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Environmental Impact on Nitrate Levels in the Water of Shallow Wells

V. Rutkoviene*, A. Kusta, L. Česoniene

Lithuanian University of Agriculture, Studentu 11, LT-4324 Akademija, Kaunas district, Lithuania

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Abstract

The rural population, estimated at one third of Lithuania's population, obtains drinking water from shallow wells. Drinking water from shallow wells is polluted, for the most part, with nitrate, which is of general concern not only in Lithuania but in other countries. The purpose of our study is to establish the relationship of nitrate pollution in the water of shallow wells to precipitation level and temperature, as well as to assess the impact of well construction and environmental conditions on this kind of pollution. The results of this work showed that about 66% of all investigated wells are nitrate polluted. The results of long-term research have demonstrated that the highest nitrate concentration in the water of shallow wells occurs in March through July, and the lowest nitrate concentration in September through February. A strong correlation between nitrate concentration, precipitation amount and air temperature was established in summer. Correlations established in other seasons are not significant. The strongest impact on nitrate pollution of the wells is related to the distances of the well to the outhouse, cowshed, manure pile and vegetable garden, as well as the surroundings of the well and local human activities. The estimated coefficients of multiple linear regression allow forecasting the nitrate pollution of the wells as a function of these factors.

Keywords: shallow wells, water quality, nitrate concentration, polluted, precipitation

Introduction

Lithuania is rich in water. The main source of drinking water in the country is groundwater. The potential of natural groundwater technically feasible for development is estimated at 3.2 million m^3 per day [1].

The rural population, estimated at one third of the country's total population, obtains its drinking water from shallow wells [2]. Generally, shallow draw on water passing into them from shallow groundwater resources. Groundwater in the shallowest aquifer is only covered by the unsaturated, commonly water-permeable sediments of the aeration zone, the thickness of which in Lithuania ranges from 1-5 meters to 10-20 meters. The characteristics of groundwater reserves and the chemical composition thereof are determined by hydro-geological conditions [3, 4]. Almost everywhere in the country the groundwater mode can be characterized by the tendency for a high water table [5], thus it is not the amount of water but rather its quality which is the important factor in this case. The groundwater aquifer is polluted with nitrate for the large part [6, 7], which is of general concern [8] not only in Lithuania, but in other countries too. A trend towards increased nitrate pollution of groundwater can be observed worldwide [7, 9]. This kind of pollution is increasing to such an extent that it is reasonable to foresee the problem of "groundwater eutrophication" [10]. It is known that intensive agricultural activity is one of the factors leading to nitrate pollution of groundwater. Developed countries, such as the USA and Australia, suf-

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*Corresponding author; e-mail: ai@nora.lzua.lt

fer from the outcomes of intensive farming, i.e., overall groundwater quality degradation [11].

In natural conditions, fresh water in shallow aquifers has a relatively short residence time, and its chemistry remains practically unchanged under the effect of a set of natural influences such as physical, geographical, geological and hydro-geological factors. Human economic activities, however, can distort the natural balance. Groundwater consumption changes the groundwater balance and the sources forming its reserves. Due to progressive pollution, natural and artificial chemical substances enter into the fresh water circulation cycle, thus modifying water quality [12].

As mentioned above, the water quality in shallow wells depends primarily on the impact of anthropogenic activities and geochemical nitrogen cycle conversions, as well as factors which, in turn, influence such conversions. Much work indicates that nitrate concentration in wells is closely related to the amount of precipitation and its flow in the ground [13]. In the case of a large amount of precipitation in a short period of time, the nutrient concentration in tile drainage and surface water from recently fertilized fields increases considerably [14]. Due to infiltration, there is a high likelihood for a part of these nutrients to seep down into groundwater. According to another opinion [15], groundwater pollution in fields with little fertilization and large amount of precipitation is lower due to dilution. The quality of groundwater and water of shallow wells in rural areas largely depends on agricultural activities and the method of use and storage of organic and mineral fertilizers. It has been established that from manure stored in open lots for eight months, 7% nitrogen, 14% phosphorus and potassium enter the environment in the form of leachate, resulting in groundwater pollution from the leachate greatly exceeding the maximum allowable concentrations for the area [16, 17].

In addition to environmental influences, the type of well, its depth, age and structural features can also influence its water quality. Nitrate pollution is more common in old and shallow wells [4]. The Richards et al. report highly significant differences in nitrate concentrations as a function of well depth [18]. The nitrate concentration in water, pH and water temperature depend on the depth and age of well [19]. In the report an inverse correlation between well depth and nitrate concentration was found [6]. Glanville et al. [20] observed a fairly strong negative correlation between nitrate and well depth ($p<0.001$), too. Baker et al. [4] state several times that shallow wells are more likely to be contaminated than deep wells. In many cases, nitrate pollution increases with anthropogenic activities in the vicinity of the well, as well as due to inappropriate location of the well [21]. S. Kutra et al. [22], attempting to find out the distance from the well within which human activities may have an impact on well water quality, proved the distance of well interference to be as high as 145 meters. Usually, this distance of up to 145 meters is the one in which the household premises (cowsheds, greenhouses, gardens and vegetable gardens, outhouse, dumps and other aggressive sources of pollution) are located from the well. The direction of groundwater flow has an important influence on the probability of contamination, too.

The purpose of this study is to establish the dynamics of nitrate pollution in the water of shallow wells in relation to the precipitation level and temperature, and to evaluate the impact of well construction and environmental conditions on this kind of pollution.

Material and Methods

The research was carried out in the Kaunas district, situated in central Lithuania. The Kaunas district is one of the largest in Lithuania. It has a long tradition of intensive farming with an area of 1,521 km^2 and a population of 81,700. The river Nemunas crosses the district and the river Nevėžis flows into the river Nemunas. Pypliai village was chosen for the work as a typical Lithuanian village. This small geographic area is relatively uniform in climate, soils, land use, elevation and other factors that can influence water quality, though there is quite a slope down to the river and some of the wells are located on that slope. Pypliai has no central water supply, so the villagers use water from shallow wells. Pypliai is situated 6 km from Kaunas, near Kačerginė, on the river Nemunas. There are seventy homesteads in the village. About 70% of its inhabitants breed livestock. Wells are not deep, with an average depth of 6 m.

All wells examined are shown in Figure 1. It can be seen that they are situated more or less evenly along the river Nemunas. Further from the river, the wells become more sparsely placed. The wells concerned are dug in type CH1 soil, which is moderately permeable and has a high leaching potential for pollutants. The soil of this type consists of non-consolidated sediments with differ-

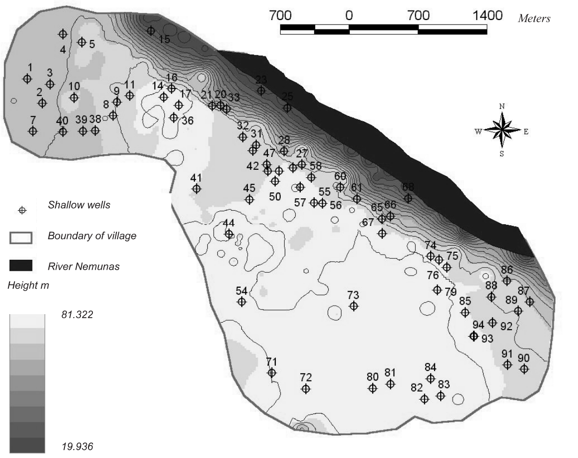

Fig. 1. Relief of Pypliai settlement showing the location of the shallow wells.

ent perme abilities. Although these sediments rarely accumulate large amounts of drinking water, they are important to local water supply and river flow. They consist of limnoglacial and alluvial silt, sand and silty sand, sandy clay, moraine and peat.

Once a month, during the period 1998-2003, water samples were taken from these wells and tested at a certified Environmental Laboratory of the Lithuanian University of Agriculture. During the study, 5,040 samples were obtained from 70 wells. The concentration of nitrate ions (NO$_3$) mg l^{-1} was measured using a nitrate ion selective electrode of the type METROHM AG CH–9101. Nitrate concentrations are reported as NO$_3^-$. Quality control procedures were used to make analysis of some samples determination of nitrate concentration by spectrometric method with 4-fluorfenol after distillation.

A hygiene standard of the Republic of Lithuania number HN 48:2001 “Hygiene requirements for raw water intended for human consumption,” which was prepared according to the Council Directive 98/83/EC of November 1998 “On the quality of water intended for human consumption,” indicates the maximal allowable value of the analyte – 50 mg l^{-1} as NO$_3^-$.

For estimation of the correlation coefficients between meteorological conditions and nitrate concentration in shallow wells and to carry out linear regression analysis, the statistical programme “Statistica 8.0” was used.

Influence of environmental factors (independent variables) on nitrate concentration (dependent variables) was analyzed using the SPSS 10.0 statistical software package. The multiple linear regression models can be represented as follows:

$$Y_i = A + B_1 x_{1i} + B_2 x_{2i} + \ldots + B_k x_{ki};$$

where Y_i – nitrate concentration in the water of shallow wells; A – constant; B – non-standardized coefficient; x – well depth and depth to water (in meters), distances (in meters) from the shallow well to potential sources of pollution (cowsheds, outhouses, manure pile and vegetable garden), keeping of cattle and poultry (categorical variable – the presence or absence), evaluation of the well environment.

The parameters of well installation and their surroundings were evaluated according to their conformity to requirements set out in the order of the Minister of Agriculture and Environment of the Republic of Lithuania “Regarding approval of requirements for water protection from pollution by nitrogen compounds from agricultural sources” (No. 452/607, 2001). Conformity with these requirements is evaluated using a five-point system.

In order to establish the dependencies between well water quality indicators and environmental conditions, 570 farmers were questioned about the well installation and environment around the well.

Meteorological conditions were evaluated using the data collected by the Kaunas Meteorological Station. In order to study the impact of meteorological conditions, water quality was evaluated on a seasonal basis– summer (June, July and August), autumn (September, October and November), spring (March, April and May) and winter (December, January and February).

Results of Research

Evaluation of Climate Conditions for the Period of Interest

Meteorological conditions for the period of interest (1998-2003) are grouped by seasons. In winter, the highest precipitation level was observed in 1998, 1999 and 2002, while the lowest level was observed in 2001. In 2000, the precipitation level was close to the long-term annual mean. The lowest winter mean temperature was observed in 2003, while the highest ones were experienced in 2000 and 1998.

In spring, the highest precipitation level was observed in 1998, 2001 and 2000, while the lowest level was observed in 2003 and 2002. The coldest spring was observed in 2003 and the warmest one was in 2002. In the spring season of all years under review, the observed air temperature was higher than the long-term annual mean.

In summer, the highest precipitation level was observed in 1998, 2001 and 2000, while the lowest level was observed in 2002 and 1999. The coldest summers were those in 2000 and 1998, while the warmest ones were those in 2002 and 1999.

In autumn, the highest precipitation level was observed in 2002, while the lowest level was observed in 2000. The lowest autumn temperature was observed in 1998, while the highest one was in 2000.

The precipitation levels of 2001, 1998 and 2002 exceeded the long-term annual mean, while in 2003, 2000 and 1999 they were lower (Fig. 2.). The mean annual temperatures of all years under review were higher than the long-term annual mean. The lowest mean annual temperatures were observed in 1998 and 2003, while the highest ones were observed in 2002 and 2000.

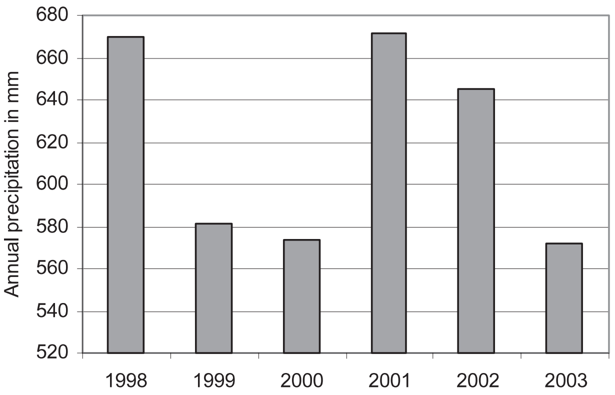

Fig. 2. Annual precipitation for 1998-2003 (in mm).

Impact of Meteorological Conditions on Nitrate Concentration in the Water of Shallow Wells

According to the data provided in Fig. 3, the highest nitrate concentration was observed in July 1998 (75mg l^{-1}). July also showed the highest monthly precipitation level (118 mm). Trends in the precipitation amount and changes in the nitrate concentration curve coincided for June through November, while they were inverted for December, and January through May.

In 1999, the highest nitrate concentration level was observed in March and August (70 mg l^{-1}). The highest monthly precipitation level was observed in August (85.9 mm). The alterations in curve shape coincided for May through November but not for March and December.

In 2000, the highest monthly precipitation level was in July (112.9 mm), while the highest nitrate concentrations were observed in March (84 mg l^{-1}) and July (81 mg l^{-1}). Alterations in the curves ran parallel for most of the year, except for November and December.

In 2001, the highest monthly precipitation level was observed in July (143.5 mm) and the highest nitrate concentration was observed in March (64 mg l^{-1}). Trends in the curve forms did not coincide for June, July, September or October.

The month of August, 2002 presented an especially small amount of precipitation (13.8 mm), while October showed a very high precipitation level (167.3 mm), exceeding the long-term monthly mean (45 mm) by a factor of 3.7. Alterations in the curve tendencies coincided all year round (see Fig. 3 for the mean monthly nitrate concentrations during 1998-2003).

In 2003, the highest nitrate concentrations were registered in July (81 mg l^{-1}) and the highest monthly precipitation level was observed in July too (120 mm).

The nitrate concentration in the water of shallow wells (Fig. 4) was higher in March-July for all years under review, while it decreased in August and showed the lowest levels in September through February.

The mean values of nitrate and precipitation levels in the summer months (June, July, August) show (Fig. 5) that the trends in the variation of monthly precipitation and mean nitrate concentration in the water of shallow wells (mg l^{-1}) coincide. The values were high in 1998

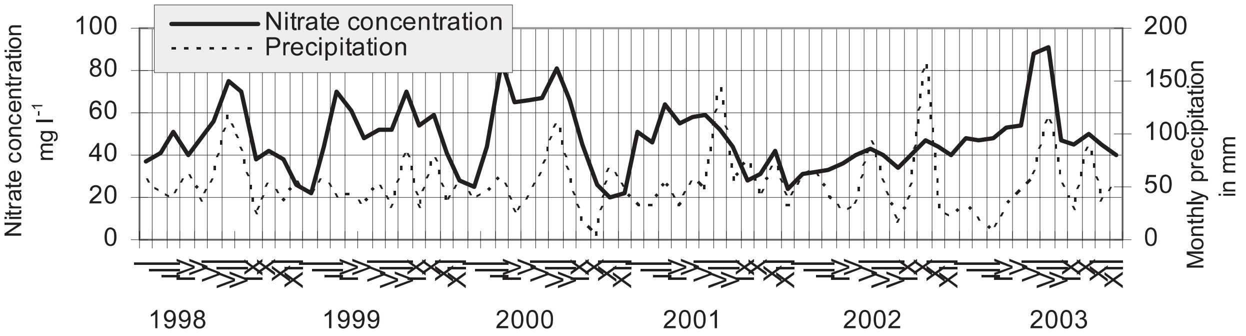

Fig. 3. Monthly precipitation in mm and nitrate concentration in (mg l $^{-1}$ as NO_3) in the water of shallow wells for 1998-2003.

Table 1. Impact of environmental factors on NO_3^- (Y) concentrations in the water of shallow wells.

Environmental factor	Non-standardized coefficients		Standardized coefficient	t	P
	B	Standard error	Beta		
Constant	(a) 26720.7	7905.497		3.380	0.001
*Cattle (x_1)	-45.294 (b_1)	11.778	-0.183	-3.846	0.000
Poultry (x_2)	-15.223(b_2)	13.724	-0.052	-1.109	0.268
*Distances from the well to cowshed, outhouse and dunghill (x_3)	-0.613(b_3)	0.219	-0.114	-2.795	0.005
*Distance to the vegetable garden (x_4)	-0.313(b_4)	0.124	-0.103	-2.530	0.012
Depth of the well (x_5)	2.242(b_5)	3.098	0.042	0.724	0.469
Water table in the well (x_6)	1.785(b_6)	3.876	0.026	0.461	0.645
*The well installation (1-5points) (x_7)	-9.040(b_7)	5.208	-0.071	-1.736	0.043

* Significance $p<0.05$

(108 mg l^{-1} and 118 mm/month respectively). In 1999, the values decreased to a minimum (60 mg l^{-1} and 30.5 mm/month), in 2000, the values noticeably increased (115 mg $l^{-1}$and 112.9 mm/month), while they decreased in 2001 (76 mg $l^{-1}$and 66.2 mm/month), and proceeded with the decrease in 2002 (63 mg l^{-1} and 45.1 mm/monthly). In 2003, the values increased again (123 mg $l^{-1}$and 57.1 mm/month).

The coefficients of correlation show the correlation between nitrate concentrations, precipitation level ($r = 0.50$; $r^2 = 0.25$; $p = 0.04$) and air temperature ($r = -0.60$; $r^2 = 0.38$; $p = 0.008$) only for the summer season. This is made particularly clear from the dispersion diagrams calculated using linear regression (Fig. 6). Thus, the derived linear regression enables forecasting tendencies dynamics of the nitrate concentration as a function of the monthly precipitation in mm and monthly mean air temperature. In rainier summers with lower air temperatures, the nitrate concentration in the water of shallow wells will be higher.

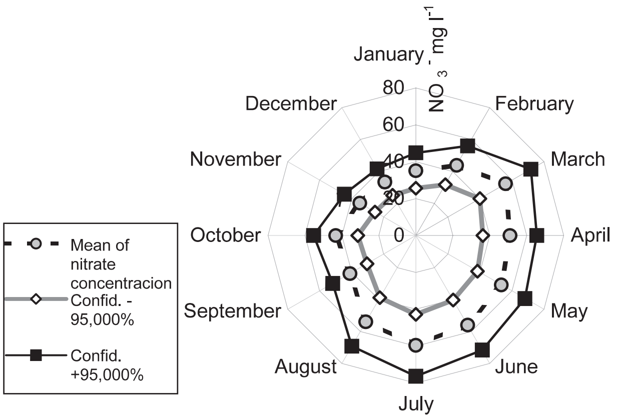

Fig. 4. Nitrate concentration (monthly mean and confidence intervals for 1998-2003) in the water of shallow wells.

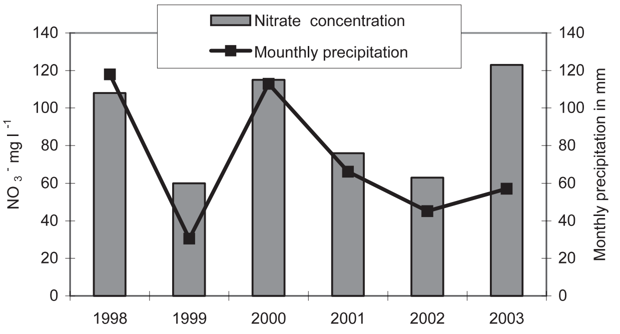

Fig. 5 Mean nitrate concentration (mg l^{-1}) in the water of wells for the period 1998-2003; summer monthly precipitation in mm.

Impact of Shallow Well Environment on Nitrate Concentration

Investigations of areas around the homesteads showed that as many as 27% of them had insufficient distance (1–10 m) between the shallow well and the vegetable garden, the distance between the shallow well and the cowshed was not adequate (11–25m) in 43% of homesteads, while in 30% of homesteads the distance from the well to the outhouse was too short.

Evaluation of the well environment is based on a five point system. The results of this evaluation show that environments of some homesteads are organized moderately well or well (66%). The surroundings of 18% of all homesteads are poorly organized, while only 11% of all homesteads have very well organized surroundings. The surroundings of 5% of all homesteads are rated as especially poorly organized. In 61% of all homesteads, cattle are kept on the property, and in 78% of all homesteads, poultry are kept. The average depth of the wells is 6.25 m, the depth of the shallow well is 1.0 m, and the deepest well is 19 m. The average depth to water in the shallow wells is 3.1 m; the minimum depth to water is 0.2 m while the maximum depth to water is 15 m.

The impact of environmental factors on the NO_3^- concentration in the water of shallow wells was calculated using the method of multiple regression analysis. Multiple regression models are suitable for forecasting when there is no correlation between all independent variables. If there is a strong correlation between variables, a prob-

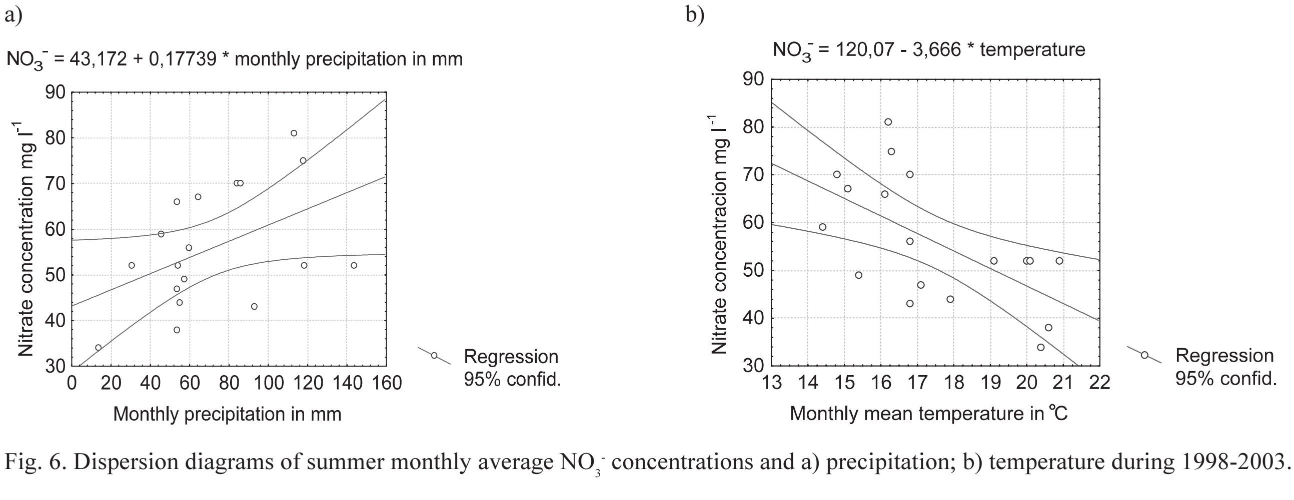

Fig. 6. Dispersion diagrams of summer monthly average NO_3^- concentrations and a) precipitation; b) temperature during 1998-2003.

lem of multicolinearity occurs. The variable is considered too multicolinear when the variance inflation factor (VIF)>4. In our case the multicolinear variables are as follows: distances to the cowshed, manure pile and outhouse (VIF>4). In order to avoid multicolinearity, an arithmetic average of the mentioned distances was calculated for each homestead. Applying the multiple regressions, the individual impact of each distance on nitrate concentration was statistically significant.

Multifactor regression relations of the impact of risk factors (surroundings factors) on the concentration of nitrate in shallow well water indicated that the nitrate concentration is mostly influenced by the keeping of cattle on farmsteads, the average distance between the well and the outhouse, cowshed, and manure pile, and the distance to the garden, as well as by factors related to the installation of the well and its protection.

The most important risk factor, in our opinion, is inadequate distance from the well to the cowshed, the manure pile and the outhouse. While this paper only presents results for nitrate, ammonia and organic nitrogen were also studied. In this larger context, these distances are important because they influence the concentration of all nitrogen forms investigated. The cattle keeping and the factors related to the installation of the well and its protection influence the concentration of organic substances, too.

Discussion

The results of this long-term study show that the highest nitrate concentrations are observed in spring and summer (March through August), while the lower ones are specific to the winter and autumn seasons (September through February). These tendencies can be explained by the fact that spring and summer are warm seasons with very active circulation of organic substances. Though the spring precipitation is estimated as the lowest, melting spring water can easily carry the pollutants to the deeper layers of the soil, which also means that such pollutants will enter the wells. Warm air temperature has another type of impact on nitrate concentration as it creates more favorable conditions for the conversion of ammonia nitrogen to nitrate nitrogen. Summer, in comparison with other seasons, has the highest level of precipitation saturating the ground to the layers which feed the wells. These climatic factors may explain the correlation between nitrate concentration and precipitation level and air temperature. The decrease in nitrate concentration in autumn and winter, however, probably has a different origin. In autumn, the ground is usually dry, and surface water and water from the upper layers cannot pass to the wells. This is perhaps the reason for the lack of correlation between nitrate concentration, precipitation and air temperature in autumn. In our opinion, the wells in autumn are fed by the water from deeper layers containing fewer substances of organic origin. Thus, the possibility for nitrates to seep down into the well water through the process of nitrification is lower in autumn. In the winter freeze, surface water does not reach the well water and the wells can only be fed by waters stemming from the deeper layers. This, in turn, results in no correlation between nitrate concentration and precipitation. Moreover, low temperatures in winter slow down the chemical reactions and processes of organic substances, which also helps to explain the lower nitrate concentration.

Multiple regression analysis carried out on the nitrate level dependence on the environmental factors has shown the following: the shorter the distance from the shallow well to the cowshed, manure pile, outhouse and vegetable garden, the higher the nitrate concentration in the shallow wells. A widely-held tenet of groundwater hydrology states that water flows downslope along the gradient of the groundwater surface or water table. This gradient generally conforms to the surface contours. Thus, water quality in wells is highly influenced by pollutants moving from upslope in the vicinity of the well [23]. The keeping of cattle on the homestead is an additional high risk factor, since it can influence the nitrate concentration through manure and manure leachate. It has been established that the worse the organization of the well surroundings, the higher the nitrate concentration. Improper construction of the well, a leaky cover, bad repair of the scoop and drawing device, are all factors contributing to the transport of organic substances to the well. An insufficiently dimensioned sanitary zone or a surface incline towards the well can lead to seeping of the surface water down into the well. A poorly organized environment around the homestead, and poultry and livestock kept near the well can also have an impact on nitrate concentration in the water of shallow wells.

This research allows the conclusion that the amount of nitrates in the water of shallow wells can be reduced by correct installation of the wells and good organization of the surrounding environment.

Conclusions

It has been established that about 66% of all investigated wells are nitrate-polluted; the mean nitrate concentration of all wells in the study (taken as a group) exceeded the maximum allowable one.

The results of long-term observations demonstrated that the highest nitrate concentration in the water of shallow wells occurs in March through July, and the lowest nitrate concentration in September through February.

A correlation between nitrate concentration, precipitation amount ($r^2 = 0.25$) and air temperature ($r^2 = 0.38$) was established in summer. Attempted correlations in other seasons were not significant.

The strong predictors of nitrate pollution of the wells are the keeping of cattle on the homestead, the average distance from the well to the outhouse, cowshed, manure pile and the distance to the vegetable garden, as well as installation of the well.

The estimated coefficients of multiple linear regressions allow forecasting of the nitrate pollution tendency of the wells depending as a function of these environmental factors ($r^2 = 0.28$).

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