Polish J. of Environ. Stud. Vol. 18, No. 3 (2009), 435-442

Original Research

The Influence of Water Use Intensity on Nitrate Concentration in Shallow Well Water

V. Rutkoviene[1], L. Česoniene[1]*, S. Kutra[2]

[1]Institute of Environment, Lithuanian University of Agriculture,
[2]Department of Ecology, Lithuanian University of Agriculture,
Studentų 11, LT-53356 Kaunas-Akademija, Kaunas district, Lithuania

Received: 1 December 2007
Accepted: 2 December 2008

Abstract

Water enters shallow wells from shallow resources of groundwater, therefore the groundwater is especially susceptible to chemical and microbiological pollution. The aim of this study is to determine the effect of intensity of shallow well usage on the nitrate concentration in water. It has been found that concentrations of nitrate ions in the water of shallow wells depends on the quality of water in the basin feeding the well, processes in the water and well depth. Concentration of nitrate ions in newly filled water is higher than that in well water, but due to chemical and biochemical reactions it decreases rather fast and in most cases becomes lower. The rate at which the drained wells refill is different. Re-establishment of the same amount of water ranges between two and five days. In the beginning because of big difference in levels, the rate is higher, and then it slows down and asymptotically approaches the main level. An average rate of filling-up makes 3% of well volume per day, ranging from 7% the first day to 1% the fifth day. The nitrate concentration decreases approximately to eight days at a rate of 8 mg l^{-1}/day, and after the eighth day it increases at a rate of 12 mg l^{-1}. Changes of concentration of nitrates in the top layer of water could be summarized as the reaction of the first order. Mathematical patterns of well refilling and changes in nitrates determine the limits of the nitrate concentration changes in water, though they are not precisely adapted to a separate well.

Keywords: shallow well, water, nitrate concentration, water usage, water level

Introduction

Most inhabitants of Lithuanian cities use water from deep underground aquifers. Inhabitants of rural areas, on the contrary, use ground water from shallow resources. The quality of this water mostly depends on agricultural activity [1]. If the tendency of deterioration of groundwater remains, half or more than a half the Lithuanian population will soon face the problem of a shortage of quality water for drinking and household purposes. Pollution of shallow groundwater will have an inevitable effect on the quality of deep water. Any pollution of ground surface with a sufficient amount of precipitation is filtered into the soil and reaches water the layer, from which it gets into drilled wells [2]. That is why the effect of environmental factors on water quality is very important to know. The process of pollution of groundwater is complicated. The source of groundwater pollution usually located in the ground may not be found for a long period of time and continue polluting ground water. Pollutants migrate in soil and therefore pollution could be noticed in a place far away from the source of pollution itself. Use of groundwater and its extraction from the ground changes the direction of groundwater flow, and even though pollution has been detected, it is always difficult to find the pollution source.

*e-mail: Laima.Cesoniene@lzuu.lt

It takes decades for groundwater to clean itself. For the reasons mentioned above, investigations of changes in groundwater quality in any aspect are of great importance to environmental research.

Many studies are dedicated to ground water research. Sources of groundwater pollution can be both anthropogenic and natural. Some such sources are rain, forests, meadows, fields of agricultural activity, places of accumulation and preservation of organic waste, waste of agricultural plants forming before and in the process of processing, and plant remains after reaping the harvest [3, 4]. U.S. scientists have determined that groundwater most polluted with nitrates is found in areas of sandy soil that contain little organic carbon. The amount of nitrates in groundwater grows continuously and reaches concentrations of a permitted level (10 mg l^{-1} nitrogen) in 5 percent of randomly selected tested areas [5, 6]. In agricultural fields the application of nitrogen fertilizers has been constantly increasing. In the last 50 years it has increased 20 times [7]. Fertilizers are believed to be the main source of nitrates in groundwater [8]. Nitrates get into the soil and accumulate in the areas of unsaturated humidity, from which after the end of the farming season, they become a source of groundwater pollution. Being an electron donor and creating a reductive environment which stimulates denitrification, organic carbon found in soil was determined to be able to diminish the potential of nitrate pollution [9-12]. This study is devoted to investigating the effect of intensity of water from shallow wells usage on the quality of water.

Results of surface water investigations have been published in many articles and reports. Investigations on shallow ground water quality have so far been significantly fewer. This is because groundwater is found under the ground and it is difficult to reach without special equipment or drilling expensive bores. Investigations are to be carried out and conclusions are made with great uncertainty.

The aim of this study is to determine the effect of intensity of shallow well usage on nitrate concentrations in water.

Subject of Research and Methodology

Wells situated in Pypliai village in the region of Kaunas were chosen for investigation. This is a typical Lithuanian village with no centralized water supply and dug well water is used for drinking and food production. The village is situated 6 km away from the border of Kaunas city near Kacergine, positioned along the Nemunas River. There are 70 farmsteads in the village, 70% of the population keeps animals, and no dung-yards have been established. Dung is kept in piles behind sheds. All farmsteads have kitchen gardens treated with organic fertilizers. In the territory of the village medium heavy or heavy and light sandy loam prevails. The position of tested dug wells in Pypliai village is shown in Fig. 1.

To determine the effect of dug well water usage intensity on the amount of nitrates in water, a certain amount of water was ladled out, the time of well filling itself was

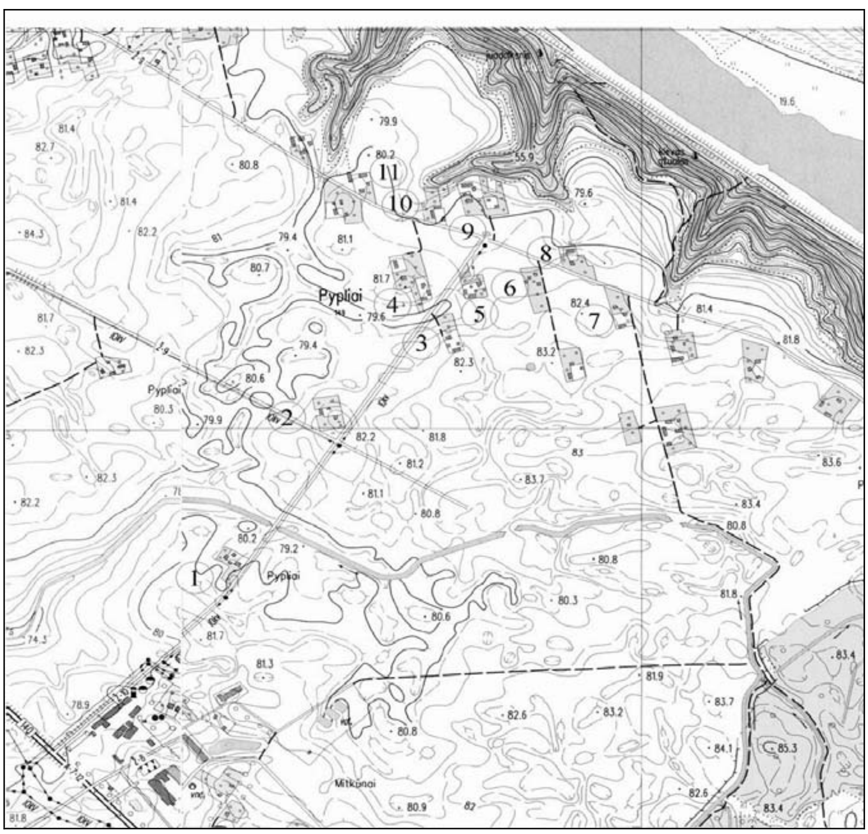


Fig. 1. Relief of Pypliai settlement and layout of the shallow wells.

measured and the quality indexes of water were determined. The influence of the size of the inflowing water basin on water quality was determined based on analysis of the relation between water quality well-filling indexes. As the size of the in-flowing water basin is dependant on the intensity of water usage, the effect of water usage intensity on the quality of water in wells also has been determined. In the course of the experiment 0.1 m^3 of water was simultaneously ladled out from six wells: Nos.1, 3, 4, 7, 9 and 13 (Fig. 1). The water level and quality was measured before ladling, right after ladling and then observed for 10 days until the water reached its previous level. During the experiment water samples were taken daily and concentration of nitrate ions (NO_3^-) was measured. Water levels with respect to the earth surface were also measured daily in shallow wells. Concentration of nitrate was measured applying the ionometric method using the nitrate ion selective electrode (a METROHM AG CH –9101 ion meter was used).

Investigation of nitrogen compounds in different depths of wells was carried out by research well water from 4 layers of different depth every 1 meter without mixing. The same nitrogen compound concentrations were determined for these samples.

Results of Research

In the area where shallow wells are positioned (Fig. 1), loamy soil of medium heaviness prevails on the top layer of the ground with a filtration coefficient (p_1) equal to 0.7 m d^{-1}. In the second layer of the ground heavy loam prevails, with filtration coefficient (p_2)=0.05 m d^{-1}. The results of water level measurements are shown in Fig. 2.

Refill of different wells took place in a different way. In well No. 13 the water re-established its previous level in two days, and water refill in wells No. 1 and No. 7 took five days. The duration of water refill in the remaining wells ranges between those two border values. The character of re-establishment of water level differed slightly, shortly after suction, later becoming similar in all the wells. Refill of well No. 1 was slightly different from the others. Refill right after suctioning out is slower and then it becomes faster. The amount of water sucked out from all the wells was the same and in this study it is expressed with the same lowering of 100 cm. However, the depth of wells was different and therefore the remaining volume of water was not the same in all the wells. Refilling water makes an unequal part of the whole well water. The changing part of well water is shown in Fig. 3. After suction out, a smaller part of water remained in a shallower well (well No. 7) than in a deeper well (well No. 1).

The volume of remaining water changes 78-87% of the well water volume depending on the depth of the well.

The average change in the concentration of nitrates in the wells is shown in Fig. 4. After sucking out a certain amount of water, the concentration of nitrates in the remaining water grows sharply approximately 29 mg l^{-1}. After that, while the well is refilling, the concentration of nitrates keeps decreasing and in the fourth day after sucking out it comes to the previous level. Later it decreases even more and in the tenth day the nitrate concentration value is 30 mg l^{-1} lower than one before sucking out. The concentration of nitrates in the wells decreases by approximately 5.66 mg l^{-1} in a day. This process is reflected by rectilinear pattern rather well, the discrimination coefficient being even 0.939. However, when the change in concentration is analyzed more precisely, it can be observed that having dropped by 30 mg l^{-1} in the eighth day, it stabilizes and remains the same until the tenth day of observation. Later, observation ceased because of the inhabitants' need to use water.

The changes in nitrate concentration as different wells refill with water are not as even and proceed differently (Figs. 5 and 6). The change of nitrate concentrations in well water is reflected by fitted patterns. As the patterns were being applied, the ones best reflecting the nature of change were chosen. Because of the different changes in concentration, a rectilinear pattern was fitted to well Nos. 4, 7 and 13 (Fig. 5). Nos. 1, 3 and 9 were fitted with a logarithmic pattern (Fig. 6).

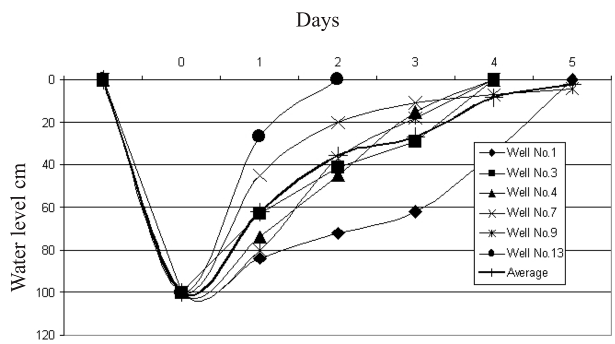


Fig. 2. Change of the water level in shallow wells.

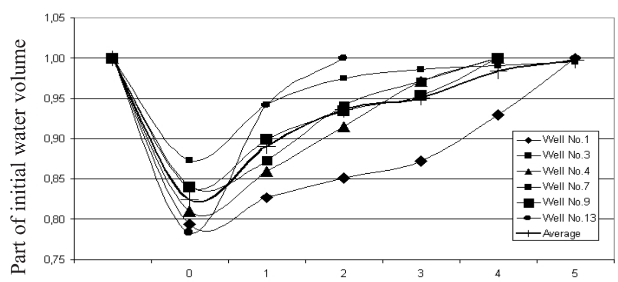


Fig. 3. A part of well water remaining after sucking out 100 cm.

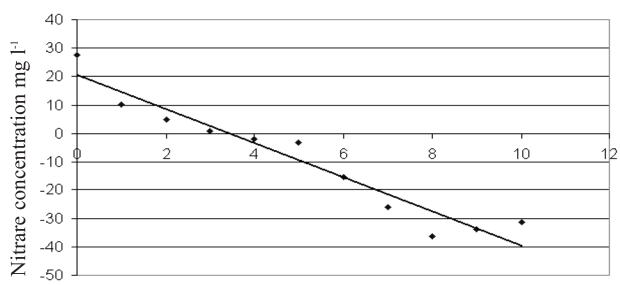


Fig. 4. The average change in nitrate concentration in well water after sucking out.

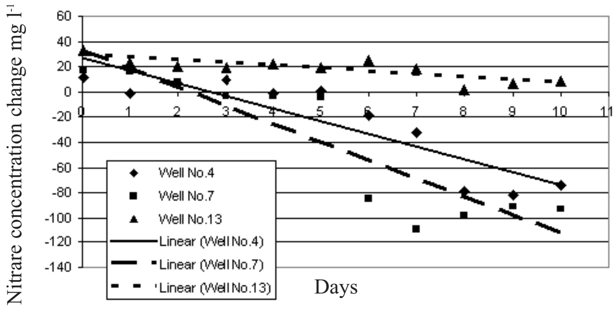


Fig. 5. The change in concentration of nitrate ions in the water of well Nos. 4, 7, 13.

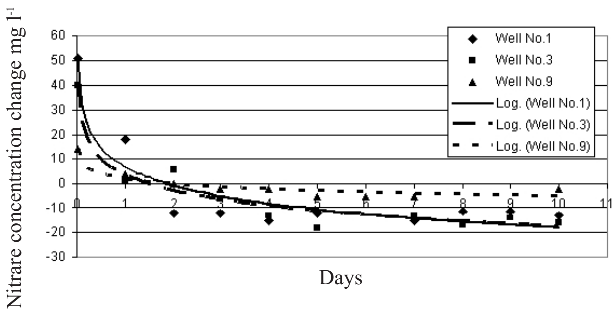


Fig. 6. The change in concentration of nitrate ions in the water of well Nos.1, 3 and 9.

The nature of decrease in nitrate concentration in all the wells with rectilinear model fitted (Nos. 4, 7 and 13), was very similar to the average nature of change in concentration in all the wells (Figs. 4 and 5). Despite the fact that the best fitted pattern for these wells was rectilinear, nitrate concentration remained practically unchanged in the last 8-10 days due to the low flow entering the well the last days of monitoring. The initial increase in nitrate concentration is approximately the same, more or less equal to 30 mg l^{-1} for all the wells in this group. But concentration measured right after sucking out is not so similar. Increase in nitrate concentration in well Nos. 4 and 7 was similar – 11 and 17 mg l^{-1}; however, the values observed in well No. 13 were double – 33 mg l^{-1}. Intensity and level of refill are also different. Nitrate concentration in well No. 7 decreased by even 90 mg l^{-1} over a period of ten days, while in the case of well No. 13, in eight days nitrate concentration decreased to the level which was superior to the initial concentration by 2 mg l^{-1}, but in the remaining two days it increased again and in the tenth day it was 9 mg l^{-1} bigger than the concentration before sucking out. Mathematical expressions of these wells are shown in Table 1.

The average level of daily decrease in nitrate concentration in well Nos. 4 and 7 was 10.1 and 14.5 mg l^{-1}, respectively, and only 2.2 mg l^{-1} in well No. 13. The water level in the well (No. 13) with the greatest increase in nitrate concentration due to sucking out was the slowest to refill and during the period of investigation failed to reach its previous value before sucking out. This well is the deepest, therefore the part of water sucked out is the smallest

Table 1. Mathematical patterns of concentration of nitrate ions change in well Nos. 4, 7 and 13.

Number of Wells	Mathematical model	Determination coefficients
4	Y = - 10.1 x + 26.9	0.799
7	Y = - 14.5 x + 32.0	0.810
13	Y = - 2.2 x + 28.7	0.655

Table 2. Mathematical pattern of concentration of nitrate ions change in well Nos. 1, 3 and 9.

Number of Wells	Mathematical model	Determination coefficients
1	Y = - 10.9 ln(x) + 7,1	0.894
3	Y = - 9.3 ln(x) + 3,7	0.944
9	Y = - 3.1 ln(x) + 2,1	0.928

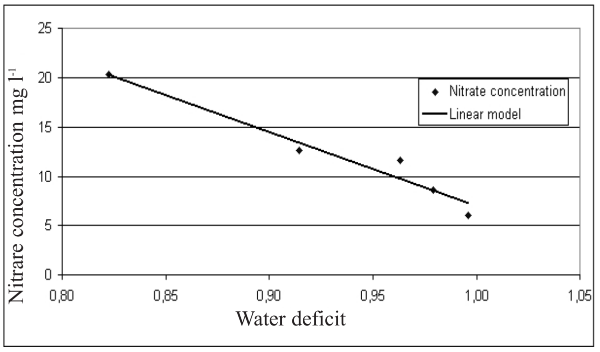
Table 3. Patterns of dependency of nitrate concentration upon water deficit in the well.

Number of Wells	Mathematical model	Determination coefficients
4, 7, 13	Y = -75 x + 82	$R^2 = 0.95$
1, 3, 9	$Y = 0.74 x^{-23} - 12$	$R^2 = 0.92$

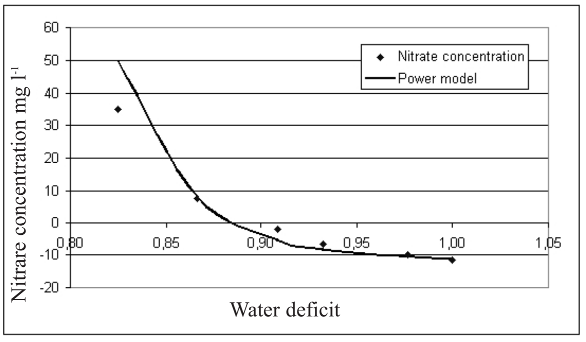
and the time of refill is the greatest. In the case of well Nos. 1, 3 and 9, the change in concentration of nitrate ions after sucking out was best described by a logarithmic model (Fig. 6).

The change of nitrate ion concentrations in wells No. 1, 3 and 9 is special, as after a sudden increase in concentration of nitrate ions after sucking out, it sharply came back to the previous level in 1-2 days time and only since the third day did it begin decreasing evenly. In the wells of this group the rise in concentration of nitrate ions was greater than the rise in the wells of the first group. In well No. 1, concentration increased to 51 mg l^{-1}, in well No. 3 the rise was to 40 mg l^{-1}, and only well No. 9 demonstrated a similar rise of 14 mg l^{-1} to the wells of the first group. A sudden drop in concentration of nitrate ions as in the case of well Nos. 4 and 7 is not characteristic to this group of wells. Since day 7-8 concentration of nitrate ions in the water of wells No. 1 and 3 stabilized at 15 mg l^{-1}, inferior to that before sucking out. And in well No. 9 the decrease was only 5 mg l^{-1}. However, sucking out had a positive effect on the water quality of all the wells in this group, as the concentration of nitrate ions decreased. Patterns of change in concentration of nitrate ions are shown in Table 2.

Similarly to the wells of the first group, the wells of the second group reach their concentration previous to sucking out in two days.



Well Nos. 4, 7, 13



Well Nos. 1, 3, 9

Fig. 7. Relationship between concentration of nitrate ions and water deficit in wells.

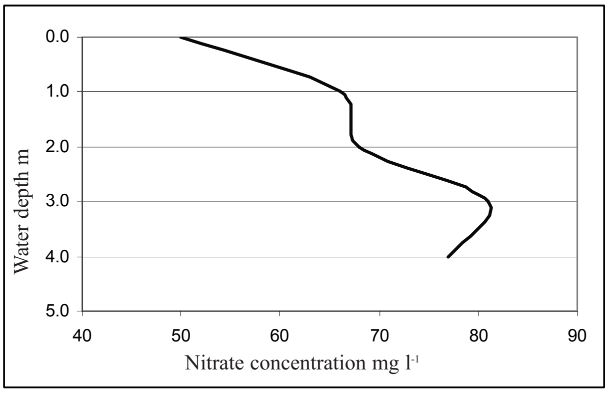
All the mathematical patterns describe well the modeled process of change of nitrate ions due to water usage. Only in well No. 13 was the coefficient of determination 0.65. Coefficients of other wells are greater and range between 0.799 and 0.944.

Comparison of the dynamics of water deficit, differences between a settled water level and concentration of nitrate ions, proved a rather uneven and dispersed dependency of the average concentration upon the average water deficit; due to this fact, none of the typical mathematical models is appropriate to describe it. A rectilinear model is a little nearer, but its coefficient of determination is only 0.7. This relation is better modeled when the wells are separated into the previous groups: group 1 consisting of well Nos. 4, 7 and 13, and group 2 consisting of well Nos. 1, 3 and 9. Dependency of concentration of nitrate ions in the wells of the first group is best described by a rectilinear model, and dependency of the second group is gradual (Fig. 7).

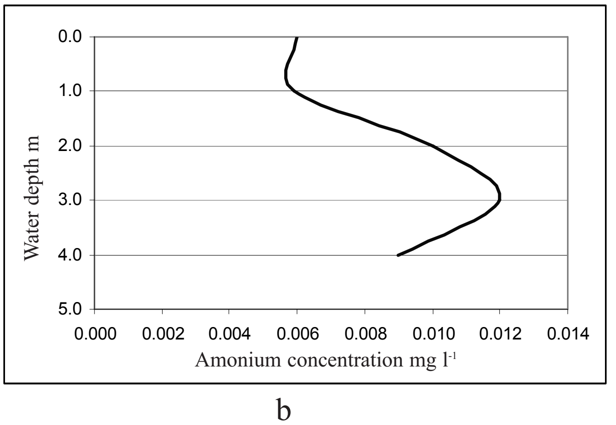
The level of water reestablishes in five days time and a disturbed balance of concentration of nitrates reestablishes in a significantly longer period of time. Ten days of observation were not enough to re-establish the concentration of nitrates. Only five days were taken to analyze the relationship between the concentration of nitrates and water deficit until the level of water is re-established. Models applied are shown in Table 3.

The models in their form are very close to changes in concentration during this time. It is comprehensible as the well refills in the same time, too; however, initial changes in concentration occur because of different concentrations of nitrogen compounds in differents levels of water in the wells. Later, the main influence becomes concentration of dissolved substances in filling-in water. In the wells that refill more or less evenly, and changes in concentration are also even, the process is modeled by a rectilinear pattern. In wells where water refill is initially more intensive and slows down with time, the process is modeled by a gradual or logarithmic pattern. However, these statements only characterize an averaged process. Characters of both refilling and concentration are different in separate wells.

During the research of nitrogen compound distribution in the different depth of wells, distinct concentrations of nitrogen compounds was found in different layers of well water (Fig. 8). Concentration is the lowest in the top layer of well water. The deeper the layer of water, the higher the concentration of nitrate and ammonium ions. Concentration of nitrate ions in the top layer is 50 mg l^{-1} while in the bottom layer of 3 meters arrives at 81 mg l^{-1} and in the layer of 4 meters nitrate concentration decreases again till 77 mg l^{-1}. Interdependence between concentration and depth is almost linear (Fig. 8 a). Alteration in concentration of ammonium ions is almost similar. In the beginning, as depth increases, concentration also increases until it reaches its maximum value of 0.012 mg l^{-1} at a depth of 3 meters. Later concentration of ammonium ions starts to decrease and at a depth of 4 meters it becomes smaller than that at a depth of 2 meters around 0.009 mg l^{-1}.



a



b

Fig. 8. Dependence of nitrate and ammonium ion concentrations on water depth in the wells.

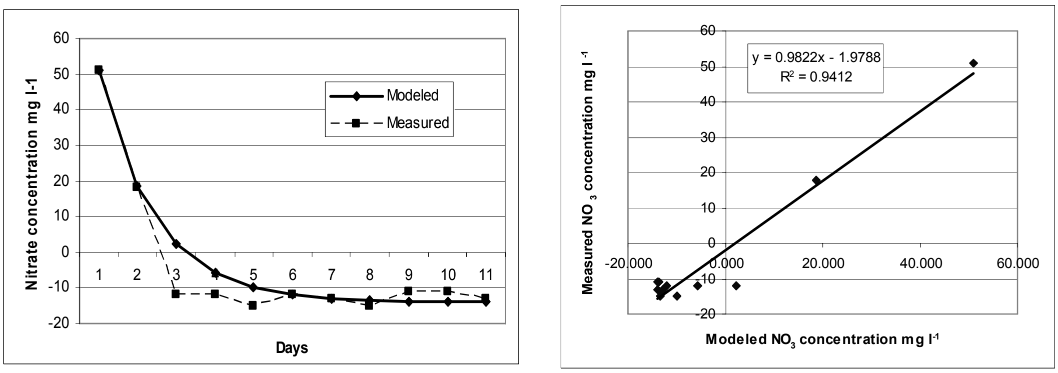
Having pumped out water from the well concentration of nitrogen compounds in the residual top layer is different from previous. Water flowing in could not influence the situation, as flowing in has just started and the amount is too small to influence the quality of well water. Later, as time flows by, on the top layer of water many different processes take place: different amount of nitrogen, organic compounds flow in, different temperature, different biochemical reactions take place. Changes of concentration of nitrates in the top layer of water could be summarized as the reaction of the first order:

$$c = b \cdot e^{k \cdot d} + a$$

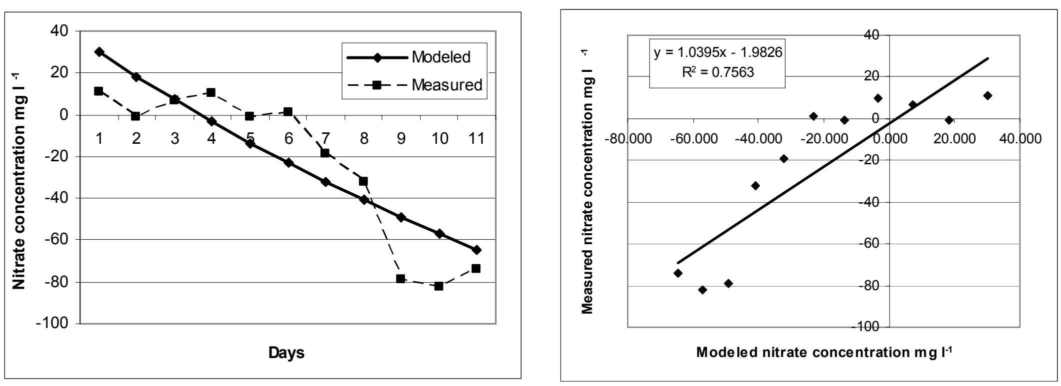
...where:

c – nitrate concentration on the top layer of water in the well;
d – days after pumping out of the top layer of water;
k, b and a – parameters of the model characterizing primary conditions and character of reaction.

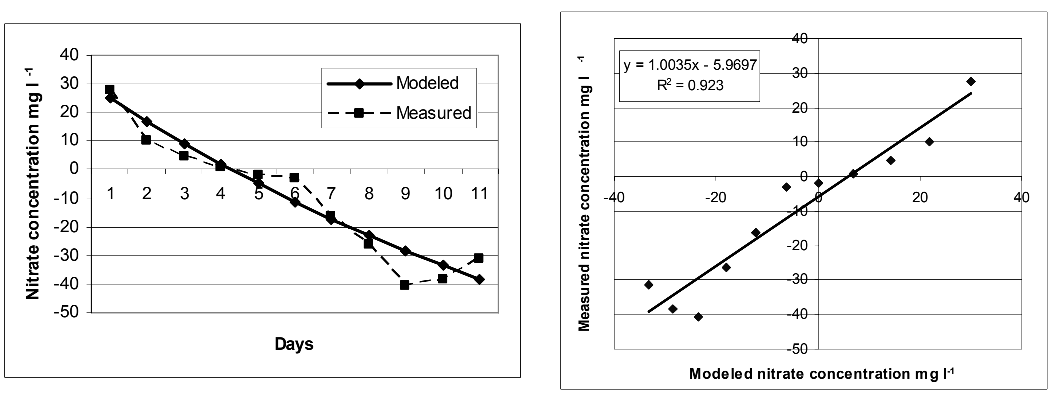
Altering parameters of the model, it can be applied to all three cases. Two wells, No. 1 and No. 4, were chosen for modeling. These wells are different in their characteristics of nitrate concentration. An average change of nitrate



a) Well No. 1 $c = 65 \cdot e^{-0.65 \cdot d} - 14$



b) Well No. 4 $c = 240 \cdot e^{-0.05 \cdot d} - 210$



c) Average $c = 140 \cdot e^{-0.06 \cdot d} - 115$

Fig. 9. Modeled nitrate concentration in the top layer of the wells.

concentration in all wells tested was modeled as well. The most characteristic trials of modeling are presented in Fig. 9. In Fig. 9a data of well No. 1 is presented. Fig. 9b shows data from well No. 4 and Fig. 9c shows a model of average alteration of nitrate concentration as well as comparison of data acquired during experiments and modeling activity.

Analogous models were obtained for ammonium concentration too. Due to comparatively low concentration in test objects, we do not present here data of change in concentration of ammonium and nitrite ions. Model of nitrate concentration coincides well with the measured ones. Trend lines acquired have inclinations close to a 45° angle. This demonstrates that coefficients of trend line equations are close to 1. At the same time, coefficients of determination show a good (r^2 = 0.92-0.94) or average (r^2 = 0.76) compliance of trend line with acquired points of diagram.

Discussion

Research has shown that water use was an effect on the size of concentration of nitrate ions in wells. Water before sucking was not mixed. The process of ladling or sucking out itself cannot affect the quality of well water. Because concentration of nitrates in water depends on depth, it seems likely that during sucking, the top layer, which is less polluted by nitrogen compounds than others, is removed. This is why the concentration of nitrates after sucking is higher. Later on, concentration of nitrates in the top layer depends mostly on in-flowing water quality, although changes in processes of mineralization, nitrification and denitrification can have a place, too, especially with better contacts of water with air. Consequent changes in quality can't be explained by the influence of flowing-in water only. Pollution with nitrates of flowing-in water in its turn depends on the processes going on in the indraught basin. It can be both the result of human activity (fertilization of agricultural plants, storage of mineral and organic fertilizers, utilization of household waste, and others) and natural environmental processes such as disintegration of organic materials or precipitation [3, 6, 8]. Regardless of the different nature of well refilling and changes in nitrate concentration, a sudden rise in nitrate concentration in the upper layer of the well water after sucking out and a rather even decrease of this concentration as the well refills is characteristic to all of them. In most wells the level of nitrate concentration reaches the level previous to suction in two days time. Later it decreases even more and stabilizes on the eighth day. Levels at which the nitrate concentrations stabilizes are different and range between 93 mg l^{-1} and 9 mg l^{-1} more compared to concentration previous to suction. It is believed that in a longer period of time the nitrate concentration would come back to its to previous level. Investigation carried out allows us to make several conclusions. Having sucked out the water from the well, the quality of refilled water will initially be worse because of the higher concentration of nitrates it contains in the remaining water. However, in certain cases the nitrate concentration will be lower after a certain period of time. It has not been determined what time the concentration will remain lower and what time it will take for the concentration to return to normal. It seems that changes of nitrate concentrations are the result of different hydrogeological and biochemical processes. It is obvious that changes in concentration of nitrate ions occur due to the flow of groundwater into the well. Changes in the amount of oxygen as groundwater flows into the well have an effect on processes of mineralization and nitrification in the water. Mathematical patterns reflect the process relatively well, and can be applied to predict the quality of well water when water usage is uneven. Predictions become a problem, because in cases of different wells rectilinear and gradual/ logarithmic patters have been applied, which depends on different hydrogeological characteristics of the basins. Hydrogeological characteristics of the basin are often unknown and enormous means are necessary to determine them. To make an approximate prediction all patterns can be used, and depending on the problem being solved, a more adequate pattern can be chosen.

It is thought that changes in concentration of nitrogen compounds on the surface layer of well water could be modeled as the reaction of the first order, parameters of equation of which could be chosen according to measurement data. However, equations composing models are "black boxes" that do not give out processes going on. In each separate case their parameters are chosen anew, and as it is seen from tests performed and cases modeled those parameters vary in rather broad boundaries, making preliminary recommendations practically impossible.

It remains uncertain how the quality of water would change in a period of time longer than 10 days. However, wells that are not used for more than 10 days are practically abandoned and the quality of their water is not as important as that of wells constantly used for household purposes.

Conclusions

1. Concentrations of nitrate ions in the water of shallow wells depends on water quality in the basin feeding the well and physical and biochemical processes in the well water.
2. Different concentrations of nitrogen compounds were found in different layers of well water. In the top layer of water, the concentration of nitrogen compounds is smaller than that in deeper layers of water.
3. Immediately after water scooping, nitrogen concentration in the top layer of water increases. Due to physical and biochemical processes, the concentration of nitrogen compounds in the top layer decreases as the well fills up, until it reaches the level characteristic of the particular (well depending on the input basin).
4. The rate with which the sucked out wells refill is different. Re-establishment of the same amount of water ranges between two and five days. In the beginning, because of the big difference in levels, the rate is higher, and then it slows down and asymptotically approaches the main level. An average rate of filling-up makes

3% of well volume per day, ranging from 7% the first day to 1% the fifth day.

5. Change in concentration of nitrate ions after scooping could be modelled as the reaction of the first order, parameters of which generally estimate conditions of well filling up and processes going in water.
6. Mathematical patterns and models of well refilling and changes in nitrates determine the limits of the nitrate concentration changes in water, though they are not precisely adapted to a separate well.

References

1. RUTKOVIENĖ V., KUSTA A., ČESONIENĖ L. Environmental Impact on Nitrate Levels in the Water of Shallow Wells. Polish J. of Environ. Stud. **14** (5), 631, **2005**.
2. LUCZKIEWICZ A. Soil and Groundwater Contamination as a Result of Sewage Sludge Land Application. Polish J. Environ. Stud. **15** (6), 869, **2006**.
3. MADISON R.J., BRUNETT J.O. Overview of the occurrence of nitrate in ground water of the United States. National Water Summary 1984 – Hydrologic events, selected water – quality trends and ground – water resources. Water-Supply Paper 2275. United States Geological Survey, Reston, VA. **1985**.
4. SPALDING R.F., EXNER M.E. Occurrence of nitrate in ground water – a rewiev. Environment Quality, **22**, 392, **1993**.
5. SPRUILL T.B., EIMERS J.L., MOREY A.E. Nitrate-nitrogen concentrations in shallow ground water of the Coastal Plain of the Albemarle-Pamlieo Drainage Study Unit, North Carolina and Virginia, Factsheet 241–96. United States Geol. Survey. Reston, VA. **1997**.
6. SPRUILL T.B, HARNED D.A., RUHL P.A., EIMERS J.L., GALEONE D.R., MCMAHON G., SMITH K.E., WOODSIDE M.D. Water Quality in the Albemarle-Pamlieo Drainage Basin, North Carolina and Virginia, 1992 – 92 Circ. 1157. United States Geol. Survey. Reston, VA. **1998**.
7. PUCKETT L.J., COWDERY T.K., LORENZ D.L., STONERJ.D. Estimation of nitrate contamination of an agroecosystem outwash aquifer using a nitrogen mass-balance approach. Environment Quality, **28**, 2015, **1999**.
8. HALBERG G.R., KEENEY D.R. Nitrate. In W.M. Alley (Ed.) Regional ground-water quality. Van Nostrand Rheinhold. New York. pp. 297-322. **1993**.
9. FIRESTONE M. Biological denitrification.. F.J. Stevenson (ed). Nitrogen in agricultural soils. ASA, Madison, WI. 289, **1982**.
10. HASSELBLAD S., HALLIN S. Intermittent addition of external carbon to enhance denitrification in activated sludge. Water Sci. Technol. **37**, 227, **1998**.
11. KNOWLES R. Denitrification. Microbial Rev. **46**, 43, **1982**.
12. VERSTRAETE W., PHILIPS S. Nitrification-denitrification processes and technologies in new contexts. International Nitrogen Conference 1998 No 1, Noordwijkerhout PAYS-BAS (23/03/1998), **102** (1 p.1/2), 717, **1998**.