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Causes of nitrate leaching from agriculture land in Slovenia

Maja PODGORNIK[1], Marina PINTAR[2]

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ABSTRACT

In Slovenia, groundwater is significant source of drinking water. It has been widely reported that contamination of groundwater from agricultural non-point source is one of the major pollution problems. The pollution of groundwater in areas of agricultural activity is a result of using of mineral nitrogenous fertilizers in large quantities. Applying excess nitrate fertilizers directly affects ground water quality, especial for NO_3-N, which is highly mobile. Non-point loss of NO_3-N from fields to water resources however is not caused by one single factor. Rather is caused by combination of factors including precipitation, crop uptake, irrigation, application of fertilizers and soil property. Although Slovenian areas of intensive agriculture have different soil characteristics, different rainfall regime and agricultural practice, their nitrate leaching regime appears to be similar and in majority related to the precipitation and fertilization.

Key words: nitrate leaching, precipitation, irrigation, fertilizers, water pollution

IZVLEČEK

VZROKI IZPIRANJA NITRATA IZ KMETIJSKIH POVRŠIN V SLOVENIJI

Podtalnica je v Sloveniji pomemben vir pitne vode. Znano je, da intenzivno kmetijstvo kot netočkovni vir obremenjevanja, predstavlja glavni problem onesnaževanja podzemnih voda. Na kmetijskih zemljiščih z intenzivno pridelavo prihaja do prekomerne porabe mineralnih gnojil, kar negativno vpliva na kakovost podtalnice. Uporaba dušičnih gnojil v količinah, ki presegajo zahteve posevkov, poveča izpiranje dušika v obliki zelo topnega in mobilnega nitrata v globlje plasti tal in podtalnico. V kolikšnem obsegu bo nitrat iz površinskih slojev obdelovalnih tal prodrl v podtalje, ni odvisno samo od količine dušičnih gnojil, ampak tudi od količine padavin, vrste vegetacije, namakanja ter lastnosti tal. Kljub temu, da se v Sloveniji intenzivna kmetijska območja razlikujejo po količini padavin, kmetijski praksi ter talnih lastnostih, je dinamika izpiranja nitrata na vseh območjih predvsem odvisna od vremenskih razmer in gnojenja.

Ključne besede: izpiranje nitrata, padavine, namakanje, gnojila, onesnaževanje voda

[1] University of Primorska, Science and Research Center of Koper, Garibaldijeva 1, 6000 Koper, maja.podgornik@zrs.upr.si

[2] University of Ljubljana, Biotechnical Faculty, Agronomy Department, Jamnikarjeva 101, 1000 Ljubljana, marina.pintar@bf.uni-lj.si

1 INTRODUCTION

Intensification of agricultural activities, such as fertilization practice and application of irrigation has dramatically increased crop yields. Like any enhanced productive activity it leads to environmental contamination if it is improperly managed (Hadas et al., 1999). Excessive use of N fertilizers and irrigation increase the risk of percolation and leaching of nitrates to groundwater (Bijay-Singh et al., 1995).

Nitrogen is a widely used plant nutrient, which is essential for the growth and development of a healthy crop. It is most often the limiting nutrient in plant growth and to overcome this limitation, N fertilizers are used to increase crop yields (Jalali and Rowell, 2003). The high inputs of N fertilizers had markedly modified the N cycle. The N cycle include several nitrogen transforming processes such as mineralization, immobilization, nitrification and denitrification which are very complex and dynamic. The nitrification process corresponds to the transformation of the manure's nitrogen into nitrate. Nitrification is a biological process during which nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*) convert ammonium to nitrate. The nitrate form of nitrogen is the form most available to plant. But, this form is very soluble in water and therefore, very mobile within soil solution.

Application of nitrogen fertilizer in excess can lead to significant nitrate leaching out of the root zone, because plant uptake and microbial immobilization can not remove the entire nitrate from the solution (Pratt and Adriano, 1973). Below this layer, nitrate is not actively absorbed by roots and has high potential to move downwards. So the amount of nitrate lost is depended on the quantity of nitrate available to be leached. Another factors affecting nitrate leaching are the precipitation-intense rainfall events or surplus of water provided by irrigation, evapotranspiration, drainage, soil texture, soil porosity and occurrence of preferential flow paths (Wu et al., 1997; Cameria et al., 2003).

Nitrogen losses not only result in lower production and subsequent increase in production costs but can also lead to groundwater deterioration and pollution (Cepuder and Shukla, 2002). Contamination can render groundwater unsuitable for human consumption. Nitrate frequently pollutes groundwater supplies (Spalding and Exner, 1993). The high concentration of nitrate in water supplies can cause ecological damage and health hazards. Several studies document adverse effects of high nitrate levels most notably metahemoglobinemia and stomach cancer (Ward et al., 1994). Nitrate also causes algal blooms that can produce toxins and lower the oxygen content of waters, both of which adversely affect aquatic organisms. This eutrophication is a widespread problem that is persistent and slow to recover.

The groundwater nitrate problem is international scope. Nitrate concentration exceeding the international (WHO, 1993) recommendations for drinking water (50 mg NO_3^-/l) have been found in groundwater under 22% of cultivated land identified nitrate and ammonium in a sandstone aquifer beneath Nottingham, England (Rivers et al., 1996).

In Slovenia, groundwater is major source of drinking water. Because of the risk of agricultural impact on groundwater contamination, also in Slovenia, the nitrate leaching received considerable attention. The aims of this paper is reviewed and discuss about the most important factors affecting nitrate leaching from agriculture land and estimate how combination of factors including precipitation, crop uptake, irrigation, application of fertilizers and soil property affect the dynamics of nitrate leaching in Slovenia.

2 MATERIALS AND METHODS

This article is written in the form of a literature review of recent scientific publications related to nitrate leaching from agricultural land in Slovenia. The review is not just a summary of the resources but it is also evaluation and shows relationships between different studies.

3 RESULTS AND DISCUSSION

3.1 The effects of precipitation on nitrate leaching

Rainfall is one of the most important factors affecting the movement of nitrate in agricultural soil. Results of study conducted in Apače valley (average annual precipitation 939 mm) in the period between March (1993) and December (1995) confirm this contention and show that groundwater nitrate pollution was more pronounced in years with higher precipitation (1994 – max $N\text{-}NO_3$ in groundwater was 71.1 mg /l in 1995 – max was 58.6 mg $N\text{-}NO_3$/l) than in year with lower precipitation (1993 – max $N\text{-}NO_3$ in groundwater was 20.5 mg/l) (Pintar et al., 1996).

Rainfall that infiltrates the soil surface may causes nitrate ions to move down through the soil profile by percolation. The more rain that falls and infiltrates in the period after application of N fertilizer, further down in the profile nitrate ions move (Bugar, 1999). If precipitation exceeds evapotranspiration, nitrate can leach to a groundwater. But where the amounts of rainfall are low and potential evapotranspiration exceeds annual precipitation, the concentration of nitrate tends to be high because the diluting effect is reduced (Leskošek, 1994).

In northeastern part of Slovenia (Prekmurje) average precipitation are low and evapotranspiration is relatively intensive, so small quantities of water percolates through the soil profile. Consequently, because of less dilution, there is a higher concentration of nitrates in the groundwater (Leskošek, 1994). In central and western part of country percolation of water through the soil profile is comparatively higher. Owing to the large volume of water flowing through, there is a dilution of nitrate content, and the probability of groundwater pollution with nitrate is consequently smaller (Action programme…, 2004).

Slovenian's climate is generally characterized by heavy precipitation (800-3500 mm/year), and there is a very high risk of nitrogen leaching even during the growing season (Leskošek, 1994). Leaching is especially intensive in autumn and through the winter, when there is no active uptake of N into plants, while at the same time evapotranspiration is low, so the water surplus is at its highest. The other period, when the danger of leaching arises in Slovenia is May and the first half of June when there is a maximum precipitation (Action programme…, 2004).

Also the study in the Slovenian cost region with submediterranean climate (900 mm) confirms that precipitation regime could significantly influence on nitrate leaching. The results show that excessive rainfall causes nitrate movements downward below the root zone, because after the heavy rain nitrate concentrations in drainage water significantly decreased (Figure 1). The highest concentration of nitrate was found during spring and autumn months. In the Slovenian cost region most of the annual precipitation falls in these months (Podgornik, 2003). The maximum nitrate concentrations (94.4 mg N-NO_3/l) in drainage water were observed in the end of growing season. Soil water nitrate concentration is the highest at the onset of the autumn rainfall and progressively decrease as nitrate is flushed out of the soil (Podgornik, 2003).

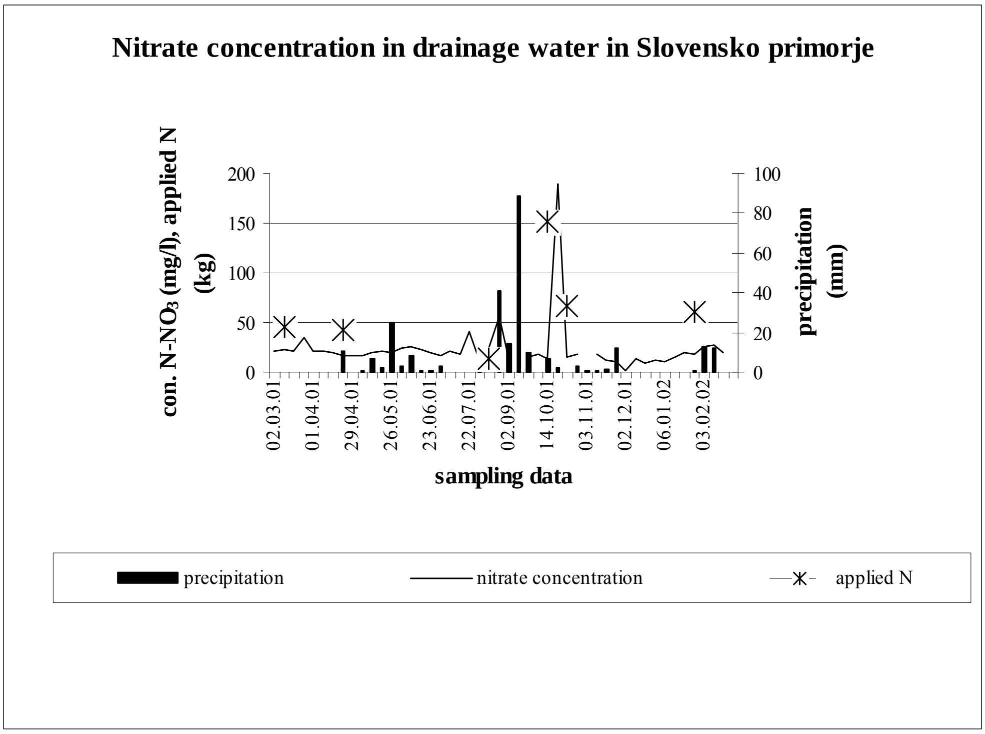

Figure 1: Impact of applied fertilizer (kg) and precipitation (mm) on nitrate concentration (mg/l) in drainage water Zontarji (in Slovensko primorje region - W Slovenia)

From data of average yearly precipitation, average yearly potential evapotranspiration, and effective filed capacity, the approximation of average yearly potentially leached water below the root zone was calculated. This was used to determine zones with potential risk of soil percolate contamination with nitrate in Slovenia. The nitrate vulnerable zones are predominantly in the north – east part of Slovenia. However because of relatively high amount of potentially leached water below the root zone there would be no risk of leachable pollution with nitrate on the 86% of Slovene territory (Mihelič et al., 2002).

3.2 Influence of some soil properties on nitrate leaching

Karst with limestone as a geological ground, occupies around 44% of the Slovenian territory. This region wasn't be identified as vulnerable for nitrogen leaching into ground water, because has limiting growing condition for agriculture crops (i.e. climate, soil depth) and clay soil with high water holding capacity. The average yields and uptake by crops are low, consequently fertilizer application rate is low and therefore non – point source pollution caused by mineral fertilization is not considered as a serious problem in this region. The high nitrogen surpluses can be caused by high animal density per hectar. In this case, manure can be considered as a serious pollution source (Matičič, 1998).

Nitrate leaching is strongly affected by the particle size distribution, the soil porosity, and the occurrence of preferential flow paths (Cameria et al., 2003). Soils have varied retentive properties depending on their texture and organic matter content. Soil texture refers to the relative proportion of particles of various sizes in a given soil (Gaines and Gaines, 1994). Due to the higher proportion of gravitational pores coarse soils are usually more vulnerable to leaching than clayey soils (Wu et al. 1997). They observed that up to 50% of applied nitrogen can be leached from coarse soils. Sandy soils are also fairly homogeneous, water moves freely through much of the soil matrix. Nitrate that is in the soil, whether from fertilizer or from microbial activity, is likely to be carried through the soil slowly but surely with little impediment (Addiscott, 1996).

Nitrogen loss to a groundwater from clay soil is smaller than those from the coarse-textured soils. Finer clay soils have more retention capacity than sandy soil, because sandy soil have less silt and clay which gives rise to lower cation exchange capacity (Gaines and Gaines,1994).

The negative charge on the clay particles retains ammonium ions (NH_4^+). Retention of ammonium ions on clay particles protects them (ammonium ions) from leaching. Nitrate ions (NO_3^-) are negatively charged and are not retained by clay particles (Leskošek, 1993). Clay soil does not specifically retain nitrates, but water does not pass easily through clay soil. Large surface areas of the individual clay particles and the large number of very small pore spaces can hold a large amount of water. Water-filed pores of clay soils lack oxygen. Lacking oxygen, a group of soil bacteria, called facultative anaerobes, substitute nitrates for oxygen for respiration. When bacteria use nitrates as a substitute for oxygen, they convert nitrates to nitrogen gas through a process called denitrification. Nitrate loss through denitrification in clay soils reduces the amount of nitrates that can be potentially leached to groundwater (Bhumbla, 2006).

But fine textured soils with frequent worm holes, cracks, or other vertical channels have the potential to allow nitrate movement deep into the soil beyond the rooting zone. In this circumstance, significant amounts of water may flow through large soil

pores (macro pores) even through they make up only small percentage of total pores. This type of water flow is called preferential (Addiscott, 1996).
Soil thickness and distance between the root zone and groundwater also determine the vulnerability of an aquifer to pollution. Nitrate leaching from shallow soils on fractured soils as limestone can cause extensive contamination of groundwater. There are numerous reports of nitrate movement to ground water from agricultural soil in karst regions (Bhumbla, 2006).

3.3 Impact of irrigation on the dynamics of nitrate movement through a soil profile

The dynamics of nitrate leaching for four different advanced irrigation and fertilization practices was studied in Savinja valley – east part of Slovenia. The filed experiment was carried out in intensive hop garden, with continental climate (790 mm precipitation per year). The first one - control consist of non-irrigated and surface fertilized hop with 217 kg N/ha in three consecutive rations. The second and the third practices comprise sprinkler and classical - drip irrigated hop, making use of the same fertilization as the first one. The fourth practice is fertigated hop, where amount of added nitrogen was 220 kg N/ha on soil surface (Pintar, 1999).

No clear differences were observed among the variations of non irrigated, sprinkler irrigated and drip irrigated hop (Fig 2, Fig 3, Fig 4). Analysis of results shows that the greater part of collected samples of percolated soil water from fields under non irrigated, sprinkler irrigated and drip irrigated hop had nitrate concentration over 50 mg NO_3^-/l.

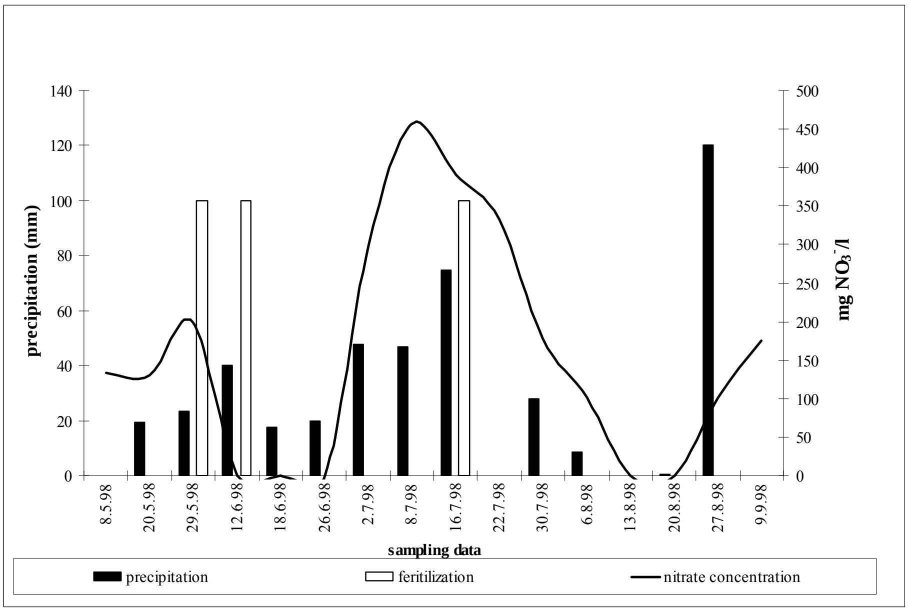

Figure 2: Impact of fertilizer application (kg) and precipitation (mm) on nitrate concentration (mg NO_3^-/l) in percolating soil water in control variant in hop garden in Savinja Valley

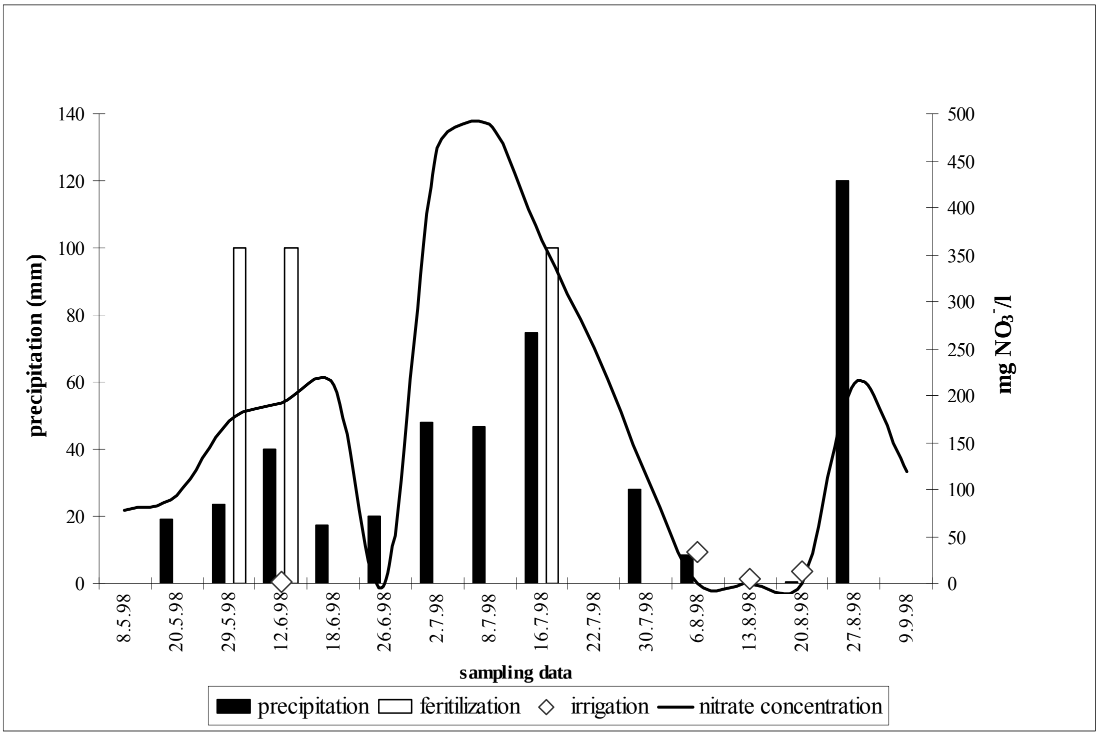

Figure 3: Impact of fertilizer application (kg) and precipitation (mm) on nitrate concentration (mg NO_3^-/l) in percolating soil water in sprinkler irrigated variant in hop garden in Savinja Valley

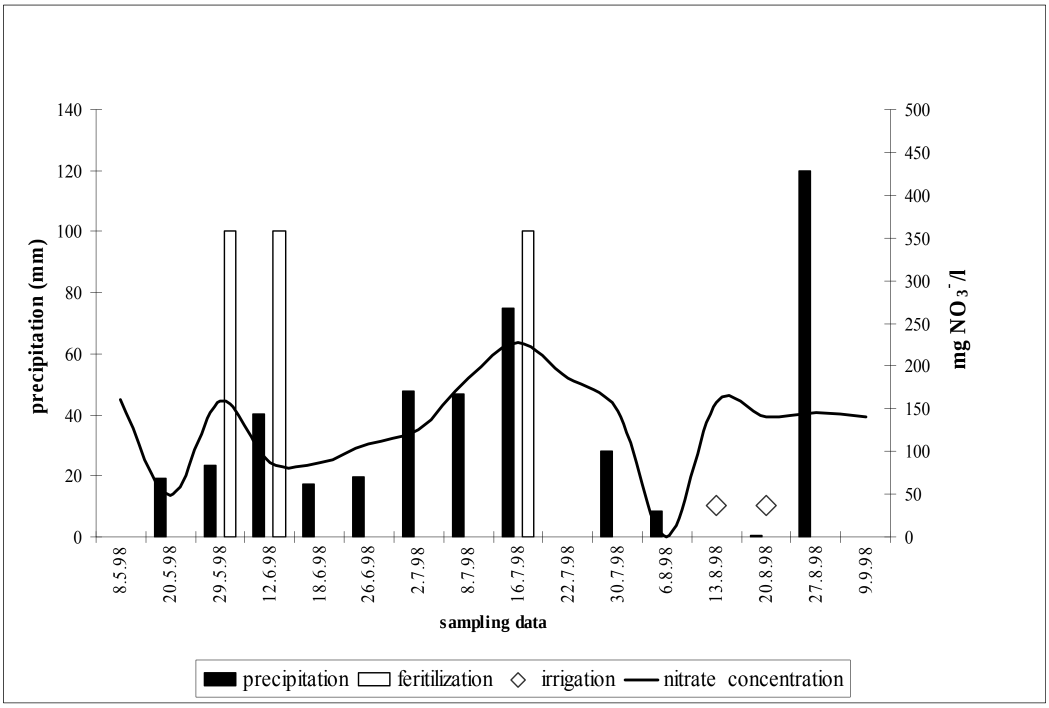

Figure 4: Impact of fertilizer application (kg) and precipitation (mm) on nitrate concentration (mg NO_3^-/l) in percolating soil water in classical – drip irrigated variant in hop garden in Savinja Valley

After rainfall events and application of fertilizer in all treatments with classic fertilizing practices significant increase of nitrate concentration in percolated soil water was observed. Present study indicated that during the rainfall period, nitrate leaching was lower in drip irrigated hop (226.70 mg NO_3^-/l) treatment than in non-irrigated treatment (457.3 mg NO_3^-/l) and sprinkle irrigated hop (488.60 mg NO_3^-/l).

The significant difference in nitrate leaching was observed only in the treatment involving fertigation (Fig 5). In fertigation treatment in percolating soil water accumulated nitrate concentration was lower than in the control variant.

The large amount of water used in agriculture makes the risk of leaching nitrates and other chemicals potentially greater in areas that are irrigated. The increase in soil moisture that results from irrigation dissolves excess nitrate present in the soil profile and makes it more susceptible to leaching (Casey et al., 2002). Higher moisture contents will also raise microbial activity including mineralization (Skopp et al., 1990). The increase in mineralization rates has been shown to directly affect nutrient leaching (Doran, 1980).

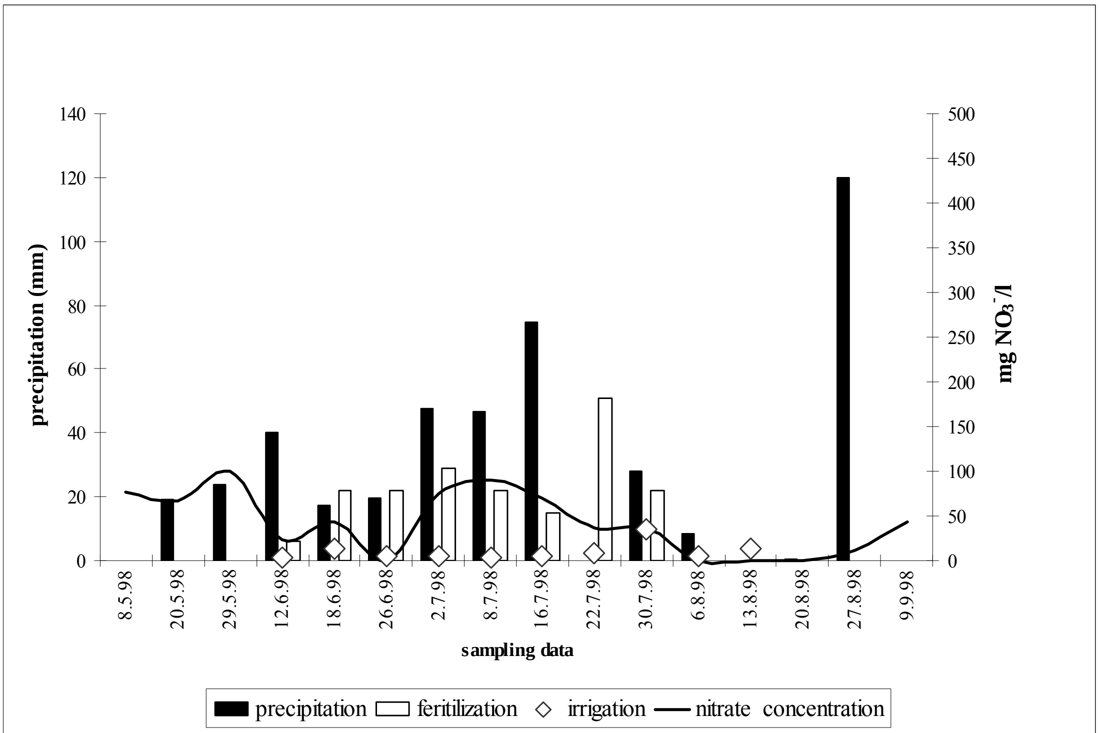

Figure 5: Impact of fertilizer application (kg) and precipitation (mm) on nitrate concentration (mg NO_3^-/l) in percolating soil water in fertigation in hop garden in Savinja Valley

Also the method of irrigation of water application influences the leaching process. Most of the irrigation in the world is surface irrigation. The efficiency of water use in such system is low and one half to one third of applied water may be lost carrying considerable amounts of nutrients with it. But there are also advanced irrigation systems available, like sprinkler and drip irrigation. Sprinkler irrigation system has a higher efficiency and water nutrient losses may be hugely controlled. Drip irrigation system can be used for fertilizer application that is known as "fertigation". Fertigation or the use of irrigation system to apply fertilizers to crop, has gained popularity in recent years, because it was demonstrated that it is possible to use N fertigation for high yield with minimum nitrate leaching (Mohammad et al., 2002). As indicated by other authors (Mohammad et al., 2002), this irrigation method restricts deep percolation losses and can be most effective for prevention of nitrate losses.

However irrigation appears to be also the most important factor in reducing potential for nitrate leaching. Schedule irrigation appropriately by monitoring soil water content and crop water use and right time water applications reduce nitrate leaching from irrigated fields (Seelig and Nowatzki, 2001).

3.4 Fertilizers and nitrate leaching

The results of study in Mediterranean part of Slovenia clearly demonstrated that fertilizer application rate have a significant influence on the amount of nitrate leached out of the root zone. On the experimental field, amount of applied N fertilizer was less then is recommended by technology. Fertilizer application was done in autumn or spring. The greatest concentration of nitrate was found in drainage water after the fertilizer application (Figure 1). The highest nitrate concentration of the study period was 94.4 mg $N\text{-}NO_3$/l found in drainage in the end of October. The lowest nitrate concentration (1.09 mg $N\text{-}NO_3$/l) was measured in December. Ninety-two percent of samples had nitrate concentration higher than the limit value for good groundwater chemical status (50 mg NO_3^-/l) (Podgornik, 2003).

Study in the early 1900s showed that many farmers planted legumes in their crop rotation to replenish soil nitrogen (Bundy et al.,1994). But after the Second World War application and availability of mineral nitrogenous fertilizers increased and demand for forage crops led to a significant reduction in crop rotations and a general substitution of purchased nitrogen for biological nitrogen (Dinnes et al., 2002). Since that time nitrogen fertilizer use has increased rapidly. One reason for the increase has been fertilizer nitrogen's low price relative to the value of the crop (Mihelič, 1997). These changes increased the amount of nitrate leached from agricultural soil.

Nitrate leaching from fertilizer use depends upon the fertilizer types (ammonium, nitrate or organic), method of application, and climate condition. Nitrate leaching may be greater when fertilizer contains the nitrate compared to the situations where ammonium nitrogen is the major component of a fertilizer (Bhumbla, 2006). Animal manure N provides many physical, chemical and biological benefits to soil, but on the other side, in mineral fertilizers nutrients are more readily available for plant uptake.

Either the N source is animal manure or commercial N fertilizer, over-application or ill-timed-application, either source can provide too much plant-available N and increase the potential for nitrate leaching (Addiscott, 1996). Nitrate losses are likely to be higher when all nitrogen is applied in one application compared to when nitrogen is applied in split applications. Nitrate losses from fertilizer use can be reduced by matching fertilizer application with nitrogen needs of a crop (Bhumbla, 2006).

Slovenian national statistical data show that fertilizer and nitrogen consumption has slightly decreased since the year 1998 (Globevnik et al., 2006), but in large part of Slovenia, farmers still use excessive amount of fertilizer, chiefly in the lowland plains, which offer the highest intensity of agricultural production. This confirms also a balance of nitrogen, which in other words means excessive use of fertilizer, calculated for individual areas as a weighted average for second level hydrogeographical areas in Slovenia. The highest surplus, (more than 120 kg N/ha per year) appears toward the east of Slovenia - lowland plains, meanwhile the lowest surplus of nitrogen (less than 80 kg N/ha per year) appears toward the west part of Slovenian hilly area (Globevnik et al., 2006).

3.5 Agricultural crops affect nitrate leaching

Due to significant difference between natural and agricultural ecosystems, the object of study in central part of Slovenia on Ljubljana filed (average annual rainfall 1400 mm) was to quantify the nitrate leaching from natural land never has been ploughed or fertilized (Karahodžič, 2006; Gvardjančič, 2006).

Percolated soil water has been sampled in a lysimeter on a depth of 2.5 m below soil surface. In a study period 2002-2005 the majority of nitrate leaching was related to several precipitation events. Nitrate concentration in percolating water showed variations among years (Figure 6).

During the first year of the study (2002), the maximum nitrate concentration in percolated water was very low (8.18 mg NO_3^-/l). In October 2003 nitrate concentration in percolating water drastically increased (33.66 mg NO_3^-/l). The highest nitrate concentration (37.80 mg NO_3^-/l) of the study was observed during the spring 2005. Furthermore samples collected in April 2005 exceeded also the recommendation for good groundwater chemical status (25 mg NO_3^-/l). Reasons may be addressed to the atmospheric N input.

In order to increase the yield of agricultural crops, addition of N fertilizer to agricultural ecosystem has markedly modified the N cycle (Sprent, 1987). Beside a disturbance of N cycle, also harvest is the point when arable land becomes most different from natural system. The soil is bare and there are no plants to take nitrate from the soil and balance between rainfall and evaporation is changing (Addiscott, 1996). The quantity of N removed during harvest is generally 30 to 70 percent of the total quantity of N applied as fertilizer (Hermanson et al., 2000). Nitrogen, not removed with the harvest, either remains as NO_3^- in the soil, in the remaining plant residue, or is lost to the atmosphere as either ammonia (NH_3) or elemental nitrogen (N_2) and nitrous oxide (N_2O) after denitrification.

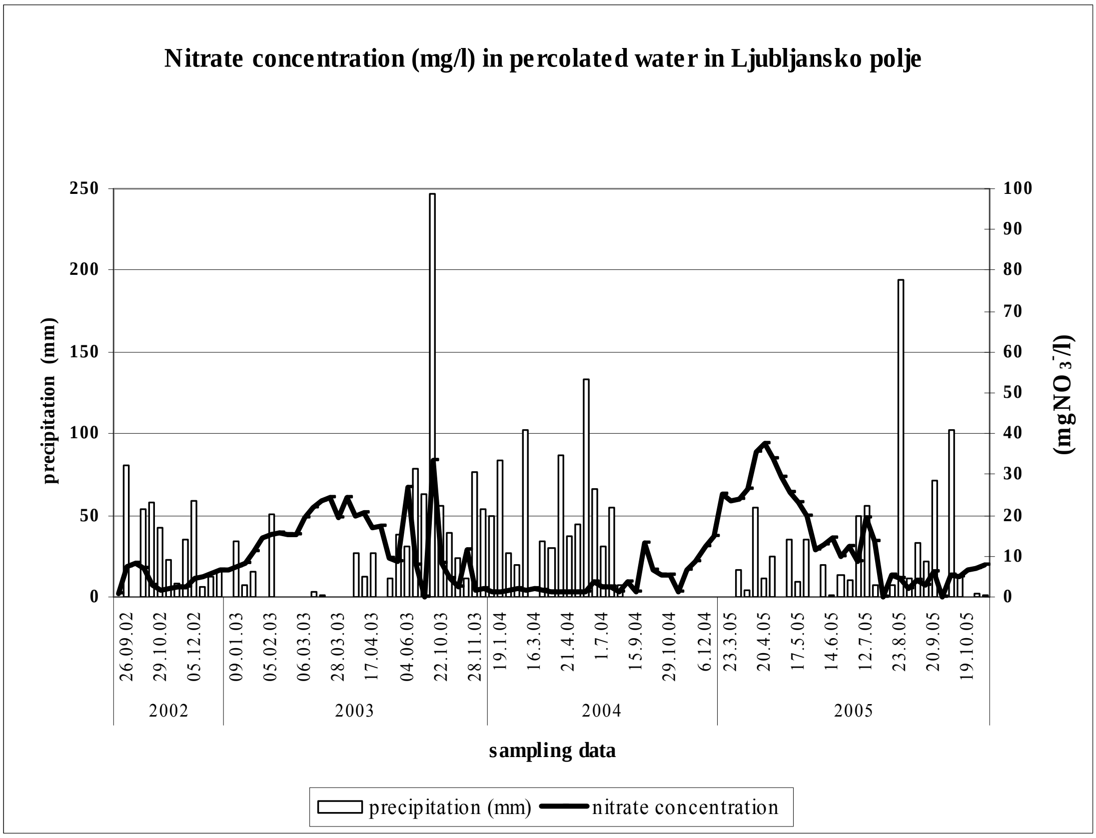

Figure 6: Nitrate nitrogen concentration (mg NO_3^-/l) in percolating water under never fertilized soil in Ljubljana field.

Due to NH_3 from agriculture activities and emission of NOx from combustion process, the atmospheric N input to natural system in Europe and North America has increase dramatically during the last decades. Natural systems of vegetation usually have small concentrations of nitrate in the water draining from soil (Addiscott, 1996). Forest ecosystem may accumulate considerable amounts of N in biomass and soil organic matter, but there is an increasing concern that forest ecosystems may be overload with N from atmospheric deposition. Indeed, increased leaching of nitrate has been observed in several areas of high N deposition (Gundersen and Bashkin, 1994).

The great diversity exists also within and between nitrogen cycles of natural ecosystems (Gundersen and Bashkin, 1994). According to data nitrate leaching in natural coniferous forests is less than 1kg N/ha/year (Hauhs and Wright, 1986), somewhat higher in deciduous forests, but still less than 2-3 kg N/ha/year. The amount of nitrate-N leached from natural background in one year (never ploughed or fertilized) in Ljubljana differed between 9 kg/ha (2003) and 15 kg/ha (2004).

4 CONCLUSIONS

Comparison of nitrate concentration in soil water of different agricultural practices and nitrate concentration in percolating soil water of natural background indicates that change from natural habitat to intensive agricultural practice leads to increased nitrate losses and pollution risks. Nitrogen fertilizers can supply large quantities of N to arable soils but also increase the amount of nitrate at risk to leaching.

In arable cropping systems with annual crops, receiving N applications in excess of agronomic rates, leaching of nitrate during winter is difficult to avoid under many conditions where precipitation are available during the non-growing season. Soils may contain substantial amounts of nitrate during this period, but crop uptake is small and rainfall exceeds evaporation. During this period the greatest quantities of nitrate are leached from arable soils.

Although Slovenian areas of intensive agricultural have different soil characteristics, different rainfall regime and agricultural practice their nitrate leaching regime appears to be similar and related in majority to the precipitation and fertilization.

Fertigation is a good way to minimise the leaching of nitrate. Improved crop water supply during dry periods also enhances crop production and often increases nitrogen uptake from the soil. Not only scheduling of irrigation, but also split application of N fertilizer and proper time of application is necessary for good N management practices that will reduce nitrate leaching.

Cover crops that would take up mineral N and reduce soil nitrate, accumulated by the beginning of spring, can also reduce the risk of nitrate leaching. The high soil nitrate accumulation during autumn and winter can be reduced by growing winter cover crops which take up N during the wet season when leaching is likely.

But nitrates, moved downward by leaching, can come from many sources, not necessarily just from fertilizers. Natural source includes nitrate incorporated in rock or nitrate from atmospheric deposition. So modest amounts of nitrate also are leached from soil under natural conditions or from undisturbed soil that are well-covered with native vegetation.

5 REFERENCES

Action programme for protection of waters against nitrate pollution from agricultural sources for the period 2004-2008 (adopted by the Slovenian Government on April 15, 2004. RS, no.354-01-24/2004.

Addiscott T. M., 1996. Fertilizers and nitrate leaching. Environmental Science and Technology 5, 1-26.

Bijay-Singh, Yadvinder- Singh, Sekhon G.S., 1995. Fertilizer–N use efficiency and nitrate pollution of groundwater in developing countries. Journal of Contaminant Hydrology 20: 167-184.

Bugar S., 1999. Ogroženost in varovanje vodnih virov pred nitratnim onasneževanje. Ogrožanje vodnih virov in naravne snovi v pitni vodi. Ljubljana, Zbornik predavanj: 125 – 152.

Bundy L.G., Knobeloch L., Webendorfer B., Jackson G.W. and Shaw B. H., 1994. Nitrate in Wisconsin Groundwater. Sources and Concerns UW-Extension publication number G3054, 8 pp.

Bhumbla D.K., 2006. Agriculture Practices and Nitrate Pollution of Water, http://www.caf.wvu.edu/~forage/nitratepollution/nitrate.htm 27.9.2006.

Cameria M.R., Fernando R.M., Pereira L.S., 2003. Monitoring water and NO_3-N in irrigated maize fields in the Sorraia watershed. Agricultural Water Management 60: 199-216.

Casey F.X.M., Derby N., Knighton R.E., Steele D.D., Stegman E.C., 2002. Initiation of Irrigation Effects on Temporal Nitrate Leaching. Vadose Zone Journal 1, 2: 300-309.

Cepuder P., Shukla M.K., 2002. Ground nitrate in Austria: a case study in Tullnerfeld. Nutrient Cycling in Agroecosystem, 64: 301-315.

Dinnes D. L., Karlen D.L., Jaynes D.B., Kaspar T.C., Hatfield J. L., Colvin T.S. and Cambardella C.A., 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils, Agronomy Journal, 94: 153-171.

Doran J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Science Society of America Journal. 44: 765-771.

Gaines T.P. Gaines S.T., 1994. Soil texture effect on nitrate leaching in soil percolates. Communications in Soil Science and Plant Analysis 25, 13&14: 2561–2570.

Globevnik L., Pintar M., Bremec U., 2006. Cross compliance of Water Faremwork and Nitrate directives in Slovenia , Acta agriculturae Slovenica 87, 1: 69-78.

Gvardjančič D., 2006. Izpiranje nitratov skozi talni profil v vodarni Kleče. Graduation thesis. Biotechnical Faculty: 31 pp.

Gundersen P., Bashkin V.N., 1994. Biogeochemistry of Small Catchments. A tool for environmental research, New York, John Wiley & Sons: 420 pp.

Hadas A., Sagiv B., Haruvay N., 1999. Agricultural practices, soil fertilitymanagement modes and resultant nitrogen leaching rates under semi-arid conditions 42, 1: 81-95.

Hauhs, M. Wright, R.F., 1986. Regional pattern of acid deposition and forest decline along across section through Europe. Water, Air, & Soil Pollution 31: 463-474.

Hermanson R., Pan W., Perillo C., Stevens R., Stockle C., 2000. Nitrogen use by crops and the fate of nitrogen in the soil and vadose zone: A Literature Search Washington State University and Washington Department of Ecology. 248 pp.

Jalali M., Rowell D.L., 2003. The role of calcite and gypsum in the leaching of potassium in a sandy soil, Experimental Agriculture 39: 379-394.

Karahodžič M. 2006. Dinamika izotopov dušika v nitratih v naravnem ozadju Ljubljanskega polja. Master of science thesis. Department of Geology, Faculty of Natural Sciences: 92 pp.

Leskošek M., 1993. Gnojenje. Ljubljana, Kmečki Glas: 197.

Leskošek M., 1994. Impact of fertilization on environment (Vpliv gnojenja na okolje). Okolje v Sloveniji, Ljubljana, zbornik, Tehnična založba Slovenije: 451-455.

Matičič B., 1998. Agricultural threats to pollution of water in a Karst region in Slovenia. International workshop on Protection of natural resources in agriculture of central and eastern Europe. Kralupy nad Vltavou and Prague- Zbraslav 30. Nov to 7 Dec. 1998. František Doležal. - Prague: Research Institute for Soil and Water Conservation:173-180.

Mihelič R., 1997. Vpliv dušika: kmetijstvo in varovanje tal. Kmečki glas. 54, 14: 12.

Mihelič R., Kastelec K., Ruprerht J., 2002. Determination of zones in Slovenia with potential risk of soil percolate contamination with nitrate-nitrogen. New challenges in field crop production 2002, Zreče 5-6 Dec. 2002, Ljubljana, Tajnšek A., Šantavec I., Ljubljana Slovenian Society of Agronomy: 196-200.

Mohammad E.A., Roberto S.C., Ashim G., Rainer L., Gunner K.H., 2002. Impacts of fertigation via sprinkler irrigation on nitrate leaching and corn yield in an acid-sulphate soil in Thailand, Agricultural Water Management 52, 3: 197-213.

Pintar M., Mihelič R. Pikel M., Lobnik F., 1996. Monitoring of nitrate and athrasyne pollution of underground and surface water in the valley of Apače. New challenges in field crop production'96, Ljubljana 9-10 Dec 1996. University of Ljubljana, Biotechnical Faculty, Agronomy Department:105-110.

Pintar M., 1999. Nitratni ion v pridelovanju in predelovanju hmelja. Ljubljana, Vodnogospodarski inštitut: 72 pp.

Podgornik M. 2003. Nitrate leaching from drained soil in Slovene primorje. Graduation thesis. Biotechnical faculty: 66 pp.

Pratt P.F., Adriano D.C., 1973. Nitrate concentrations in the unsaturated zone beneath irrigated fields in southern California, Soil Science Society of America 37:321-322.

Rivers C.N., Hiscock K.M., Fast N.A., Barrett M.H., Dennis P.F., 1996. Use of nitrogen isotopes to identify nitrogen contamination of the Sherwood sandstone aquifer beneath the City of Nottingham, UK, Journal of Hydrology 4, 1: 90-102.

Seelig B.D., Nowatzki J., 2001. Working to Avoid Nitrogen Contamination. North Dakota State University, Fargo, ND 58105. (24. Aug. 2006) http://www.ext.nodak.edu/extpubs/watnut.htm (29.Sep.2006)

Skopp J., Jawson M.D., Doran J.W., 1990. Steady-state aerobic microbial activity as a function of soil-water content. Soil Science Society of America Journal. 54:1619-1625.

Spalding R.F., Exner M.E., 1993. Occurrence of nitrate in groundwater Journal of Environmental Quality 22: 392-402.

Sprent J.I., 1987. The Ecology of the Nitrogen Cycle. Cambridge University Press, 151 pp.

Ward M.H., Zahm S.H., Blair A.,1994. Dietary factors and non Hodgkin's lymphora. Cancer Causes Control 5, 5: 422-432.

Wu J.J., Bernardo D.J., Mapp H.P., Geleta S., Teague M.L., Watkins K.B., Sabbagh R.L., Elliott R.L., Stone J.F., 1997. An evolution of nitrogen runoff and leaching potential in the high plains. Journal of Soil and Water Conservation 52: 73–80.

WHO, 1993. Guidelines for drinking water quality. 1. Recommendations, second ed. World health organization, Geneva.