Monitoring of surface waters of mountainous Polish river with the use of MONERIS and SWAT models

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Abstract. Presented study has been carried out in the ESA PECS Project: "Application of remotely sensed data for transboundary water resource management". The Institute of Geodesy and Cartography developed the method supporting the management of surface waters by integrating Earth Observation using land cover / land use data into specialized water quality and agri-economical models. The method elaborated within the project is based on application of models which enable to estimate pollution of surface waters by nitrogen and phosphorus compounds. Two models were tested: SWAT (Soil and Water Assessment Tool) and MONERIS (Modelling Nutrient Emissions in River Systems). The MONERIS model is very popular in Europe and USA but less in Poland. Both models are enriched with numerous thematic layers, considering various aspects of environment. Land cover / land use map is one of the most valid layers in both models; it is generated using high-resolution satellite images (IRS LISS 4). The experiment was conducted over the Ropa river catchment (974 km2), which is located in the south part of Poland and as a mountainous river, has a high volatility of river flows. In the first step of the project the SWAT model was used, while the second step of the methodology was focused on evaluating water quality based on MONERIS model. Data created by SWAT model about river flows were used as an input data and to enhance the MONERIS model. Analysis of the results obtained through application of different scenarios, as well as comparison of both models, were presented at final part of the article.

Keywords. Water quality, SWAT model, MONERIS model, nutrient emission

1. Introduction

Complex management of quality of water resources should be based on reliable evaluation of levels of water pollution and on monitoring their changes. Management systems of water resources aim at assessment of impact of agriculture, environmental conditions and anthropogenic factors on water quality. The main objective is to prepare instructions for implementing programs of sustainable development, according to Water Framework Directive and related directives.

System of water resource management proposed within ESA PECS Project "Application of remotely sensed data for transboundary water resource management" assumes integration of data, compiled as thematic layers within spatial model. Source data for creating particular layers include remotely sensed information (land cover, vegetation indices) calibrated with in-situ measurements. Next, after feeding model with multi-source data the process of modeling is performed in order to obtain information on type and amount of water pollutants. Two models are applied in the presented study: SWAT (Soil and Water Assessment Tool) and MONERIS (Modelling Nutrient Emmissions in River Systems). Linking of the databases used in both models is an additional asset for creating system of water management. Results of applying SWAT model, related to intensity of river flows, can be used as input data for MONERIS model, enabling to make analyses within this model in a greater spatial detail.

2. Study area

Catchment of Ropa river has been selected as a study area in the presented work. The catchment is located in southern Poland, in Carpathian mountains. The total area of catchment is 974 km^2 and differences in elevation reach 300 meters. Precise boundaries of the catchment and sub-catchments were determined automatically, on the basis of Digital Elevation Model with 90 m spatial resolution, using GIS analytical tools (ArcHYDRO, ArcSWAT). Finally, catchment of Ropa river was divided into 9 sub-catchments; all further calculations were performed for these units. Sketch map of the catchment with division into sub-catchments was presented in fig. 1.

Figure 1. Map of the study area with division into sub-catchments

There are two dominant types of land cover within the study area: agricultural areas covering 41% and forest areas occupying 38% of the total area. Two types of soil prevail: soils with medium water transparency (e.g. brown, mold, alluvial soils, rendzinas) and those with low transparency, consisting of heavy clays and loamy dusts. Retention conditions are shaped by sedimentary rocks (sandstones) as well as by sands, gravels, loess and alluvial deposits. Ropa catchment is located at the zone of mountainous climate with distinct gradient of temperature and high rainfall (mean long-term rainfall 1999 – 2011 is 774 mm).

3. Data and methodology

3.1. Justification of model selection

MONERIS model has been selected as a primary model for analysis of levels of water pollution by nitrogen and phosphorus compounds. This model, developed at the Leibnitz Institute of Freshwater Ecology and Inland Fisheries in Berlin, Germany is predestinated to:

- identification of sources of nitrogen and phosphorus emissions at river catchments
- determination of annual amount of biogenic compounds
- examination of pollution transport and retention
- forecasting based on scenarios of changes

It must be mentioned, that MONERIS is a type of static model. Calculations are done for annual or periodical data, averaged for basic analytical units. Scenarios created by the model are not probabilistic, but they are based on changes of assumptions and input parameters. Process of modeling is performed in temporal scale (monthly, annual, long term) and in spatial scale (basic analytical units – sub-catchments or administrative units)

MONERIS model has been selected, as it is highly adequate to analyses of water quality in agricultural catchments, irrespective on intensity of agricultural production and on physiographic features. It is recommended due to its efficiency in estimating both nitrogen and phosphorus pollution. Modules of simulation of changes in water quality are based on modification of catchment parameters, enabling manipulation of agricultural pressure through changes in fertilization levels. MONERIS model has been verified in many catchments in Europe, including mountainous regions, confirming its usability in different environmental conditions. It can be used both for estimating magnitude and sources of pressure and for supporting decision processes aimed at water quality management. A certain drawback of the model is time-consuming process of data collection due to wide range of required input data and sometimes their limited availability in Polish conditions.

3.2. Input data

Range of input data covers the following types:

1. Spatial data prepared with the use of GIS tools
2. Statistical data related to administrative division of Poland
3. Numerical data with spatial reference – e.g. data of hydrological and meteorological monitoring, data on water quality
4. Results of analysis with the use of SWAT model related to flow rate

Spatial data formed the following layers: boundaries of administrative units, hydrographic network, digital elevation model, hydrogeological map, soil map, soil loss data, atmospheric deposition, depth of underground water, land cover map. The land cover map was prepared on the basis of high-resolution satellite data (IRS images with 5 m ground resolution).

Statistical data related to administrative units covered information on number of inhabitants, area of agricultural land, area under drainage, length of sewage network, loads of pollutants discharged to ground / water. The important group of data was spatially referenced; it included the following information:

- data from monitoring of water quality, related to nitrogen and phosphorus loads
- data from hydrological monitoring, comprising mean annual values of river flows
- data from meteorological monitoring, including rainfall information (monthly and annual)
- data with geolocation of discharge points and admissible levels of sewage discharge

The flow rate data were obtained as a result of applying SWAT model at first stage of the project. Utilizing this model data concerning values of river flows for particular sub-catchments could be determined and further used for modeling with MONERIS. Two exemplary maps, demonstrating land cover and slope distribution are presented in figures 2 and 3.

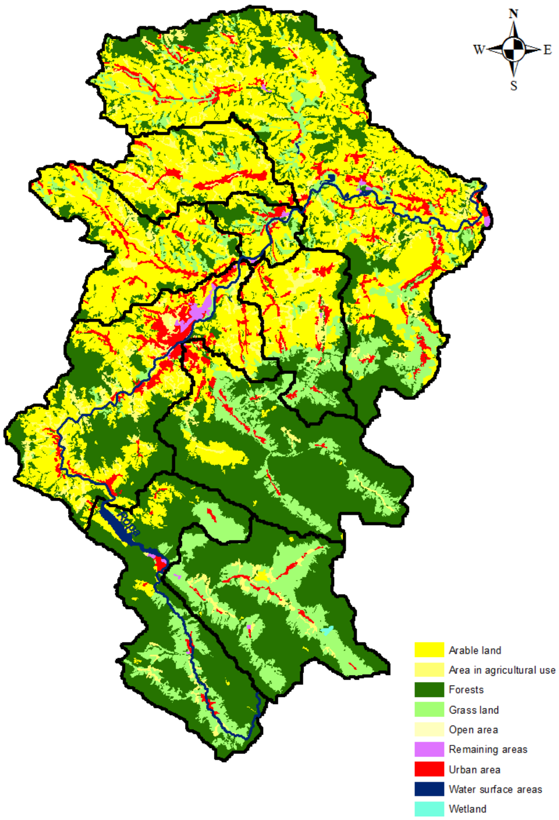

Figure 1. Land cover map

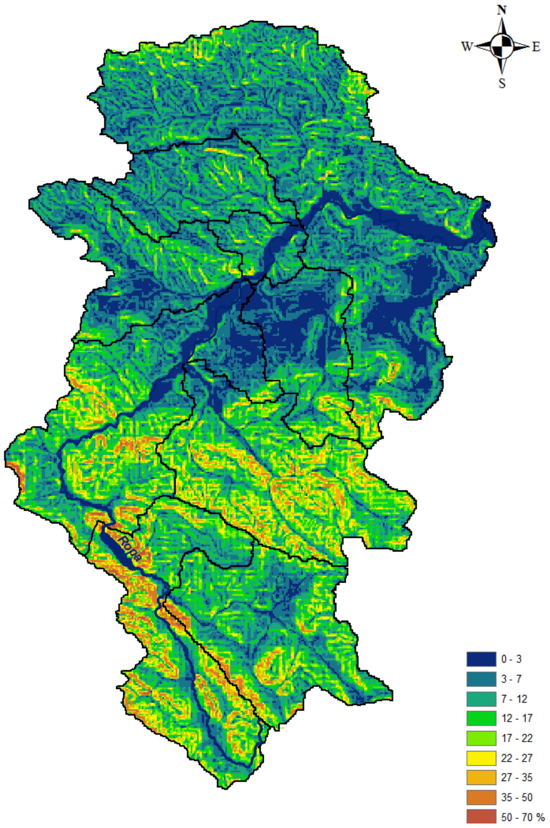

Figure 3. Slope map

On the basis of statistical and spatially referenced input data to MONERIS model factors which are hazardous to quality of surface waters were characterized. These factors were grouped into pressure indices resulting from agriculture and from built-up land (sewage systems). The performed analyses demonstrated, which sub-catchments are prone to high pressure due to drainage systems, high contribution of arable land, animal production and sewage pollution.

3.3. Data implementation and analysis

When all data necessary for feeding MONERIS were collected and prepared, they were implemented into the model database. Next analyses determining state of water quality were performed in two basic variants: variant for reference year (2005) and for long term period (LDW variant). In case of multi-year analysis calculations were done on the basis of four groups of data: reference year, dry year, wet year and long term period. Four scenarios were applied in the process of modelling water quality:

- reduction of agricultural pressure
- limitation of emission from urban areas
- minimization of nitrogen surplus in soil
- pressure of municipal sewage

First scenario assumes change of land use in catchment through simulation of partly moving arable land to grasslands and pastures. It results in changes of nitrogen/phosphorus emissions due to changed erosion, runoff and water discharge from drainage systems.

Second scenario concerns change of non-permeable areas into non-sealed. This parameter is estimated according to number of inhabitants and population density. In case of Ropa catchment 10 % level of change was assumed.

Third scenario enables to simulate changes in water quality caused by limitation of nitrogen/phosphorus surplus in 0 – 30 % range. Reduction in done in comparison to reference year (2005). In case of Ropa catchment 30 % reduction of nitrogen surplus was assumed.

Scenario related to pressure of municipal sewage allows to simulate nitrogen emissions while changing number of people using sewage systems connected to sewage refinery. Due to limited amount of data two extreme variants of simulation were applied: all inhabitants are connected to sewage refinery of none of them.

The results of modelling analyses were presented in the next chapter.

4. Results and discussion

Two types of information were generated as a results of applying MONERIS model:

- nitrogen and phosphorus emission, measured as loads in t/year or t/ha/year, delivered from 7 ways: atmospheric deposition, groundwater, overland flow, tile drainage, erosion, urban systems, point sources.
- Retention in surface waters illustrating sum a long-term and short-term loss of nitrogen and phosphorus in t/year and in percent.

Results of nitrogen and phosphorus emission were analyzed in various combinations: in reference year, long-tem period (1999 – 2010), in wet and dry year. Depending on year situation was different, as it is illustrated in figures 4 and 5:

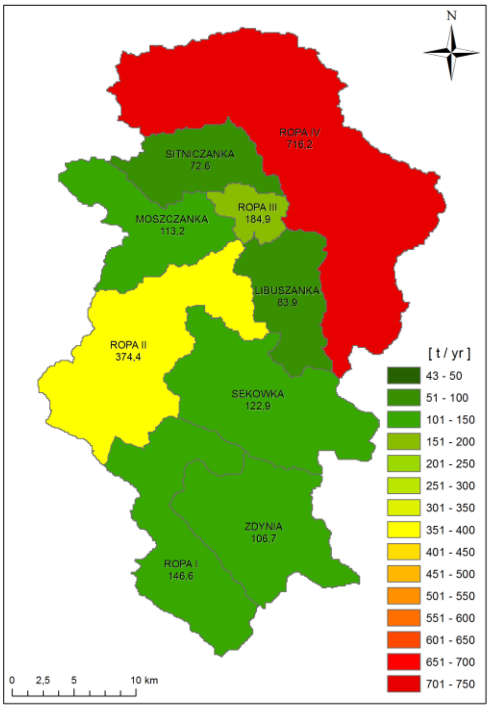

Figure 4. N emission in dry year

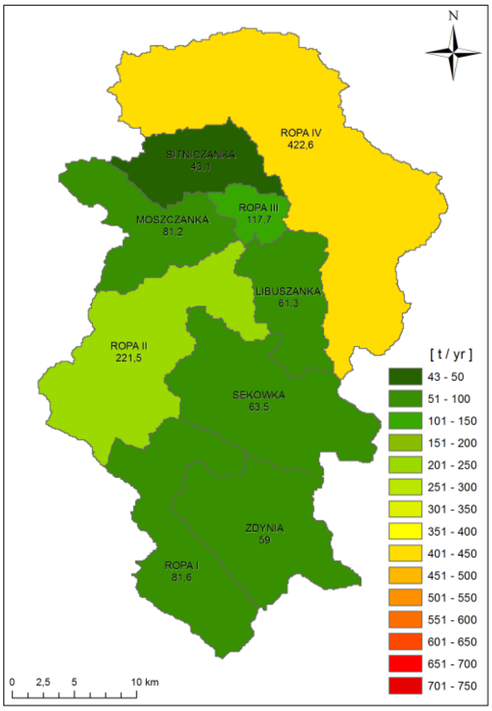

Figure 5. N emission in wet year

Determination of contribution of particular emission ways to delivery of nitrogen and phosphorus loads was very important part of the analysis. Such an analysis enables to distinguish causes of water pollution and to make conclusions on mitigation activities, supporting systems of water quality management. Contribution of seven ways of delivery of emissions (for nitrogen an phosphorus) is presented in figure 6.

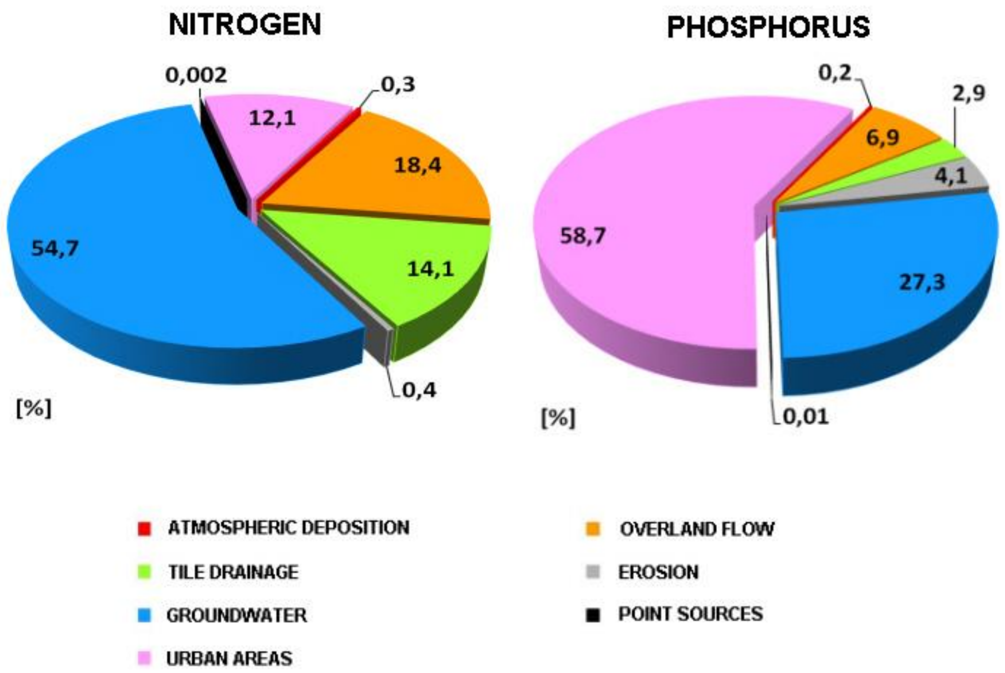

Figure 6. Sources of nitrogen and phosphorus emission in Ropa catchment

Separate analysis has been done in order to quantify contribution of different sources of pollution. They can be included into seven categories: background, urban sources, manure and fertilizer, NHy from agriculture, NOx from agriculture, NHy from other sources, NOx from other sources. The analysis revealed, that the most important sources are fertilization (38 % for N and 20 % for P) as well as urban areas (59 % for P and 12 % for N). The MONERIS model also enables to analyse differences in emissions due to rainfall conditions. It was observed that in dry year nitrogen and phosphorus loads are higher than in wet year, by 20-30 % for nitrogen and 5-25 % for phosphorus.

One of the important aspects of the analysis was to characterize pressure on water quality from agriculture. MONERIS model allows to generate the detailed information on nitrogen and phosphorus loads related to particular agricultural sources. The performed analysis revealed, that the highest surplus on nitrogen exists in these sub-catchments, where high level of fertilization joined with its low effectiveness causes high losses of nitrogen as a result of their washing out of root zone.

Two models for analysis water quality were applied in the project – SWAT and MONERIS, so in the final stage of the works it was attempted to compare the the estimates on nitrogen and phospohorus loads generated by using both models. The comparison was not straightforward, due to several reasons. The most important reasons are different input databases and calculation procedures, as well as various divions into sub-catchments. SWAT model delivers information on nitrogen and phosphorus loads with division into various forms (eg. NH4, NO2, NO3, organic or mineral phosphorus), so in order to make comparison it was nesessary to make proper re-calculations. After this procedure the results obtained from both models became comparable. They were presented in figure 7.

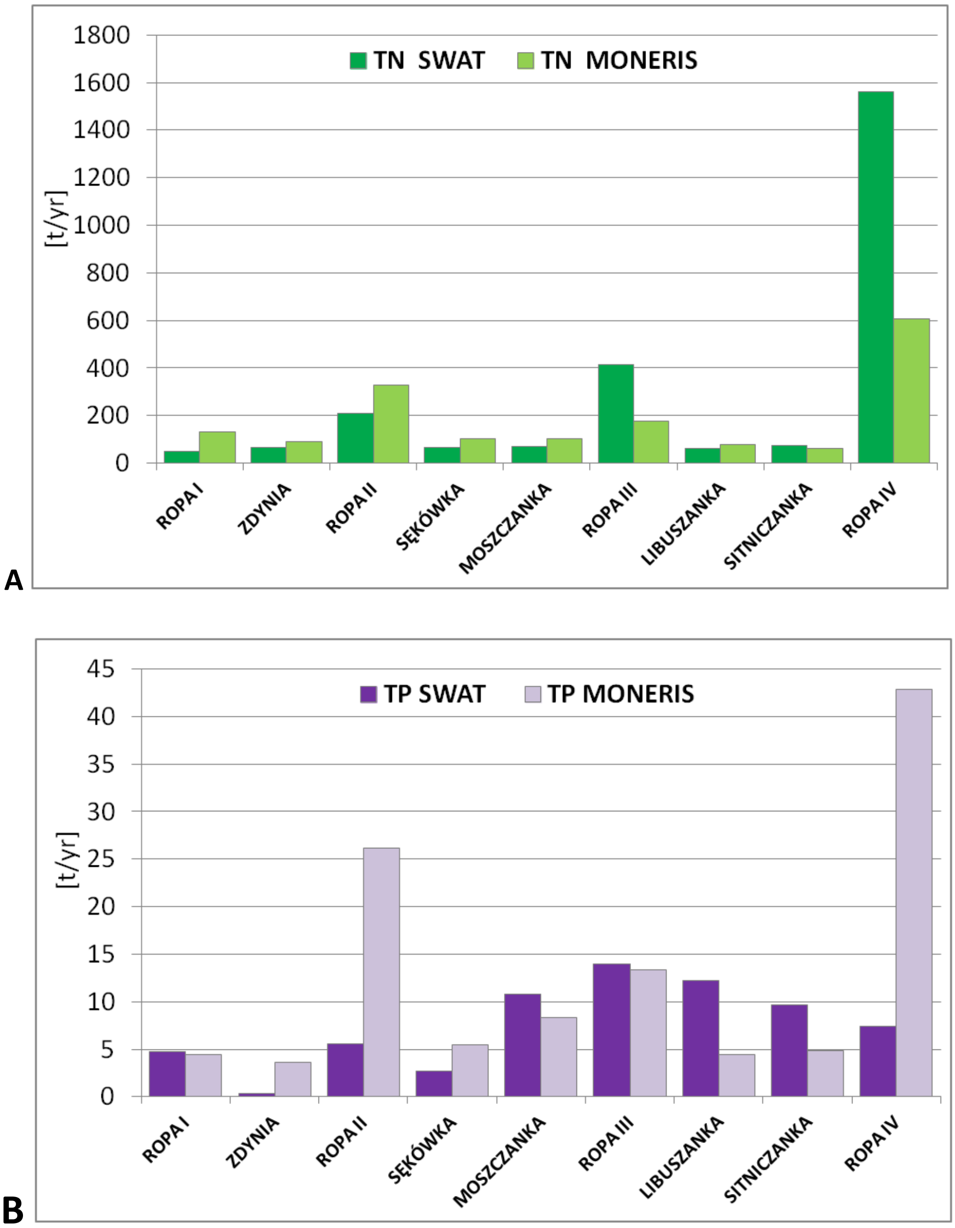

Figure 7. Diagrams illustrating loads of nitrogen (A) and phosphorus (B) derived from SWAT and MONERIS models

The comparative analysis revealed, that in case of nitrogen loads they are higher from SWAT model than from MONERIS model (on the average by 154 % for the whole Ropa catchment). For phosphorus loads situation is reverse; SWAT-derived values are lower by half (on the average) than those obtained from MONERIS. It should be mentioned here, that phosphorus loads obtained by using SWAT model are less reliable (the model is less sensitive), so values derived from MONERIS can be treated as appropriate.

Differences between nitrogen and phosphorus loads obtained from two models result from variant ranges and types of input data. In MONERIS model numerous statistical data derived from the Central Statistical Office and from other sources are applied (Voivodship Inspectorate of Environmental Protection, Agency for Restructuring and Modernisation of Agriculture, Voivodship Directorate of Drainage). SWAT model does not need these types of data. Spatial distribution of differences for nitrogen loads can be also atributed to variable sub-catchment characteristics (intensity of agricultural use and dynamics of relief in mountainous region).

Spatial distribution of differences between two models, for nitrogen and phosphorus loads, expressed as ratio of SWAT to MONERIS derived values, is presented in fig. 8.

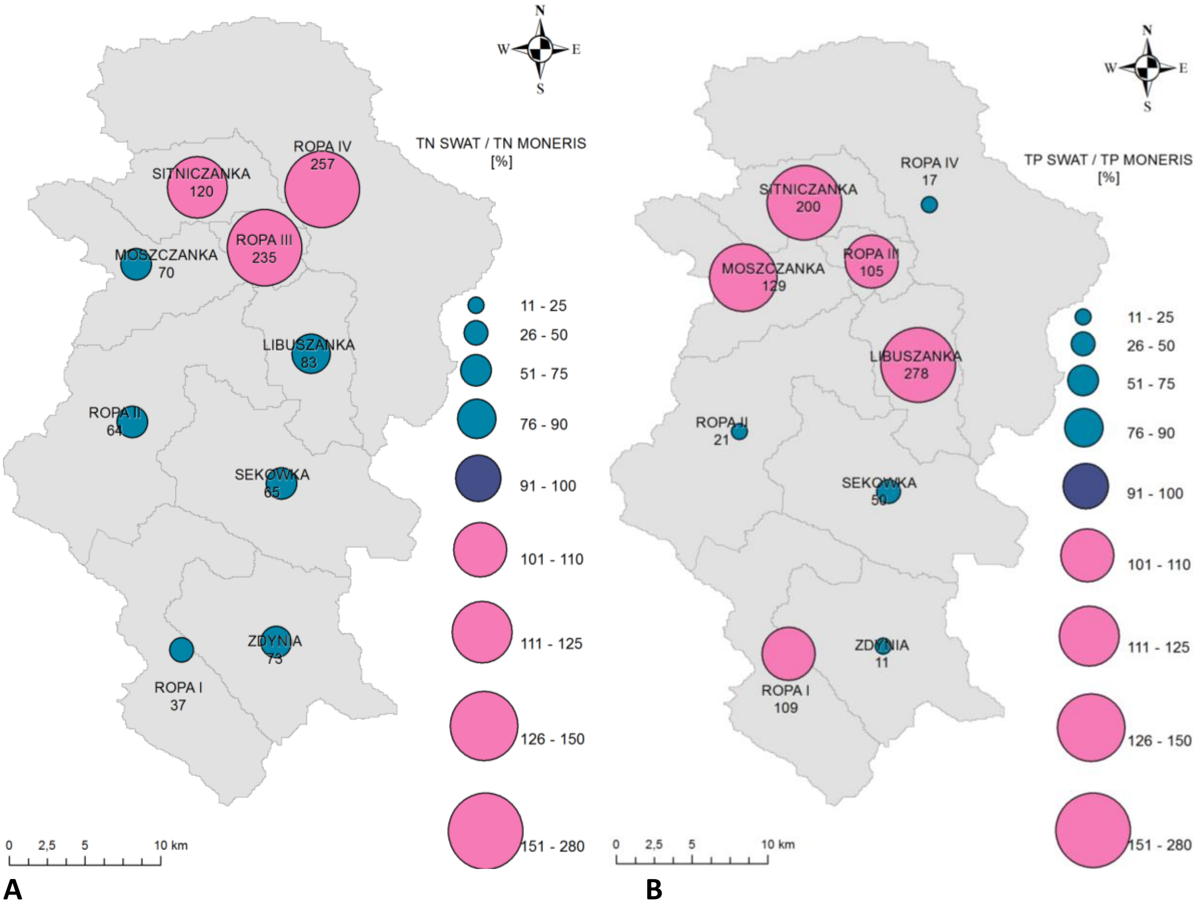

Figure 8. Results of comparison of nitrogen (A) and phosphorus (B) loads for SWAT and MONERIS

5. Conclusions

The analyses of the results generated by application of MONERIS model confirmed that this model is an effective tool for monitoring water quality and migration of biogenic compounds in the catchment. Comprehensive database enables to conduct multi-criteria analyses at decision and operational level, including prevention and mitigation activities. MONERIS model also gives a possibility to use the modern types of source data, as high-resolution satellite images and processed soil or climatic information. Despite multiplicity of input data available tools enable to replace inaccessible data from conventional sources by other ones. There is also possible to support MONERIS with results derived from other models e.g. SWAT. Such a support was done in the presented work, by including results of SWAT modeling related to assessment of river flows to the input MONERIS database. This aspect is especially important in case of catchments, which are poorly equipped with network of monitoring river flow discharge. So, it can be concluded that the MONERIS model, enhanced with information derived from other models, is an effective tool for evaluating water quality and identification of pressure factors, including their weighting. It can also serve for generating forecasts of water quality, depending on activities aimed at change of pressure elements.

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