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A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Calibration and validation of SWAT model for estimating water balance and nitrogen losses in a small agricultural watershed in central Poland

Karolina SMARZYŃSKA$^{1)\ \mathrm{ABCDEF}}$, **Zygmunt MIATKOWSKI**$^{2)\ \mathrm{AD}}$

Institute of Technology and Life Sciences in Falenty, Kuyavian-Pomeranian Research Centre in Bydgoszcz, ul. Glinki 60, 85-174 Bydgoszcz, Poland; e-mail: k.smarzynska@gmail.com, zygmunt.miatkowski@gmail.com

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Abstract

Soil and Water Assessment Tool (SWAT) ver. 2005 was applied to study water balance and nitrogen load pathways in a small agricultural watershed in the lowlands of central Poland. The natural flow regime of the Zgłowiączka River was strongly modified by human activity (deforestation and installation of a subsurface drainage system) to facilitate stable crop production. SWAT was calibrated for daily and monthly discharge and monthly nitrate nitrogen load. Model efficiency was tested using manual techniques (subjective) and evaluation statistics (objective). Values of Nash–Sutcliffe efficiency coefficient (NSE), coefficient of determination (R^2) and percentage of bias for daily/monthly discharge simulations and monthly load indicated good or very good fit of simulated discharge and nitrate nitrogen load to the observed data set. Model precision and accuracy of fit was proved in validation. The calibrated and validated SWAT was used to assess water balance and nitrogen fluxes in the watershed. According to the results, the share of tile drainage in water yield is equal to 78%. The model analysis indicated the most significant pathway of NO_3-N to surface waters in the study area, namely the tile drainage combined with lateral flow. Its share in total NO_3-N load amounted to 89%. Identification of nitrogen fluxes in the watershed is crucial for decision makers in order to manage water resources and to implement the most effective measures to limit diffuse pollution from arable land to surface waters.

Key words: *agricultural watershed, calibration, diffuse pollution, nitrogen losses, Soil and Water Assessment Tool, water balance*

INTRODUCTION

Progress in development of hydrologic/water quality mathematical models is focused on the most complete description of processes controlling the water and nitrogen cycling, with regard to spatial differentiation of natural conditions in the study area: topography, geohydrology, soil types, land use and meteorological conditions. The dynamic development of GIS techniques, coupled with digital information on topography, soil and land use, has led to creation of a complex modeling system combining GIS with hydrologic/water quality models, where the GIS interface helps in preparation of input data required for the model.

A modeling system is a basic tool to conduct the cause-and-effect analysis of human activity on hydrology and nitrogen cycling on the watershed scale. It can be a useful, supplementary (to field measurements and observations) source of knowledge about water balance of the watershed and nitrogen load pathways. One of the most suitable models used worldwide to study hydrologic, biogeochemical and ecological processes on the watershed scale is Soil and Water Assessment Tool (SWAT) [AKHAVAN *et al.* 2010; FRANCOS *et al.* 2001; GEYING *et al.* 2006; LAM *et al.* 2009; 2010; OEURNG *et al.* 2011; PINIEWSKI, OKRUSZKO 2011; PISINARAS *et al.* 2009; SHANTI *et al.* 2001; ZHANG *et al.* 2013], which integrates both hydrologic and water quality components [ARNOLD *et al.* 1998]. The coupling of hydrologic pathways and biogeochemical processes has major implications for watershed management strategies [PETRY *et al.* 2002]. SWAT has been successfully applied in numerous studies for simulations of discharge and nutrient transport in watersheds with varying climatic, geologic and hydrologic conditions [CHAHINIAN *et al.* 2011; CONAN *et al.* 2003; GIKAS *et al.* 2006; GRIZZETTI *et al.* 2003; LAM *et al.* 2010; TONG, NARAMNGAM 2007]. However, number of studies applying the SWAT model to analyze hydrology and nutrient transport in strongly anthropogenically transformed watersheds has been still limited [KOCH *et al.* 2013].

There is a general belief that without a precise and detailed calibration and validation of a model for local conditions of the system under investigation, no further useful analyses based on the model predictions are trustworthy [BÄRLUND *et al.* 2007; BELLOCCHI *et al.* 2010; KANNAN *et al.* 2007a, b; MORIASI *et al.* 2012; SHANTI *et al.* 2001].

Small agricultural watersheds can be treated as an indicator of trends in the agricultural sector and can help to understand the cause-and-effect relation between agricultural production and water quality. The small watersheds with relatively homogeneous soil cover, climate and human pressure level are the most suitable objects to study geochemical cycle of nitrogen. The chemical composition (in terms of nitrogen from diffuse sources) of small watercourses draining agricultural watershed influences water quality of larger rivers flowing into the Baltic Sea, which state is alarming in that many of the sub-regions have become overloaded with nutrients [PASTUSZAK *et al.* 2005]. Therefore, to protect water quality of larger rivers as well as the Baltic Sea ecosystem, the measurements to control diffuse sources of nitrogen must be most of all undertaken in small agricultural watersheds – at the source of pollution.

The first trials to apply SWAT model to an agricultural watershed in the Kujawy region (Kuyavia) in Poland have already been undertaken [BRZOZOWSKI *et al.* 2011; ŚMIETANKA *et al.* 2009], but no calibration and validation of the model has been described there. Thus the objectives of this study were to: (1) examine if the SWAT model version 2005 could be successfully calibrated and validated for discharge and mineral nitrogen load from a small watershed strongly modified by agricultural use; (2) understand precisely the water and nitrogen cycle dynamics based on the model results; (3) calculate the water balance of the watershed under investigation; and (4) determine and characterize the nitrate-loading pathways in the watershed by using the verified model. That is the crucial knowledge for decision makers in order to manage water resources and to implement the most effective measures to limit diffuse pollutions from arable land to surface waters.

STUDY AREA

The Zgłowiączka River watershed is located in central Poland, in the Kujawy region (Fig. 1). The region is characterized by the lowest annual precipitation in Poland (450–500 mm), whereas mean annual precipitation in Poland is 628 mm [IMGW-PIB 2013]. During the growing period (April–September), precipitation amounts to only around 300 mm [BAC *et al.* 1993; KOŹMIŃSKI, MICHALSKA (eds) 2001]. The mean value of potential evapotranspiration (*PET*) in the growing season (April–September) amounts to 550 mm [ŁABĘDZKI *et al.* 2011], compared to 120 mm in winter time (December–March) [KĘDZIORA 1995]. One of the features of the Kujawy region climate is a very frequent, irregular and long-lasting occurrence of periods without rainfall (on average 22 days, maximum 38 days) [BĄK 2003; BŁAŻEJCZYK *et al.* 2005; KASPERSKA-WOŁOWICZ *et al.* 2003]. Kujawy belongs to regions of substantial and frequent water deficits in plant production. The mean annual sum of precipitation is far too low to satisfy crop water demands [ŁABĘDZKI 2002].

The Zgłowiączka watershed is characterized by small surface water resources. It is located in the zone with the lowest specific mean annual runoff in Poland, which is equal to 2 $dm^3 \cdot s^{-1} \cdot km^{-2}$ [LESZCZYCKI (ed.) 1994].

The dominant soil types are Phaeozems [FAO 2006] (about 85%) and Luvisols (15%). The soils are underlain by poorly permeable glacial till. The basin area is relatively flat, with local depressions. Due to poor natural hydraulic conductivity of Phaeozems, most of the basin area (about 65%) is drained. The drainage system is a combination of subsurface drainage and open ditches. It allows farmers to create favorable conditions for cultivation and plant growth in wet years and seasons.

Despite unfavorable climatic conditions, the Kujawy region is one of the most intensively agriculturally used areas in the country, most of all due to the good quality of soils. Around 90% of the basin is used as arable land, while permanent grasslands are only in small local depressions. The main cultivated crops are: cereals (mainly winter wheat and spring barley, 24% and 12% of the area, respectively), maize (12%), winter oilseed rape (12%) and sugar beet (12%). The average nitrogen fertilization is around 220 kg $N \cdot ha^{-1}$ of arable land, more than 2.5 as high as the average for the country (83.4 kg $N \cdot ha^{-1}$) [GUS 2014]. Besides, fertilization in the Zgłowiączka watershed is not balanced. In 2004–2007 the average difference between

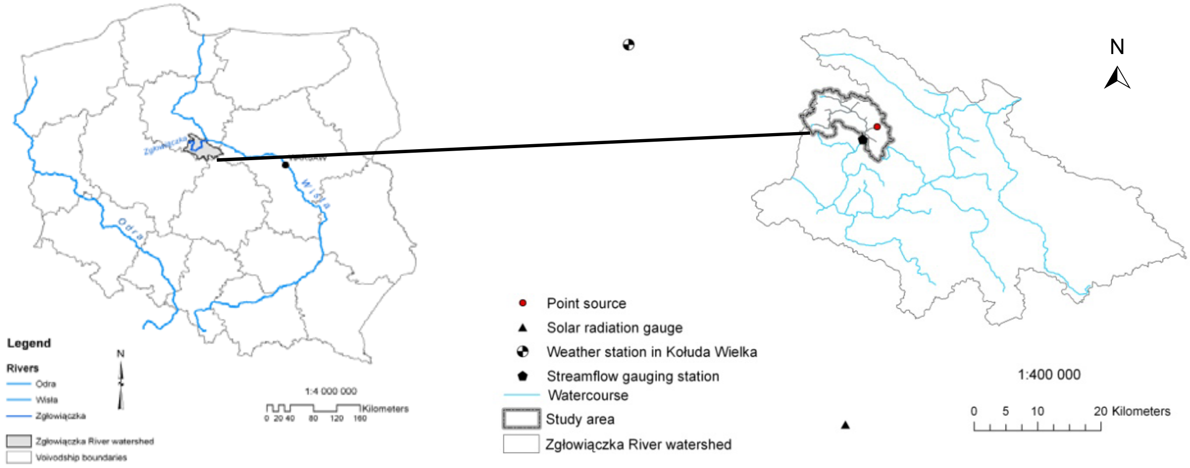

Fig. 1. Location of the study area in the Kujawy region, central Poland; source: own elaboration

the quantity of nitrogen introduced into and removed from the environment (in the course of plant and animal production) was 114 kg·ha^{-1} of arable land [GUS 2012]. The effectiveness of nitrogen fertilization use is thus lower than 50%.

Intensive agriculture under conditions of unfavorable climatic water balance leads to significant problems with surface water quality in terms of nitrate concentrations. According to the results of the State Monitoring Program in that region [MIATKOWSKI, SMARZYŃSKA 2014], since the year 2000 an upward trend of nitrates concentration in surface waters is observed, especially in the upper part of the Zgłowiączka (from the river head to the river mouth in the Głuszyńskie Lake). Therefore, to protect water quality, the upper Zgłowiączka River watershed (129.6 km^2) in 2004 was designated as a Nitrate Vulnerable Zone according to regulations of the Nitrate Directive of the European Union [Council Directive 91/ 676/ EEC].

For modeling purposes, our study area was a part of the Zgłowiączka watershed from the river head to the point where water discharge is regularly measured (river cross-section Samszyce) (Fig. 1). In the study we treated that point as a research basin outlet, so calibration and validation of discharge and nitrogen loads were executed for that point. The study area covers 78 km^2, which corresponds to 60% of the total upper Zgłowiączka watershed. Table 1 presents physical and geographical parameters of the study area.

Table 1. Physical and geographical parameters of the study area

Parameter	River cross-section Samszyce
Study area, km^2	78
Length of main watercourse, km	11.2
Total length of watercourses, km	26.5
River network density, km·km^{-2}	0.3
Average slope, ‰	3.6
Average slope of main watercourse, ‰	0.8
Forest, % of study area	4
Urban areas, % of study area	2

Source: own study.

MONITORING OF THE STUDY AREA: SOURCE OF DATA FOR SWAT CALIBRATION AND VALIDATION

Results of hydrologic (2007–2011) and water chemistry monitoring (2008–2011, in terms of nitrogen compounds) were used in this study. The hydrologic regime of the upper Zgłowiączka River, typical for the lowland small rivers in Poland, has been significantly altered by an extensive draining system and arable land use. The upper and middle part of the Zgłowiączka River (7.6 km long) is an intermittent stream, fed by water flowing from the drainage system in periods when soil water content exceeds field capacity (mainly in early spring after snow melt or incidentally after heavy rainfall in summer). Water discharge in the Samszyce cross-section varied within a wide range and changed rapidly in time (Fig. 2).

The high values of daily discharge occurred in spring, up to 8 m^3·s^{-1}). In summer the discharge was very low, less than 0.01 m^3·s^{-1}. Discharge irregularity coefficient (maximum/minimum ratio) varied from 12 in average years to 1398 in wet years, due to the changes in the natural hydrologic regime of the Zgłowiączka River caused by human activity.

Natural topographic conditions of the study area (average difference in elevation around 3 m) are not favorable for surface runoff to occur, hence its share in water yield is relatively small.

In Poland, discharge of main rivers is regularly monitored by the Institute of Meteorology and Water Management, but very limited hydrologic and water quality data exist for small rivers. In the case of small watercourses, like the upper part of the Zgłowiączka River, there are problems with availability of hydrologic and water quality long-term data for model calibration.

Since October 2006, water level has been continuously recorded by the Voivodship Environmental Protection Inspectorate in one point on the Zgłowiączka River (Fig. 1) with hourly time step. These data were the only information available about the hydrology of the study area. In 2008, we started regular bi-

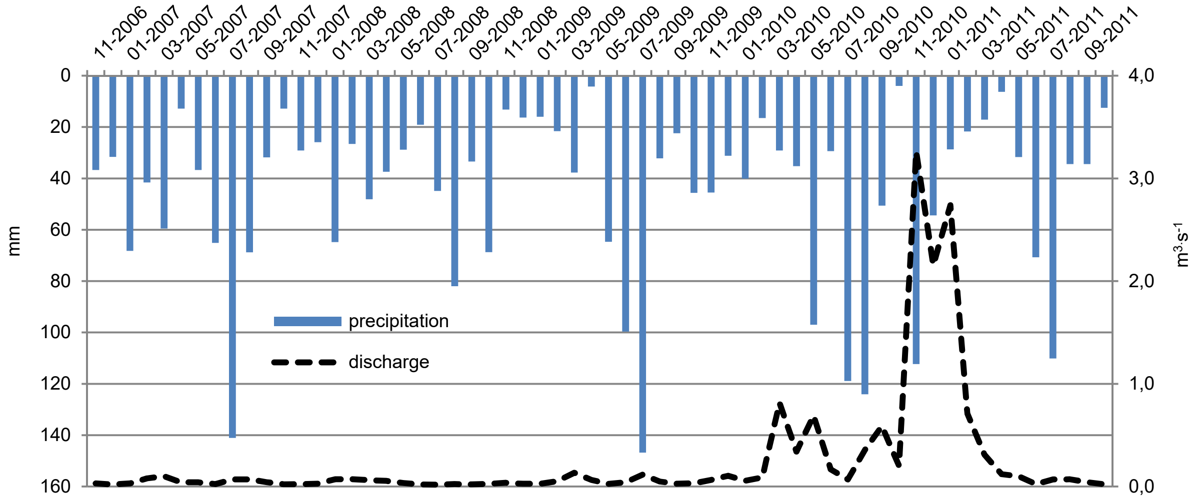

Fig. 2. Monthly values of precipitation and discharge; source: own study

weekly measurements of water discharge at the same point. On the basis of these data and the information about water level, the rating curve equation was determined. On its basis, hourly values of discharge were calculated and averaged for each day. These data were further used for calibration and validation of the SWAT model in terms of hydrology.

From 2000, monthly data about water quality (in terms of nitrate concentration in surface water) are available from the State Monitoring Program for two control points along the river (including the point where water level is measured). The high temporal variability of discharge influences nitrate concentration dynamics in surface waters. Due to large seasonal changes in nitrate concentration [MIATKOWSKI, SMARZYŃSKA 2014], in 2008 we decided to monitor nitrate concentration every two weeks to have more precise data for load calculations and hence for model calibration and validation. In particular periods of the year (after rapid snow melt or heavy rains), water samples were collected every day and discharge was measured once a week. Nitrate concentrations in the collected water samples were determined using the FIA (Flow Injection Analysis) method combined with spectrometric detection according to Polish Standards PN-EN ISO 13395:2001.

Discharge and water quality data were used to calculate NO_3-N load according to equation (1):

$$L = \sum_{t=1}^{t=T} (86.4\overline{Q_t}\,C_t^{\,I}) \tag{1}$$

where: L = NO_3-N load, kg; C_t^I = mean daily NO_3-N concentration, $mg \cdot dm^{-3}$; $\overline{Q}_t$ = mean daily discharge, $m^3 \cdot s^{-1}$; t = time, days.

For periods between two chemical analyses of water samples, the NO_3-N concentration was determined using interpolation.

METHODS

MODEL DESCRIPTION

SWAT is a semi-distributed physically-based model, developed to predict the impact of management practices on water and agricultural chemical yields on a basin scale [ARNOLD *et al.* 1998]. It is a continuous time model and operates on a daily time step. As all physically-based models, SWAT uses a number of mathematical formulas to describe water movement in the watershed (both for overland flow and through porous media) and energy balance for evapotranspiration. The equations are based on laws of conservation of mass, momentum and energy [KRYSANOVA, ARNOLD 2008; VIEUX 2004].

Regardless of the type of analyses to be performed using SWAT, water balance is the driving force to all processes occurring in the watershed [NEITSCH *et al.* 2005]. Hence, the correct simulation of nitrogen load is strongly related to simulation of water cycling in the system as well as accurate determination of water balance and its components (surface runoff, groundwater flow, tile drainage, etc.).

In SWAT, water cycling in the watershed is divided into the land phase and routing phase. The land phase is based on soil water balance equation for each day of simulation (2):

$$SW_t = SW_0 + \sum_{t=1}^{t=T} (P_d - SURQ - E - w_{seep} - GWQ) \tag{2}$$

where: SW_t = final soil water content, mm; SW_0 = initial soil water content, mm; t = time, days; P_d = precipitation, mm; $SURQ$ = surface runoff, mm; E = evapotranspiration, mm; w_{seep} = amount of water entering the vadose zone from the soil profile, mm; GWQ = groundwater flow, mm.

Using the information about topography (Digital Elevation Model, DEM), SWAT divides the basin into a number of subbasins. Further division into Hydrologic Response Units (HRU) is based on the soil map and land use information. Each HRU is a homogenous area in terms of soil and land use type as well as slope. Water yield from each HRU is aggregated for subbasins and routed via the reach network to the watershed outlet (routing phase of hydrology). The amount of water yield for every day is calculated according to equation (3):

$$WYLD = SURQ + LATQ + GWQ + TQ - TLSS \qquad (3)$$

where: $WYLD$ = water yield, mm; $SURQ$ = surface runoff, mm; $LATQ$ = lateral flow, mm; GWQ = groundwater flow, mm; TQ = tile drainage flow, mm; $TLSS$ = transmission losses, mm.

To simulate tile drainage in HRU, four parameters must be specified:

- the distance between soil surface and drain tile depth (mm),
- time required to drain the soil from saturation to field capacity (hours),
- time between the transfer of water from the soil to the drain tile and the release of the water from the drain tile to the reach (hours).
- depth from the soil surface to the impermeable layer (mm).

Tile drainage occurs when the groundwater table rises above the depth of the drainage system and it is further simulated as lateral flow.

In terms of nitrogen cycle simulation, SWAT monitors five different forms of the element in the soil profile and shallow aquifer: two mineral forms (NO_3-N and NH_4-N) and three organic (fresh as well as active and stable nitrogen, both related to the soil humus). Partition of nitrogen related to soil humus was introduced to the model to account for the variation in availability of humic substance for mineralization [NEITSCH *et al.* 2005].

The most important chemical processes occurring in the environment in relation to nitrogen are simulated with the model: mineralization, immobilization, nitrification and denitrification, volatilization, bacterial fixation and plant uptake.

Detailed description of the SWAT model can be found in a research report [ARNOLD *et al.* 1998] and in theoretical documentation [NEITSCH *et al.* 2005]. For this study we used ArcSWAT 2.1.6 interface for SWAT 2005.

ADAPTATION OF THE MODEL FOR THE STUDY AREA

Input data required for SWAT were obtained from various data sources (Tab. 2). Meteorological data (daily: precipitation, relative humidity, maximal and minimal air temperature and wind speed) originated from one weather station in Kołuda Wielka (located 40 km from the watershed border). The meterological data set was supplemented with solar radiation data from two stations located in Toruń and Koło.

Table 2. Categories, sources and description of SWAT input data for the study area

Data type	Source	Data description
DEM (topography)	NASA Shuttle Radar Topography Mission	resolution 90 m
Hydrographic network	Digital map of Hydrographic Division of Poland (Institute of Meteorology and Water Management)	layer of selected reaches
Digital map of soils	Digital soil map (Institute of Soil Science and Plant Cultivation)	scale 1:100 000
Digital map of land use	– Landsat – statistical data about land use	– multispectral satellite image – Regional Water Management Authority in Warsaw [ŚMIETANKA *et al.* 2009]
Meteorological data	Institute of Meteorology and Water Management (1997–2011)	Weather station in Kołuda Wielka, RHMS[1] in Toruń and HMS[2] in Koło

[1] Regional Hydro-Meteorological Station.
[2] Hydro-Meteorological Station.
Source: own study.

The input database (DEM, soil and land use map) was based on data collected and elaborated during implementation of an international project „Pilot implementation of Water Framework Directive and creation of a tool for catchment management" [ŚMIETANKA *et al.* 2009].

A conventional agricultural-soil-suitability map of the Kujawy region on a scale of 1: 100 000 (1987) was a primary source of information about the soil cover of the study area. The map contained generalized information about polygons, soil textural classes and agricultural suitability of soil types based on soil surveys and soil maps made in the 1950s and 1960s. Soil properties are among the essential input data for biophysical models [BELLOCCHI *et al.* 2010], so to determine soil texture and basic physical as well as chemical properties of soil types, field research was carried out in 2006. During that study, 22 soil profiles were described in detail and classified, and soil samples of each genetic horizon were taken. In the collected samples, soil texture, pH and both organic carbon and actual nitrate content were determined. Based on results of the soil survey and soil analyses, both the soil map and input database of soil properties were created.

After delineation of the study area based on DEM, SWAT divided the area into 17 subbasins. With a threshold value of 10% for soil types, land use and slope, the subbasins were further separated into 429 HRU.

Simulations were performed for five most significant crops cultivated in the watershed: winter wheat, spring barley, winter oilseed rape, sugar beet and maize. A simplified crop rotation (including planting date, amount of fertilizer and date of application and harvesting date) was introduced into SWAT. These dates were determined on the basis of the authors' expert knowledge about the timing of agrotechnical practices in the Kujawy region. The amounts of fertilizer were determined on the basis of fertilizing plans (Tab. 3).

Table 3. Average nitrogen fertilization for the main crops cultivated in the study area

Crop	Nitrogen fertilization, kg N·ha^{-1}		
	mineral N	organic N	total
Winter wheat	164	60	224
Spring barley	145	30	175
Maize	168	50	218
Winter oilseed rape	167	50	217
Sugar beet	160	50	210

Source: own study.

Nitrogen added to soil in rainfall amounted 22 kg N·ha^{-1}. Similar loads were reported by SAPEK *et al.* [2003] for central Poland. Daily values of discharge (0.01 dm^3·s^{-1}) and nitrogen load from one sewage treatment plant were implemented into the model as a point source of pollution.

The amount of applied P fertilizer in the model was proportional to N fertilizer and to crops needs.

SENSITIVITY ANALYSIS

One of the most important steps in calibration of the distributed model, characterized by a large amount of parameters, is its correct parameterization, which – as emphasized by ARNOLD *et al.* [2012] – has to be based on knowledge of the hydrologic processes in the system under study. Correct parameterization can result in faster and more accurate model calibration, with smaller prediction uncertainty. Parameter specification and estimation are two major stages of calibration [SOROOSHIAN, GUPTA 1995]. The goal of sensitivity analysis is to determine the cause-and-effect relation between model parameters and modeling results. In the case of watersheds, where no long-term data sets are available, the number of calibrated parameters should be minimized [MULETA, NICKLOW 2005].

Another advantage of sensitivity analysis is that it allows to avoid the problem with overparameterization of the model [WHITTAKER *et al.* 2010], which can lead to e.g. a loss of control over the model behavior [KRYSANOVA, ARNOLD 2008]. The complementarity of sensitivity analysis and calibration was emphasized by some authors [HOLVOET *et al.* 2005; VANDENBERGHE *et al.* 2001]. Because of the above-described reasons, sensitivity analysis was the first step of SWAT calibration to local conditions in the study area.

In this study, we used the sensitivity analysis developed, applied to SWAT and tested by VAN GRIENSVEN *et al.* [2006] for the Sandusky River watershed. Their method is a compilation of the global sampling Latin Hypercube (LH) method with One-Factor-At-a-Time (OAT) method.

In our study the parameter sensitivity for discharge and nitrogen load was tested separately, using the combined LH-OAT method. During LH analysis the range of changes in values of individual parameters (upper and lower bounds) is divided into m equal intervals. During sensitivity analysis, SWAT runs $(p + 1)\cdot m$ times, where p is the number of parameters being evaluated and m is the number of LH intervals. The final effects are ranked, with the largest effect given rank 1 and the smallest effect given a rank equal to the total number of parameters analyzed. If some parameters have no effect on model simulations, they are all given a rank equal to the number of parameters plus 1.

SWAT-CUP – A TOOL FOR MODEL CALIBRATION

For semi-automated calibration, the tool called SWAT-CUP (Calibration and Uncertainty Programs) was used. It has been developed in the Swiss Federal Institute of Aquatic Science and Technology – Eawag [ABBASPOUR 2009]. A recent version of SWAT-CUP includes several calibration and uncertainty analysis techniques: SUFI-2 (Sequential Uncertainty FItting), GLUE (Generalized Likelihood Uncertainty Estimation), PARASOL (Parameter Solution), MCMC (Markov Chain Monte Carlo) and PSO (Particle Swarm Optimization) [ABBASPOUR 2011]. A detailed description of the theoretical basis of the SWAT-CUP platform can be found in the manual of the program [ABBASPOUR 2009].

SUFI-2 proved to be a very efficient optimization algorithm [BILONDI *et al.* 2013] and could be run with the smallest number of model runs to achieve good prediction uncertainty ranges [YANG *et al.* 2008]. This technique takes into account parameter uncertainty for all sources of uncertainties (both in input and observed data, as well as in the conceptual model). The degree to which all uncertainties are accounted for is quantified by the *p-factor*. It is the percentage of measured data bracketed by the 95 percentage prediction uncertainty (95PPU) [ABBASPOUR 2005; 2009; SHOUL, ABBASPOUR 2006]. Previous studies have shown that SUFI-2 program is very efficient in calibration of SWAT for small watersheds [ABBASPOUR *et al.* 2007b].

MODEL EVALUATION TECHNIQUES

Model evaluation techniques include subjective and/or objective estimates of how close model predictions fit to the observations. For objective evaluation, mathematical estimation of errors between observed and predicted values must be conducted [KRAUSE *et al.* 2005] by the use of different model evaluation statistics. Currently the most popular evaluation statistics for the SWAT model [ARNOLD *et al.* 2000; 2012; GASSMAN *et al.* 2007; GREEN, VAN GRIENSVEN 2008; OEURNG *et al.* 2011; POHLERT *et al.* 2005] are:

- Nash–Sutcliffe efficiency coefficient (NSE), interpreted as the proportion of variation in the observed values explained by the model [NASH, SUTCLIFFE 1970]; it ranges between –∞ and 1, where 1 indicates perfect agreement between observed and simulated values;
- percentage of bias (PBIAS), measuring the average tendency of the model predictions to be larger or smaller, as compared with observed data; the optimal value is 0.0.
- coefficient of determination (R^2), describing the proportion of the variance in measured data explained by the model; it ranges from 0 to 1, where 1 is the optimal value meaning the ideal fit between observed and simulated values.

LEGATES and MCCABE [1999] stated that simply a "goodness-of-fit" measure is not enough to evaluate the model and suggested to use a compilation of at least one dimensionless statistic, one absolute error index statistic and to include one of the graphical techniques in the evaluation process. To meet these demands, the following statistics for model evaluation were used: standard regression (R^2), dimensionless statistic (NSE) and several error indices (*MAE* – mean absolute error; *RMSE* – root mean square error; *PBIAS* and *RSR* – ratio of *RMSE* to standard deviation of measured data). The statistical approach was combined with subjective graphical techniques (hydrograph analysis and comparison of both mean and cumulative values) to evaluate model simulations both for discharge and NO_3-N load.

RESULTS AND DISCUSSION

PARAMETER SENSITIVITY

Sensitivity analysis was conducted in two steps for the 15-year data set (1997–2011). In the first step we tested the sensitivity of simulated discharge to changes of parameters describing the processes of water cycle in the system (both for land and routing phases). The number of intervals in the LH method was equal to 10.

We tested 26 parameters. Detailed descriptions of the parameters and the results of sensitivity analysis are presented in Table 4. Depending on the process to which the parameters pertain, they can be divided into 7 groups, related to:

1) calculation of actual evapotranspiration (transpiration, evaporation): EPCO, BLAI, ESCO and interception CANMX;
2) soil properties: SOL_Z, SOL_AWC, SOL_ALB, SOL_K;
3) groundwater: APLHA_BF, GWQMN, REVAPMN, GW_REVAP, GW_DELAY;
4) snowfall and snow melt: SFTMP, SMTMP, SMFMX, SMFMN, TIMP;
5) surface runoff: CN2 (curve number for average soil moisture conditions used in the SCS method for surface runoff calculation), SLOPE, SLSUBBSN, SURLAG;
6) channel processes: CH_K2, CH_N2;
7) others: BIOMIX, TLAPS.

According to the results of discharge simulations, the most sensitive parameters were those related to calculation of actual evapotranspiration: ESCO, BLAI, EPCO and interception – CANMX and were placed among the first 10 parameters in the ranking. Knowing that evapotranspiration is the key component of the hydrologic cycle in the Zgłowiączka watershed, it is not surprising. Based on sensitivity analysis, simulated discharge was insensitive to changes in SFTMP, SMFMN, SMFNMX, SMTMP and TLAPS, so they were excluded from calibration.

Table 4. Ranking of parameters related to discharge calculations considered for sensitivity analysis

Parameter, unit	Definition	Ranking
SOL_Z (1), mm	depth from soil surface to bottom of first soil layer	1
ESCO	soil evaporation compensation coefficient	2
ALPHA_BF, days	baseflow recession constant	3
SOL_AWC(1), mm $H_2O \cdot mm^{-1}$ soil	available water capacity	4
BLAI	potential maximum leaf area index (LAI) for plant	5
CANMX, mm	maximum canopy storage	6
EPCO	plant uptake compensation factor	7
TIMP	snow temperature lag factor	8
GWQMN, mm H_2O	threshold water level in shallow aquifer for base flow	9
CN2	curve number	10
CH_K2, $mm \cdot h^{-1}$	effective hydraulic conductivity of channel	11
BIOMIX	biological mixing efficiency	12
SOL_ALB	soil albedo	13
SLOPE, $m \cdot m^{-1}$	average slope of subbasin	14
SURLAG	surface runoff lag coefficient	15
CH_N2	Manning's *n* value for main channel	16
SOL_K (1), $mm \cdot h^{-1}$	saturated hydraulic conductivity of first layer	17
REVAPMN, mm H_2O	threshold water level in shallow aquifer for "revap"[1)] or percolation to deep aquifer to occur	18
GW_REVAP	groundwater re-evaporation coefficient	19
GW_DELAY, days	delay time for aquifer recharge	20
SLSUBBSN, m	average slope length	21
SFTMP, °C	mean air temperature at which precipitation is equally likely to be rain as snow/freezing rain	27
SMFMN, mm $H_2O \cdot °C^{-1} \cdot day^{-1}$	melt factor on December 21	27
SMFMX, mm $H_2O \cdot °C^{-1} \cdot day^{-1}$	melt factor on June 21	27
SMTMP, °C	threshold temperature for snow melt	27
TLAPS, $°C \cdot km^{-1}$	temperature lapse rate	27

[1)] Movement of water into overlying unsaturated zone.
Explanations: (1) first layer of soil profile.
Source: own study.

One more parameter related to soil properties – not included into sensitivity analysis – was added for calibration: soil bulk density (SOL_BD). It pertains to several important processes (such as calculation of volumetric water content at a permanent wilting point and percolation) as well as to the soil nitrogen pool [NEITSCH *et al.* 2005].

In the second stage the sensitivity of nitrogen load resulting in changes in parameters describing the process of nitrogen cycle in the watershed was evaluated and 5 parameters were tested. Two of them – RCHRG_DP and NPERCO – were found to be the most sensitive (Tab. 5). The number of intervals in the LH sampling procedure was equal to the number in the first stage.

Table 5. Ranking of parameters for NO_3-N load calculations considered for sensitivity analysis

Parameter, unit	Definition	Ranking
RCHRG_DP	aquifer percolation coefficient	1
NPERCO	nitrate percolation coefficient	2
SHALLST_N, $kg \cdot N \cdot ha^{-1}$	amount of nitrate in shallow aquifer	6
SOL_NO_3 (1), $mg \cdot kg^{-1}$	initial NO_3 concentration in first soil layer	6
SOL_ORGN (1), $mg \cdot kg^{-1}$	initial humic organic nitrogen in first soil layer	6

Explanations: (1) first layer of soil profile.
Source: own study.

CALIBRATION

Natural hydrological regime of the Zgłowiączka River and water cycle in the watershed were strongly modified due to installing of artificial drainage (surface ditches and subsurface tile drains). The hydrologic responses of the landscape have been significantly altered and natural preferential flow paths changed. The time of water flow from the landscape to the river has been shortened, the risk of floods and nitrogen outflow increased. Hydrological regime of the Zgłowiączka River, originally typical to small lowland watercourses, is nowadays similar to mountainous streams in terms of: the range of flow variability and rapidity of water level increase. In 2011 the maximum daily discharge amounted 8.38 $m^3 \cdot s^{-1}$, whereas the minimum – 0.01 $m^3 \cdot s^{-1}$.

Tile drainage water is highly contaminated with nitrates, thus concentration in the Zgłowiączka River also vary rapidly in time. Modelling of hydrology and water quality in rapidly changing conditions is complicated and requires detailed knowledge about processes controlling water cycle in the watershed.

The crucial and most time-consuming stage of model calibration was the determination of the water balance of the watershed and its components inherently. The data set from the first 10 years of the study (1997–2006) were used as a warm-up period for SWAT. Model calibration was performed using data from January 2007 to December 2010. The results of the first model simulations indicated that SWAT did not predict the components of water balance correctly. It was noticeable that the model overestimated surface runoff, and consequently underestimated actual evapotranspiration (*AET*). Moreover, soil water content was permanently too high during the growing season in each year of simulation, thus no water deficits for crops were predicted. However, investigations on evapotranspiration have shown that the greatest crop water deficits in Poland occur in the Kujawy region [BĄK 2003]. Since the model predictions of water balance were far from reality, manual calibration was undertaken using the trial-and-error procedure to improve water balance of the study area before we started to calibrate the model using the semi-automated procedure SUFI-2.

Some studies show that the manual calibration outperformed the autocalibration tool in simulation of the range in magnitude of daily flows and point out the fact that autocalibration approach suffered from the inability to maintain control on mass balance [VAN LIEW *et al.* 2005].

Trial-and-error calibration (manual)

While calibrating model with trail-and-error procedure successive stages were done as follow:

1) determination of preferential flow and nitrates paths based on field observations, consultations with local authorities and farmers and control of water quality on tributaries of the Zgłowiączka River;
2) basic technical parameters of artificial drainage system;
3) determination of water balance components based on historical data or by simplified estimation methods;
4) verification of statistical data about fertilization and crop yield based on survey research on farms.

Firstly, we focused on proper calculations of both *PET* and *AET*, as evapotranspiration is the key driving force of the hydrologic cycle in the Zgłowiączka watershed. Three methods of *PET* calculation have been incorporated into SWAT: Priestley–Taylor, Hargreaves and Penman–Monteith [NEITSCH *et al.* 2005]. Several studies worldwide concerned the influence of different *PET* estimation methods on model results [KANNAN *et al.* 2007b; WANG *et al.* 2006]. Table 6 presents results of *PET* and water yield estimations for the study area using each of them. Annual mean value of *PET* in the study area amounts to about 680 mm [KĘDZIORA 1995; ŁABĘDZKI *et al.* 2011]. This value is very close to the one calculated using the Penman–Monteith method, hence it was used for *PET* calculation in further simulations. All values reported in Table 6 are based on the uncalibrated model results.

Once *PET* is calculated, *AET* is determined. Actual transpiration is estimated as a linear function of *PET* and *LAI*, whereas actual evaporation is calculated using exponential function of soil depth and soil water content [ARNOLD *et al.* 1998]. Two parameters were

Table 6. Average values (1997–2011) of potential evapotranspiration (*PET*) and water yield estimated using different methods

Variable	*PET* estimation method		
	Priestley–Taylor	Penman–Monteith	Hargreaves
PET, mm	566	679	764
Water yield, mm	100	53	32

Source: own study.

incorporated into equations determining evaporative demands of soil layers and potential water uptake by plants. These are ESCO (soil evaporation compensation coefficient) and EPCO (plant uptake compensation coefficient). ESCO allows the user to modify the depth distribution used to meet the soil evaporative demands, whereas EPCO allows to compensate water deficits in the soil profile for plant uptake from lower soil layers. During manual calibration the fitted values of EPCO and ESCO amounted 0.85 and 0.40, respectively. Changes in both parameters during the trial-and-error procedure resulted in more realistic estimations of *AET* (increase) and surface runoff (decrease), but still the proportion of these two components of water balance was incorrect. Average *AET* was still too low, amounting to only 70% of total precipitation, whereas according to BRENDA [1998] its share in water balance of the Kujawy region can reach 90%. According to KĘDZIORA *et al.* [2014], the outflow coefficient (relation between total annual outflow and annual precipitation) of watersheds located in adjoining regions is lower than 20%, and specific mean annual runoff is lower than 2.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$ [BRYKAŁA 2009].

In the next step, we paid attention to evaporation from canopy interception, which was found to be one of the most important processes in hydrologic modeling of water balance in the Zgłowiączka watershed. According to the results, in conditions of Poland, interception of cereals can reach 30% of rainfall [KOŁODZIEJ *et al.* 2005]. SAVENIJE [2004] highlighted the role of interception in hydrologic modeling, as the first stage in the chain of rainfall-runoff processes, and pointed out that an error introduced in modeling of interception automatically introduces errors in the calibration of subsequent processes.

Canopy interception (maximum amount of water held in canopy storage) simulated with SWAT is a function of LAI [NEITSCH *et al.* 2005] and varies between days according to the equation (4):

$$can_{day} = can_{\max} \frac{LAI}{LAI_{\max}} \qquad (4)$$

where: can_{day} = maximum amount of water intercepted in a canopy for a given day (mm H_2O); $can_{\max}$ = maximum amount of water intercepted when canopy is fully developed (mm H_2O); LAI = leaf area index for a given day; $LAI_{\max}$ = maximum leaf area index for the plant.

Simulations of individual water balance components during the trial-and-error procedure were significantly improved after implementation of realistic value of maximum canopy storage (CANMX), which for crops amounted 5 mm. It resulted in further increasing of average *AET* and decreasing of surface runoff. The share of average *AET* in simulated water balance of the study area finally reached about 90% of precipitation and realistic simulated water volume at the outlet was obtained.

After preparing the model in terms of more realistic representation of water balance of the research watershed, further adjustment of simulated discharge to observations was conducted using the SUFI-2 procedure.

Semi-automated calibration for discharge and NO_3-N load

Calibration of the SWAT model using SWAT-CUP platform was performed in two steps, using NSE as an objective function. At the beginning, parameters related to discharge were adjusted. Searching for the best value of each parameter was carried out between reasonable lower and upper ranges (Tab. 7). After obtaining good fit between observed and simulated discharge, a fitted value of each calibrated parameter was implemented into the model. Parameters related to groundwater and *AET* can vary between particular HRUs. Due to the relatively small size of the watershed and homogenous conditions, parameters' values were the same for each HRU. CANMX (10 mm) and curve number CN2 (45) were changed for forest conditions, if it had occurred in HRU.

Table 7. Range and fitted values of calibrated parameters for hydrology and NO_3-N load

Parameter		Min	Max	Fitted value
Parameters sensitive to discharge	r_CN2 for arable land	–0.300	0.300	–0.005
	v_ALPHA_BF	0.000	0.500	0.073
	v_GW_DELAY	1.000	45.000	18.820
	v_CH_N2	0.000	0.080	0.051
	v_CH_K2	5.000	13.000	8.000
	r_SOL_AWC(1)	0.020	0.400	0.391
	r_SOL_K(1)	–0.200	0.800	0.253
	r_SOL_BD(1)	–0.050	0.060	–0.042
	v_EPCO	0.010	1.000	0.662
	v_ESCO	0.010	1.000	0.350
	v_GWQMN	0.010	50.000	39.552
	v_GW_REVAP	0.010	0.200	0.113
	v_REVAPMN	100.000	500.000	166.800
	v_SOL_Z(1)	300.000	400.000	368.700
	v_CANMX	0.000	10.000	2.350
Parameters sensitive to	v_RCHRG_DP	0.000	1.000	0.550
	v_NPERCO	0.000	5.000	1.250
	v_SOL_CBN(1)	0.000	2.500	1.625
	v_ERORGN	0.000	1.000	0.850
	r_CMN	0.000	0.0004	0.00014

Explanations: r = existing parameter value is multiplied by (1+ given value); v = existing parameter value is to be replaced by given value [ABBASPOUR 2009]; (1) first layer of soil profile.
Source: own study.

After implementation of parameters sensitive to discharge, in the next step of calibration the best value for parameters related to calculation of NO$_3$-N load was determined. Based on literature review [ABBASPOUR *et al.* 2007b; GREEN, VAN GRIENSVEN 2008; LAM *et al.* 2009] some additional parameters not included into sensitivity analysis were calibrated. These were:

- SOL_CBN(1) – organic carbon content in the first soil layer (% soil weight);
- ERORGN – organic nitrogen enrichment ratio for loading with the sediment; it is defined as a ratio of organic nitrogen concentration transported with the sediment to the concentration in the soil surface layer;
- CMN – rate coefficient for mineralization of the humus active organic nutrients.

Model performance evaluation

Manual (subjective) techniques of model performance evaluation were based on hydrograph and cumulative values analysis, as well as visual comparison of simulated and observed values of discharge and NO$_3$-N load. Daily and monthly hydrographs show that on days 1–103 (Fig. 3a) and in the first three months of 2007 (Fig. 3b) the model simulated significantly higher values of discharge, as compared with the observed data. This was caused by a sequence of events starting from soil water content near to field capacity at the end of previous year of simulation (2006), which was not included into calibration process. These conditions were the result of intensive rainfall at the beginning of August 2006, when the sum of precipitation on successive six days was 137 mm. At the same time, water uptake by crops was limited, because the growing season of winter wheat and winter oil seed rape ended. Rainfall water supplemented soil water resources, which were depleted after the intensive growing season. The conditions of field capacity remained similar during three winter months (January, February and March) of the next year of simulation (2007). It resulted in simulations of high discharge but it was not confirmed by observations. Any efforts to reduce this overestimation resulted in underestimation of discharge at the beginning of the extremely wet year 2010.

Calibration of discharge for small intermittent watercourses is difficult and challenging due to rapid variation of flow conditions and chemical composition of the reach. This problem was also reported by CHAHINIAN *et al.* [2011] while modeling flow and nutrient transport in intermittent Vène River in southern France using SWAT.

Once an acceptable fit between observed and predicted discharge was obtained, calibration of NO$_3$-N turned out to be much less laborious and time-consuming. Values of each calibrated parameter sensitive to NO$_3$-N load were obtained only automatically, using the SUFI-2 procedure with satisfactory fit between predicted and observed nitrogen load (Fig. 4).

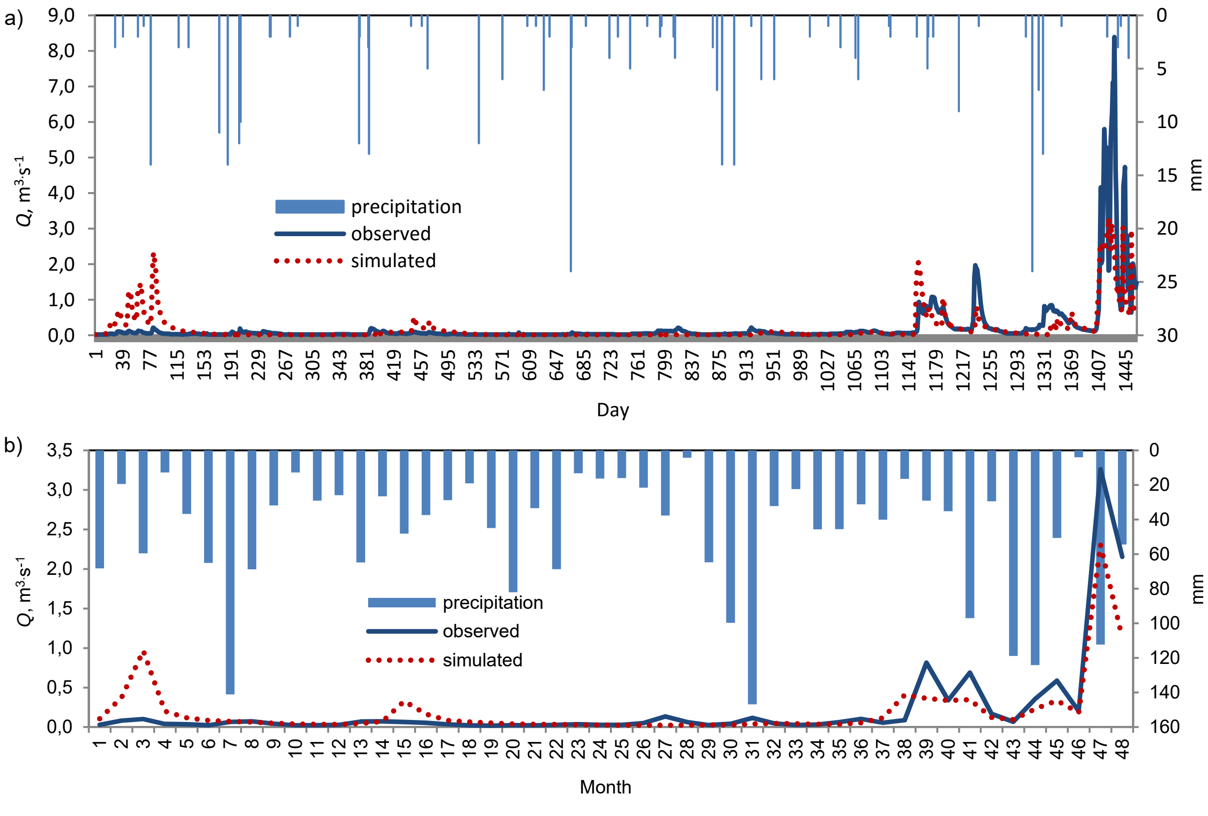

Fig. 3. Calibration results of discharge (2007–2010): a) daily, b) monthly; source: own study

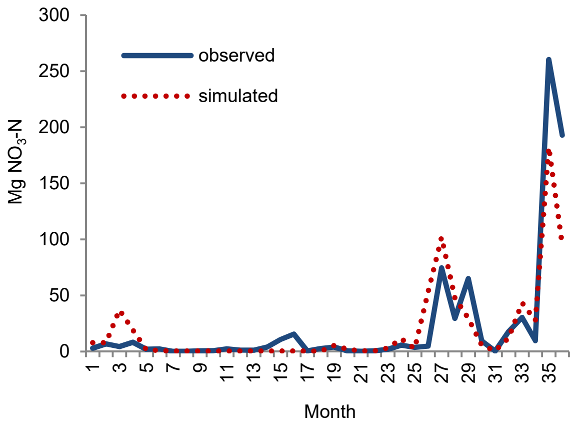

Fig. 4. Monthly calibration of NO_3-N load (2007–2010); source: own study

Comparison of cumulative values of simulated and observed daily discharge and monthly NO_3-N load proves the good fit (Fig. 5).

Manual assessment of model performance was supported with several statistics (Tab. 8). To determine if the values of NSE, PBIAS and RSR are satisfactory, we used the guidelines of model evaluation established by MORIASI *et al.* [2007] based on the review of results and project-specific considerations. According to the guidelines, all values of selected model evaluation statistics for monthly discharge and NO_3-N load indicate a very good fit of simulated values to the observed data set, except PBIAS for discharge, which indicates good fit. Positive values of PBIAS mean the average tendency for underestimation of model predictions compared with observed values.

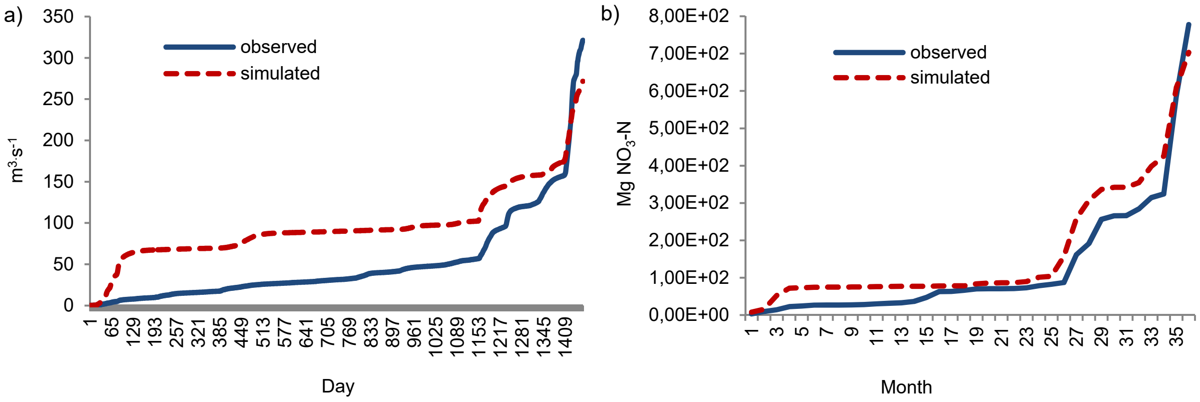

Fig. 5. Cumulative values of daily discharge (a) and monthly NO_3-N load (b) for calibration; source: own study

Table 8. Model evaluation statistics for calibration

Statistics	Discharge		Mineral nitrogen (NO_3-N) load
	monthly	daily	monthly
NSE	0.77	0.53	0.78
R^2	0.82	0.55	0.82
PBIAS, %	10.07	15.44	9.58
MAE$^{1)}$	0.13	0.17	12.40
RMSE$^{1)}$	0.27	0.48	25.01
Standard deviation$^{1)}$ (of observed data)	0.56	0.70	53.70
RSR	0.48	0.68	0.47

$^{1)}$ Units: $m^3 \cdot s^{-1}$ for discharge, Mg for load.
Source: own study.

SINGH *et al.* [2004] stated that *RMSE* and *MAE* values smaller than half the standard deviation of the measured data may be considered low. According to this assumption, *MAE* for monthly and daily discharge and monthly NO_3-N load can be considered low and proves the good fit between model predictions and observations. *RMSE* for daily discharge was slightly higher than half of standard deviation.

Comparison of mean observed and estimated values of discharge (0.22 and 0.20 $m^3 \cdot s^{-1}$, respectively) and NO_3-N load (22.0 vs. 20.0 Mg, respectively) confirmed additionally the model predictions.

Worse results were obtained in the calibration of SWAT with daily time step. Generally, the poorest results for daily predictions, compared with simulations with monthly time step, are reported in most of the studies using the SWAT model [ARNOLD *et al.* 2012]. Originally SWAT was intended to predict accurately monthly or annual hydrologic parameters [GREEN *et al.* 2006]. SINGH *et al.* [2004] pointed out that comparison of observed and simulated monthly or annual stream flows yields better statistics than those obtained from the daily stream flow comparison, when using the SWAT model for hydrologic studies. It is because SWAT, as any other model, is only an approximate description of the complex reality and therefore its abilities to mimic the natural processes occurring in the system are limited.

Accounting for uncertainty bounds

The above statistical indices only apply to the comparison of two signals and are not adequate when outputs are expressed as uncertainty bounds. In this case, as the simulation results are usually expressed by the 95 percent prediction uncertainties (95PPU), they cannot be compared with the observation signals using the traditional R^2 and *NSE* statistics. For this reason, ABBASPOUR *et al.* [2007a] suggested two

Table 9. Model evaluation statistics for calibration

p-factor			*r-factor*		
monthly		daily	monthly		daily
discharge	load	discharge	discharge	load	discharge
0.90	0.71	0.81	0.76	0.22	0.66

Source: own study.

measures, referred to as the *p-factor* and the *r-factor*. The *p-factor* is the percentage of the measured data bracketed by the 95PPU. This index provides a measure of the model's ability to capture uncertainties. Ideally, the *p-factor* should have a value of 1, indicating 100% bracketing of the measured data, hence capturing or accounting for all the correct processes. The *r-factor* is a measure of the quality of the calibration and indicates the thickness of the 95PPU. Its value should ideally be near zero, indicating small uncertainty bound of prediction. The combination of *p-factor* and *r-factor* indicates the strength of the model calibration and uncertainty assessment, as these are closely linked [SHUOL *et al.* 2006] (Tab. 9).

VALIDATION

Demonstration that the specific configuration of input data, parameter sets (defined in calibration) and model structure are correct for a particular application is one of the goals of model validation. After parameterization of the model both for hydrology and NO_3-N load with parameter values obtained from calibration, validation of the model was carried out on an independent data set from January–December 2011. Validation was performed with daily and monthly time step for discharge and monthly time step for NO_3-N load (Figs. 6, 7). The model evaluation statistics *NSE* and R^2 (Tab. 10) were much better than those obtained in the calibration. It proves the ability of the model to mimic discharge and NO_3-N load in a wide range of hydrologic conditions.

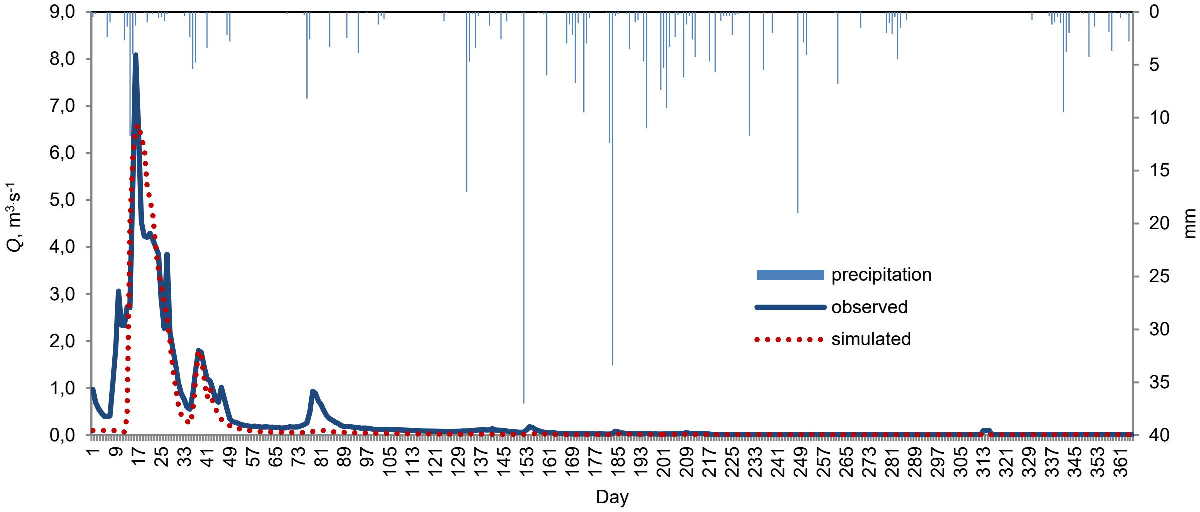

Fig. 6. Daily validation of discharge (2011); source: own study

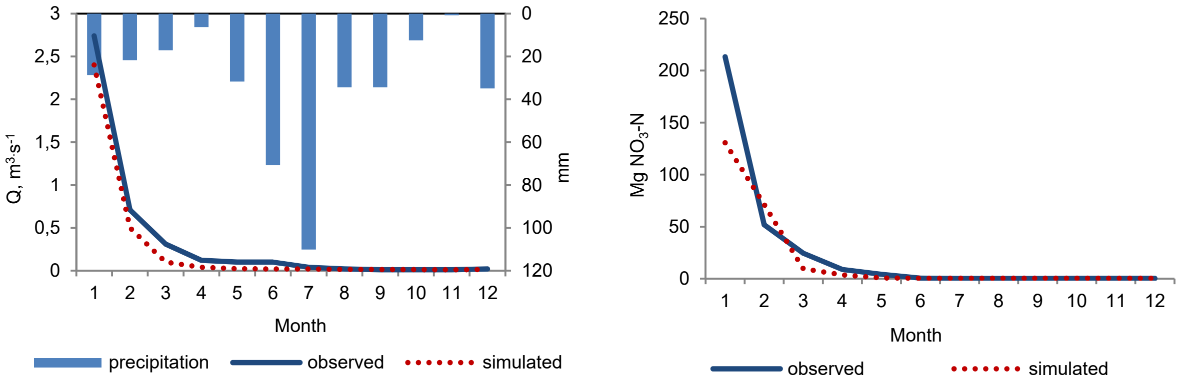

Fig. 7. Monthly validation of: a) discharge (2011), b) NO_3-N load (2011); source: own study

Table 10. Model evaluation statistics for validation

Statistics	Streamflow		NO_3-N load
	monthly	daily	monthly
NSE	0.96	0.83	0.82
R^2	0.99	0.85	0.92
PBIAS, %	24.61	25.06	28.12
MAE$^{1)}$	0.09	0.14	10.61
RMSE$^{1)}$	0.14	0.38	24.94
Standard deviation$^{1)}$ (of observed data)	0.78	0.94	61.18
RSR	0.17	0.41	0.41

$^{1)}$ Units: $m^3 \cdot s^{-1}$ for discharge, Mg for load.
Source: own study.

WATER BALANCE OF THE WATERSHED AND NO_3-N LOADS

The calibrated SWAT model was used as a tool for determination of outflow components, such as surface runoff, groundwater flow, lateral and tile drainage flow. That was possible only using a modeling technique, because for the Zgłowiączka watershed there were no long-term monitoring data sets available about discharge, surface runoff or groundwater flow, which would make calculation of outflow components possible.

The share of individual outflow components in water yield illustrates the main hydrologic process in the watershed, as well as the level of changes in the natural hydrologic regime by human activity. According to the results, the average (for 15 years of simulation) yearly outflow through tile drainage was 45.7 mm (Tab. 11) and comprised 78% of total water yield. It is not surprising, as 65% of the watershed is tile drained. The shares of the other outflow components do not exceed 15% each. The relief of the watershed, dominated with a monotonous moraine plain with insignificant differences in elevation, in combination with poorly permeable deposits, creates conditions for water stagnation at the surface after heavy rains or after snow melt in spring rather than for surface runoff to occur.

Table 11. Outflow components and water yield of the upper Zgłowiączka watershed calculated with the SWAT model and average number of water stress days (*WSD*)

Outflow components, mm					Water yield mm	*WSD*
surface runoff	lateral flow	groundwater flow	tile drainage flow	transmission losses		
6.4	4.2	2.4	45.7	0.2	58.5	29

Source: own study.

Determination of outflow components and their percentage shares in total water yield allowed us to define the main pathways of water and nitrate nitrogen cycling within the study area. The results of model analyses indicate that the main pathway of nitrate movement to the basin outlet in Samszyce is tile drainage flow. According to our results, the sum of average annual load of NO_3-N outflow through both the tile drainage system and lateral flow amounted to 15.2 kg NO_3-N·ha^{-1}, whereas the sum of NO_3-N load with surface runoff and groundwater flow was less than 2 kg NO_3-N·ha^{-1} (Tab. 12).

Table 12. Calculated NO_3-N load from the study area and its share in outflow components

Calculated NO_3-N load, kg·ha^{-1}							
surface runoff		subsurface flow with tile drainage		groundwater		total	
value	percentage share	value	percentage share	value	percentage share	value	percentage share
0.6	3	15.2	89	1.3	8	17.1	100

Source: own study.

CONCLUSIONS

This paper presents results of sensitivity analysis, calibration and validation of the hydrologic/water quality SWAT model for a small agricultural watershed in central Poland. Sensitivity analysis of SWAT parameters for discharge and NO_3-N load allowed us to determine the cause-and-effect relations in changes of individual parameter values in simulation results. Parameters related to actual evaporation calculation (ESCO, BLAI, CANMX and EPCO), soil properties (SOL_Z and SOL_AWC) as well as groundwater (ALPHA_BF and GWQMN) were found to be the most sensitive to discharge simulations, whereas NPERCO and RCHRG_DP were the most sensitive to NO_3-N load.

SWAT was calibrated for daily and monthly discharge and monthly NO_3-N load. Model efficiency was tested using manual techniques and evaluation statistics. Values of NSE for daily/monthly discharge simulations and monthly load (0.53/0.77 and 0.78, respectively), R^2 (0.55/0.88 and 0.82, respectively) and PBIAS (15.44/10.07 and 9.58, respectively) indicate a good or very good fit of simulated values to the observed data set. Model precision and accuracy of fit was proved in validation. Fitted values of parameters related to discharge and NO_3-N load may provide a good framework for calibration of SWAT in other agricultural watersheds, comparable in terms of natural conditions and changes in the natural flow regime.

The calibrated and validated SWAT model was used to assess water balance in the study area and the preferential pathways of N in the watershed, thus highlighting possible factors controlling the transfer of dissolved contaminants on the watershed scale. According to the simulation results, the share of tile drainage in water yield was equal to 78%. Tile drainage with lateral flow is the most significant pathway of NO_3-N transfer to surface waters in the study area. Its share in total load of NO_3-N amounted to 89%. The summarized contribution of other water yield components (surface runoff and groundwater) in total load is lower than 15%. Moreover, model simulation demonstrated also that the mean yearly number of water stress days for crops amounts to 29. In an average year of simulation in terms of precipitation sum, significant depletion of soil water content in the root zone (<20 mm) and consequently reduction of *AET* in the growing season were noticeable. This can be one of the explanations of low fertilizer use efficiency in the study area. Further analyses with the use of the verified SWAT model will be focused on synergetic influence of crop irrigation and fertilization on nitrogen load.

From our experience and studies application of SWAT model to describe processes of nutrients movement in the small watershed where natural flow regime was strongly modified requires specifically detailed knowledge of hydrological processes as well as reliable data about soil properties and land use (especially in terms of fertilization). Automatic calibration and determination of values of the most sensitive parameters is not sufficient to create a model, which describes water balance of the watershed as well as water yield and nitrogen load correctly and must be preceded by expert calibration.

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Karolina SMARZYŃSKA, Zygmunt MIATKOWSKI

Kalibracja i walidacja modelu SWAT do określania bilansu wodnego i strat azotu w małej rolniczej zlewni rzecznej w centralnej Polsce

STRESZCZENIE

Słowa kluczowe: *bilans wodny, kalibracja, rozproszone źródła zanieczyszczeń, Soil and Water Assessment Tool, straty azotu, zlewnia rolnicza*

W pracy przedstawiono zastosowanie modelu Soil and Water Assessment Tool (SWAT – wersja 2005) do analizy bilansu wodnego i dróg przemieszczania się azotu w obrębie małej zlewni rolniczej (Zgłowiączka) w paśmie Nizin Środkowopolskich. Naturalny reżim hydrologiczny Zgłowiączki został silnie przekształcony w wyniku działalności antropogenicznej (wylesianie terenu i instalacja systemu drenarskiego) związanej z prowadzeniem intensywnej produkcji rolniczej. Model SWAT został skalibrowany z krokiem dobowym i miesięcznym w odniesieniu do natężenia przepływu oraz z krokiem miesięcznym dla wielkości ładunku azotu azotanowego. Do oceny skuteczności modelu zastosowano techniki manualne (subiektywne) oraz miary statystyczne (obiektywne). Wartości wskaźnika efektywności Nash–Sutcliffe (NSE), współczynnika determinacji (R^2) oraz współczynnika *PBIAS* odnoszące się do natężenia przepływu z krokiem dobowym/miesięcznym i wielkości ładunku z krokiem miesięcznym wskazują na dobrą lub bardzo dobrą zgodność symulacji z danymi empirycznymi. Przeprowadzona następnie walidacja modelu potwierdziła dokładność i trafność symulacji. Wyniki wskazują, że woda odpływająca systemem drenarskim stanowiła 78% całości odpływu. Analizy modelowe umożliwiły również określenie najważniejszej drogi przemieszczania się azotu do wód powierzchniowych. Jest nią system podpowierzchniowego drenażu wraz z odpływem bocznym. Ładunek azotu azotanowego przemieszczający się tą drogą stanowił 89% całkowitego ładunku tej formy azotu. Określenie dróg przemieszczania się azotu w obrębie zlewni ma zasadnicze znaczenie dla decydentów zarządzających zasobami wodnymi. Informacja ta pozwala na wybór i wdrożenie najbardziej efektywnych, dla danej zlewni, działań zmierzających do ograniczenia ilości zanieczyszczeń przedostających się ze źródeł rozproszonych do wód powierzchniowych.