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Assessment of the influences of climate variability on nitrogen leaching rate into groundwater

Ocena vplivov podnebne spremenljivosti na stopnjo izpiranja dušika v podzemno vodo

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Abstract
This article presents preliminary model results of climate change impact on biogeochemical processes in soil. With the use of DNDC (DeNitrification-DeComposition) model, a simulation with climate data over seventy years period (1947–2016) from central part of Slovenia has been carried out. Amongst assessed sources of variability, time variability has been estimated to around 10% of the total annual nitrogen leaching. In some cases, a statistically significant downward trend was observed with a 5 kg reduction in nitrogen per hectare in seventy years period. This study represents the first quantitative assessment of nitrogen leaching variability due to precipitation and air temperature variability in three representative soil profiles in the central Slovenia. It offers a starting point for future regional research for the purpose of farming practice optimization, especially in catchment areas of major regional water resources in Slovenia.

Key words: climate variability, denitrification, nitrogen leaching

Izvleček
Članek predstavlja preliminarne rezultate modeliranja vpliva klimatske spremenljivosti na biogeokemične procese v tleh. Na simulacijah z modelom DNDC (De-Nitrification-DeComposition) so bili v sedemdeset-letnem obdobju (1947–2016) za osrednjo Slovenijo ocenjeni posamezni viri variabilnosti letne količine izpranega dušika, med katerimi zavzema časovna spremenljivost okoli 10%. V nekaterih primerih je bil ugotovljen statistično značilen trend zniževanja s 5 kilogramskim zmanjšanjem dušika na hektar v sedemdesetletnem obdobju. Študija predstavlja prvo kvantitativno oceno spremembe izpiranja dušika v treh reprezentativnih profilih tal v osrednjem delu Slovenije zaradi spremenljivosti padavin in temperature zraka ter ponuja izhodišče nadaljnjim regionalnim raziskavam za potrebe optimizacije kmetijske prakse, predvsem na prispevnih območjih pomembnih regionalnih vodnih virov v Sloveniji.

Ključne besede: podnebna spremenljivost, denitrifikacija, izpiranje dušika

Introduction

Groundwater is a dominant source of public water supply in Slovenia [1]; the inalienable right to drinking water is also enshrined in the Constitution of the Republic of Slovenia [2]. With this definition, our society has accepted responsibility and a clear commitment to preserve natural water resources for the sustainable water supply. The quantitative status of all groundwater bodies in Slovenia is assessed as good with the share of yearly pumped water quantity being only 3,1% of long-term available groundwater quantities [3]. Groundwater chemical status, however, has been assessed as poor in three groundwater bodies, mainly due to exceeding nitrate threshold value [4]. Groundwater quantities in water bodies with poor chemical status exceed quantities of yearly pumped groundwater in the country. Knowing the variability of the effects of individual processes in the nitrogen cycle is therefore crucial for the planning of measures to reduce nitrate pollution, with a simultaneous need for sustainable agriculture in varying climatic conditions [5].

The first projection of nitrogen leaching into the groundwater, taking into account climate change, was prepared for individual regions of Slovenia within the framework of the *Climate change and impacts on water supply "CC-WaterS"* [6] project. Given the great uncertainty of the results of climate models (ALADIN, RegCM3, PROMIS), the simulation of nitrogen leaching with the dynamic and process-based model NDICEA (unchanged land use and agricultural technologies) [7] indicated only a slight impact of climate change on the period 2021–2050 on the extent of nitrogen leaching.

In the framework of the reporting by the Republic of Slovenia under Article 10 of the Council Directive 91/676/EEC concerning the protection of water against pollution caused by nitrate from agricultural sources for the period of 2012–2015 [8], the model-based system GROWA – DENUZ / WEKU [9] was used to model the nitrate flux through the root zone of the soil. The importance of speed and quantity of seepage water or water balance was highlighted. Time variability of annual averages of nitrate content in seepage water, which was estimated at up to 20 mg NO_3/l by individual groundwater bodies during the period 2007–2014, was otherwise associated to hydrological conditions. The effects of climate parameters on the denitrification in soil and on the rate of nitrate leaching have, however, not yet been assessed.

One of the most comprehensive overviews of denitrification simulation tools describes over fifty numerical modelling approaches [10]. The selection of the proper approach that will used in a study depends on scientific and management perspectives [11]. The most frequently used approach in Europe is a regional assessment of the impact of management practices that provides support to the implementation of the European Directives. However, the models are frequently not able to accurately represent the spatial variability of the denitrification process [12]. One of the most recent studies of the climate impact on denitrification for four districts in the Upper Danube catchment for the years 1996–2005 and 2011–2060 uses regional DANUBIA simulation system approach and shows that climate changes alone will not lead to serious changes in nitrate leaching [13]. One of the mainstream tools for exploring denitrification in terrestrial soils is the denitrification–decomposition (DNDC) model [14], which can be applied in regional as well as field site scales.

Data and methods

Using the site model DNDC [14], simulations of biogeochemical processes in the root zone of the soil were conducted for two farming scenarios [15] carried out on three representative pedological profiles [16] of the shallow aquifer layers of lower Savinja Valley. Seventy years (1946–2016) of daily climate data was used to assess the impact of climate change on the denitrification in soil and the annual rate of nitrogen leaching.

Study area

Lower Savinja Valley is an 80 km^2 large alluvial aquifer (Figure 1), represented by gravel-sandy medium to poorly permeable Pleistocene and well-permeable Holocene aquifer. There are three main terraces along the Savinja river – the lower terrace is covered with shallow eutric flu-

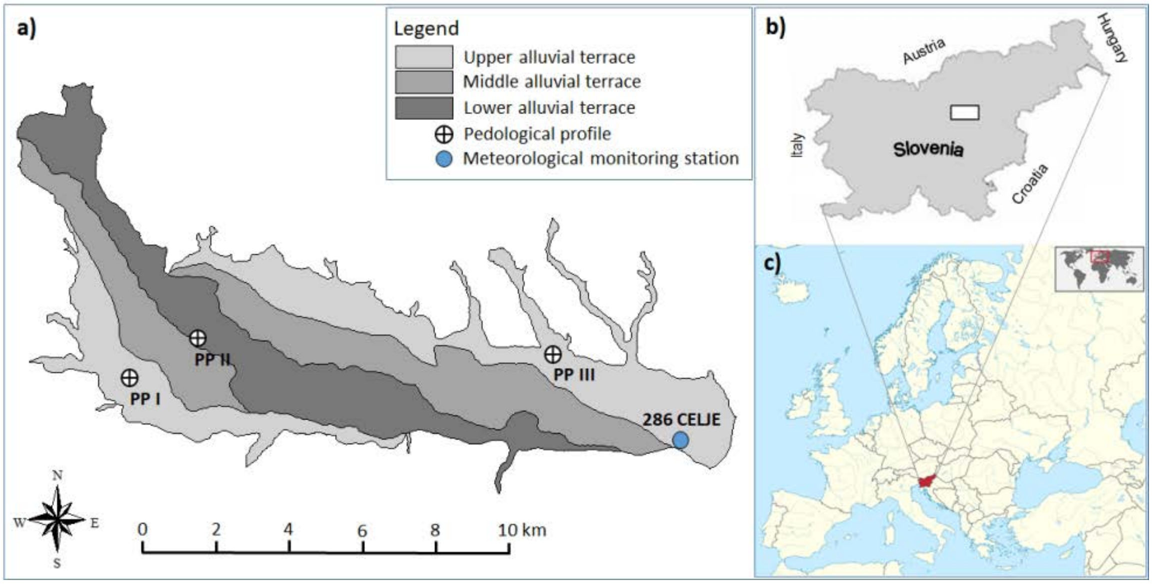

Figure 1: *Study area of Lower Savinja Valley (a), position of the study area on the map of Slovenia (b) and position of Slovenia on the map of Europe (c).*

visoil; the middle terrace on both banks of the river is covered with eutric cambisoil; and the upper terrace is covered with poorly permeable eutric gleysoil (Figure 1). Approximately half of the study area is in agricultural use, dominated by meadows, pastures, fields, gardens, as well as hopfields. The national monitoring of groundwater quality in the water management plan 2016–2021 defined the groundwater chemical status of this water body as poor, due to exceeding nitrate threshold value [1]. This water body also includes regionally important water-supply resources.

Climate data

The area of Lower Savinja Valley has the characteristics of moderate continental climate of central Slovenia [17] with peak rainfall in the summer and a great difference between winter and summer air temperatures. The Meteorological Station 268 CELJE in Medlog (Figure 1) measured the annual precipitation in the period from 1947 to 2016, ranging from 669 to 1407 mm, with the average of 1042 mm [18]. The spread between the driest and the wettest year is as much as 738 mm, and the standard deviation is 142,7 mm. This exceeds the monthly rainfall in the average vegetation period in this area. Additional to the high variability in rainfall, we also discovered great variability in air temperature, which determines the duration of the vegetation period and significantly increases the level of denitrification in the soil. In the analyzed period of seventy years, the average of the maximum daily temperatures was 15,6°C, and the average of the minimum daily temperatures was 4,3°C. The duration of the period with an average daily temperature above 5,0°C, which is the threshold of determining vegetation period, has changed greatly over the years. According to these temperature data, the start of the vegetation period ranged from mid-March to mid-April, while the end of the vegetation period ranged from mid-October to mid-November.

Pedological profiles

There are three generalized groups of soil in the study area: eutric fluvisoil, cambisoil and gleysoil. Three representative soil profiles were selected for modeling of nitrogen leaching from the soil: the Trnava profile (PP I), Orla vas profile (PP II), and Arja vas profile (PP III) (Figure 1). Input model data on pedological characteristics were drawn from the database of the pedological map of Slovenia [19], as well as from the national database of research on soil contamination in Slovenia [20]. To assess the hydraulic properties of the soil, we relied on the SAXTON [21] and the SWAP model [22], with the latter already being tested in Slovenia on the soil of the grass lysimeter site of the Biotechnical Faculty in Ljubljana [23].

Farming scenarios
As the modeling of nitrogen leaching from the soil should primarily assess the impact of climate change on the denitrification process, we selected two simplified annual recurrent scenarios of farming practice. The first scenario (FS I) was an example of the prevailing extensive agricultural land use. The second scenario (FS II) was an example of the most intensive agricultural land use with the foreseen use of mineral fertilizers in the annual amount of 180 kg N per hectare. Model-needed data on plants were taken from the DNDC model data library [21].

Model approach
The DNDC model [14] was used to assess the impact of climate change on the level of nitrogen leaching from the root zone of soil profile, which simulates the processes between the main nitrogen pools, including denitrification (Figure 2).
The DNDC model represents the link between the environmental driving forces and the outputs from the nitrogen cycle of the soil in the form of biomass, gases and leaching. Model processes are driven by primary ecological driving forces: climate, soil and vegetation, and farming practices. The DNDC model consists of two components that solve the equations of the soil climate by calculating the water outflow and the equations of biogeochemistry of nitrogen in the soil. The first model component consists of three sub-modules: soil climate, vegetation growth and decomposition. Based on climate, soil, vegetation and farming activities data, this component enables assessment of the following soil factors: soil temperature and moisture, pH and oxidation-reduction potential, and content of substrates. The second component consists of nitrification, denitrification and fermentation submodels, enabling the simulation of the emission of gases from the soil-plant system. The DNDC model incorporates the classical laws of physics, chemistry and biology as well as empirical equations from field and laboratory studies, thus representing

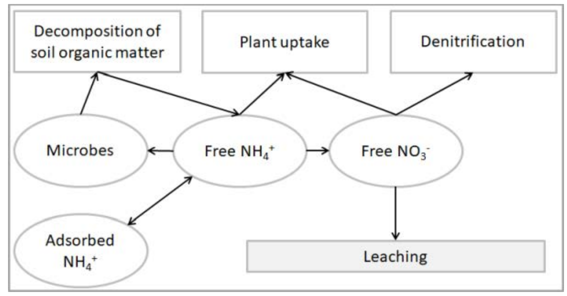

Figure 2: *Major nitrogen pools and fluxes simulated in DNDC [24].*

the connection between the carbon and the nitrogen biogeochemical cycles and primary driving forces. The simulation results of the DNDC model, applied to the study area of the Lower Savinja Valley, were evaluated by comparison to the results of the measurements of the field experiment in 2000 and the parallel simulation of nitrogen leaching in the GLEAMS model [25, 26]. The trend analysis [27] and analysis of variance [28] were performed on the timeline of the model simulations results.
The estimation of trends in time series of annual values is based on the nonparametric approaches. The presence of a monotonic increasing or decreasing trend is tested with Mann-Kendall test and the slope of a linear trend is estimated with Sen's method. These methods offer many advantages that have made them useful in analyzing climate and related data [27].

Results and discussion

The average daily air temperatures at the national meteorological monitoring station 268 CELJE in Medlog in the period 1947–2016 indicate a significant upward trend of about + 1,8 °C. A significant upward trend is also calculated for average annual minimum and maximum air temperatures. The average annual minimum air temperatures are among the most important restrictive environmental conditions for the denitrification process, and they have increased at this monitoring station with a statistically significant trend (α = 0,01) from 3,0 to 5,5 °C (Figure 3a) during the same time period. Statistically significant decrease in precipitation during the vegetation season is typical mostly for the northwestern part and

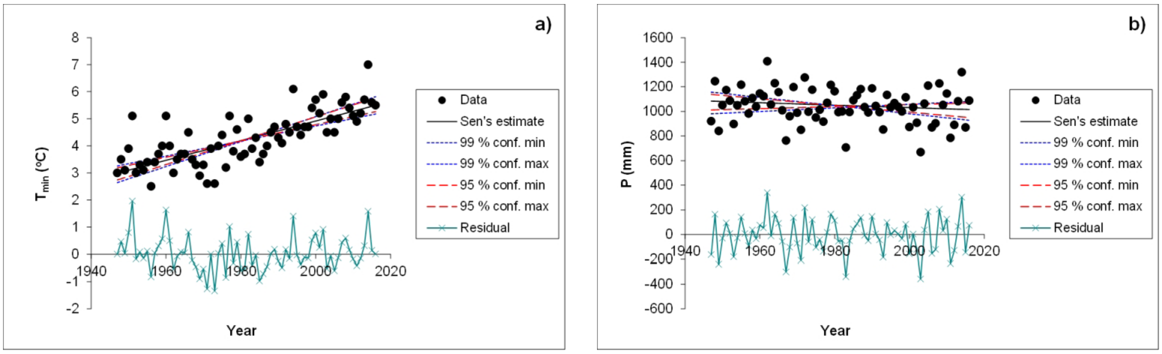

Figure 3: *Trend of average annual minimum air temperature (a) and annual precipitation (b) at the meteorological monitoring station 268 CELJE in Medlog in the period 1947–2016.*

Table 1: *Statistics of DNDC model results of the annual nitrogen leaching simulation in kilograms per hectare in the period 1947–2016.*

Pedological profile (PP)	PP I (Trnava)		PP II (Orova vas)		PP III (Arja vas)	
Farming scenario (FS)	**FS I**	**FS II**	**FS I**	**FS II**	**FS I**	**FS II**
Xmin	0,7	8,9	1,2	6,9	0,6	3,6
X max	6,4	39	8,8	34,7	4	14,2
Mean	2,4	24	4,2	21,3	2,1	9,6
Standard deviation	1,3	6,4	1,7	5,9	0,8	2,4
Trend Z-test	α > 0,1	α = 0,1	α > 0,1	α = 0,1	α > 0,1	α > 0,1

the southern edge of the country [4]. The meteorological monitoring station in Medlog, however, shows a negative trend line for the period 1947–2016, which is not statistically significant neither at the annual level (Figure 3b), nor for the level of the vegetation season, mainly due to the high variability. With these findings, the potential evapotranspiration statistically increased and impacted the amount of water in the soil, as expected. In some parts of southwestern and northeastern Slovenia, potential evapotranspiration increased by as much as 20% or more [4].

Seventy annual simulations were carried out on two representative pedological profiles (PP) for two farming scenarios (FS), accounting for 420 model launches. This gave us a satisfactory insight into the time variability of the impact of climate change on denitrification in the case of six scenarios of an agriculturally heavily burdened area in Slovenia.

The leaching of nitrogen in the case of the first two pedological profiles of more permeable cambisoil and fluvisoil deviates from leaching in the case of third pedological profile represented by gleysoils. On average, this is the difference between the annual quantity of 24 kg in the case of the pedological profile I and 9,6 kg N per hectare in the case of the pedological profile III (Table 1). Even greater differences, however, occur between the scenarios of extensive and intensive farming practice, as evidenced by the two-level nested analysis of variance. In addition to the variability between the scenarios of farming practice and the variability between pedologic profiles, our main interest in the hierarchical scheme lied in the third level of variability: the time variability of the annual amount of nitrogen leaching per hectare, calculated by the model simulation of DNDC. Taking into account the entire time period from 1947 to 2016 (n = 70), time variance compo-

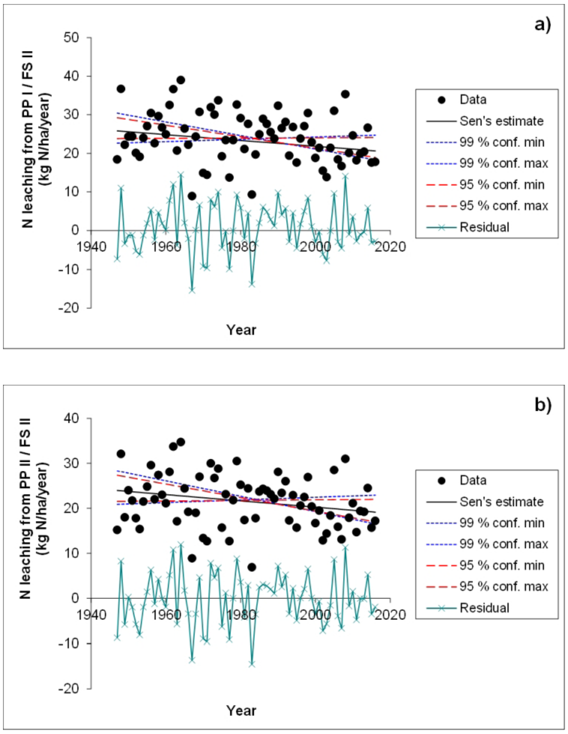

Figure 4: *Statistically significant trend (a = 0,1) of annual nitrogen leaching per hectare in the pedological profile PP I (a) and pedological profile PP II (b) while taking into account intensive farming scenario (FS II).*

nent reached 9,6%. However, this percentage drops to 8,0% of total variability of the selected three-level variance scheme when taking into account only the last water balance period from 1981 to 2010 (n = 30).

In addition to the share of the variability of nitrogen leaching, which may be contributed by the time and climate variability, the information about the annual nitrogen leaching quantity trend for individual scenarios of farming practice and for individual pedological profiles is also of strategic importance in the long-term. In all six scenarios, the trend analysis of the annual quantity of leached nitrogen reveals statistically significant downward trends ($\alpha = 0,1$) only in the case of intensive farming practice (FS II) on cambisoil (PP I) and fluvisoil (PP II) (Figure 4). Based on the Sen's estimation, we can speak of reduction of the annual leaching quantity by 5,2 kg N per hectare for the first case (PP I / FS II), and by 4,8 kg N per hectare for the second case (PP II / FS II).

Conclusions

A positive trend of air temperature by 2,5°C was observed for the period 1947–2016 in the research area of central Slovenia. This is within the range of 1,1 to 6,4°C, which is the increase of global air temperature in the 21st century, predicted by the Intergovernmental Panel on Climate Change - IPCC [29]. We did not detect a statistically significant trend in the annual precipitation in the study area. This is also in line with the findings of the IPCC report, which foresees changes in the precipitation pattern in the 21st century, with more frequent and intense but short-term precipitation events.

The influence of climate variability on denitrification and nitrogen leaching from the root zone of the soil in the study area of the Lower Savinja Valley was assessed by modeling the scenarios of extensive and intensive farming practice on representative pedological profiles. Three-level nested analysis of variance revealed only 9,8 % of the variance for the entire analyzed time period. This can be attributed to climate variability. For remaining variability, the reasons need to be found in the farming practices, types of vegetation and soil properties. Statistically significant trends in the annual amount of leached nitrogen per hectare of agricultural area were found in the case of intensive farming practices in more permeable eutric cambisol and fluvisoil. A decrease in the annual quantity of leached nitrogen by 4,8 kg in the first case and 5,2 kg of nitrogen per hectare of agricultural area in the second case of model simulation was estimated with a relatively poor statistical significance for a period of 70 years (1947–2016).

The influence of the variability of climate parameters on soil denitrification and the level of nitrogen leaching in the three selected soil profiles of the study area in the central part of Slovenia is not negligible, however, the annual levels do not indicate the significance of a long-term increase in nitrogen leaching. The future studies should be extended to the regional level and should estimate the time variability of nitrogen leaching in climatically very diverse and extreme areas of the territory of Slovenia. The results of such research could provide the basis for planning of optimal farming practices in areas which are in the wider zones of aquifers with significant quantities of groundwater for public supply of drinking water.

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