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The influence of permanent grasslands on nitrate nitrogen loads in modelling approach

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Abstract

The water pollution in areas with intensive agriculture is growing rapidly. Computer model is a tool which can help in finding solutions for water pollution reduction and help in creation of catchment management plans. In this research the SWAT model (Soil and Water Assessment Tool) was used to test the influence of introduction of permanent grasslands into the catchment on nitrate nitrogen load in surface water. Small catchment of upper Zgłowiączka River in central Poland with intensive agriculture was chosen as a test site. Model was fed with data about land use, soils, weather, elevation and management practices and calibrated and validated using flow data and nitrate nitrogen loads data. Then 2 scenarios with land use change were tested. A part of arable land was changed into permanent grasslands. The results show that permanent grasslands are effective in reducing nitrate nitrogen load. The load was reduced by 19% when permanent grasslands constituted 10% of arable land and by 38% with permanent grasslands taking up 20% of arable land.

Key words: *land use, modelling, nitrogen, permanent grasslands, SWAT, water pollution*

INTRODUCTION

The problem of clean water will be one of the biggest problems for mankind in the future. There are many sources of water pollution and many substances that influence water quality. It is quite easy to deal with point sources of water pollution, but much harder with diffuse ones. One of the most important diffuse source of pollution is agriculture. Nitrogen from agriculture is transported into water and increasing its eutrophication. In Poland 50–60 % of nitrogen flowing to the Baltic Sea originates from agriculture [DUER *et al.* 2004]. Eutrophication manifests itself in increased organic matter production, reduction of light accessibility and oxygen shortage [FORSBERG 1991]. It is a dangerous process because it leads to decrease in biodiversity.

According to the Water Framework Directive Poland is obliged to provide normative quality of all

water resources till 2015. There are many mitigation strategies to prevent water pollution. Unfortunately it is hard to measure the impact of management changes on water pollution in larger scale. Field experiments are expensive and possible to conduct in small scale. According to LAURENT [2011] for research in catchment scale there is a need to use physical models for evaluation of different solutions. Models can represent the variety of reactions between environmental components. Modelling is used mostly for forecasting of phenomena which are complicated and depending on many different factors. In Polish conditions, as reported by SKORBIŁOWICZ [2010], attempts to build models to predict the concentration of minerals in the water are rarely undertaken.

Agriculture contributes to an increase in the amount of nutrients, pesticides and heavy metals in environment. There are some ways to limit this influence and improve the state of ecosystems. One of the

ways, considered as priority in contemporary world, is sustainable development [KUKUŁA, KRASOWICZ 2007]. In Poland there is still no list of parameters characterizing the sustainable agriculture. Various authors define it in different ways, but there are some factors presented in many studies. One of them is land use. In intensive agriculture areas the scenery is monotonous while in sustainable agriculture there is not only arable land but the landscape is diverse, with parts of land used less intensively. As studies of various authors show [JANKOWSKA-HUFLEJT 2006; SAWICKI 2006; HARASIM 2009; MORACZEWSKI 2006] the presence of permanent grasslands in catchment has a great influence on the amount of biogens flowing to surface water. As JANKOWSKA-HUFLEJT [2007] reports permanent grasslands are the best biological filters from agricultural land use types.

This article describes an attempt to test the influence of land use diversification on nitrate nitrogen loads in surface water. The tested change is to implement to the catchment permanent grassland replacing part of arable land. It is assumed that increasing the amount of permanent grasslands in the catchment will decrease the nitrate nitrogen load in surface water.

MATERIAL AND METHODS

The research shown in this paper was conducted in the small catchment in central Poland (Fig. 1). The Zgłowiączka River is a left tributary of the Vistula River and the tested part of catchment has an area about 100 km². Administratively the area is located in Kujawsko-Pomorskie province and lies within the four municipalities: Dobrze, Osiecin, Bytów and Topólka in the Radziejowski county. The area of catchment is characterized by very high quality of agricultural production space, due to high quality of soils. The landscape of Zgłowiączka River catchment is

typical for intensive agriculture areas: almost forestless and arable land constitutes about 90% of catchment area. The average yearly sum of precipitation is 500 mm (with average 600 mm for Poland), of which 300 mm falls during the vegetation period. Potential evapotranspiration in Zgłowiączka River catchment is 650 mm per year and in the vegetation period between 450–500 mm [ZŁONKIEWICZ *et al.* 2007]. Zgłowiączka upper basin has been recognized by the Regional Waterboard Management as an area particularly exposed (nitrate vulnerable zones) to runoff pollution. The Inspectorate of Environmental Protection conducts water quality measurements in the area. Measured concentration of nitrogen reaches 200 mg NO₃·dm⁻³ [ALABRUDZIŃSKA *et al.* 2009]. More detailed description of the catchment is presented by BRZOZOWSKI *et al.* [2011].

As research tool the SWAT 2005 [NEITCH *et al.* 2005] was used. Discussed issue in the area with intensive agriculture was the first such application in Poland [ŚMIETANKA *et al.* 2009]. SWAT is an abbreviation from Soil and Water Assessment Tool. It is a model invented in Texas, USA in the early 90. It is a combination of earlier existing tools working in a river basin scale and was developed to quantify the impact of land management practices. SWAT enables to model processes in complex watersheds, with various land use, soils and management practices. It allows predicting the impact of different management practices on water, sediment and crop yields in diverse areas with varying soil types, land use and management, and in the long term in a catchment scale. The key features that distinguish this tool among others are, according to its developers: being a physical model, the use of easily available data, computational efficiency and predicting longterm effects [NEITSCH *et al.* 2005].

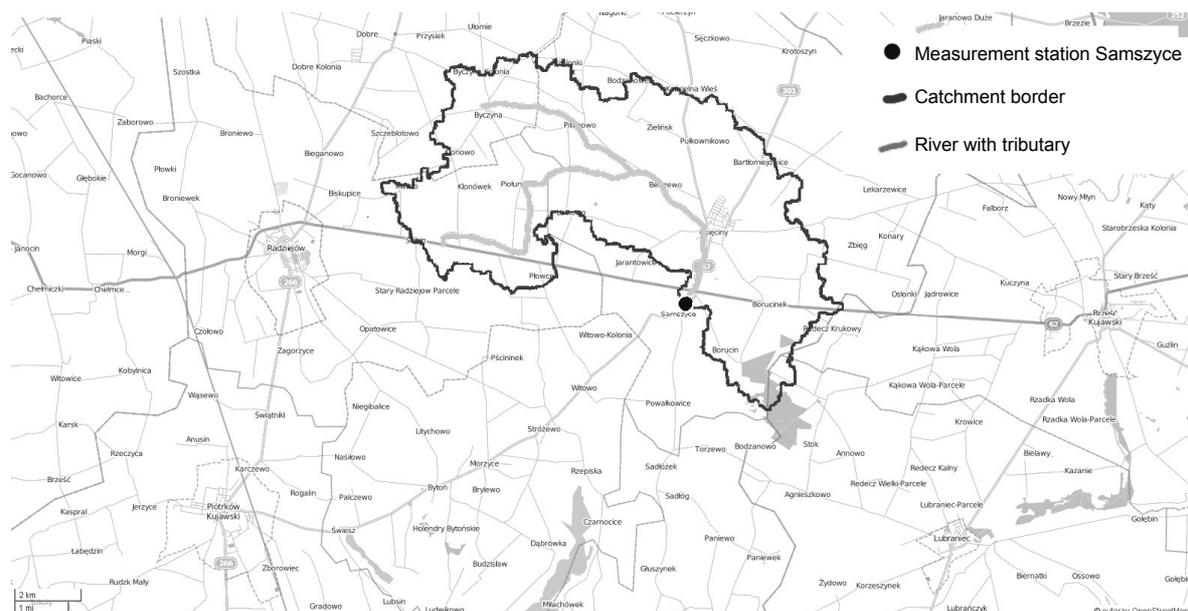


Fig. 1. Zgłowiączka catchment; source: own elaboration based on <http://www.openstreetmap.org>

A commonly used approach in studies with computer models is to create a model that reflects the actual conditions, which is then used as a point of reference, in comparison with scenarios of change developed for the specified area. In this way many authors work [LAURENT, RUELLAND 2011; LEE *et al.* 2010] and this approach was also used in this study.

The SWAT model requires a large amount of input data. Their quality has a most significant effect on the quality of the results. A diagram showing the required data and way of processing is shown in Figure 2. For the Digital Elevation Model (DEM) the image from satellite radar mission called Shuttle Radar Topography Mission (SRTM) with an accuracy of 90m was used. The soil map was created from a scanned paper map in the scale of 1:100 000 created by IUNG (Institute of Soil Science and Plant Cultivation), which was vectorized, and then geometrically corrected. The detailed information about each soil type was acquired from soil pits made by previous IMUZ Bydgoszcz Branch in frames of the grant “Pilot Implementation of the Water Framework Directive and Construction Tools for catchment management”, financed by the Norwegian Financial Mechanism. SWAT requires using a land use map. Obtaining accurate information about every field is challenging on such a scale. Therefore, to create a map for the modeling satellite image was used and enhanced with statistical data from field surveys. An image from Landsat, May 2001, was used as considered to be well suited to

distinguish between different types of land use [MIATKOWSKI *et al.* 2006]. Visual interpretation enabled to distinguish forests, urban areas, grassland and arable land. This was followed by a more detailed classification within the arable land, using statistical data from surveys. It was assumed that the surveys represent well the structure of crops throughout the studied area (the surveyed farms constituted about 70 percent of the total farm number in the study area). On this basis, the extrapolation to the whole catchment area was made. After satellite image processing, the areas were selected to specified classes representing various crops in such a way that they correspond to the surface area of statistical surveys. Result was a land use map with arable land divided into various crops. The model required also daily weather data, including maximum and minimum temperatures and rainfall. Data from the measuring station of the Institute of Meteorology and Water Management in Kołuda were used. Available data cover the period from 1 January, 1997 to 31 December, 2009. The gauging station is located outside the river basin (about 30 km from its border), but the proximity to the border area, while maintaining very similar terrain allows the use of this data. Based on consultation with the Agricultural Advisory Centre, local farmers and experts a set of management practices was developed for each plant common in the area. Practices scheduled by date were used in the model.

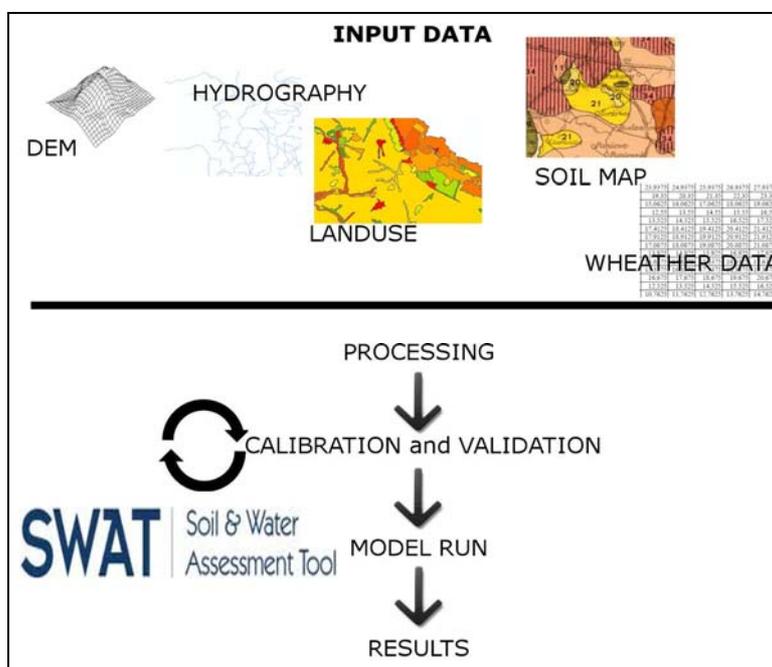


Fig. 2. SWAT model schema; source: own elaboration

Running the model with a set of required data does not guarantee obtaining the correct results. The SWAT model, like any tool of this type, requires calibration and validation. It is a process during which selected parameters are modified in a given range, to

the point where the simulation results are close to the measurement data. It is important to note that even after calibration the model is only a simplification of the real processes. For modeling of biological systems, it is difficult to speak of a single correct model

phenomena [VANHOOREN *et al.* 2003]. Therefore, according to SOCHACKI [2009] calibration target should not be to fit the model to reality but only to reduce the inconsistency between the measurements made in the field, and the simulation results. To calibrate and validate the model for the Zgłowiączka catchment measurements from the period January 1, 2007 to December 31, 2009 were used for flow and from 2001 to 2009 for nitrogen load. The calibration period was from January 1, 2007 to December 31, 2008 for flow and from 2001 to 2008 for nitrate nitrogen loads, the rest of the period was used as a validation period. The calibration was carried out in two stages. The first stage, hydrological, aims to correctness in terms of the quantity of water. Calibrated flow rates are compared with the measured data. Daily data were used. The flow rate is a variable that is most often used for the calibration of hydrological models [MORIASI *et al.* 2007]. The second stage is calibration in terms of water quality. It uses monthly measurements of nitrate nitrogen loads. For calibration purposes the program SWAT-CUP [ABBASPOUR 2011] was used. It allows modifying the parameter values in an automatic manner in the specified range. For evaluation of the results two methods were chosen. First was visual comparison of hydrographs which, according to LEGATES and MCCABE [1999], is necessary for a proper assessment of hydrograph. Also the Nash-

-Sutcliffe [NASH, SUTCLIFFE 1970] coefficient was used as a second evaluation method. The coefficient is calculated as follow:

$$NS = 1 - \frac{\sum_{t=1}^T (Q_{estimated_t} - Q_{observed_t})^2}{\sum_{t=1}^T (Q_{estimated_t} - \overline{Q_{observed_t}})^2}$$

where:

NS – Nash-Sutcliffe coefficient,

t – time,

T – total time,

$Q_{estimated_t}$ – estimated value,

$Q_{observed_t}$ – observed value.

Figure 3 shows the simulated and measured hydrograph. The grey line shows the modeled flow rates and the black measured ones, bars refer to rainfall. The chart includes a total period of calibration and validation of the model. According to WANG [2011] and MORIASI [2007] calibration results can be considered satisfactory if the NS values for validation are above 0.5. The study gave NS coefficient values 0.59 for calibration and 0.51 for validation of flow rate, and for nitrate nitrogen loads respectively – 0.81 and 0.78. The resulting model can therefore be used for further analysis and testing of the change scenarios.

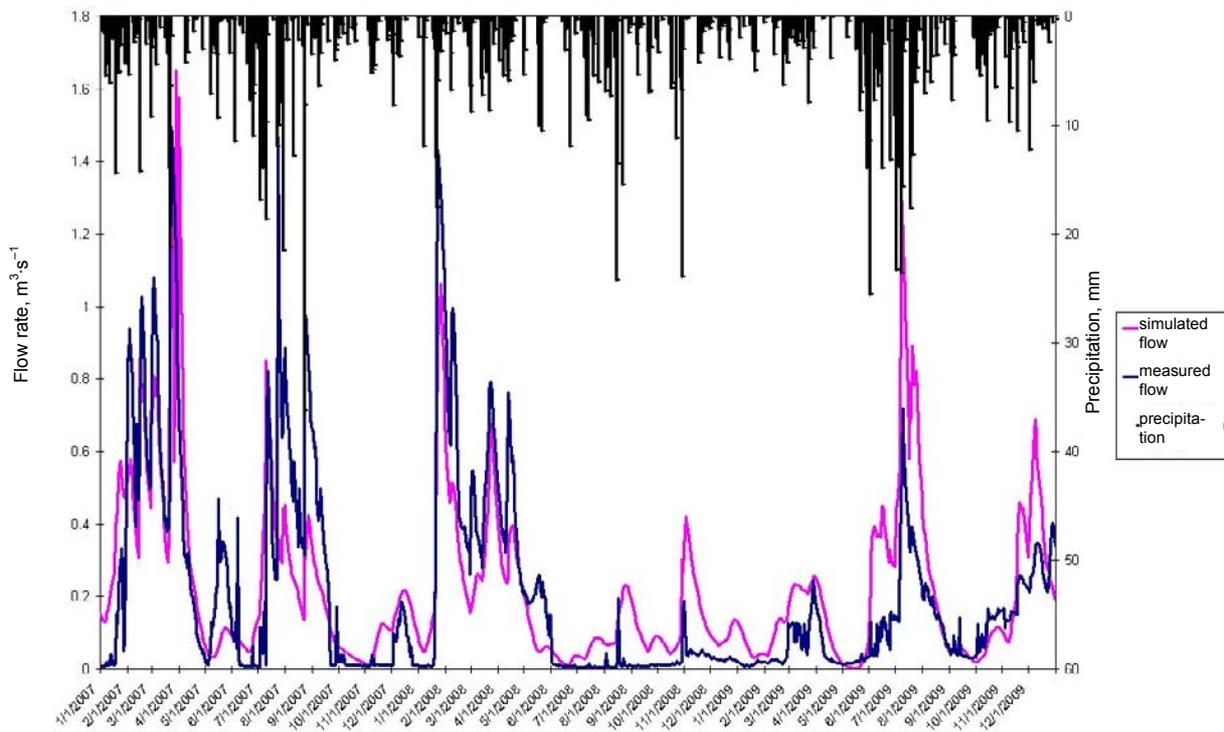


Fig. 3. Calibration and validation – flow rate; source: own study

Test catchment area is almost devoid of permanent grasslands. In order to simulate the presence in the area of permanent grasslands the input layer containing land use map was modified. There were two

scenarios tested in which permanent grasslands took respectively 10 and 20% of arable land. This means that in first scenario 10% of arable land from basis scenario (reality) was converted into grasslands. In

the second scenario 20% of arable land from basis scenario was converted into grasslands. The grasslands were put randomly in the catchment to distribute the effect of their presence in the whole catchment and to avoid uneven impact. The results of the two scenarios were compared with basis scenario (almost none permanent grasslands). In conclusion there were three scenarios:

- 1) basis, real situation, almost none permanent grasslands,
- 2) 10% of arable land converted into grasslands,
- 3) 20% of arable land converted into grasslands.

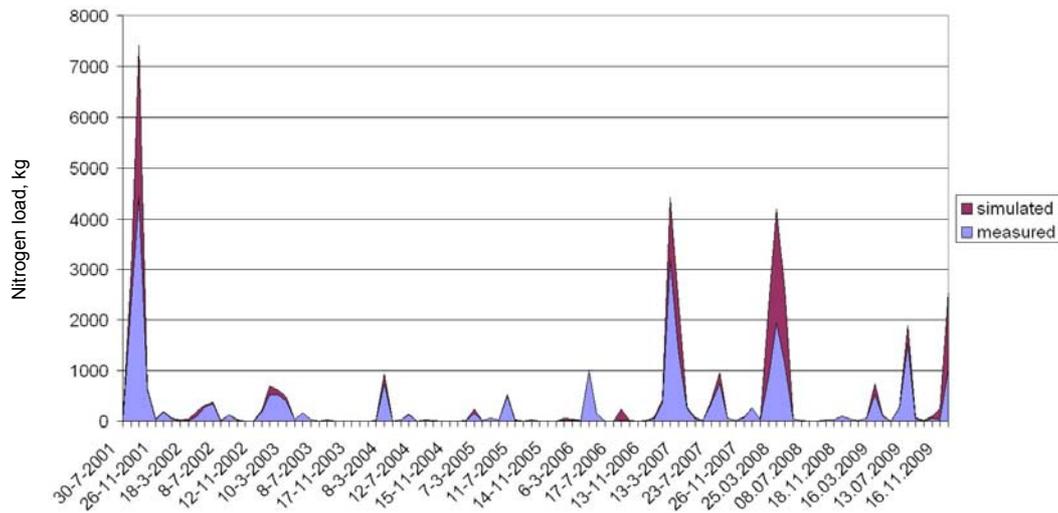


Fig. 4. Calibration and validation – N-load; source: own study

RESULTS AND DISCUSSION

The diagrams in Figures 5a and 5b show respectively the changes in nitrate nitrogen load in the Zgłowiączka River catchment outlet for two scenarios – with 10 and 20% of permanent grasslands in the catchment. The plots compare the load in the baseline scenario (the current situation in the field) with the changed scenario. The horizontal axis represent the nitrate nitrogen load in the baseline scenario, and the vertical – analysed one. For greater clarity there is a line on the graph showing the possible “no change” situation. Points lying below the line illustrate a situation in which there is less nitrogen in tested scenario than in the base one, and the overlying – more nitrogen. This method allows a quick visual assessment of the scenario and its impact on the presence of nutrients in the water. Results include a three-year period, from January 2007 to December 2009.

The graph in Figure 5 shows that the presence of 10% of permanent grasslands in the catchment area leads to a significant reduction the nitrate nitrogen load in the stream. This is confirmed by studies of other authors quoted earlier about the positive impact of land use diversification on the state of water. Distinct changes are visible in almost whole range of loads.

The Figure 5b shows the results in a scenario of permanent grassland occupying 20% of the catchment. The results clearly indicate lowering nitrate nitrogen loads as well for low as for high loads.

Change is greater than in the scenario shown on Figure 5a.

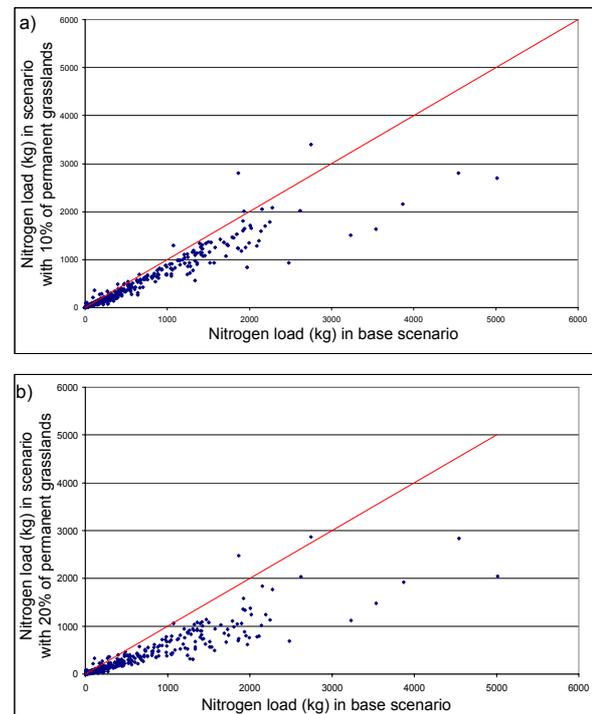


Fig. 5. Changes in nitrate nitrogen load in the Zgłowiączka River catchment for the scenarios of permanent grassland share in the catchment: a) 10%, b) 20%; source: own study

Tested scenarios show the consequences of introduction permanent grasslands into the Zgłowiączka River catchment. Similar as in many empirical studies

in more local scales the presence of permanent grasslands has a positive influence on surface water quality. The bigger is the area covered with grasslands the smaller amount of nitrogen in the Zgłowiączka River. But the further growth of the permanent grasslands area causes slower pollution reduction. So it is important to find the balance between land use diversity, water pollution level and economical aspects.

In Table 1 the results of all three scenarios (basis and two change scenarios) aggregated to a monthly level are presented. It is clearly visible that permanent grasslands are working effectively. They are particularly useful for medium loads. The reduction of load can reach almost 20% when 10% of arable land is turned into permanent grassland and almost 40% when 20% of arable land is turned into permanent grassland.

Table 1. Nitrate nitrogen load in tested scenarios (monthly means from 3 years)

| Month | N load, kg | | |
|-----------|---------------|--------------------------------------|--------------------------------------|
| | base scenario | 10% of permanent grasslands scenario | 20% of permanent grasslands scenario |
| | kg | | |
| January | 212.95 | 188.48 | 112.58 |
| February | 678.79 | 540.66 | 389.39 |
| March | 1 509.78 | 1 217.85 | 947.02 |
| April | 243.26 | 205.04 | 153.06 |
| May | 5.17 | 5.01 | 4.89 |
| June | 6.90 | 6.11 | 4.76 |
| July | 53.31 | 40.13 | 28.86 |
| August | 90.92 | 67.51 | 46.13 |
| September | 29.66 | 21.19 | 18.18 |
| October | 0.38 | 0.36 | 0.38 |
| November | 2.40 | 2.42 | 2.36 |
| December | 18.34 | 16.35 | 15.73 |
| Year | 257.60 | 210.63 | 159.50 |

Source: own study.

The implementation of permanent grassland into the Zgłowiączka River catchment has significant, positive impact. According to sustainable development ideas increased biodiversity and diversity in land use has favorable influence on water state. It is confirmed in modeling approach also in the Zgłowiączka River catchment. The actual situation with almost only arable land can be improved thanks to diversity in land use. Permanent grasslands have a great influence on water state. Its role is important because of the time during which permanent grasslands have various functions. The arable land is during some parts of the year left without vegetation, when permanent grassland is always vegetated. It means that it can also have an influence on nitrate nitrogen load in the winter, early spring and autumn. The difference in nitrate nitrogen load could be caused both by higher amount of nitrogen taken by plants and lower fertilization needed by permanent grasslands.

One of the great advantages of modeling is a possibility to get the results quickly. It also gives a chance to test different scenarios without its real implementation, the cost of research is much smaller than field measurements and it allows making analysis for future, concerning specific conditions. Of course, in using the results of the model there is a need to remember that this is only an imperfect representation of complex processes taking place in reality and not the reality itself. MOSTAGHIMI [1997] points out the limitation of models – they have to be calibrated and validated to local conditions, which may hinder the generalization of results from one basin to other areas. In addition, the accuracy of the modelling results is affected by quality of the input data [WHITE, CHAUBEY 2005]. Diversity of terrain, budget limitations and difficulties in access to the data can cause uncertainty in model results [LENHART *et al.* 2002]. But the experience of many authors shows that it is possible to obtain satisfactory results which may be guidelines for practice and serve in developing management plans for specific areas.

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Wpływ trwałych użytków zielonych na ładunek azotu azotanowego w świetle badań modelowych

STRESZCZENIE

Słowa kluczowe: *azot, modelowanie, SWAT, trwałe użytki zielone, użytkowanie ziemi*

Zanieczyszczenie wody substancjami biogennymi pochodzenia rolniczego zwiększa się na obszarach intensywnie rolniczo użytkowanych. Wykorzystując model komputerowy, można wskazać skuteczne sposoby zmniejszenia ilości biogenów spływających do wód. W niniejszych badaniach wykorzystano model SWAT do oceny wpływu wprowadzenia trwałych użytków zielonych do zlewni na ładunek azotu w cieku. Badania przeprowadzono w małej zlewni rolniczej na Kujawach – górnej Zgłowiączki. W ramach badań symulowano wprowadzenie na obszar zlewni trwałych użytków zielonych zajmujących 10 i 20% powierzchni gruntów ornych. W wyniku modelowania stwierdzono, że znacząco zmniejszył się ładunek azotu w cieku w punkcie zamykającym zlewnię. W warunkach 10-procentowego udziału trwałych użytków zielonych odnotowano zmniejszenie ładunku od kilku procent do ponad 20. Gdy udział ten wynosił 20%, zmniejszenie to wyniosło od kilku procent do ponad 40% ładunku wyjściowego.