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EVALUATION OF SOIL WATER EROSION RISK IN THE MŚCIWOJÓW WATER RESERVOIR DRAINAGE BASIN ON THE BASIS OF NUMERIC MODELLING

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Summary

The paper presents the evaluation of soil water erosion risk of the Mściwojów water reservoir drainage basin. In the present study, modelling with the use of GIS (*Geographical Information Systems*) and RUSLE (*Revised Universal Soil Loss Equation*) erosion models were exploited. Values of topographic factor (*LS*) were calculated after formulas proposed by Moore et al. [1991] as well as Desmet and Govers [1996].
The results of erosion prognosis by means of RUSLE method after Moore's formula are by 40% higher than values evaluated after Desmet and Gover's formula. Eroded soil mean mass from area unit during the year is estimated at the level of 10.35–14.53 Mg $\cdot$ ha^{-1} $\cdot$ year^{-1}, depending on computable formula used. Results of this research enabled to divide the drainage basin area into soil water erosion intensity zones based on predicted soil loss values according to Marks et al. [1989]. The study shows that water erosion risk of soil in the Mściwojów water reservoir drainage basin is very high. Almost one third of its area is located in the high and very high class of erosion risk.

Keywords

soil water erosion • RUSLE • GIS • spacial modelling • the Wierzbiak River • the Mściwojów water reservoir

1. Introduction

Proper recognition of spacial arrangement of water erosion size of soil is a necessary condition for effective drainage basin management and the conducting a rational water economy. Identification of areas which in the extreme contribute to surface water pollution with eroded soil material simplifies decision making in planning activities that restrict that process.

Negative effect of soil water erosion on natural environment concerns not only the place or area where it takes place. The results of that process have got much bigger spacial range and can strike areas that are considerably distant from places where soil material diminution is observed. Knowledge of spacial arrangement of soil water erosion size is especially important in context of quality of surface water which supply retaining water reservoirs. Because in these water basins, sediments transported by supplying water are stopped. It may take effect in water pollution and eutrophication and in the course of time also in decreasing of disposable capacity of reservoirs.

The example of area that is greatly endangered by soil water erosion is The Wierzbiak River drainage basin, placed in Lower Silesia Voivodeship, which supplies Mściwojów retaining reservoir with water. Initial recognition of water erosion risk at the phase of reservoir's designing and some years after its starting showed that in the space of reservoir drainage basin intensive surface erosion could take place [Czamara 2002]. However, these researches were not the type of spacial analysis and their results were only partially published [Kasperek and Wiatkowski 2008].

Gaining reliable spacial information about soil erosion size on the basis of nothing but *in situ* measurements is practically impossible. In that case, Geographical Information Systems (GIS) prove to be helpful as they make natural processes modelling possible and they enable gaining information about spacial diversity of potential and real erosion size.

Pilot project of the European Regional Development Foundation (ERDF), named VITAL LANDSCAPES, that is carried out by Agriculture University in Cracow workers' team became occasion to conduct many complex studies in the region of the Mściwojów water reservoir. Some of them concerned the problem of soil water erosion. Their aim was to evaluate the degree of risk of the Mściwojów water reservoir drainage basin both in quality (classification of risk degrees) and quantity (evaluation of eroded material size) aspects. To reach that aim, modelling with use of GIS and RUSLE (*Revised Universal Soil Loss Equation*) erosion models were exploited.

2. Characteristics of research area

The research area is placed in Sudeckie Foothills macroregion (332.1), in Strzegomskie Hills mesoregion 332.1 [Kondracki 1998]. It possesses features characteristic for a piedmont area. Mściwojów reservoir drainage basin is the hilly space and almost all area is occupied by farming grounds with dominance of arable land. The Wierzbiak River is a right-bank tributary of the Kaczawa River in the Odra River basin. In the upper section of the Wierzbiak River, in the neighbourhood of Mściwojów town, water reservoir was built and came into use in 2000 [Szafrański and Stefanek 2008]. Its main purpose is agricultural usage of stored water and fire protection. Apart from the Wierzbiak River there is left-bank tributary named the Kałużnik which flows into the Mściwojów water reservoir. Total surface of the Mściwojów water reservoir drainage basin at the mouth of the river from the water basin is 49.12 km^2, from which 35.72 km^2 falls on the Wierzbiak River and 13.40 km^2 – on the Kałużnik River one. The drop of drainage basin is 160.6 m and its mean fall is 11.5%.

3. Materials and methods

To estimate valuation of the degree of soil water erosion risk in Mściwojów reservoir drainage basin, database of spacial data was built. It was composed of:

- digital terrain model (DTM) with resolution of 25 m,
- soil-agronomic vector map in scale 1 : 25 000,
- topographic objects database (TBD) in scale 1 : 10 000,
- vector map of level 2 (VMapL2) in scale 1 : 50 000,
- topographic map in scale 1 : 10 000,
- map of Polish hydrographic partition (MPHP),
- ortophotomap.

Digital Terrain Model (DTM) was elaborated on the support of photogrammetric surveying of black and white air-images in scale 1 : 26 000 that were performed within the framework of PHARE project. It was prepared on the basis of height points network with a 25-m hole. Its height accuracy is 1.5 m on the flat areas and to 2.5 m on hilled and mountainous ones. DTM was used to appoint direction of water confluence, to estimate confluence of accumulation size, to shape hydrographic net and partial drainage bases delimitations as well as to evaluate so called secondary topographic factors. Height data and course of rivers net from the map of Polish hydrographic partition (MPHP) were verified and corrected on the basis of topographic objects database (TBD) in scale 1 : 10 000 and topographic map in scale 1 : 10 000.

Soil-agronomic map in scale 1 : 25 000 was used to design the map of soil kinds in studied drainage basin (Figure 1) whereas the map of land cover of the Mściwojów water reservoir drainage basin (Figure 2) was prepared on the basis of data from TBD and vector map of level 2 (VMapL2) in scale 1 : 50 000. Covering data were verified in the basis of ortophotomap and topographic map in scale 1 : 10 000.

The method proposed by Józefaciuk and Józefaciuk (1996) is commonly used in Poland for evaluation of soil water erosion risk. It enables to estimate erosion risk only in quality aspect which means classification of risk degree. Estimation of not only eroded material quantity but also its quality is possible by means of USLE method (*Universal Soil Loss Equation*) elaborated by Wischmeier and Smith (1978) on the basis of long-standing experimental studies. USLE model is an empiric equation that describes mean annual losses of soil in the result of surface and linear erosion:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{1}$$

where:

A – mean annual soil loss per unit of area, $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$,
R – rainfall-runoff erosivity factor, $\mathrm{MJ \cdot ha^{-1} \cdot cm \cdot h^{-1}}$,
K – soil erodibility factor, $\mathrm{Mg \cdot ha^{-1} \cdot (MJ \cdot ha^{-1} \cdot cm \cdot h^{-1})^{-1}}$,
L – slope length factor, non dimensional,
S – slope steepness factor, non dimensional,

C – cover management factor, non dimensional,
P – support practice factor, non dimensional.

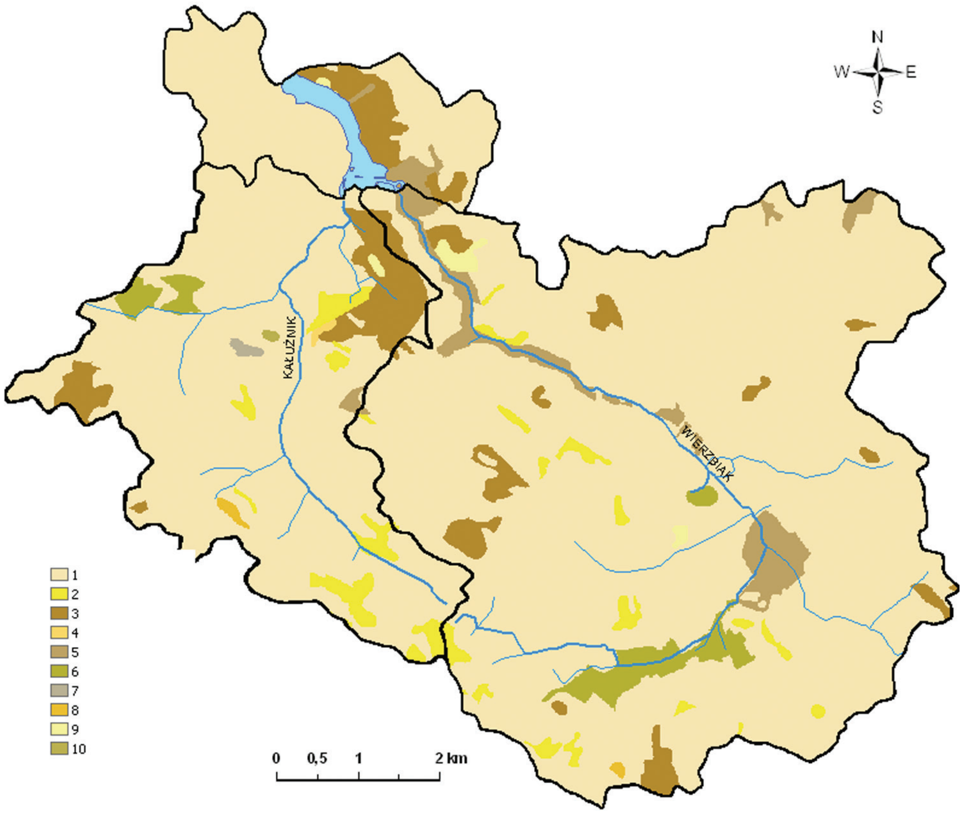

Fig. 1. The map of soil kinds in the Mściwojów water reservoir drainage basin: 1 – loess, 2 – silty clay loam, 3 – loam, 4 – loamy sand, 5 – sand, 6 – silty clay, 7 – silt loam, 8 – sandy loam, 9 – loamy very fine sand, 10 – sandy clay loam

In the present studies, spacial arrangement analysis of soil water erosion process was performed by means of its modified version of RUSLE model (*Revised Universal Soil Loss Equation*) (Renard et al. 1997). RUSLE model modification relates to the way of evaluation of non dimensional factor of length (*L*) and slope steepness (*S*). In RUSLE model both factors were combined into one non dimensional topographic factor (*LS*). Spacial data indispensable for modelling were submitted to rasterisation process to spacial resolution 25 m and recorded in geodetic coordinates system '1992'. Hydrographic analysis and hydrologic modelling was done by means of Arc Hydro Tools instrument which works in range of ARC GIS software from ESRI company. Topographic factor calculation (*LS*) as well as RUSLE model implementation for estimations was made with help of SAGA GIS software.

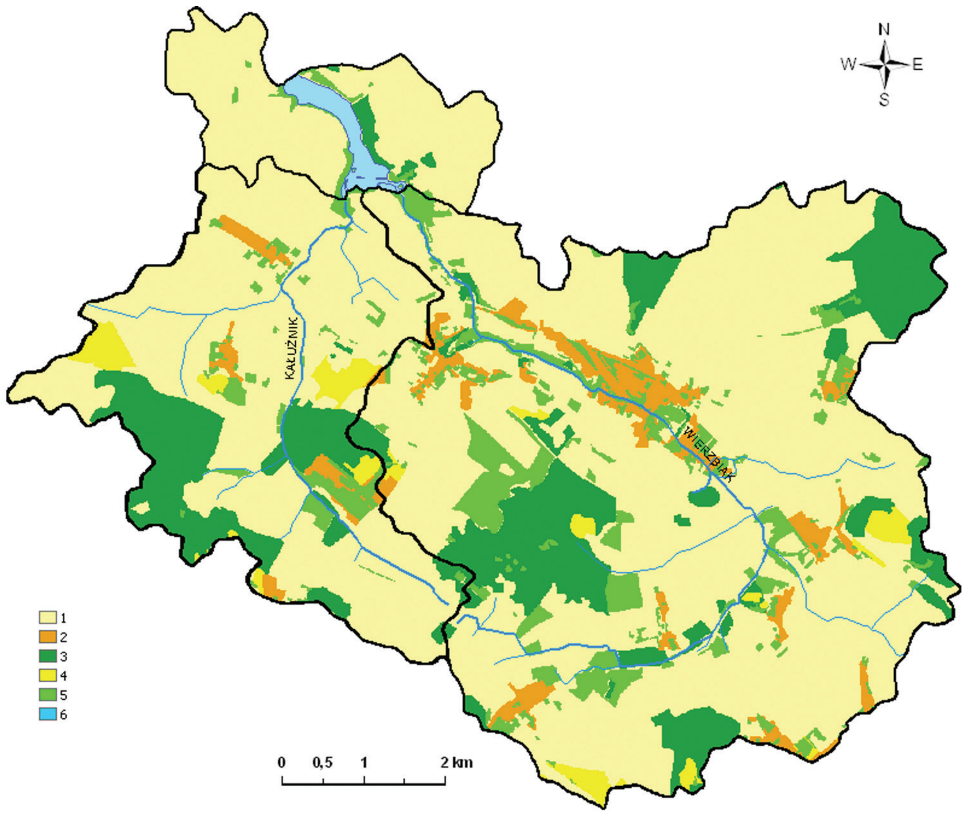

Fig. 2. The map of land cover of the Mściwojów water reservoir drainage basin: 1 – agricultural areas, 2 – urban areas, 3 – forests, 4 – artificial, non-agricultural vegetated areas, 5 – grassland, 6 – water bodies

4. Results

Rainfall-runoff erosivity factor (R)

Rain erosivity factor describes drop rain capacity to loosening and transportation of soil bits. It was calculated on the basis of Fournier index in modification suggested by Arnoldus [1997]. Its usage in evaluations made with use of SI system units needs multiplying by 17 [Drzewiecki and Mularz 2005]:

$$R = 17\sum_{i=0}^{12}\frac{p_i^2}{P} \tag{2}$$

where:

R – rainfall-runoff erosivity factor, MJ · ha^{-1} · cm · h^{-1},
p_i – rainfall sum in i^{th} month, mm,
P – annual rainfall sum, mm.

Rain erosivity factor (R) estimated on the basis of mean monthly sums of falls (1961–1995), that was registered in the meteorological observation post IMGW in Jawor, amounted to 957 MJ $\cdot$ ha^{-1} $\cdot$ cm $\cdot$ h^{-1}.

Soil erodibility factor (K)

Soil erodibility factor expresses eroded soil mass from the unit of model field. It can be evaluated after Renard et al. [1997]:

$$K = 0.0034 + 0.0405 \cdot \exp\left(-0.5 \cdot \left(\frac{\log D_g + 1.659}{0.7101}\right)^2\right) \tag{3}$$

when:

$$D_g = \exp\left(0.01 \cdot \sum_{i=1}^{n} f_i \cdot \ln\frac{d_i + d_{i-1}}{2}\right) \tag{4}$$

where:

- K – soil erodibility factor, Mg $\cdot$ ha^{-1} $\cdot$ (MJ $\cdot$ ha^{-1} $\cdot$ cm $\cdot$ h^{-1})$^{-1}$
- d_i – upper limit of fraction range, mm,
- d_{i-1} – lower limit of fraction range, mm,
- f – mass fraction content, %.

Studied drainage basin is mostly covered with loess soil and loess formations (83%) (Figure 1). According to the soil-agricultural map, medium clays account for 7%, light clays – 5% whereas flour claystones and loose sands 3% of cover, each.

Values of soil susceptibility to water erosion factor (K) that were estimated for analyzed drainage basin varied from 0.0123 to 0.0421 Mg $\cdot$ ha^{-1} $\cdot$ (MJ $\cdot$ ha^{-1} $\cdot$ cm $\cdot$ h^{-1})$^{-1}$. For the whole tested drainage basin, mean surface value of K factor was 0,0386 (MJ $\cdot$ ha^{-1} $\cdot$ cm $\cdot$ h^{-1})$^{-1}$.

Topographic factor (LS)

Topographic factor (LS), which is also called sediment transportation ability factor, is characterized by erosive potential. It is determined by relationship between size of the area that takes part in surface confluence (fragment of drainage basin) and value of its slope. In the present study, formulas proposed by Moore et al. [1991] as well as Desmet and Govers [1996] served to evaluate LS factor. Both teams of scientists proved that area shape influence on behaviour of water floating at its surface would be described in better way when the length of a slope in LS factor would be replaced by float area or actually by value that is quotient of contributing area and length of given slope fragment (so called unit upslope contributing area). According to Moore et al. [1991] topographic factor (LS) is calculated on the basis of the below formula:

$$LS = 1.4\left(\frac{A_S}{22.13}\right)^{0,4} \cdot \left(\frac{\sin q}{0.0896}\right)^{1,3} \tag{5}$$

where:

- LS – topographic factor, non dimensional,
- A_s – local upslope contributing area from flow accumulation raster, m^2,
- q – slope angle.

Values of topographic factor (LS) calculated after Moore et al. (1991) formula for analyzed drainage basin varied from 0 to 30.55. Territorial mean of the factor (LS) for the whole tested drainage basin was 2.44.

According to Desmet and Govers (1996), topographic factor (LS) is calculated on the basis of the below formula:

$$LS = \frac{\left(A_S + D^2\right)^{m+1} - A_S^{m+1}}{x^m \cdot D^{m+2} \cdot \left(22.13\right)^m} \cdot S \tag{6}$$

where:

- LS – topographic factor, non dimensional,
- A_s – local upslope contributing area from flow accumulation raster, m^2,
- D – raster resolution, m,
- x – coefficient that corrects the length of flow way through a raster cell, non dimensional,
- m – index of slope's length factor, non dimensional,
- S – slope steepness factor, non dimensional.

Index of slope's length factor (m) can be calculated by McCool et al. [1989] from formula:

$$m = \frac{\beta}{\beta + 1} \tag{7}$$

when:

$$\beta = \left(\frac{\frac{\sin q}{0.0896}}{3(\sin q)^{0.8} + 0.56} \right) \cdot r \tag{8}$$

where:

- q – slope angle,
- r – usage factor: forests – 0.5, rural areas – 1.0, built-up areas – 2.0.

Slope steepness factor (S) can be evaluated after Renard et al. [1991] from formulas:

$$S = 10.8 \sin q + 0.03 \text{ dla } q < 9\% \tag{9}$$

$$S = 16.8 \sin q + 0.5 \text{ dla } q < 9\% \tag{10}$$

where:

S – slope steepness factor, non dimensional,

q – slope angle.

Values of topographic factor (LS) evaluated for analyzed drainage basin according to Desmet and Gover's formula (1996) varied from 0.03 to 16.21, whereas area mean for the whole examined area was 1.72.

Cover management factor (C)

Cover management factor (C) is a relation of the soil quantity that eroded from the field with specified flora and way of usage to the soil eroded from the model field in black fallow with up and down slope ploughing [Jozafaciuk and Jozafaciuk 1996].

In covering and usage structure of examined drainage basin (Figure 2) the biggest share belongs to farmlands(70%) and forests (15%). Grasslands compose 8%, built-up areas 4% and wastelands 2%. On the basis of covering and land usage map that was elaborated for analyzed drainage basin, values of C factor were estimated. Their appropriate values were accepted after Koreleski [1992]: wastelands – 0.350, farmlands – 0.240, grasslands – 0.020, forests – 0.003, built-up areas and surface waters – 0.000.

Values of plant covering and way of usage factor (C) appointed for analyzed drainage basin fluctuated within limits from 0 to 0.35 whereas area mean for the whole drainage basin was 0.18.

Support practice factor (P)

Support practice factor (P) characterizes importance of using procedures that limit water erosion intensity. It is a relation of soil losses while using anti-erosion procedures to those from model fields on which cultivations along the slope angle are conducted. As there is lack of data of such kind, lack of anti-erosion procedures (value of factor $P = 1$) was accepted for modelling needs.

Mean annual soil loss (A)

As a result of conducted modelling of water erosion, information about spacial distribution of soil losses size in the tested drainage basin was obtained (Figure 3). Mean quantity of eroded soil in the drainage basin was calculated following Moore's formula and amounted 14.52 $Mg \cdot ha^{-1} \cdot year^{-1}$ whereas according to Desmet and Gover's formula it was 10,35 $Mg \cdot ha^{-1} \cdot year^{-1}$. Total annual mass of eroded soil from the drainage basin calculated after Moore's formula (68 622 $Mg \cdot year^{-1}$) is almost 40% bigger than the values obtained by means of Desmet and Grover's formula (49 147 $Mg \cdot year^{-1}$) (Table 1). It results from different way of topographic factor (LS) determination.

Modelling also allowed to determine the level of contribution of particular drainage basins to the total mass of eroded soil material (Table 1). Together with surface flow, 63% of that mass finds its way to Mściwojów reservoir from the Wierzbiak

River drainage basin whereas from the Kałużnik River drainage basin – 27%. The rest 10% relates to surface flow from areas that are directly adjacent to Mściwojów reservoir which is partial drainage basin between the section from the Wierzbiak and Kałużnik Rivers' mouths to the reservoir and the section on the outlet of the Wierzbiak River from the reservoir.

Table 1. Eroded soil mass evaluated for Mściwojów reservoir drainage basin

Model	Mean annual soil loss (A) [Mg · year^{-1}]		
	Wierzbiak River drainage basin	Kałużnik River drainage basin	Mściwojów reservoir drainage basin
RUSLE after Moore et al. [1991]	43 269	18 552	68 622
RUSLE after Desmet and Govers [1996]	30 934	13 399	49 147

On the basis of predicted soil loss (Figure 3), research area division into water erosion risk zones was performed on the grounds of criteria proposed by Marks et al. [1989] (Table 2). Classification map of erosion risk is presented on the Fig 4.

High and very high erosion risk is predicted on the area that makes up 31% of analyzed surface, small and medium one on 20%, whereas very small risk or lack of it can be found on 51% of that surface (Table 2).

Table 2. Classification of erosion risk criteria according to Marks et al. [1989]

Risk class	Erosion risk	Annual soil loss [Mg · ha^{-1}]	Contribution of risk classes [%]		
			Wierzbiak River drainage basin	Kałużnik River drainage basin	Mściwojów reservoir drainage basin
1	lack	< 1	33	32	33
2	very small	1–5	18	18	18
3	small	5–10	10	11	11
4	average	10–15	9	8	9
5	high	15–30	15	15	15
6	very high	> 30	15	16	16

Taking categories of covering and usage of the area into consideration, the biggest loss of soil material concerns arable lands, grasslands as well as wastelands and post-drift areas. Their proportional contribution in the total area of examined drainage basin is presented in Table 3. What results from Table 3, 28.2% of arable lands, 1.4% of wastelands and 0.4% of grasslands are exposed to high and very high erosion risk.

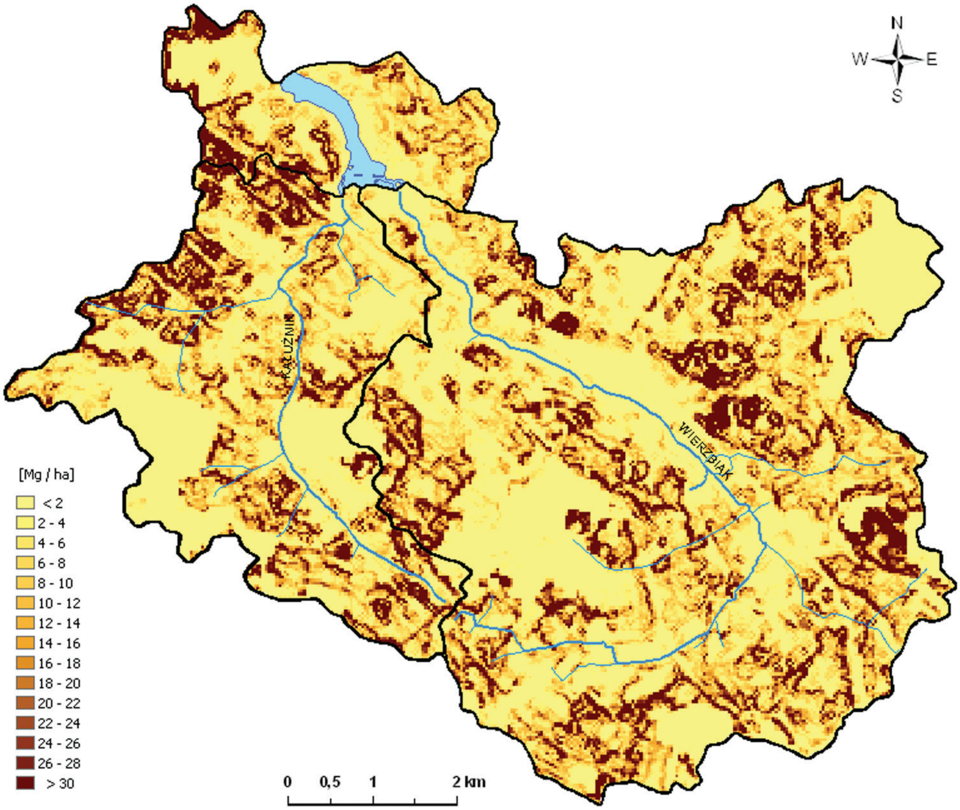

Fig. 3. Spacial distribution of eroded soil mass [Mg · ha^{-1} · year^{-1}]

Table 3. Proportional contribution of usage of the area categories in erosion risk classes

Risk class	Contribution in whole examined area [%]		
	Arable lands	Grasslands	Wastelands, post-drift areas
1	13.2	3.7	0.4
2	11.7	2.9	0.1
3	9.2	0.7	0.2
4	7.8	0.3	0.1
5	13.9	0.3	0.4
6	14.3	0.1	1.0

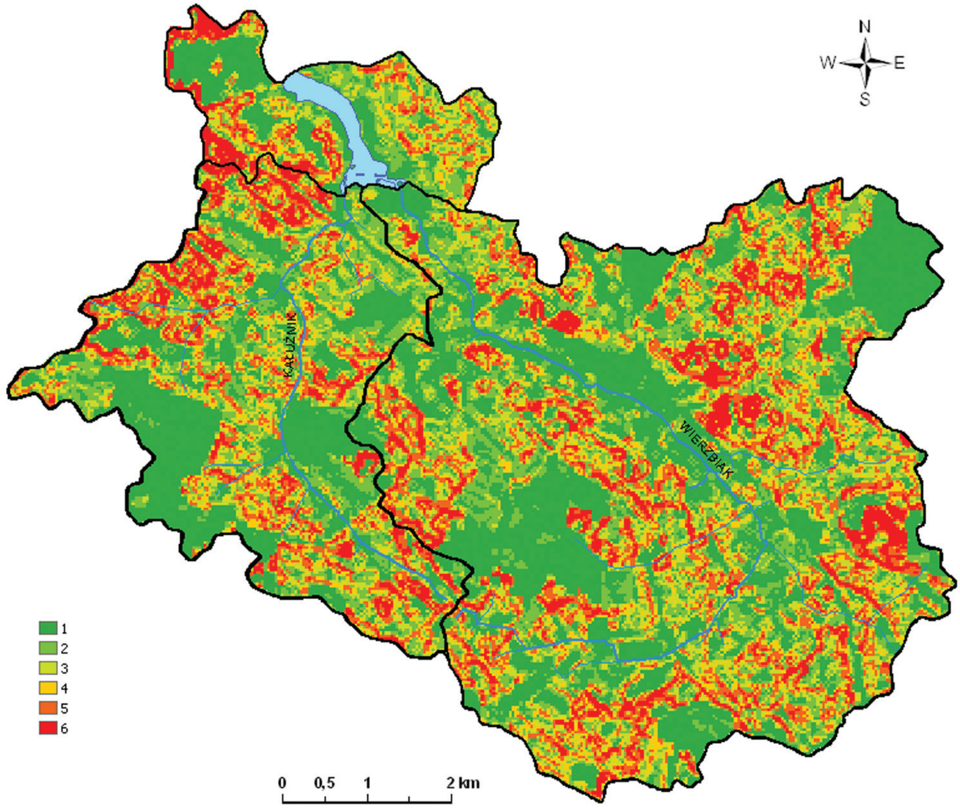

Fig. 4. Erosion risk classification: 1 – lack, 2 – very small, 3 – small, 4 – average, 5 – high, 6 – very high

5. Summary and conclusions

RUSLE model used in the present research is commonly applied in the world method of soil erosion risk evaluation. Its usage prevalence enables possibility to compare gathered results of modelling with the other authors' researches results which were conducted in different parts of the country or the world [Kowalczyk and Twardy 2012, Mularz and Drzewiecki 2007, Jianguo 2001, Auerswald 2006, Gumiere et al. 2009, Ranzia et al. 2012]. Beside many advantages of RUSLE model, its disadvantage is lack of the possibility to take into account the areas of deposition of eroded soil material. In situ measurements reveal existence of quantity restraint of soil material which can be transported together with surface flow [Mitasova et al. 2005, Pistocchi et al. 2002].

On the basis of conducted modelling, following conclusions can be presented:

1. Water erosion risk of soil in the Mściwojów water reservoir drainage basin is very high. Almost one third of its area is located in the high and very high class of erosive risk.

2. Results of erosion prognosis by means of RUSLE method after Moore's formula are by 40% higher than values evaluated after Desmet and Gover's formula.
3. Eroded soil mean mass from area unit during the year is estimated at the level of 10.35–14.53 $Mg \cdot ha^{-1} \cdot year^{-1}$, depending on accepted computable method.
4. Total mass of eroded soil which can annually flow into the Mściwojów water reservoir is evaluated at 49 147–68 622 $Mg \cdot year^{-1}$, depending on computable formula used.

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