.
2. Busch W., Busch M. A. 1997. Laboratory studies on magnetic water treatment and their relationship to a possible mechanism for scale reduction. *Desalination.* ***109.*** 131–148.
3. Diliūnas J., Jurevičius A. 1998. Geležis Lietuvos gėlame požeminiame vandenyje. Monografija. Vilnius: Utenos Indra. 76 p.
4. Diliūnas J., Sakalauskas A. 1996. Geležies ir mangano šalinimo iš požeminio vandens technologijų pagrindimo ypatumai Lietuvos hidrocheminėmis sąlygomis. *Aplinkos inžinerija.* ***2(6).*** 25–39.
5. Hallberg R. and Martinell R. 1976. Vyredox *in situ* purification of ground water. *Ground Water.* ***14(2).***
6. Higashitani K., Kage A., Katamura S., Imai K., Hatade S. 1993. Effects of magnetic fields on the formation of $CaCO_3$ particles. *Journal of Colloid and Interface Science.* ***156.*** 90–95.
7. James D. Navratil. 2000. A magnetic field enhanced filtration / sorption device and its potential for inexpensive water and wastewater treatment. *Plenary Lecture at 7th Conference of Nuclear Sciences and Applications.* Cairo, Egypt. 3 p.
8. Lipus L., Krope J., Garbai L. 1994. Magnetic water treatment for scale prevention. *Hungarian Journal of Industrial Chemistry.* ***22(4).*** 239–242.
9. Rinkevičienė E., Mockutė V. 2003. Intensification of Technical Water Clarification by a Magnetic Water Conditioner. *Materials Science.* ***9(3).*** 303–307.
10. Shadrin G. N., Sergienko T. V., Krymova V. V., Tarimov O. E., Katsev A. M. 1993. Change in the aggregate stability of aqueous suspensions of Fe_2O_3 and Fe_3O_4 iron oxides stabilized with saponin before and after magnetic treatment. *Colloid Journal of the Russian Academy of Sciences.* ***55(1).*** 131–133.
11. Классен В. И. 1982. Омагничивание водных систем. *Химия.* 296 с.
12. Крайнов С. Р., Рыженко Б. Н., Швец М. В. 2004. Геохимия подземных вод. Москва: Наука. 677 с.
13. Плотников Н. А., Алексеев В. С. 1990. Проектирование и эксплуатация водозаборов подземных вод. Москва: Стройиздат. 256 с.

Jonas Diliūnas, Kazimieras Jonaitis, Arūnas Jurevičius, Elvyra Rinkevičienė

GELEŽIES IR KITŲ SMULKIADISPERSINIŲ JUNGINIŲ ŠALINIMO IŠ POŽEMINIO VANDENS (*IN SITU*) INTENSYVINIMO MAGNETINE AKTYVACIJA TYRIMAS

S a n t r a u k a

Tyrimų tikslas – ekologiškiausio požeminio geriamojo vandens gerinimo būdo tobulinimas taikant magnetinį kondicionavimą, kuris šalina geležies ir kitus smulkiadispersinius junginius iš vandens *in situ*. Tyrimų rezultatai grindžiami lauko (veikiančių vandenviečių gręžtiniuose šuliniuose) ir laboratorinių eksperimentų (fizikinio modeliavimo) duomenimis.

Nustatyta, kad praleidus vandenį pro nuolatinio magneto principu veikiantį magnetinį vandens kondicionierių pagerėja vandenyje esančių dvivalentės geležies jonų oksidacija atmosferiniu deguonimi ir trivalentės geležies nusodinimas vandeningajame sluoksnyje, oksidacijos procesai infiltruojamame vandenyje būna aktyvesni iki 1,5 karto, ilgą laiką išlieka gana stabili deguonies koncentracija. Siurbiant požeminį vandenį po aeravimo ir magnetinio apdorojimo tebevyksta intensyvi geležies junginių oksidacija: jų žemos koncentracijos išsilaiko 2–3 kartus ilgiau nei analogiškos koncentracijos nenaudojant vandens magnetinio kondicionavimo. Aeruoto vandens magnetinis apdorojimas papildomai stabilizuoja ištirpusį deguonį požeminiame vandenyje ar adsorbuotą ant uolienų paviršiaus.

Ионас Дилюнас, Казимерас Ионайтис, Арунас Юрявичюс, Эльвира Ринкявичене

ИНТЕНСИФИКАЦИЯ ПРОЦЕССОВ МАГНИТНОЙ АКТИВАЦИЕЙ ПРИ УДАЛЕНИИ ЖЕЛЕЗА И ДРУГИХ МЕЛКОДИСПЕРСНЫХ СОЕДИНЕНИЙ ИЗ ПОДЗЕМНОЙ ВОДЫ *IN SITU*

Р е з ю м е

Цель исследований – совершенствование метода удаления железа из подземной воды непосредственно в водоносном пласте (*in situ*) при использовании аэрированной и

намагниченной воды. Результаты исследований и выводы обосновывают опыты в производственных и лабораторных (физическое моделирование) условиях.

После пропуска аэрированной атмосферным кислородом воды через магнит постоянного действия значительно интенсифицируется окисление ионов двухвалентного железа. В водоносном пласте продолжительное время сохраняется достаточно стабильная концентрация растворенного кислорода. Как следствие этого при откачке подземной воды после аэрации и намагничивания низкие концентрации железа сохраняются в 2–3 раза дольше, чем без магнитной обработки. Магнитное конденсирование нагнетаемой в пласт аэрированной воды стабилизирует растворенный кислород не только в жидкой фазе, но и адсорбированный на поверхности твердых частиц водоносной породы. Использование магнитообработанной воды для подземной аэрации может быть весьма полезным для повышения эффективности технологического процесса удаления железа из подземной воды непосредственно в водоносном пласте.