REPORT FROM PILOT ACTION - Report from testing the dynamic model to assess cumulative effect of N(S)WRM

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1. APPLICATION OF THE HYDROLOGICAL MODEL

The hydrological model Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012) was applied in the Kamienna catchment. It is a process-based, semi-distributed, continuous-time model simulating the movement of water, sediment, and nutrients on a catchment scale. The steps for the implementation of the model included model setup, calibration and validation. The following subsections describe in detail subsequent steps. All details about the input data used to develop the SWAT model setup are listed in the Appendix A.

1.1 Description of the catchment

The catchment is located in the south-central Poland (Fig. 1). It occupies 2020 km2 and has a highland part in the west and south-west and a lowland part in the east. Thus, it is quite representative for the Polish landscape, also in terms of climate (mean annual temperature and precipitation are similar to the country mean). Table 1 provides more detailed catchment characteristics.

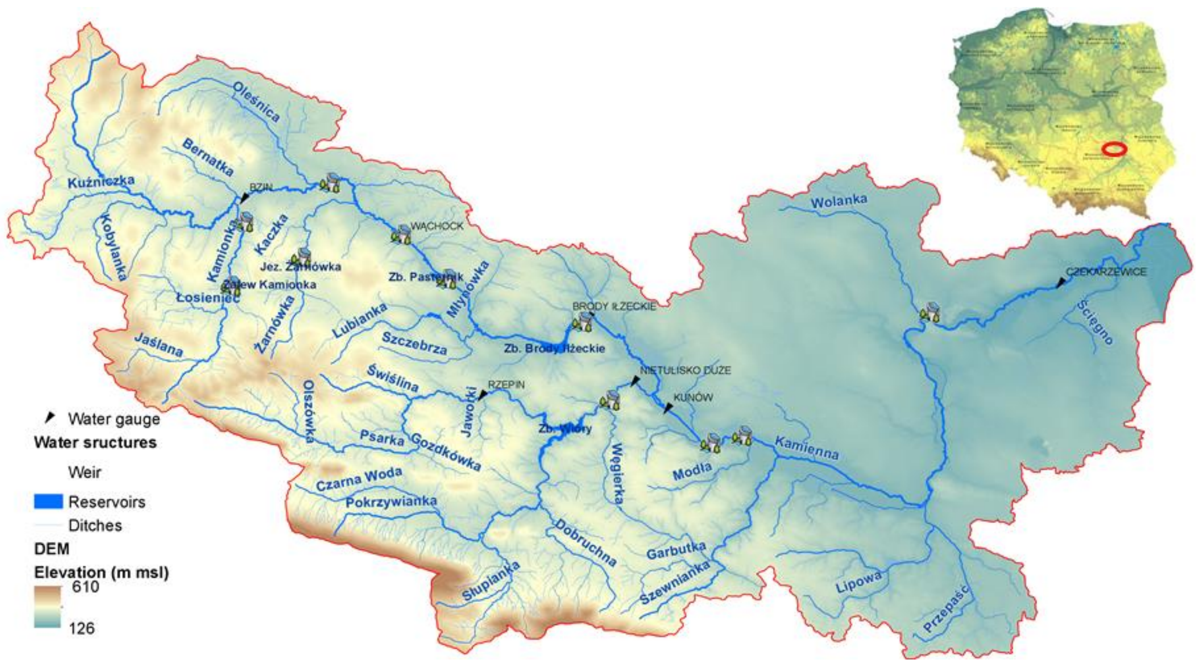

Figure 1 Location of the Kamienna catchment

Table 1 – Characteristics of the Kamienna catchment.

Characteristic	Unit	Value
Character of catchment		Lowland
Catchment size:	km^2	2020
Average flow	m^3/s	8.3
Extreme flow low/high	m^3/s	1.4/113
Annual precipitation	mm	620
Annual average air temperature	°C	7.8
Agriculture area	%	49.0
Urban area	%	6.4
Forest area	%	44.2
Open Water area	%	0.4

1.2 SWAT model description

SWAT is a process-based, semi-distributed, continuous-time model simulating the movement of water, sediment, and nutrients on a catchment scale with a daily time step. The basic calculation unit – hydrologic response unit (HRU) is created by an overlay of land use, soil, and slope maps. Water balance and water quality components are computed separately for each HRU and aggregated at the sub-basin level and routed through the stream network to the main outlet to obtain the total flows and loadings for the river basin [NEITSCH et al. 2011].

1.3 Watershed delineation

The watershed was delineated in ArcMap using the ArcSWAT interface. In this study a 20-meter resolution Digital Elevation Model (DEM) (Fig. 2), with mean elevation error of 0.8–2.0 m, has been used for automatic catchments delineation. Initial delineation output was manually corrected to account for errors in and the final division of the Kamienna had 228 sub-basins (average area of 8.8 km^2) (Fig. 3). Comparison with automatic delineation output with real sub-catchment delineation according to the official hydrographic map of Poland (MPHP) showed good results (Fig. 3)

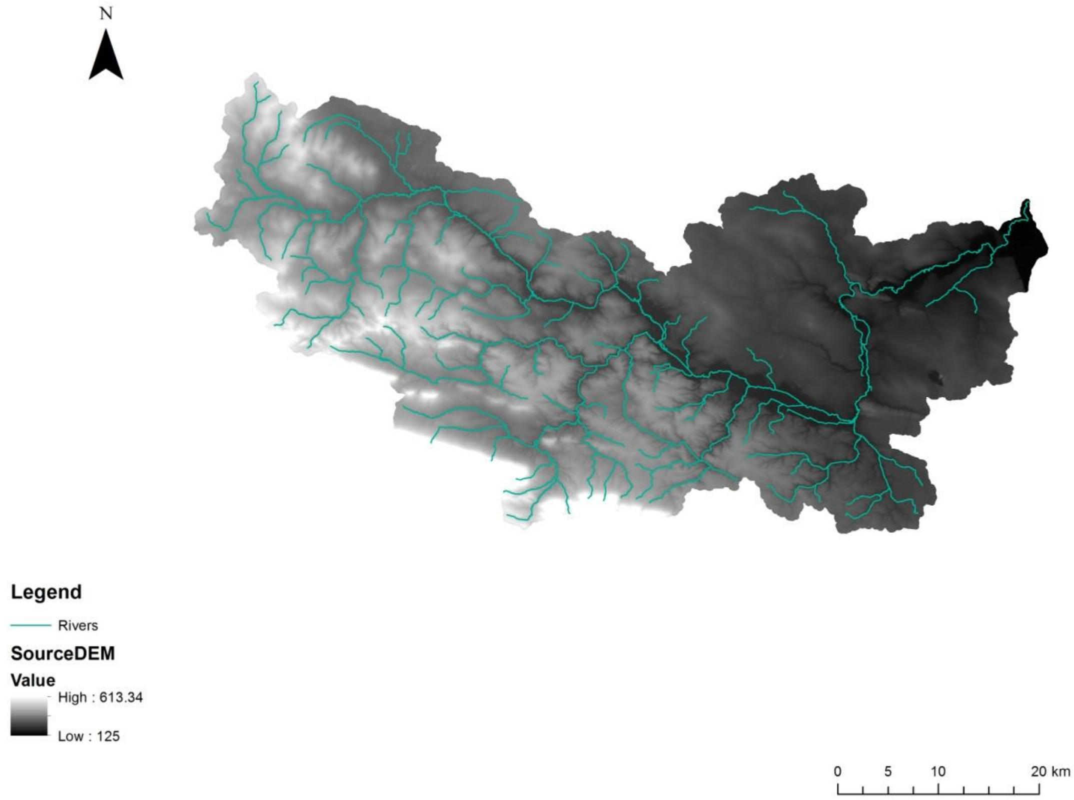

Figure 2 – Input DEM for the watershed delineation and river network obtained from the watershed delineation process

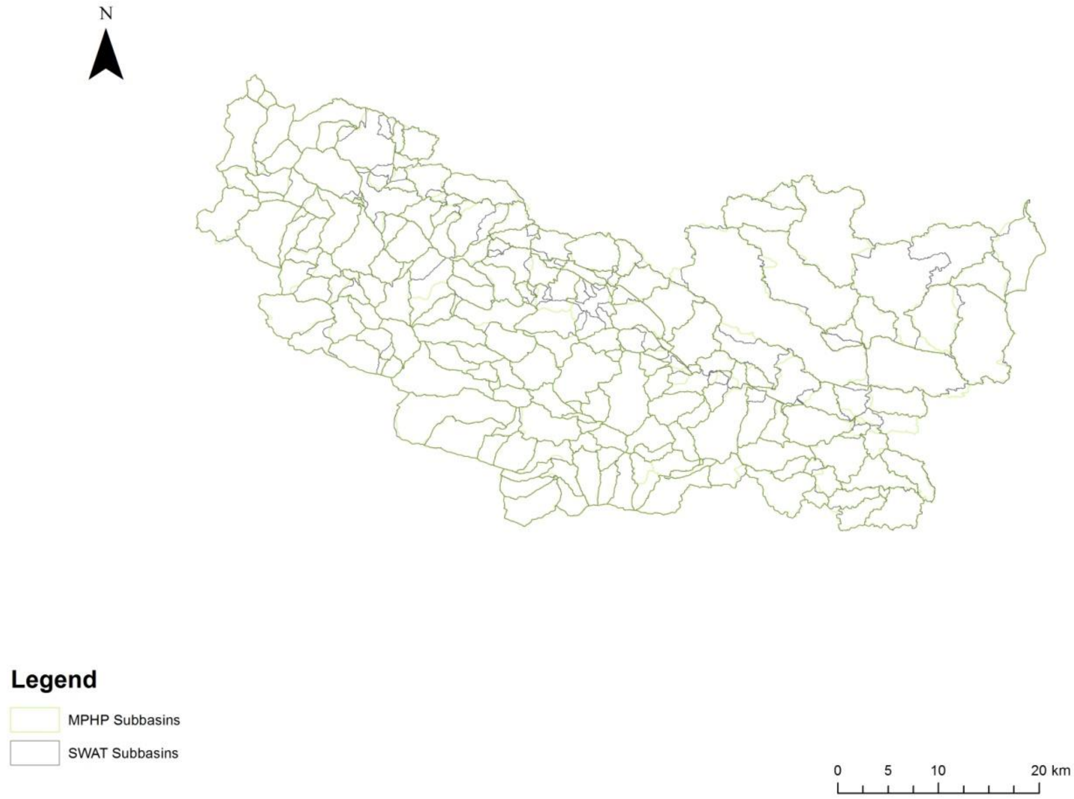

Figure 3 – Subcatchments subdivision of the delineated watershed compared to real subbasin division (MPHP – official hydrography map).

1.4 Land cover, soils and HRUs definition

The Corine Land Cover (CLC) 2012 layer was used as the primary data source for the land use/land cover map. However, this layer was enhanced by a polygon layer of paved roads from Polish Topographic Database and the commune-level agricultural census statistical data (2010) (Figure 4). The latter was used to sub-divide the "Non-irrigated arable land" into classes that represented particular crops that were cultivated in the Kamienna catchment. This subdivision was done using a set of GIS techniques, including the "Create Random Raster" tool in ArcGIS. Thus, the arable land area was divided into 3 classes, representing dominating crops: winter wheat (WWHT), spring barley (BARL) and potatoes (POTA).

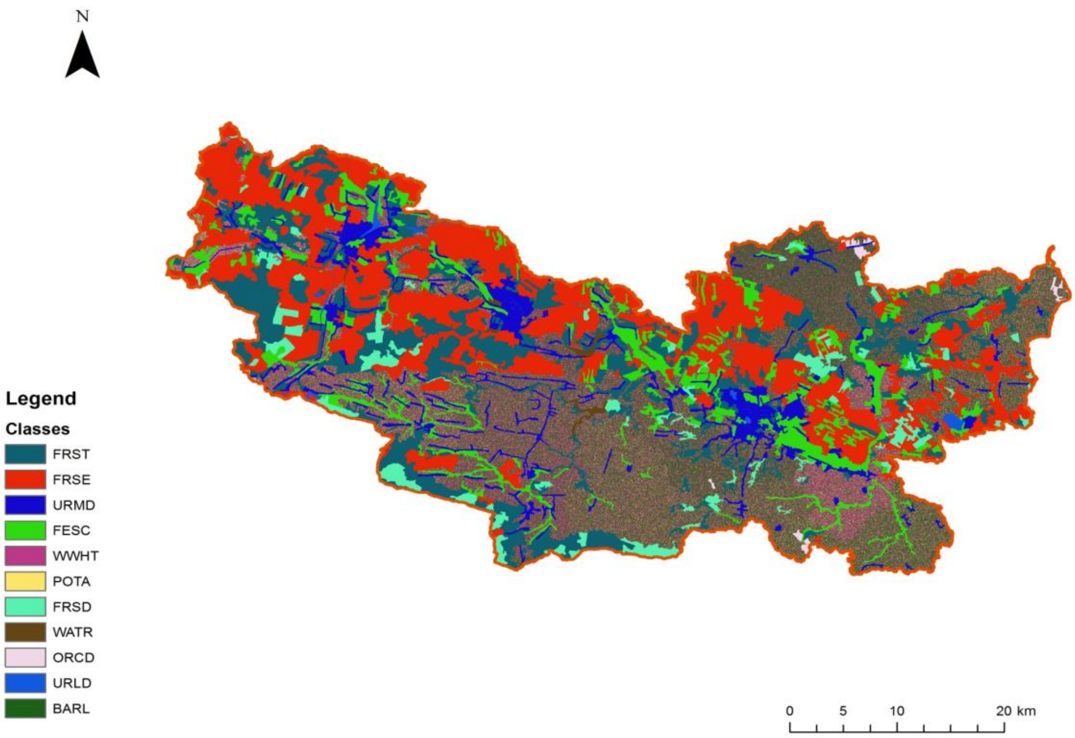

Figure 4 – Reclassified land use map.

The soil map was obtained by combining the soil data from the Polish Institute of Soil Science and Plant Cultivation and the Forest Data Bank. As a result 47 soil classes were distinguished in the Kamienna catchment. Table 5 lists all soil classes exceeding 1% of the share in the catchment. Dominating classes are: loess (l) – 27%, coarse sand (pl) – 8% and medium-coarse sand (ps.pl) – 7%.

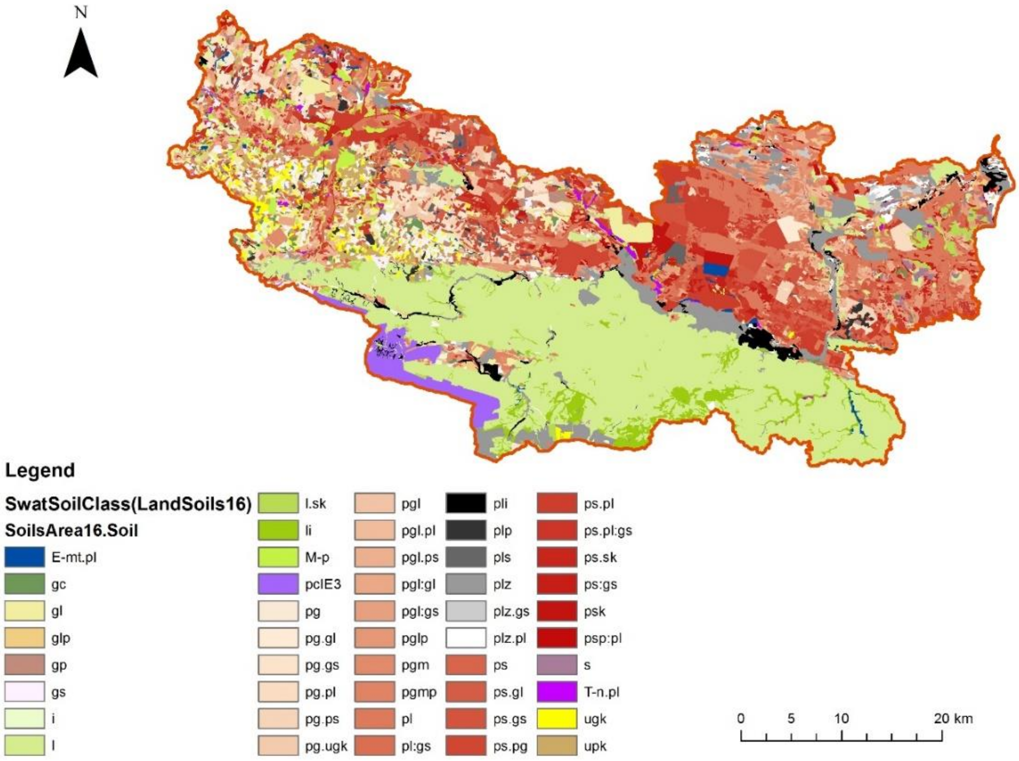

Figure 5 – Soil classes

By overlaying the slope, land use and soil maps, 2045 HRUs were delineated in the catchment. The following area thresholds were used in the HRU delineation: 60 ha for land cover and 30 ha for soils and 20 ha for slope. Thus, when using this method, all land cover types below the first threshold in each sub-basin were removed and aggregated into the remaining classes, which will speed up the computational time. The final distribution of HRUs characteristics is presented in Tables 2-4.

Table 2 – Land use distribution. Default SWAT crop parametrization was used.

Land use	SWAT Code	Area [ha]	Area [%]
Forest-Mixed	FRST	30561.61	15.19
Forest-Evergreen	FRSE	49120.67	24.41
Residential-Medium Density	URMD	13835.41	6.87
Tall Fescue	FESC	18509.15	9.2
Winter Wheat	WWHT	32555.07	16.18
Potato	POTA	8507.27	4.23
Forest-Deciduous	FRSD	7710.36	3.83
Water	WATR	672.5	0.33
Orchard	ORCD	549.7	0.27
Residential-Low Density	URLD	796.14	0.4
Spring Barley	BARL	38438.23	19.1

Table 3 – Soils distribution (only classes occupying over 2.5% of the total area). Soil class names accrpding to the USDA classification are given in parentheses.

Soil name	Area [ha]	Area [%]
l (loess)	54471.15	27.07
pl (sand)	16371.44	8.13
ps.pl (sand)	14305.47	7.11
plz (silt)	11436.78	5.68
gl (sandy loam)	6105.53	3.03
ps (sand)	5234.41	2.6

Table 4 – Slope distribution

Slope class	Area [ha]	Area [%]
0-6%	146365.56	72.73
>6%	54890.58	27.27

1.5 Model structure

In this study, channel routing was modeled using a Muskingum method. The modified USDA Soil Conservation Service (SCS) curve number method for calculating surface runoff and the Hargreaves method for estimating potential evapotranspiration (PET) were selected. Runoff-infiltration split up is simulated with the daily curve number method and the Curve Number is adjusted daily based on the ICN method (Neitsch et al., 2011).

1.6 Weather data

Weather data for 9 weather stations and 35 rain stations were used in the model (Figure 6), covering the time period 1952 – 2017. Weather variables used in the model included daily precipitation and temperature. Those variables were interpolated in the whole catchment area using Thiessen polygons method. Climate stations were discarded in case of lack of time coverage or in case of inconsistent data (e.g. too many gap days in the time series).

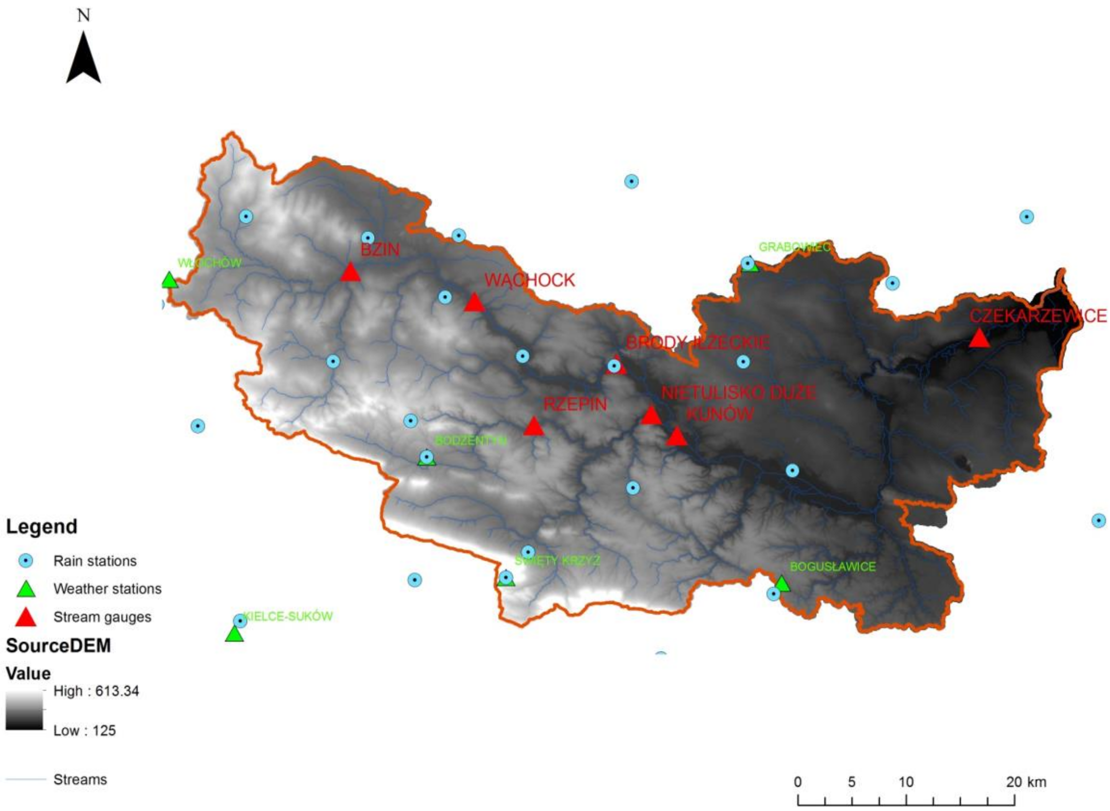

Figure 6 – Climate stations spatial distribution in the catchment.

1.7 Ponds and reservoirs

In the Kamienna catchment 2 major reservoirs were defined in the model structure (Wióry and Brody Iłżeckie) (Figure 7). Among the main parameters describing their geometry, surface area and volume (separately for principal and emergency spillway), can be found. Such information was obtained from official documentations provided by the Regional Water Management Authority in Warsaw. The Wióry reservoir has emergency surface area of 408 ha and emergency volume of $1767*10^4 m^3$. The Brody Iłżeckie reservoir has emergency surface area of 203.5 ha and emergency volume of $657.8*10^4$ m^3. Another important reservoir parameters in terms of SWAT modeling like NDTARGR (Number of days to reach target storage from current reservoir storage) were obtained during calibration stage.

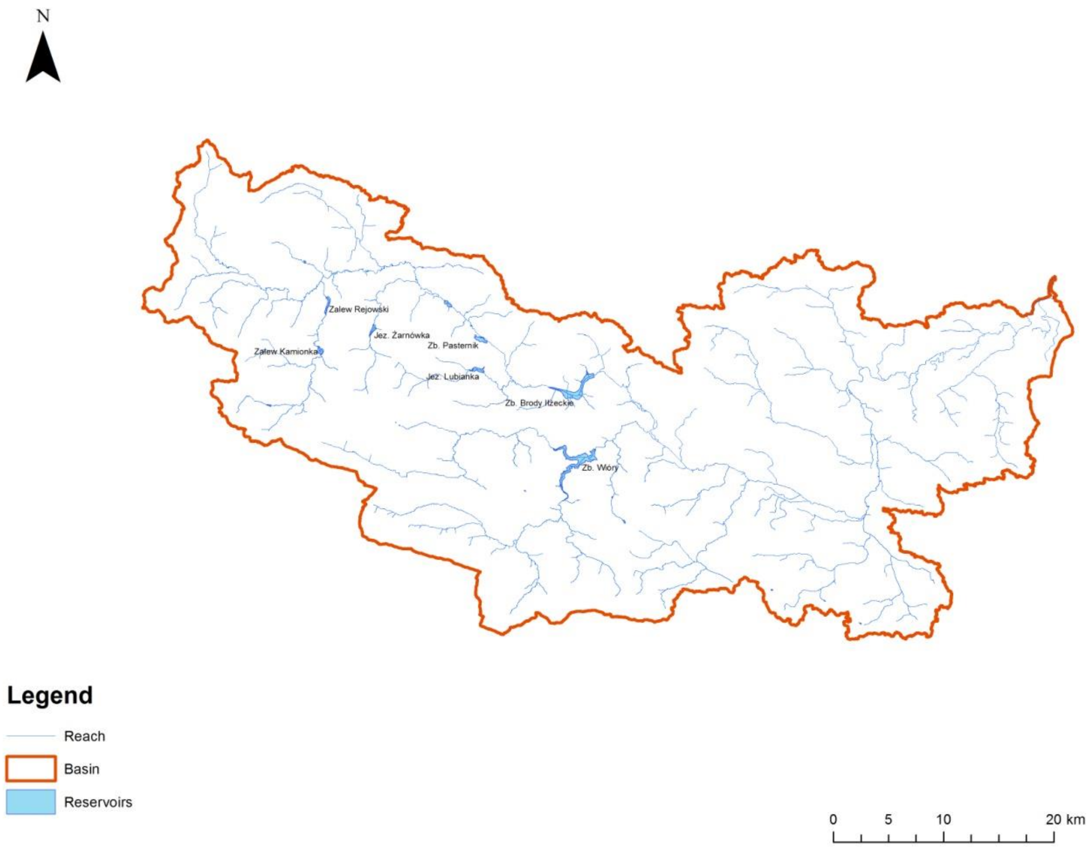

Figure 7 Location of reservoirs in the Kamienna catchment

1.8 Model calibration and validation for flow

The Kamienna catchment model was calibrated and validated using SWAT- CUP interface where the sequential uncertainty fitting (SUFI2) algorithm was used as the optimization function. A multi-site calibration against daily discharge data for 8 gauging stations was applied in the study (Table 5). The calibration and validation period were set to 2005 – 2010 and 2011 – 2015, respectively.

Table 5 – Gauging station names and position on SWAT subcatchments network

Gauge	River	Corresponding subbasin
Bzin	Kamienna	31
Wąchock	Kamienna	46
Czekarzewice	Kamienna	65
Brody Iłżeckie	Kamienna	90
Nietulisko Duże	Świślina	124
Rzepin	Świślina	125
Wióry	Pokrzywianka	139
Włochy	Pokrzywianka	182

Table 6 lists the names and initial ranges of parameters used in the calibration and validation procedures. The Kling-Gupta efficiency (KGE) was used as a major objective function (Gupta et al., 2009), and additionally Percent Bias (PBIAS) have been analyzed to check the overall accuracy of water volume simulations.

Table 6 Discharge calibration parameters – definitions and ranges.

Name	Definition	Min value	Max value
r__CN2.mgt	initial SCS runoff curve number for moisture condition	-0.3	0.3
v__GW_DELAY.gw	Groundwater delay time, days	0	20
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur, mm H_2O	500	1000
v__GW_REVAP.gw	Groundwater “revap” coefficient	0.02	0.2
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0	0.5
v__ESCO.hru	Soil evaporation compensation factor	0	1
v__EPCO.hru	Plant uptake compensation factor	0	1
r__SOL_AWC().sol	available water capacity of the soil layer, mm $H_2O \cdot mm^{-1}$ soil	-0.3	0.3
v__CH_N2.rte	Manning's n value for the main channel	0.05	0.15
r__OV_N.hru	Manning's n value for overland flow	0.1	0.3
r__SLSUBBSN.hru	Slope length	-0.5	0.5
v__NDTARGR.res	Number of days to reach target storage from current reservoir storage	15	50
v__RES_EVOL.res	Volume of water needed to fill the reservoir to the emergency spillway	1600	1900
v__EVRSV.res	Lake evaporation coefficient	0.7	1
v__OFLOWMN.res	Minimum daily outflow for the month	0.3	0.7
v__TIMP.bsn	Snow pack temperature lag factor	0	0.6
v__CNCOEF.bsn	Plant ET curve number coefficient	1.3	1.7
v__SMTMP.bsn	Snow melt base temperature, °C	-0.5	2
v__SURLAG.bsn	Surface runoff lag coefficient	0.05	5

Multi-site calibration and validation approach implemented in the Kamienna catchment gave satisfactory results for all gauging stations (Table 7). Figure 8 and 9 illustrate modeled vs observed daily hydrographs for all gauges. It is noteworthy that the model generally underestimates high peak flows but performs quite well for medium and low flows (although not all parts of the hydrograph are captured well). Additionally, the results for the calibration slightly prevail over those for the validation period in the summary statistics. Hydrographs and statistics for Nietulisko Duże and Wióry are slightly worse compared to others as they are both highly influenced by large reservoirs situated directly upstream from the gauges (cf. Fig. 7). The reason is a rather simplified approach used in SWAT to simulate reservoir operation. Nevertheless, KGE values for all gauging stations exceed 0.6 which can be assumed as good fitting according to Moriasi et al. (2012).

Table 7 Summary statistics for calibration and validation

Gauge	Calibration		Validation	
	KGE	PBIAS	KGE	PBIAS
Bzin	0.73	-11.5	0.70	11.7
Wąchock	0.71	-17.8	0.68	1.6
Brody Iłżeckie	0.80	-11.1	0.77	8.2
Rzepin	0.85	-1.5	0.69	19.7
Nietulisko Duże	0.76	-3.4	0.60	5.8
Włochy	0.71	2.4	0.61	-0.7
Czekarzewice	0.79	-7.4	0.79	13.8
Wióry	0.68	-4.7	0.65	-18.4

Figure 8 – Modeled vs observed daily flows for gauging stations used in calibration.

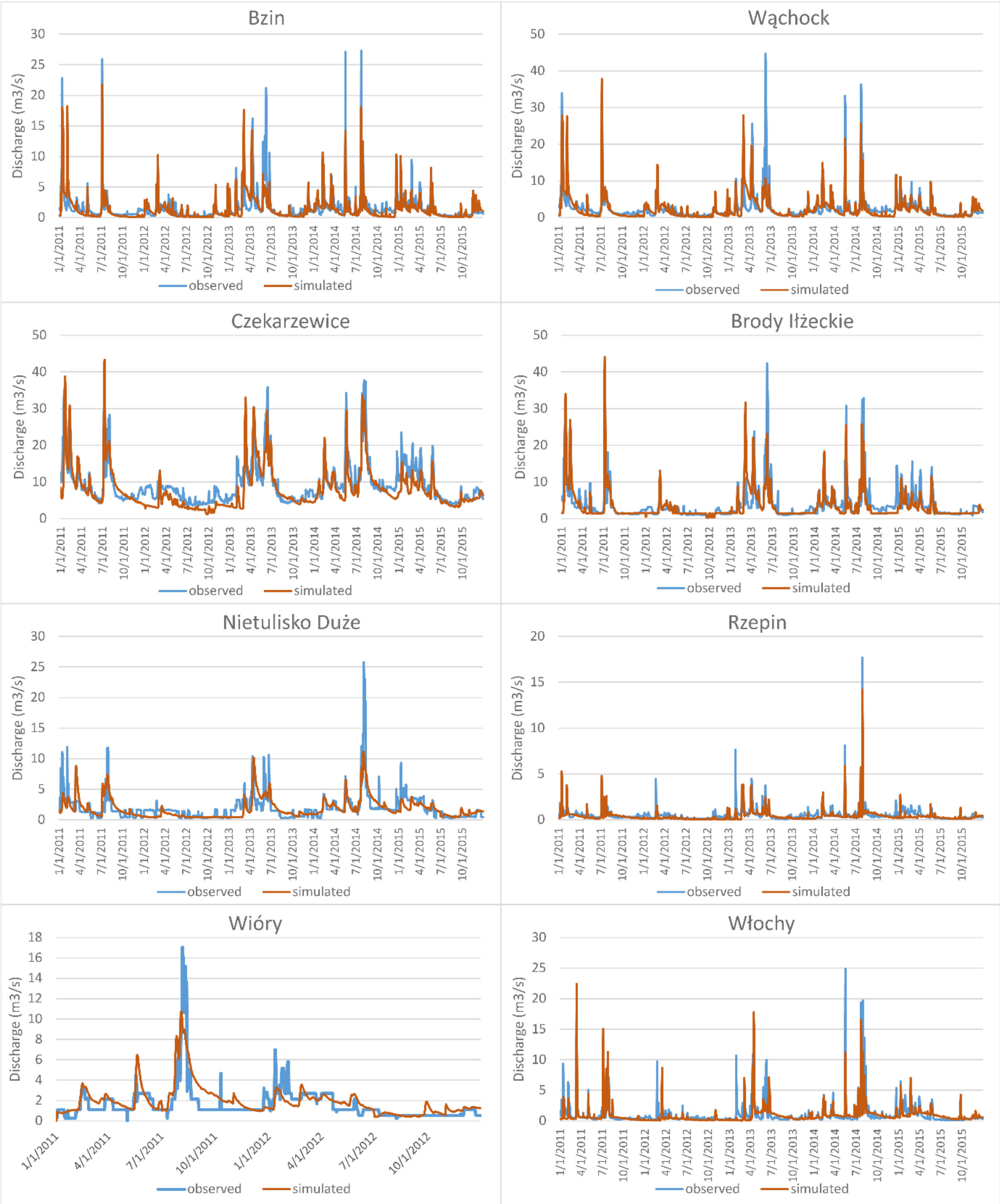

Figure 9 Modeled vs observed daily flows for all gauging stations in the validation period.

1.9 Model calibration and validation for sediment, nitrogen and phosphorus loads

A multi-site calibration against daily sediment, nitrate, total nitrogen and total phosphorus loads for 8 gauging stations was applied in the study (Table 8). The calibration and validation period were set to 2000 – 2005 and 2006– 2012, respectively.

Table 8 Water quality monitoring point names and position on SWAT subcatchments network

Gauge	River	Corresponding subbasin
Bzin	Kamienna	31
Wola Pawłowska	Kamienna	44
Michałów	Kamienna	103
Nietulisko Duże	Świślina	131
Ostrowiec Świętokrzyski	Szewnianka	164
Krasków	Kamienna	183

Tables 9-11 lists the names and initial ranges of parameters used in the calibration and validation procedures. The Kling-Gupta efficiency (KGE) was used as a major objective function (Gupta et al., 2009), and additionally Percent Bias (PBIAS) have been analyzed to check the overall accuracy of water volume simulations.

Table 9 Sediment calibration parameters – definitions and ranges

Name	Definition	Min	Max
v__PRF_BSN.bsn	Peak rate adjustment factor for sediment routing in the main channel (-)	0.99	0.99
v__ADJ_PKR.bsn	Peak rate adjustment factor for sediment routing in the sub-basin (-)	0.7	0.7
v__SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing (-)	0.000123	0.000123
v__SPEXP.bsn	Exponent parameter for calculating sediment reentrained in channel sediment routing (-)	1.07	1.07
v__LAT_SED.hru	Sediment concentration in lateral and groundwater flow ($mg * L^{-1}$)	0.5	9.79
v__CH_COV1.rte	Channel erodibility factor (-)	0.003	0.78
v__CH_COV2.rte	Channel cover factor (-)	0.41	0.95
r__USLE_P.mgt	USLE equation support practice factor (-)	-0.38	-0.04
r__USLE_K.sol	USLE equation soil erodibility (K) factor (-)	-0.49	0.36
v__RES_NSED.res	Equilibrium sediment concentration in the reservoir ($mg * L^{-1}$)	5	30
v__RES_D50.res	Median particle diameter of sediment (µm)	5	40

Table 10 Nitrogen calibration parameters – definitions and ranges

Name	Definition	Min	Max
v__ERORGN.hru	Organic N enrichment ratio for loading with sediment (-)	1.77	2.92
v__BIOMIX.mgt	Biological mixing efficiency (-)	0.19	0.56
v__HLIFE_NGW.gw	Half-life of nitrate in the shallow aquifer (days)	98.21	149.76
v__SOL_ORGN.chm	Initial organic N concentration in the soil layer ($mg N * kg^{-1}$ soil, dry weight)	125.25	250.5
r__SOL_CBN.sol	Organic carbon content (% soil weight)	-0.19	-0.09

r__RS4.swq	Rate coefficient for organic N settling in the reach at 20º C (day^{-1})	0.01	0.044
r__RS3.swq	Benthic source rate for NH4-N in the reach at 20º C (mg NH_4-N * $(m^2 \cdot day)^{-1}$)	0.29	0.46
v__AI1.wwq	Fraction of algal biomass that is nitrogen (mg N * mg alg^{-1})	-	-
v__CDN.bsn	Denitrification exponential rate coefficient (-)	0.67	0.67
v__N_UPDIS.bsn	Nitrogen uptake by plants distribution parameter (-)	3.5	3.5
v__CMN.bsn	Rate factor for humus mineralization of active organic nutrients (-)	0.0022	0.0022
v__SDNCO.bsn	Denitrification threshold water content (-)	1.02	1.02
v__NPERCO.bsn	Nitrate percolation coefficient (-)	0.98	0.98
v__NSETLR1.lwq	Nitrogen settling rate in reservoir for months IRES1 through IRES2 (m * $year^{-1}$).	-	-
v__NSETLR2.lwq	Nitrogen settling rate in reservoir for months other than IRES1 through IRES2 (m * $year^{-1}$).	-	-
v__SHALLST_N.gw	Initial concentration of nitrate in shallow aquifer (ppm)	5.25	9.55

Table 11 Phosphorus calibration parameters – definitions and ranges

Name	Definition	Min	Max
v__P_UPDIS.bsn	Phosphorus uptake distribution parameter (-)	1.5	1.5
v__PPERCO.bsn	Phosphorus percolation coefficient (10 m^{-3} * Mg^{-1}).	16.56	16.56
v__PHOSKD.bsn	Phosphorus soil partitioning coefficient (m^{-3} * Mg^{-1}).	118.5	118.5
v__PSP.bsn	Phosphorus availability index (-)	0.54	0.54
v__CH_OPCO.rte	Organic phosphorus concentration in the channel (ppm)	8.25	56.5
v__RS2.swq	Benthic (sediment) source rate for dissolved phosphorus in the reach at 20º C (mg dissolved P * $(m^2 \cdot day)^{-1}$)	-	-
v__RS5.swq	Organic phosphorus settling rate in the reach at 20º C (day^{-1})	0.05	0.09
v__SOL_ORGP.chm	Initial organic P concentration in soil layer (ppm).	10	390
v__ERORGP.hru	Phosphorus enrichment ratio for loading with sediment (-)	0.47	3.82
r__GWSOLP.gw	Concentration of soluble phosphorus in groundwater contribution to streamflow from subbasin (ppm).	0.001	0.14
v__PSETLR1.lwq	Phosphorus settling rate in reservoir for months IRES1 through IRES2 (m * $year^{-1}$)	-	-
v__PSETLR2.lwq	Phosphorus settling rate in reservoir for months other than IRES1-IRES2 (m * $year^{-1}$)	-	-

Multi-site calibration and validation approach implemented in the Kamienna catchment gave satisfactory results for most of water quality monitoring points (Table 12). Figures 10-17 illustrate modeled vs observed daily hydrographs for all water quality monitoring points in calibration and validation period.

Table 12 Summary statistics for calibration and validation

Variable	**Calibration**		**Validation**	
	PBIAS	**KGE**	**PBIAS**	**KGE**
Sediment				
Bzin	13.4	0.79	1.9	0.21
Wola Pawłowska	6.5	0.44	-1	0.29
Michałów	51.9	0.16	22.3	0.69
Nietulisko Duże	60.4	0.12	-90	-0.5
Ostrowiec Świętokrzyski	14.7	0.49	-29.4	0.43
Krasków	58	-0.01	59.5	-0.18
NNO3				
Bzin	6.8	0.27	24	0.23
Wola Pawłowska	9.6	0.41	-25.4	0.3
Michałów	13.9	0.54	5.1	0.24
Nietulisko Duże	35.7	0.4	4.5	0.13
Ostrowiec Świętokrzyski	24.4	0.57	-11	0.46
Krasków	12.7	0.4	1.8	0.73
Total N				
Bzin	52.2	0.18	43.2	0.24
Wola Pawłowska	22	0.6	-6.8	0.69
Michałów	30.8	0.37	21.8	0.54
Nietulisko Duże	0.9	0.54	-5.6	-0.13
Ostrowiec Świętokrzyski	30.8	0.55	20.3	0.64
Krasków	23.3	0.62	23.7	0.59
Total P				
Bzin	-69.5	0.07	-53.6	0.12
Wola Pawłowska	17.8	0.77	19.8	0.56
Michałów	20.1	0.43	-1.1	0.55
Nietulisko Duże	-2.4	0.82	5.4	0.5
Ostrowiec Świętokrzyski	28.8	0.5	88.7	-0.47
Krasków	15.2	0.8	23.8	0.45

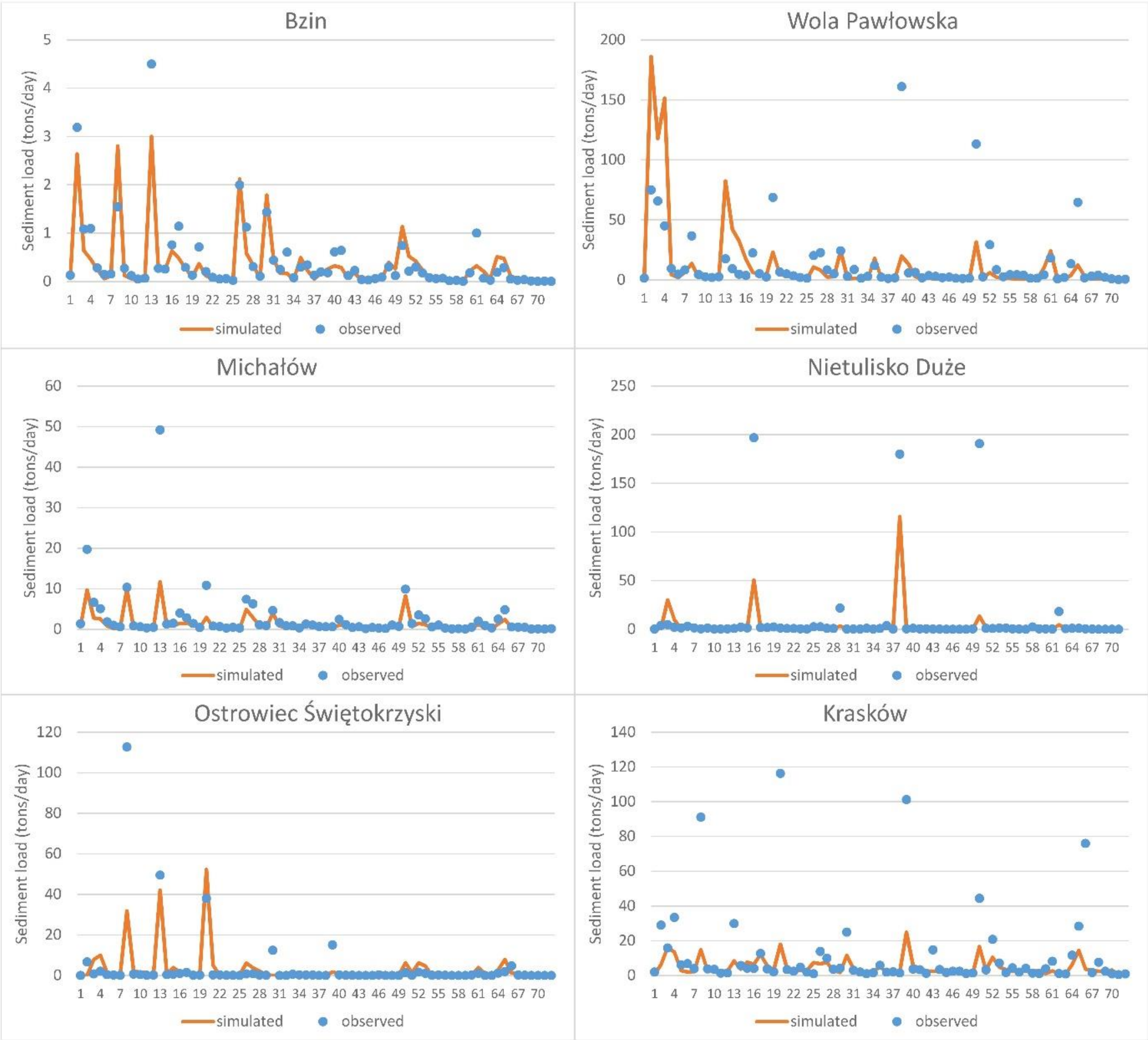

Figure 10 Modeled vs observed daily sediment loads for all water quality monitoring points in the calibration period

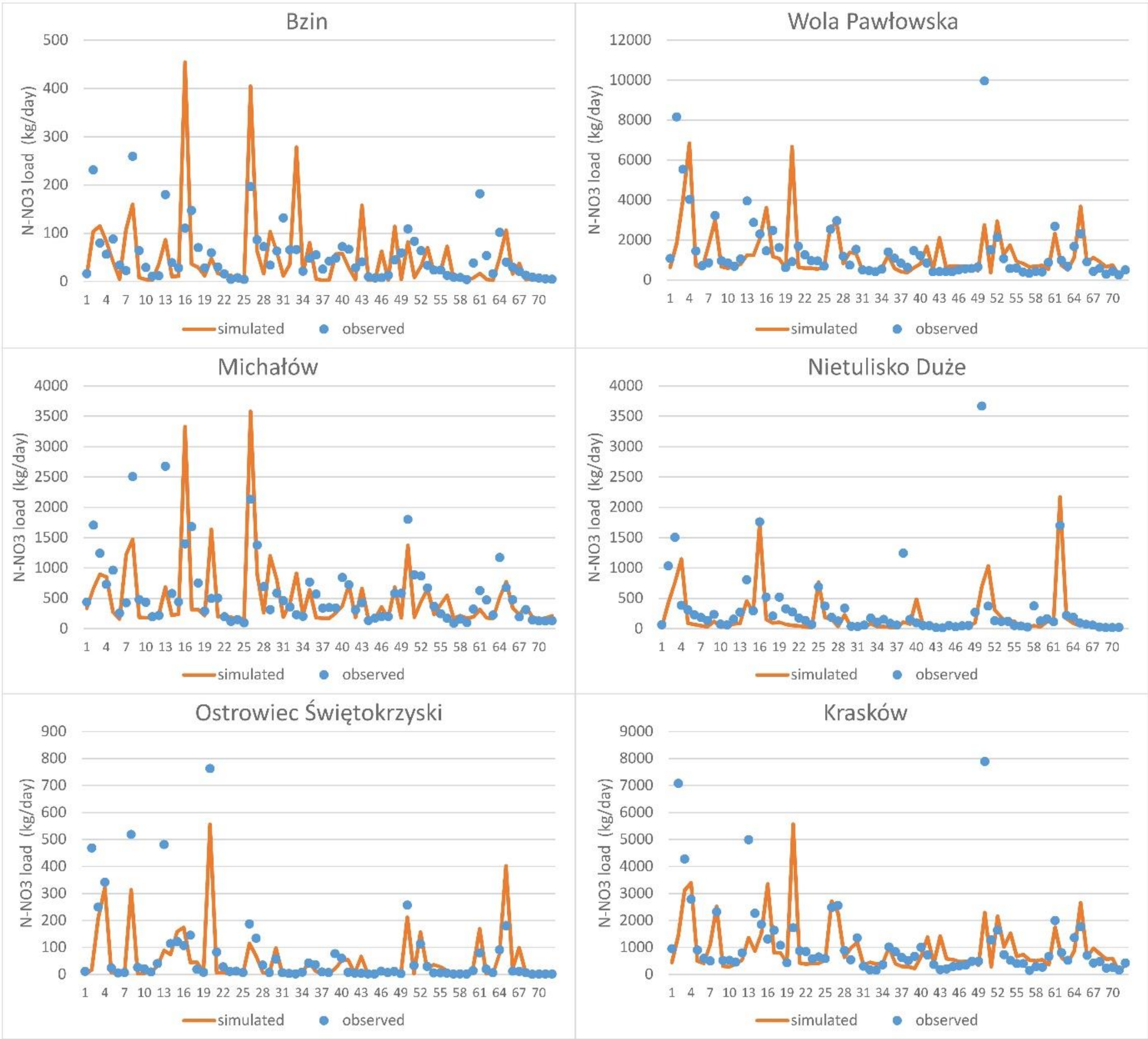

Figure 11 Modeled vs observed daily nitrate loads for all water quality monitoring points in the calibration period

Figure 12 Modeled vs observed daily total nitrogen loads for all water quality monitoring points in the calibration period

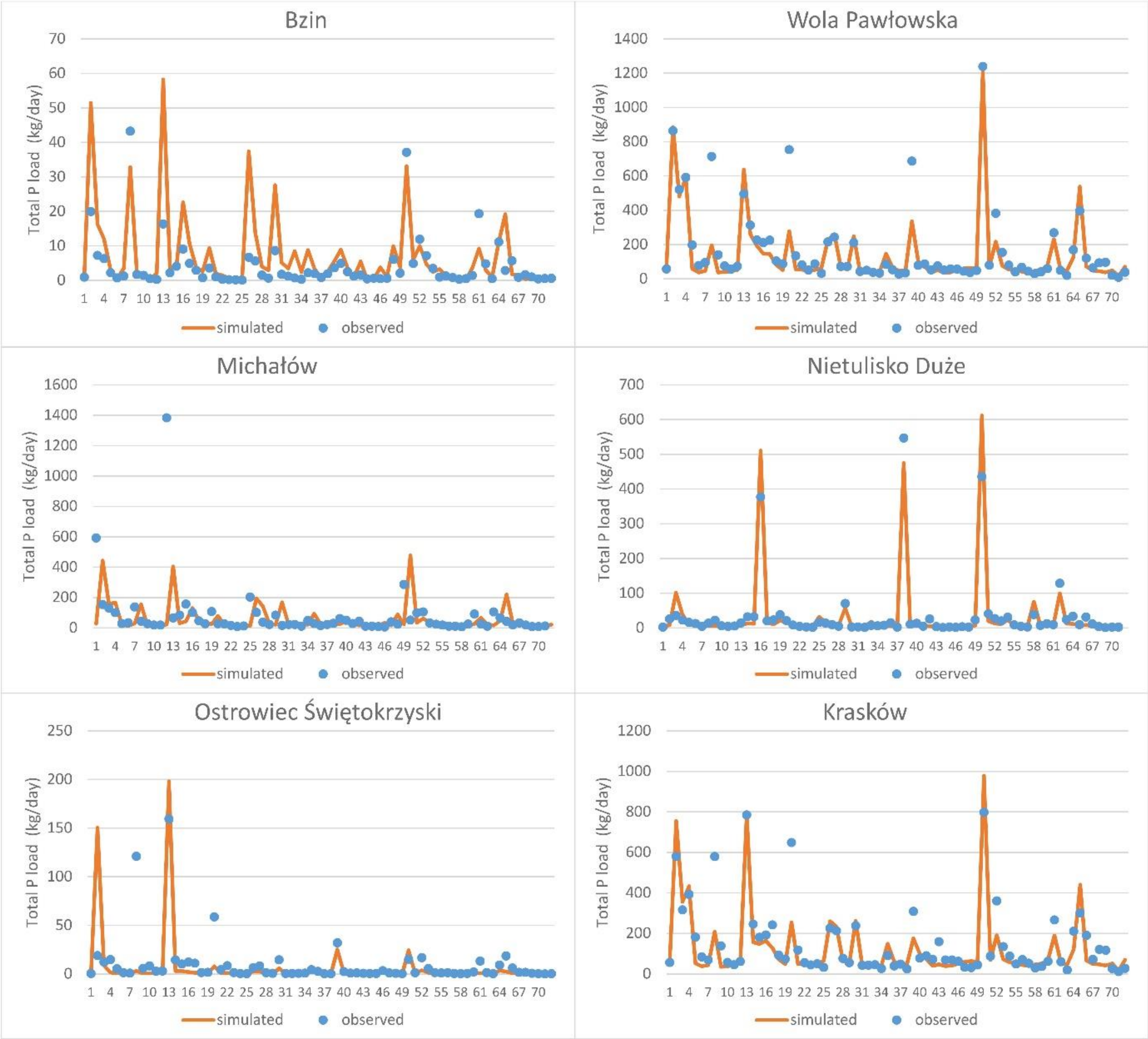

Figure 13 Modeled vs observed daily total phosphorus loads for all water quality monitoring points in the calibration period

Figure 14 Modeled vs observed daily sediment loads for all water quality monitoring points in the validation period

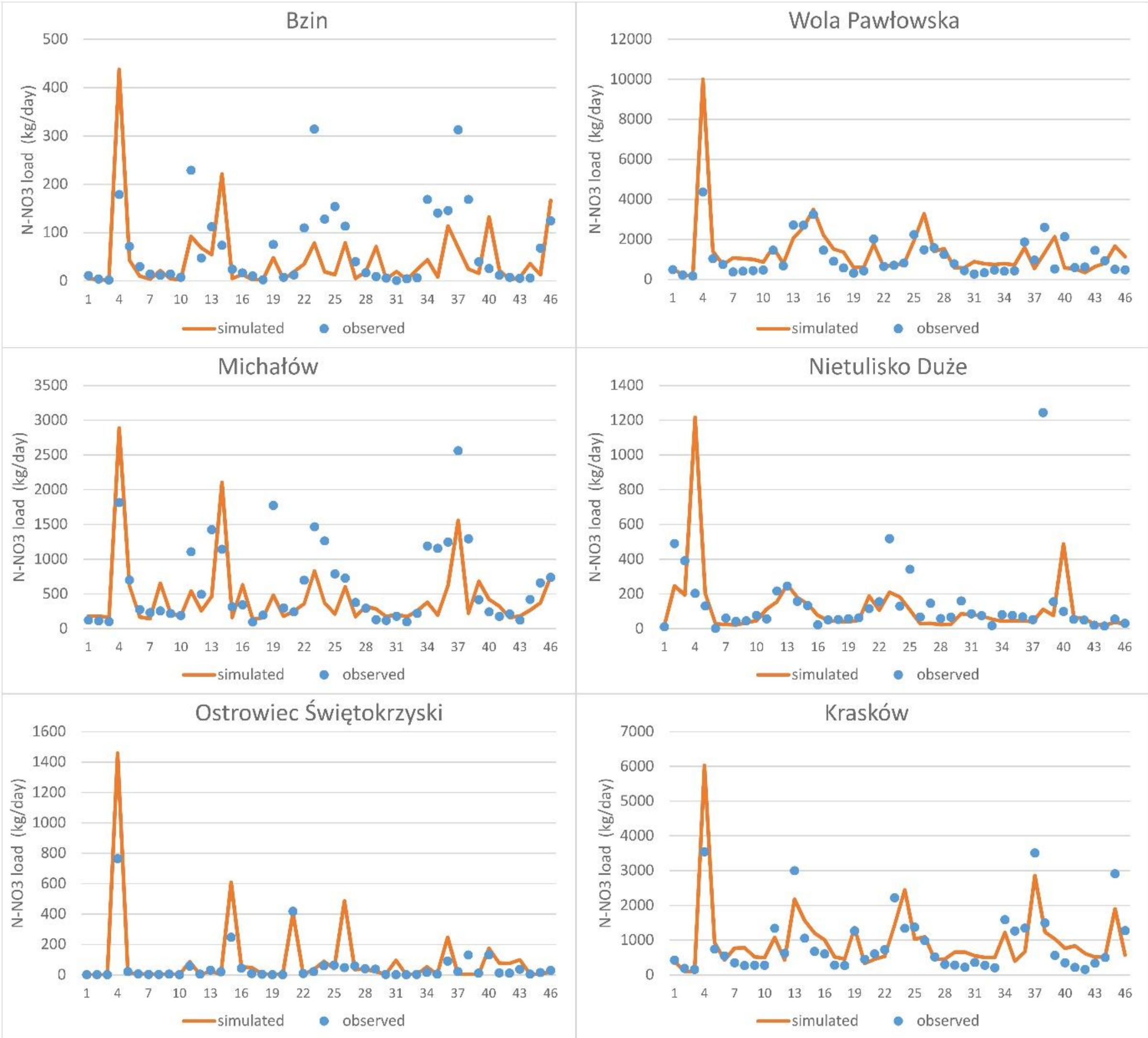

Figure 15 Modeled vs observed daily nitrate loads for all water quality monitoring points in the validation period

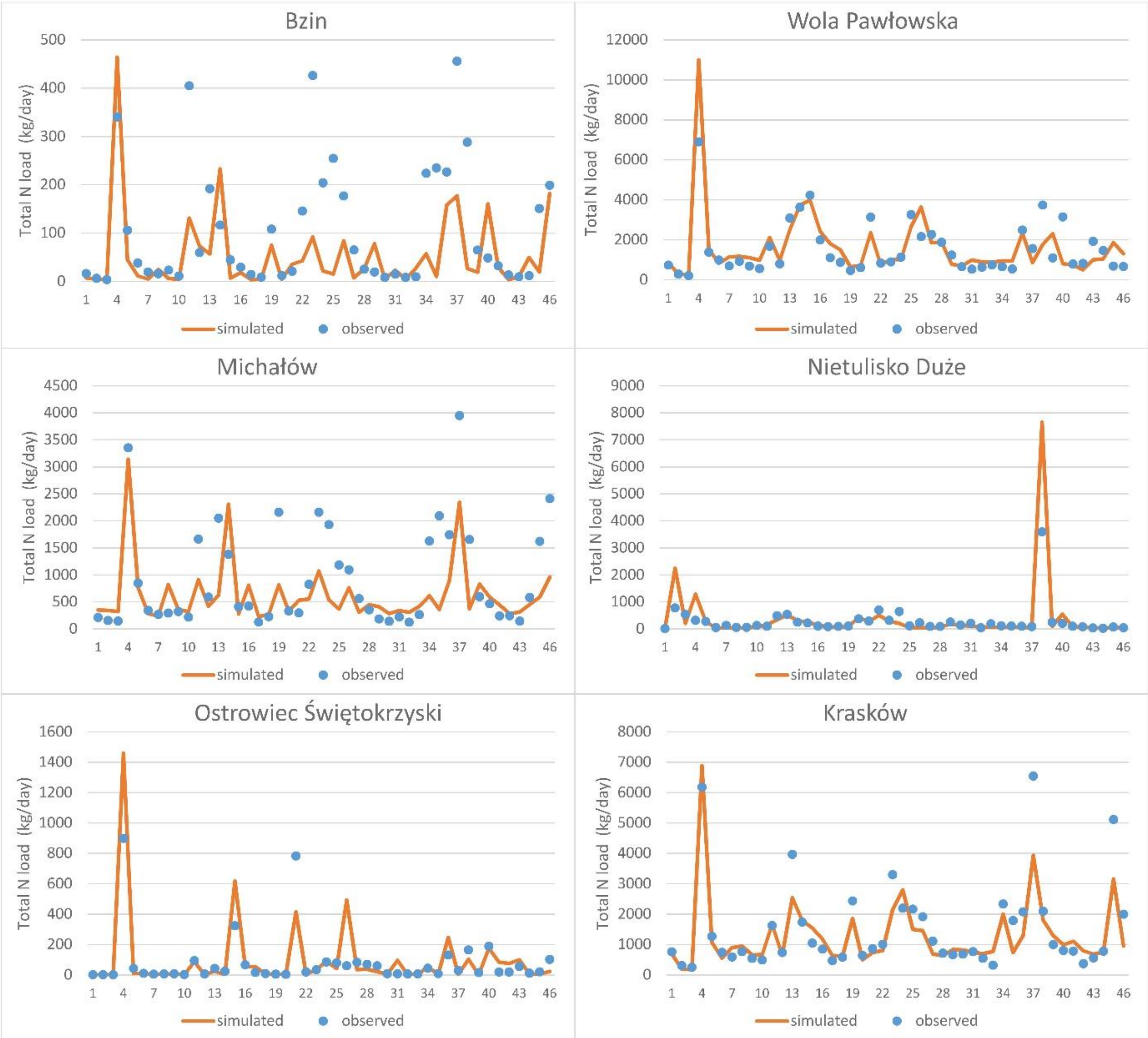

Figure 16 Modeled vs observed daily total nitrogen loads for all water quality monitoring points in the validation period

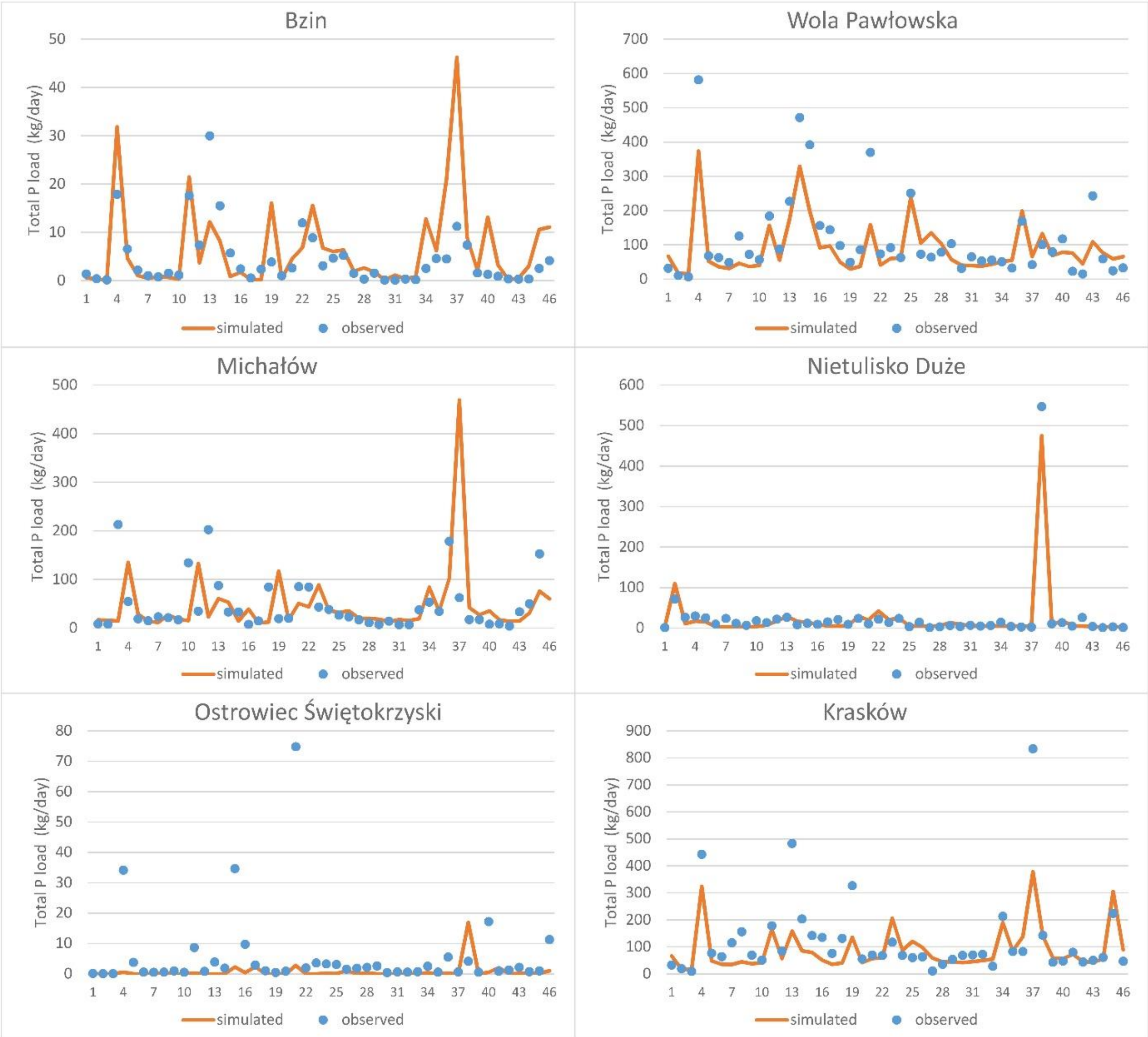

Figure 17 Modeled vs observed daily total phosphorus loads for all water quality monitoring points in the validation period

2. HYDRAULIC MODELING

2.1 Description of the river network

River Kamienna is 138 km long, with a catchment of roughly 2000 km^2. For the purpose of this workpackage, a section of Kamienna – from Skarżysko - Kamienna to Czekarzewice discharge gauge (101 km long) was selected for hydraulic modelling. Lower section of Kamienna (16 km between Czekarzewice and the outflow to Vistula) river was not included since there are no discharge gauges and the backwater from Vistula significantly influences the flow pattern. Upper sections of Kamienna river (above Skarżysko-Kamienna discharge gauge) was not included in hydraulic model. As a small river, it was splitted between HRUs of hydrological model (Fig.2). Both models were designed using HEC-RAS 5.0.5 modelling system.

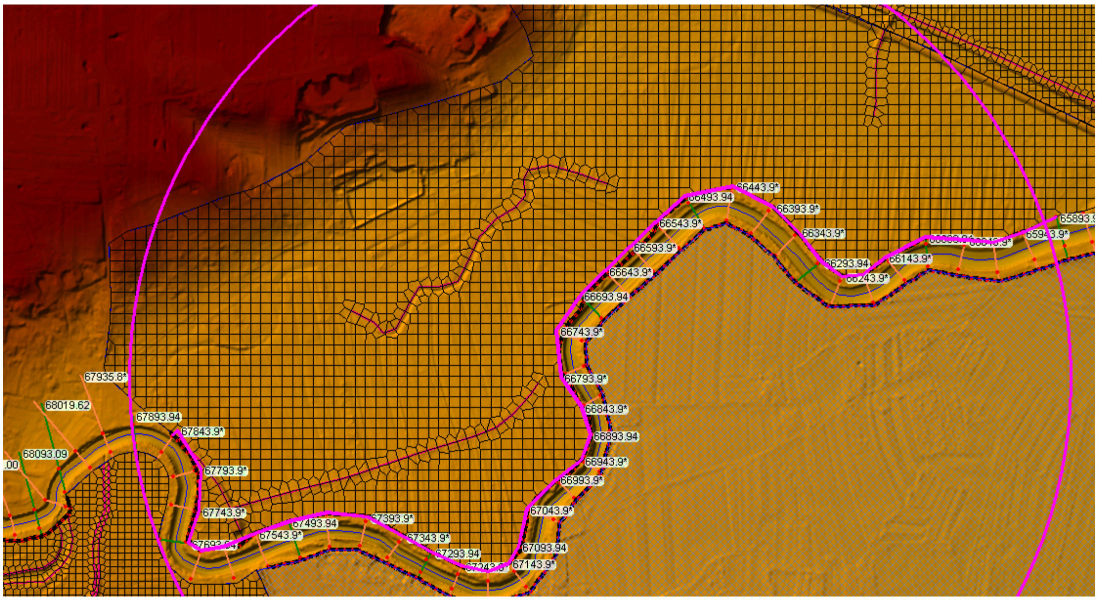

Figure 18 Example section of Kamienna river, linked with a flood plain via lateral hydraulic structure

2.2 Geometric data (DEM, cross-sections)

As a source of river geometry data, cross-sections from ISOK project[1] were used. River cross-sections were surveyed in 2011, with spatial frequency at least 200 meters. In order to keep the hydraulic model numerically stable, cross-sections were linearly interpolated to a spatial step of 50 meters and used to reproduce the 1D river geometry within the model.

For the 2D part of the model (flood plains) DEM of 1 meter resolution was used. Raster layers with DEM were obtained using airborne lidar scan also within the ISOK project. DEM was imported into HEC-RAS Geometry Editor and interpolated on a 2D grid. Resolution of the 2D domain was 5x5 or 15x15 meters (depending on local topography complexity).

For roughness coefficient, Manning coefficient was used with initially uniform in space value for both river channel (n=0.02 $[m/s^{-1/3}]$) and overbanks (n=0.03 $[m/s^{-1/3}]$). Later on, this values were subject of calibration. For 2D domain, roughness coefficient was assumed based on Corine Land Cover landuse map.

1 ISOK – Polish govermental project, which aimed to simulate floods on major rivers in Poland in order to fulfill the requirements of European Floods Directive (2007/60/EC). Results of the project were not only inundation maps, but also large amount of spatial data like DEM or landuse layers.

2.3 Description of the model structure

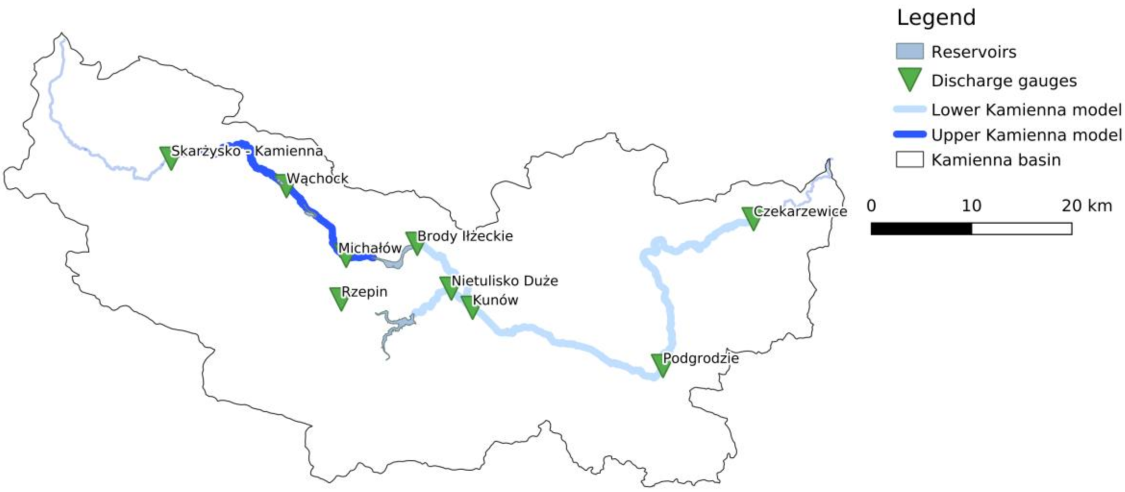

Figure 19: Model structure - division between Lower and Upper Kamienna models

Modelling domain was splitted into two submodels:

- from Skarżysko-Kamienna gauge to Brody reservoir (section length 68,7km)
- from the outflow from Brody reservoir to Czekarzewice gauge (section length 33,7km)

Such decomposition of modelling domain can be justified by two factors:

1. Total length of modeled river section (from Skarżysko-Kamienna gauge to Czekarzewice gauge) exceeds 100km. When only 1D modelling is performed – computation speed is satisfactory, but in case of water flow over floodplains, 2D modelling is involved and the computational cost increases rapidly. Therefore domain decomposition splits also the demand for computational power between two independent models.
2. The flow pattern in Lower Kamienna model highly depends on Brody reservoir. Thus the discharge from the reservoir is usually based on man made decision (not natural factors). Using discharge timeseries from Brody Iłżeckie gauge is a natural upper boundary condition for Lower Kamienna model.

Two models were run independently with boundary conditions coming from historical discharge record (May and September 2010). Proposed measures considered within this project were implemented in both hydrological and hydraulic models. For measures in hydrological model – lateral hydrographs (coming from HRUs) were updated and hydraulic model was re-run. For measures implemented in hydraulic model – river geometry was modified.

2.4 Boundary conditions

Upper Kamienna model

As an upstream boundary condition, discharge timeseries from Skarżysko-Kamienna discharge gauge was used. As downstream boundary condition, constant water level was used in order to simulate the effect of Brody Reservoir.

Lower Kamienna model

As an upstream boundary condition, discharge timeseries from Brody discharge gauge was used. As downstream boundary condition, rating curve from Czekarzewice gauge was used.

For both hydraulic models – outflow timeseries from hydrological model HRUs were used as lateral boundary conditions (representing both tributaries discharge and runoff from direct sub-basins).

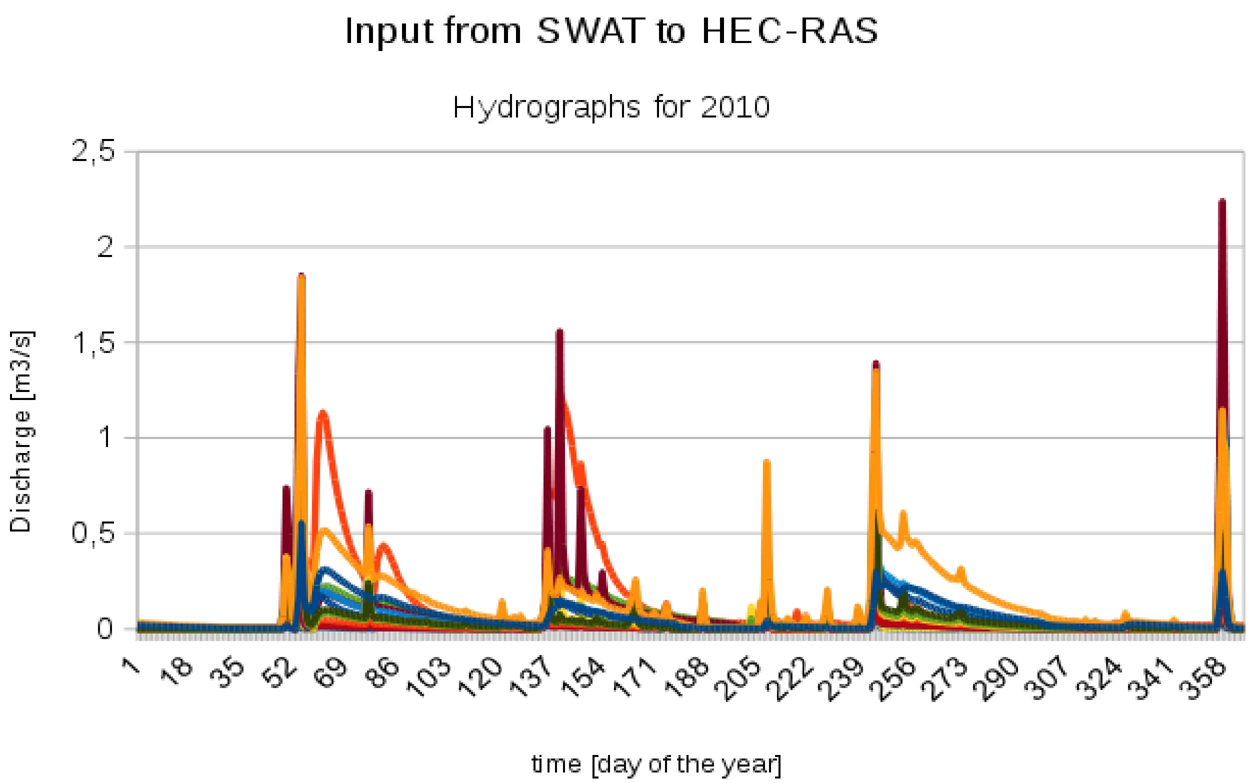

Figure 20: Outflow timeseries from hydrological model, used as lateral boundary conditions in hydraulic model

2.5 Hydrologic data

As hydrologic data, archive discharge data from gauges located within the Kamienna catchment were used. Year 2010 was used as a reference year, since neither the river geometry nor the climate changed significantly from that time. Moreover, two comparatively large flood waves occurred during that year – in May and in September. The former was used for model validation, the latter for model calibration. Figure 2 presents location of discharge gauges. The timestep of discharge data was 24 hours, which may lead to under-sampling of rapid flood wave, however no better data were available for Kamienna river and its tributaries. For lateral inflows, results from hydological model (SWAT) were used (Fig. 3). Hydrological model results were produced also with 24h time step. Such frequency is sufficient for seasonal modelling, however when modelling rapid flood waves on subbasins with short concentration time, this may lead to underestimation of discharge maximum.

2.6 Hydraulic data

Additionaly to DEM, for the construction of models' geometry, cross-sections of hydraulic structures were used. There are in total 5 hydraulic structures, which influence flow pattern of Kamienna river, within the modelled section. They were implemented either as in-line weirs or as a combination of weir and culvert.

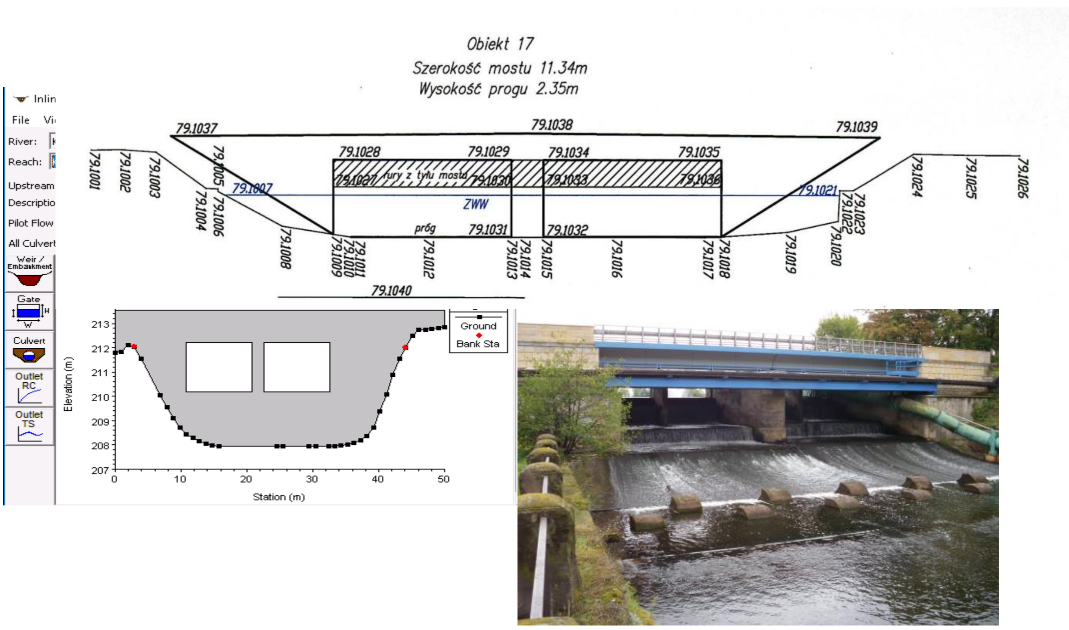

Figure 21 Example bridge, implemented in model: surveyed data (top), implementation (bottom left) and photo (bottom right)

2.7 Model calibration

Hydraulic model calibration was based on historical flood discharge data from 29 August 2010 to 20 September 2010. The subject of calibration was the roughness coefficient (n) as it is assumed to be the source of model uncertainty. Kamienna river is also known for intensive interaction with groundwater (due to karstic material within river bed). Therefore subsurface outflow was also considered during the calibration process.

The objective of calibration was to reproduce:

- The time of observed peak flow
- The maximum observed discharge value of the outflow hydrograph

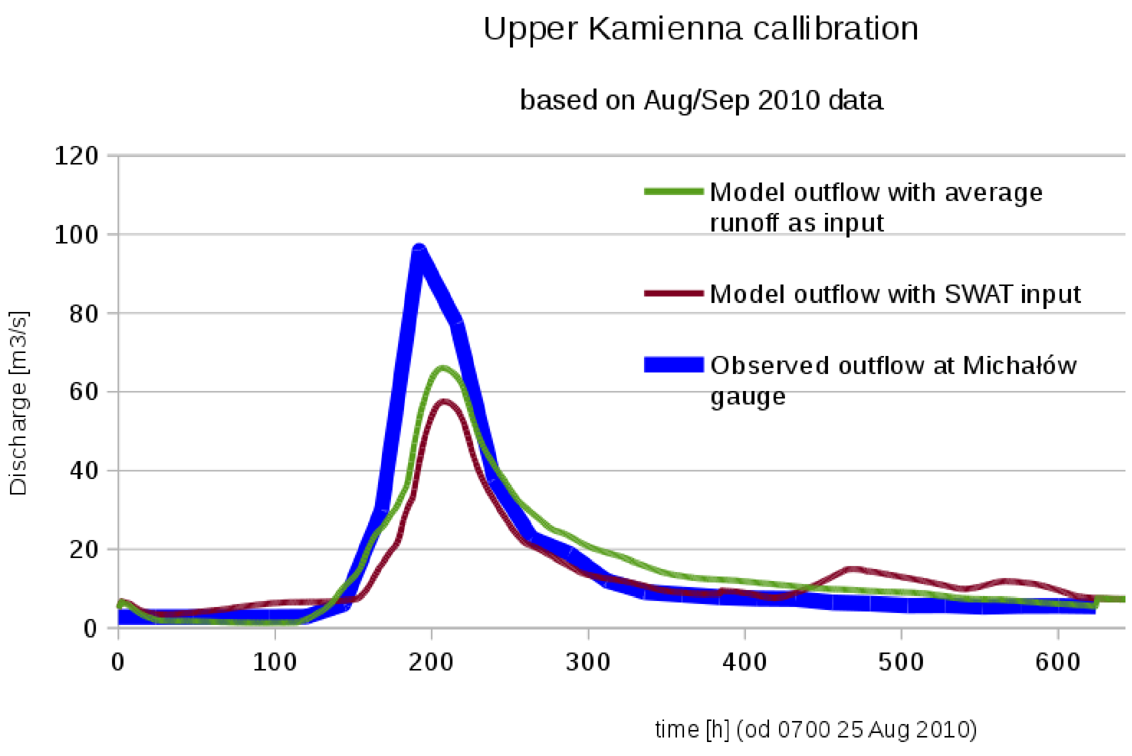

Figure 22 Results of Upper Kamienna model calibration

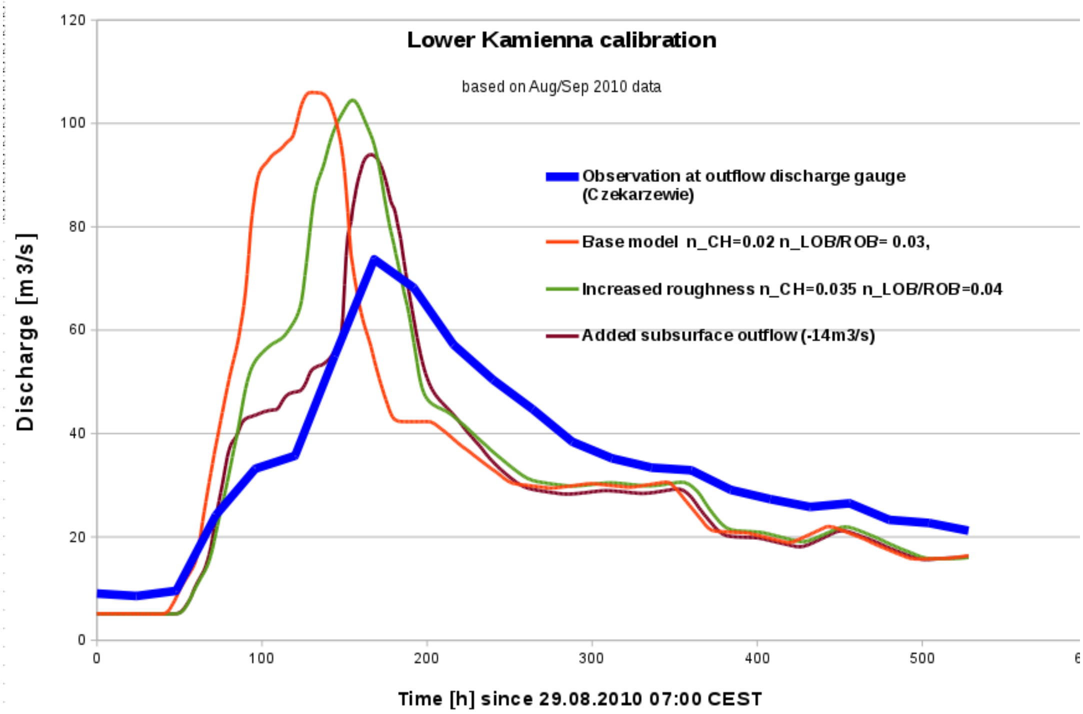

Figure 23 Results of Lower Kamienna model calibration

As the calibration resulting hydrographs reveal (Fig. 15) the dynamics of both hydraulic models are calibrated correctly (time ordinate of peak discharge and shape of the hydrograph are reproduced). Significant problems affect maximum discharge and total volume.

In case of Lower Kamienna, the peak discharge is overestimated, whilst for the recession part of hydrograph, model underestimates the outflow discharge. Such a behavior cannot be fixed during calibration. The most probable explanation for such results is the complex interaction between river water and groundwater.

In case of Upper Kamienna, both peak discharge and total volume seem to be underestimated. This can be explained by depression storage within the 2D domain. When peak discharge exceeds ~60 m^3/s, dikes of the main river channel get over-toped. Part of the river flow gets into the 2D domain and does not come back to main channel. This effect cannot be overcome during calibration. Significant modification of topography has to be performed.

2.8 Model validation

The goal of model validation was to check model performance on independent data set. During validation, the best set of parameters, obtained during calibration was kept. The motivation for model validation was:

- To avoid potential overcalibration of the model, in case a non-universal set of parameters resulted from calibration.
- To confirm (or reject) hypothesis drawn from calibration, i.e. to check if the justification of differences between modeled and observed discharge at models' outflow boundary condition remains valid for an independent set of data.

Model validation was performed using hydrological data from May 2010.

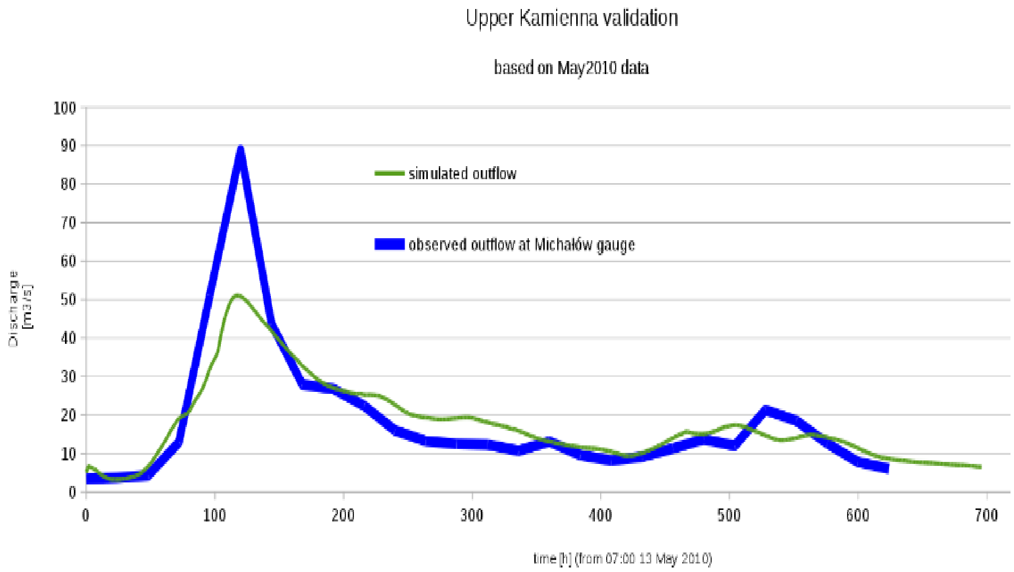

Figure 24 Results of the Upper Kamienna model validation

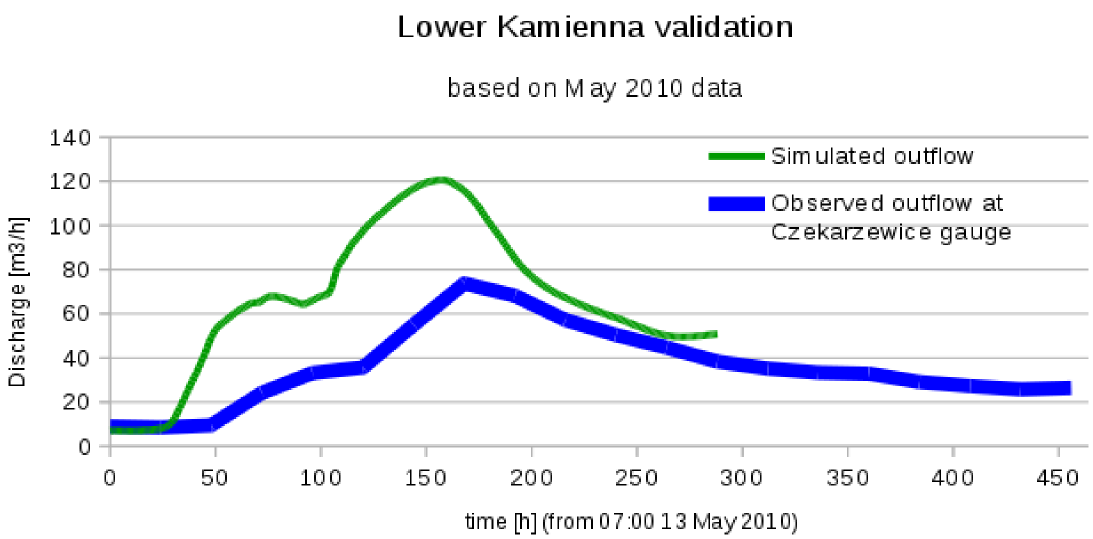

Figure 25 Results of the Lower Kamienna model validation

2.9 Conclusions

Hydraulic model of Kamienna river was implemented in two parts – upper and lower Kamienna. Obtained calibration and validation results seem satisfactory, however further works are required in geometry modification as well as in measures implementation.

3. NSWRMS TESTING IN THE KAMIENNA CATCHMENT

3.1 Hydrological model

In the Kamienna catchment NSWRMs were applied in the calibrated and validated SWAT model in order to test their efficiency in sediment and nutrient (nitrogen and phosphorus) loads reduction as well as their impact on water balance. Each NSWRM scenario has been comapred with the baseline scenario (current state) and the relative change of selected water quality and quantity variables has been presented. Following measures were tested in the model:

- A01: meadows and pastures – applied in different variants with increasing share of arable lands changed into meadows/pastures (14%, 25%, 37% and 47%). In SWAT model implemented by *landuse update* function. Expected effect in the model: slower runoff, erosion reduction, nutrient assimilation.
- A08: green cover (catch crops / cover crops) – applied in the model for all arable lands. Implementated in SWAT by modification of management practices schedules in selected HRUs (adding plant operation for a cover crop). Expected effect in the model: slower runoff, erosion reduction, mitigation of the loss of soluble nutrients.
- F05: land use conversion (afforestation) - applied in different variants with increasing share of agricultural lands changed into forests (22%, 40%, 60% and 73%). In SWAT model implemented by landuse update function. Expected effect in the model: slower runoff, erosion reduction, nutrient assimilation.
- F09: sediment capture ponds – applied for all sub-catchments in different variants with increasing volume. Implementated in SWAT by adding and parametrising (geometry and volume) of ponds. Pond volume has been assigned for each sub-catchment and variant as 200, 400, 600, 800 m^3/ha (total volume was calculated based on the sub-catchment area) and a draining area equal to 25% of the sub-catchment area. Expeced effect in the model: slower runoff, erosion reduction.

In the Kamienna model impact of NSWRMs was tested for the catchment averaged values of surface runoff (mm), lateral soil flow (mm), groundwater flow (mm), total water yield (mm), total sediment load (tons/ha), total nitrogen load (kg/ha) and total phosphorus load (kg/ha). To support the perception of relative changes with respect to baseline scenario absolute values for each tested variable in current state are presented below.

Table 13 Baseline scenario values for selected water quality and quantity variables

Variable	Value
SURFACE RUNOFF (mm)	57.6
LATERAL SOIL FLOW (mm)	25.9
GROUNDWATER FLOW (mm)	64.9
TOTAL WATER YIELD (mm)	162.9
TOTAL SEDIMENT LOAD (tons/ha)	1.75
TOTAL NITROGEN LOAD (kg/ha)	3.03
TOTAL PHOSPHORUS LOAD (kg/ha)	0.08

SURFACE RUNOFF

Among the implemented NSWRMs only sediment capture ponds (F09) indicated no impact on surface runoff. Remaining measures caused its reduction, which was escalating with the increasing extent of variant application (A01, F05). The highest reduction (12%) has been observed for F05 (afforestation) in its most extensive variant.

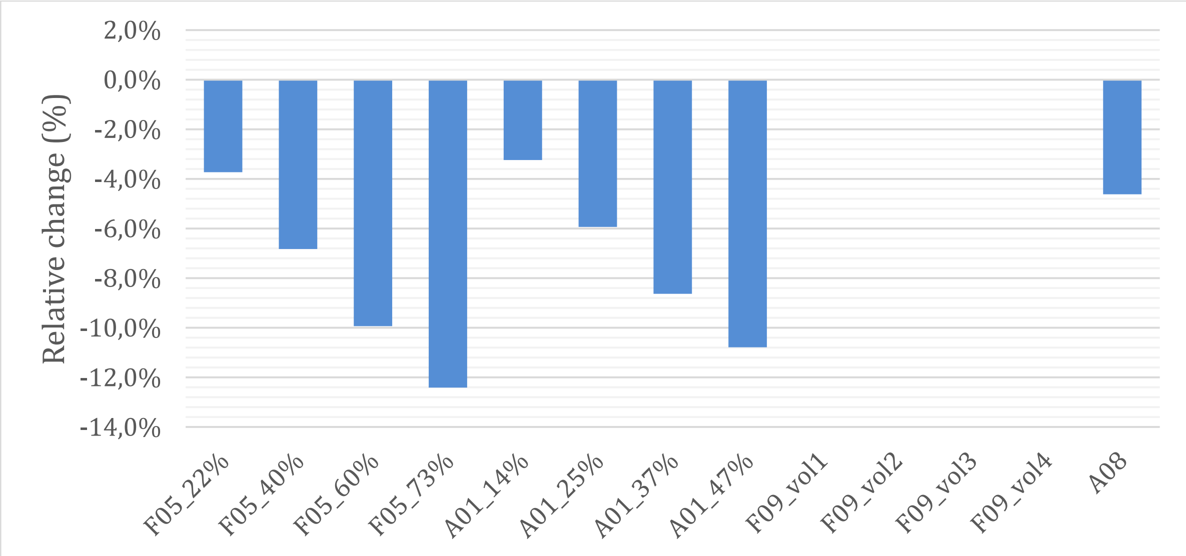

Figure 26 Relative change of catchment averaged surface runoff for implemented NSWRMs

LATERAL SOIL FLOW

For lateral soil flow results are more diverse, as both, decrease and increase is observed for applied scenarios. Afforestation (F05) of the catchment leads to increase in lateral soil flow, which intesifies with the variant extent. Change of arable lands into meadows (A01) indicates the opposite change, which also intenses with variant extent. The highest reduction in lateral soil flow (60%) was observed for construction of sediment capture ponds (F09_vol4). Catch crops seem to have no impact on this component.

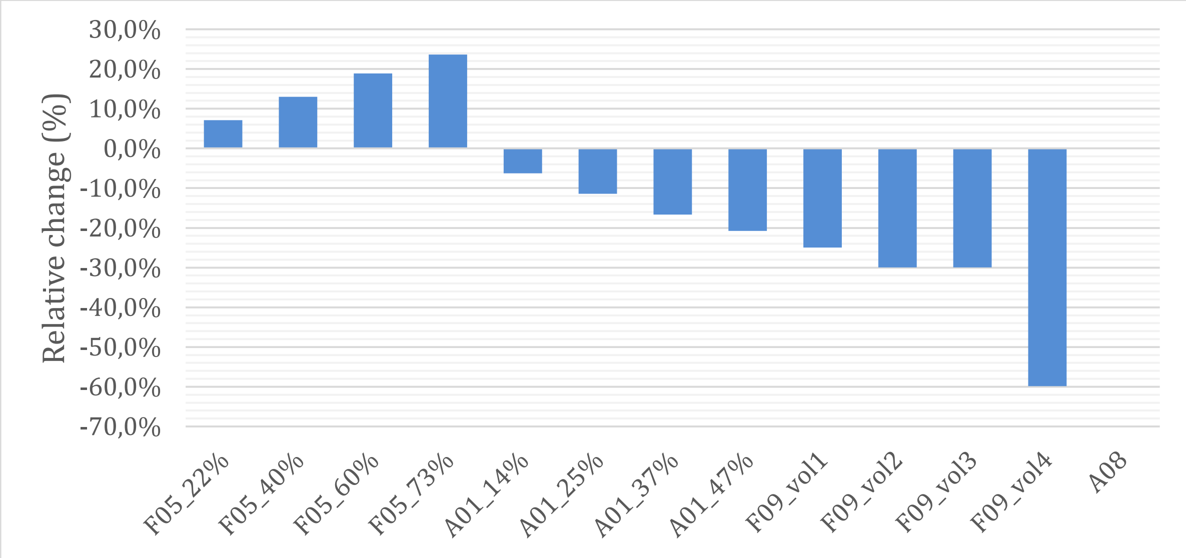

Figure 27 Relative change of catchment averaged lateral soil flow for implemented NSWRMs

GROUNDWATER FLOW

For the groundwater flow most of the measures indicate negligible change, beside the A01 (changing of arables lands into pastures), which indicates its increase. In its most extensive variant the increase reaches nearly 16%.

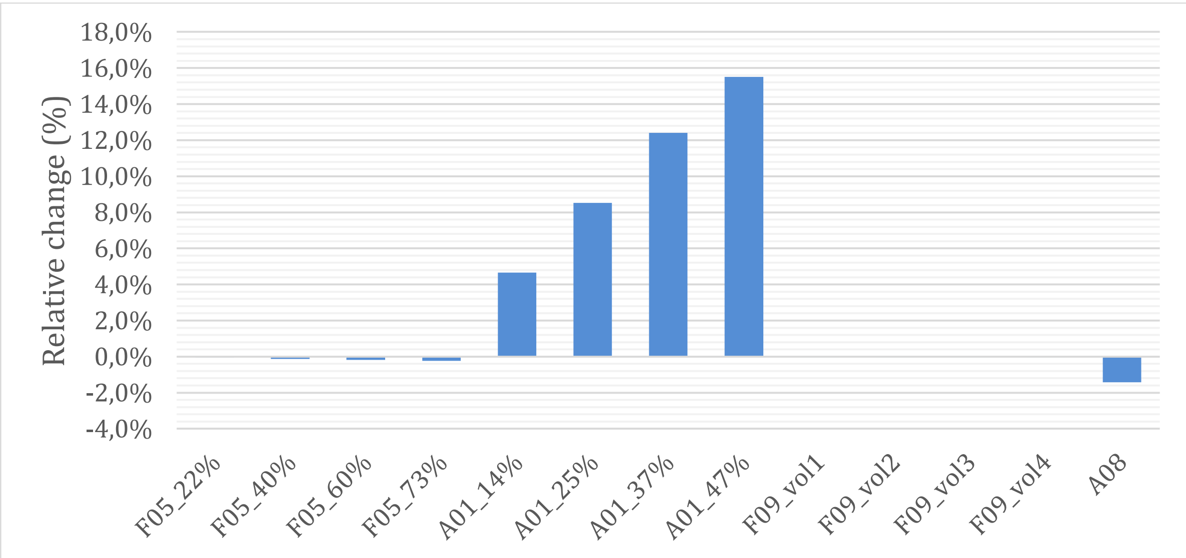

Figure 28 Relative change of catchment averaged groundwater flow for implemented NSWRMs

TOTAL WATER YIELD

In general most of the NSWRMs caused a slight decrease in totla water yield at the catchment scale, with maximum value reaching 8% for the variant F05_73%. It can be partially explained by increased evapotranspiration due to increase in the share of forests in the catchment. Construction of sedimentary ponds indicate no change in total water yield.

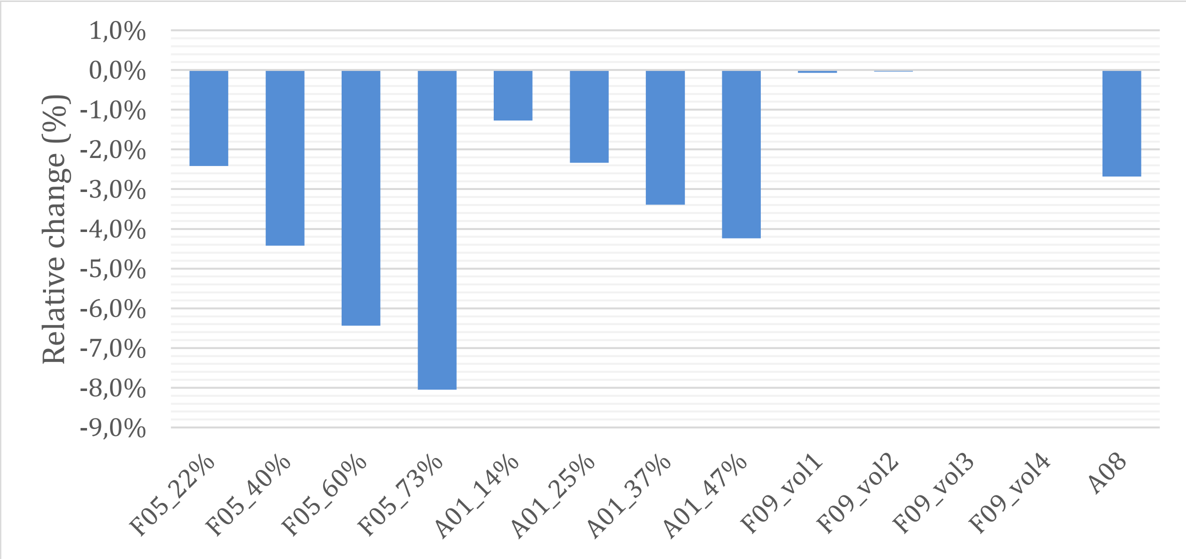

Figure 29 Relative change of catchment averaged total water yield for implemented NSWRMs

TOTAL SEDIMENT LOAD

In general all implemented NSWRMs have significant impact on sediment load in the Kamienna catchment. The lowest reduction has been noted for A01_14% (18%) and the highest for F05_73% (71%). In all scenarios reduction gradually decreases with the extent of measure application.

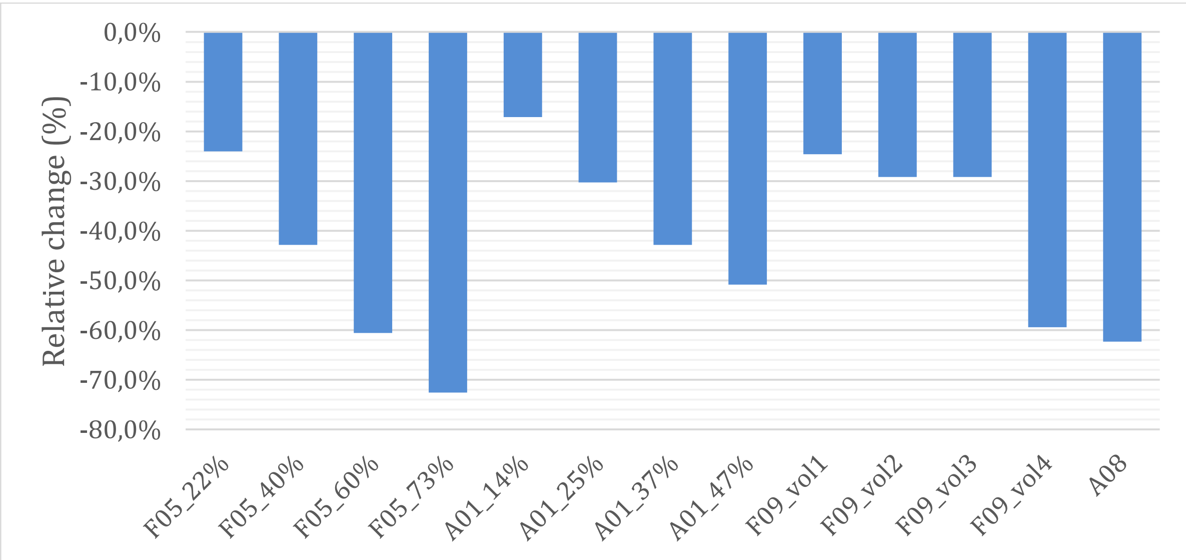

Figure 30 Relative change of catchment averaged sediment load for implemented NSWRMs

TOTAL NITROGEN LOAD

For the nitrogen load the reduction is observed for almost all NSWRMs, however much more diverse and less efficient compared to sediment. The highest reduction rate, reaching 40% is observed for F05_73% and negligible increase (0.5%) for catch crops (A08) implementation.

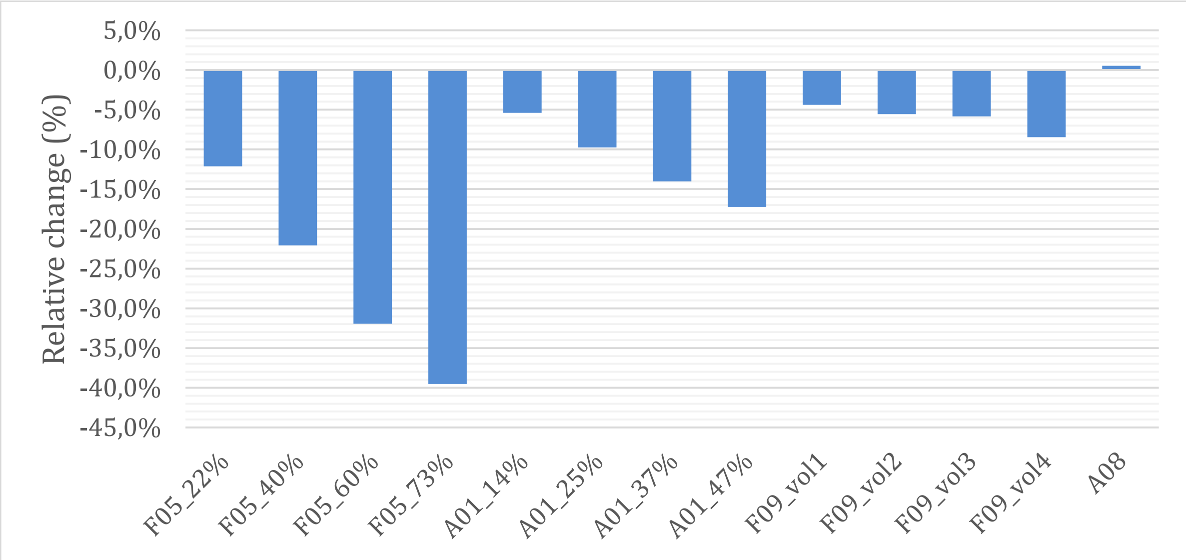

Figure 31 Relative change of catchment averaged nitrogen load for implemented NSWRMs

TOTAL PHOSPHORUS LOAD

For phosphorus loads similar effect and reduction efficiency is observed as for nitrogen. The reduction is observed for almost all NSWRMs. The highest reduction rate, reaching 34% is observed for F05_73%. The only difference is noted for the catch crops implementation, which seem to reduce the phosphorus loads by nearly 20%.

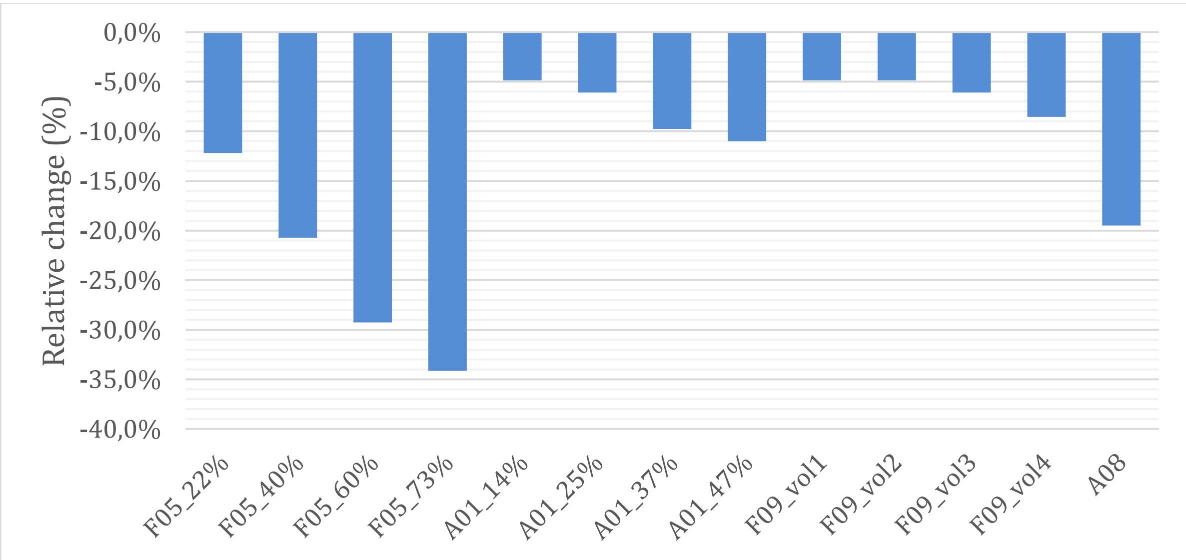

Figure 32 Relative change of catchment averaged phosphorus load for implemented NSWRMs

Applied NSWRMs were expected to decrease surface runoff, reduce erosion and assimilate nutrients. Simulations obtained in SWAT model for the Kamienna catchment seem to generally prove such impact of the proposed NSWRMs. The highest impact was observed for reduction of sediment and nutrients loads.

3.2 Hydrodynamic model

4. REFERENCES

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5. APPENDIX A – SOURCES OF SWAT INPUT DATA

Item		Source	Resolution / scale
Watershed delineation	DEM	CODGIK (Centre for Geodetic and Cartographic Data)	10 m
	River network	MPHP (Map of Hydrographic Division of Poland)	1:10 000
	Water use and transfer locations	RZGW (Regional Water Management Authority) / WZMiUW (Land Reclammation Board)	2 small hydropower plants, 12 weirs, 15 objects drained areas, 1 fish ponds
	Lake/reservoir map	MPHP (Map of Hydrographic Division of Poland)	1:10 000
	Gauge stations locations	IMGW (Institute of Meteorology and Water Management)	7 points
	Point source locations	RZGW (Regional Water Management Authority) / WIOŚ (Voivodship Institute of Environmental Proetection)	14 municipal, 2 industrial
HRU delineation	Land cover map	CORINE Land Cover 2012	The smallest polygon ~100 ha
		BDOT (Database of Topographic Objects)	1:10 000
		Copernicus Land Monitoring Service (Imperviousness 2012) http://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness	20 m
		ODR (Agricultural Advisory Centres)	Commune level statistics on crop structure
	Soil map	IUNG	1:25 000
Weather data definition	Precipitation data	IMGW (Institute of Meteorology and Water Management)	12 stations (+16 stations outside of catchment)
	Temperature data		2 stations (+2 outside)
	Wind speed data		2 outside station
	Relative humidity data		2 stations (+2 outside)
	Solar radiation data		2 outside station
Land management	Crop structure	ODR (Agricultural Advisory Centres)	Commune-level data
	Mineral fertilisers	ODR (Agricultural Advisory Centres)	Commune-level data
	Livestock / manure	ODR (Agricultural Advisory Centres)	Commune-level data
	Other practices (tillage)	ODR (Agricultural Advisory Centres)	Commune-level data
	BMPs	ODR (Agricultural Advisory Centres)	Commune-level data
Water management	Reservoirs	RZGW (Regional Water Management Authority)	Data for each object
	Fish ponds	RZGW (Regional Water Management Authority)	Data for each object

	Irrigation	WZMiUW (Land Reclammation Board)	Data for each object
	Water withdrawals	RZGW (Regional Water Management Authority)	Data for each object
	Wastewater treatment plants	WIOŚ (Voivodship Institute of Environmental Protection) + own survey	Data for each object
Groundwater	Hydrogeology maps	PIG (Polish Hydrogeological Institute)	1:50 000
	Ground water monitoring	PIG (Polish Hydrogeological Institute)	15 wells
Channel	Channel cross-sections	KZGW (National Water Management Authority)	One cross-section per 500 m on main rivers and estuaries of main tributarys
Soil properties	Soil physical parameters	Literature	Data for each soil class in SWAT
	Soil chemical parameters	OSChR (Chemical-Agricultural Stations)	32 locations
Atmospheric deposition	N and P deposition data	GIOŚ (Chief Inspectorate of Environemntal Protection)	3 stations outside catchment
Calibration & validation	Discharge	IMGW (Institute of Meteorology and Water Management)	7 flow gauges
	Crop yields	ODR (Agricultural Advisory Centres)	Commune-level data
	Sediment concentrations	WIOŚ (Voivodship Inspectorate of Environemntal Protection)	19 water quality monitoring stations;
	N & P concentrations	WIOŚ (Voivodship Inspectorate of Environemntal Protection)	19 water quality monitoring stations;
	TOC (Total organic carbon)	WIOŚ (Voivodship Inspectorate of Environemntal Protection)	19 water quality monitoring stations;
	BOD5	WIOŚ (Voivodship Inspectorate of Environemntal Protection)	19 water quality monitoring stations;
	Other observational data (soil moisture, groundwater levels, ET measured)	PIG (Polish Hydrogeological Institute)	Groundwater levels from 6 locations; daily/monthly interval
		PIG (Polish Hydrogeological Institute)	Groundwater quality from 5 locations; bi-annual interval