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The hydrological modeling in terms of determining the potential European beaver effect

Marta Szostak[*], **Jadwiga Jagodzińska**

University of Agriculture in Krakow
Faculty of Forestry, Institute of Forest Resources Management
Department of Forest Management, Geomatics and Forest Economics
Al. 29 listopada 46, 31-425 Krakow, Poland
e-mails: m.szostak@ur.krakow.pl, jadzia.jagodzinska@gmail.com

* Corresponding author: Marta Szostak

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Abstract: The objective of the paper was the hydrological analysis, in terms of categorizing main watercourses (based on coupled catchments) and marking areas covered by potential impact of the occurrence and activities of the European beaver *Castor fiber*. At the analysed area – the Forest District Głogów Małopolski there is a population of about 200 beavers in that Forest District. Damage inflicted by beavers was detected on 33.0 ha of the Forest District, while in the area of 13.9 ha the damage was small (below 10%). The monitoring of the beavers' behaviour and the analysis of their influence on hydrology of the area became an important element of using geoinformationtools in the management of forest areas.

ArcHydro ArcGIS Esri module was applied, as an integrated set of tools for hydrographical analysis and modelling. Further steps of the procedure are hydrologic analyses such as: marking river networks on the DTM, filling holes, making maps of the flow direction, making the map of the accumulation flow, defining and segmentation of streams, marking elementary basins, marking coupled basins, making dams in the places, where beavers occur and localization of the area with a visible impact of damming. The result of the study includes maps prepared for the Forest District: the map of main rivers and their basins, categories of watercourses and compartments particularly threatened by beaver's foraging.

Keywords: hydrological modeling, Digital Terrain Model, categorization of watercourses, drainage basin

1. Introduction

The application of geoinformation techniques in environmental management is widespread. The monitoring of natural phenomena, also potentially destructive phenomena such as floods, fires, water and soil pollution became necessary and it is a duty of institutions, the activities of which are connected with and dependent on ecological conditions. Geomatic technologies are indispensible element and significantly facilitate collecting this information and analysis of the processes taking place in the environment (Będkowski, 2010; Calka et al., 2016; Dębski, 2004; Drzewiecki et al., 2014; Gaździcki, 2010; Kogut et al., 2016; Szostak et al., 2014; Urbański, 2008; Wężyk, 2014; Wężyk and Pierzchalski, 2014).

In hydrology the application of Geographical Information System (GIS) became everyday routine. Important area of the application of GIS is modelling of water flow in the area, the analysis of point and non-point pollution sources in the basins, calculating summary inflow of nitrogen and phosphorus compounds and bacteria to lakes or coastal waters, or the analysis of retention processes. The application of geomatic techniques allows us to define the exact shape of hydrological objects in any area. Hydrologic analyses of GIS make a good tool in smooth categorization of watercourses, determining the borders of basins, mapping the accumulation of flows as well as many other elements, depending on needs. They allow earlier determination of areas threatened by floods or pollution. Their accuracy depends on the accuracy of field measurements and the resolution of cartographic materials.

Hydrology of a forest ecosystem is implied by interdisciplinary problem-oriented approach to water in this ecosystem (Miler, 2008). Its relationship with zoology is visible e.g. in the case of the presence of animals in water and forest ecosystems. Nowadays in the area of the State Forest Holding a factor shaping the hydrologic objects becomes the European beaver (*Castor fiber*). The increase of the beaver population has been observed for many years. This species is fully protected by the Polish law. Thus only natural factors (predators, overcrowding of the ecosystem) can stop the growth of their populations. The population growth is connected with the damage inflicted by these mammals. In 2012 damage caused by beavers all over Poland, was estimated as 10.5 million zlotys (PAP, 2013). Beaver dams in the upper part of rivers are some of the best visible and characteristic effects of the engineering activities of beavers, causing renaturization. In forest management even small flooding of a tree stand can destroy it, but the further situated forest complexes can be protected from fire (Czech, 2007).

The monitoring of the beavers' behaviour of and analysis of their influence on hydrology of the area becomes an important element of using geoinformation tools in the forest and environmental management (Danilov and Fyodorov, 2015; Nyssen at al., 2011; Puttock et al., 2017). The construction of beaver dams facilitates a suite of hydrologic, geomorphic, and ecological feedbacks that increase stream complexity and channel–floodplain connectivity. Depending on where beaver build dams within a drainage network, they impact connectivity that fundamentally change the timing, delivery, and storage of water, sediment and organic matter. While the local effects of beaver dams on streams are well understood, broader coverage network models that predict how beaver dams impacts on connectivity across diverse drainage networks are lacking (Macfarlane et al., 2017).

The objective of this paper is offer a new approach for researching rivers that are impacted by the European beaver *Castor fiber*. The hydrological analysis were done of the Forest District Głogów Małopolski, in terms of the categorization of main watercourses (based on drainage basin) and marking the areas potentially influenced by the presence and activities of the European beaver *Castor fiber*. The presented methodology is universal and can be used for different area and hydrological task.

2. Study Area

The study area was the Forest District of Głogów Małopolski (the Podkarpackie Voivodeship). In terms of administrative division of the State Forest Holding, the area is in the Regional Directorate Forest State Krosno (Figure 1). The Forest District is situated between 50° 04' N, 21° 37'E and 50° 18' N, 22° 08'E.

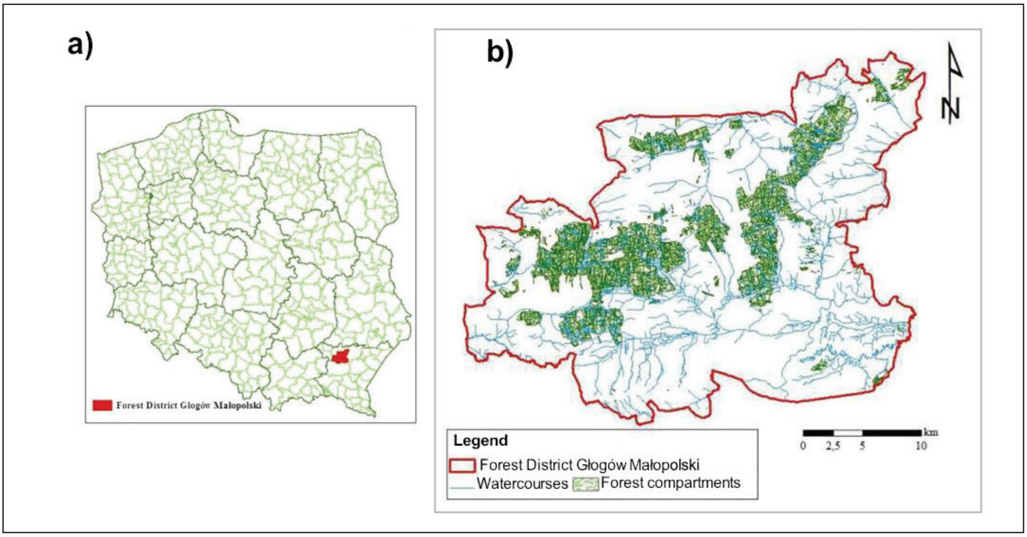

Fig. 1. The study area: a) the general map of Poland, (b) the borders of the Forest District Głogów Małopolski

3. Materials and Methods

In the paper the following materials were applied:

1) The Plan of the Forest Management of the Forest District Głogów Małopolski, according to the state of 1st January 2011:
   - data referring to the area of the Forest District and habitat conditions;
   - data referring to the presence of the European beaver (*Castor fiber*), received from the Forest District (state of 2009-2011) with the flooded areas marked.

2) A part of the Forest Digital Map (FDM, *pl. Leśna Mapa Numeryczna – LMN*) provided by the Forest District Głogów Małopolski, of the range covering the area of the whole Forest District (state of 2014) in the form of vector layers in format ESRI Shape file in the coordinate system „PUWG 1992". Layers of the FDM:
   - *wateres (pl. ciek_lin)* – watercourses (Polyline);
   - *comp (pl. fiz_wyd*) – comparmetnts (Polygon);
   - *distr (pl. nadl)* – the area of the Forest District Głogów Małpolski (Polygon).

   Objects in the layer *waters* include:
   - watercourses, including rivers *(pl. cieki)*;
   - streams *(pl. potoki)*;
   - drainage trenches *(pl. rowy).*
3) Digital Terrain Model (DTM) as GRID (pixel 100m), obtained from the Central Unit of the Geodetic and Cartographic Documentation and written in the ASCII format.

The main objective of the analysis was to mark the Forest District areas most exposed to beavers' activities, i.e. making a map of compartments threatened by potential depreciation. Additional element was making classification of river streams based on the map of flow accumulation and data of the Forest District. The study was done in ArcGis (version 10.2) by ESRI with free extension ArcHydro, helping in the analysis and management of water resources. Two elements were used: ArcHydro Data Model and ArcHydro Tools, making the integrated set of tools for hydrographic analysis and modelling (Urbański, 2008).

A database of the project contained vector layers FDM *(LMN)* and the Digital Terrain Model of the Podkarpackie Voivodeship (initially written as XYZ coordinates, processed into a raster form – GRID). The materials were in a coordinate system PL-PUWG 1992.

Data processing of the Forest District Głogów Małpolski consisted of many hydrological analyses. Initial stages of hydrological modelling were done in sequence:

- mark river networks on the DTM – function *DEM Reconditioning;*
- fill holes – *Fill Sinks*;
- generate the map of the flow direction – *Flow Direction*;
- generate the map of the accumulation flow – *Flow Accumulation*;
- define watercourses – *Stream Definition*. To all the cells of the grid identical identifiers were attributed;
- segmentation of watercourses – *Stream Segmantation*.

As a result of the initial process a map of streams was made after the segmentation, on which a separate identifier is given to every part of the network of streams.

The further steps of hydrological analyses were:

- create elementary basins – *Catachment Grid Delineation*

- convert raster layers: streams and elementary basins to vector – *Drainage Line Processing* and *Catachment Polygon Processing*;
- generate coupled basins – *Adjoint Catachment Processing*;
- create vector layer *Polyline* – dams in the places, where beavers occur;
- convert vector dams to raster – *Euclidean Distance*;
- visualization of the area with a visible impact of damming – *Watershed* (Spatial Analyst).

4. Results

As the effect of the carried out initial stages of hydrological modelling the following was obtained: the Digital Terrain Model with marked streams and hollows filled in (Figure 2a, b), the map of flow directions (Figure 2c) and the flow accumulation map, where streams are found (Figure 2d). Then watercourses were defined (Figure 2e). As a result of the process of the segmentation of watercourses, a map of streams was made (Figure 2f). It consists of 371 fragments containing from 1 to 53 cells. The numeration streams runs subsequently, starting from the stream directed most to north-east.

The further step of this procedure was marking elementary basins, the effect of which was to obtain a layer consisting of 370 areas of basins, with the number of cells in each area ranging between 1 and 831 (Figure 3a). Then the raster: streams and elementary basins were convert to vector layers (Figure 3b) and drainage basins were made (Figure 3c). 166 drainage basins were created. The smallest area is 226 ha and the biggest – 32 295 ha. Attribute tables include areas: ObjectID, Shape Length, Shape Area, HydroID, DrainID, GridID. These are individual hydrological identifiers attributed to all the linked vector objects. After indicating the places of the occurrence of beavers – dams simulated as lines (Figure 3d), the vector layer of dams on watercourses on the raster layer (Figure 3e) and as a result of making the dam affected areas, the raster layer of three main flood-threatened areas was marked. The areas consist of several elementary basins, situated on three different watercourses (Figure 3f).

The final stage of the work is changing the raster layer of flood-threatened area into the layer consisting of three polygons (Figure 4a), located in the threatened basins and making, as a result of function of excluding a part of common polygons, the layer of compartments, on which one can theoretically notice the impact of damming (Figure 4b). This layer means 970 threatened compartments.

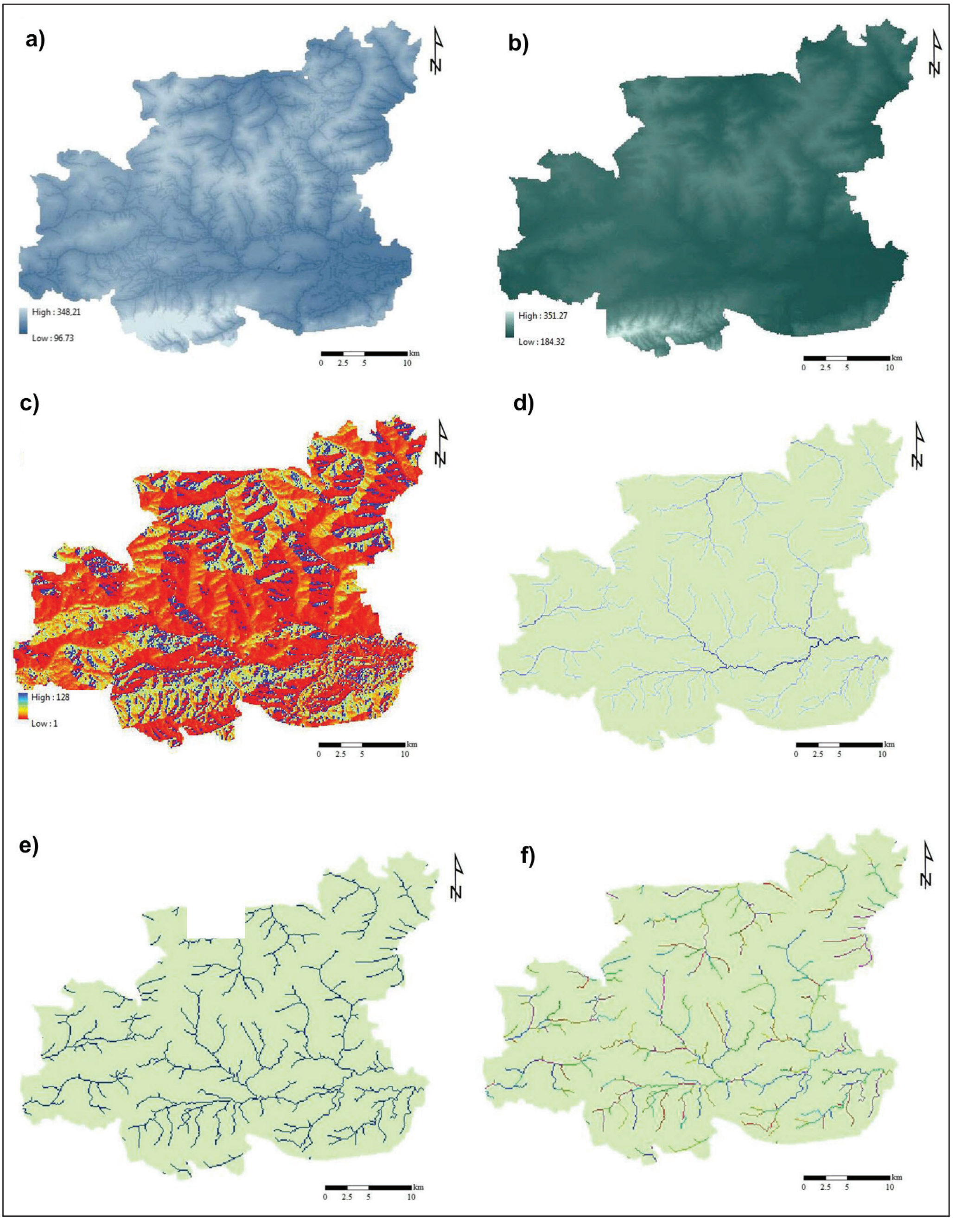

Fig. 2. Initial stages of hydrological modelling: a) DTM with streams; b) DTM with the hollows filled in; c) map of the flow directions; d) map of accumulation flow; e) defined watercourses; f) watercourses after segmentation

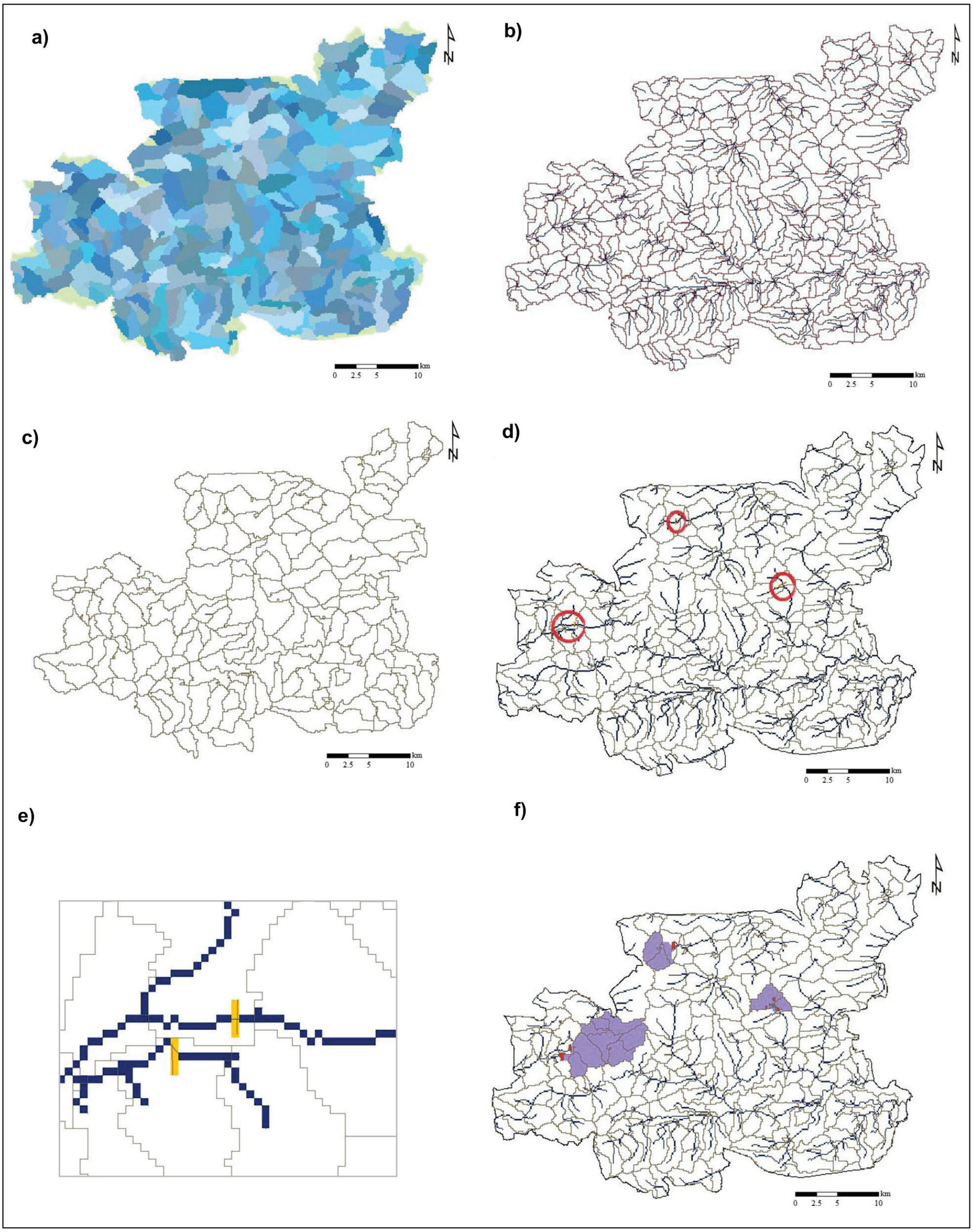

Fig. 3. Subsequent stages of hydrological modelling: a) elementary basins; b) elementary basins and watercourses; c) overlapping coupled basins; d) dams – places of the occurrence of beavers; e) dams (zoom) in the raster form; f) areas threatened by flooding

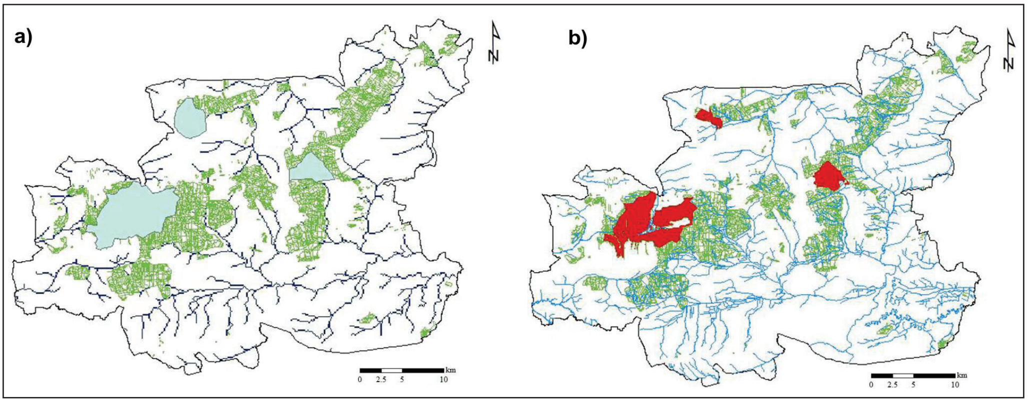

Fig. 4. The effects of hydrological modelling: a) polygons of the threatened areas, b) threatened compartments

As a result of hydrological analysis a map (Figure 5) of compartments threatened with damming was made on river streams, where beavers occur. Analyzing the results, it can be concluded that 970 of 4067 compartments can be threatened, which makes 23.85% of the total number. It makes the area of 2 665.23 ha z 13 570.10 ha of the forest (19.64%). This map is the effect of purely theoretical analysis, defining maximal range of the results of damming, not taking in the account the retention abilities of forest habitats, subtypes of soil, tree species, groundcover etc. In terms of the carried out function, these compartments have mainly protective significance (772 compartments – protective function, 10 – economic function, 72 – nature reserve, 116 – other function e.g. stores, roads, ponds). Most soils, occurring in these areas are humid soils, moderately or poorly permeable (podsols, precipitation soils, peatlands). A far as the habitat is concerned, the moist mixed pine forest dominates (213 compartments make 29% of the threatened area). In terms of humidity of the threatened area, the dominant type is the fresh type (322 compartments) and moist type (321 compartments), 38% of the threatened area, each.

Additionally, in the paper, the categorization of watercourses was carried out. Twenty three rivers of different rows were differentiated. Then the main streams, their tributaries and basins were marked. Watercourses were divided into five categories. The first category included main watercorses (rivers) and the last – small unnamed brooks. Six streams of category I were distinguished (Wisłok, Młynówka, Czarna Rzeka, Trzebośnica, Tuszymka, Turka), five streams of category II (Mrowla, Stary Wisłok, Świerkowiec, Zyzoga, Gądka), eight streams of category III (Strugi, Wężówka, Węgorzyn, Czarna, Szuwarka, Terliczka, Kłapówka, Widełka) and three streams of category IV (Szlachcianka, Osina, Gołębiówka). Comparing the results to the data of the Instrumental Operate, in the area of the Forest District one can determine three main river basin tributaries: Łęg, San and Wisłoka. Their tributaries are main streams running through the Forest District (Figure 6) and marked in the analysis: Wisłok, Trzebośnica – San; Młynówka, Tuszymka – Wisłoka, Turka – Łęg. The surface covers the basins of Wisłok – 31 399 ha, then, respectively: Młynówka – 9 896 ha, Tuszymka – 3 759 ha, Turka – 2 763 ha, Czarna Rzeka – 2 503 ha and Trzebośnica – 1 734 ha. The summary surface of the drainage basins for main streams is 55 642 ha.

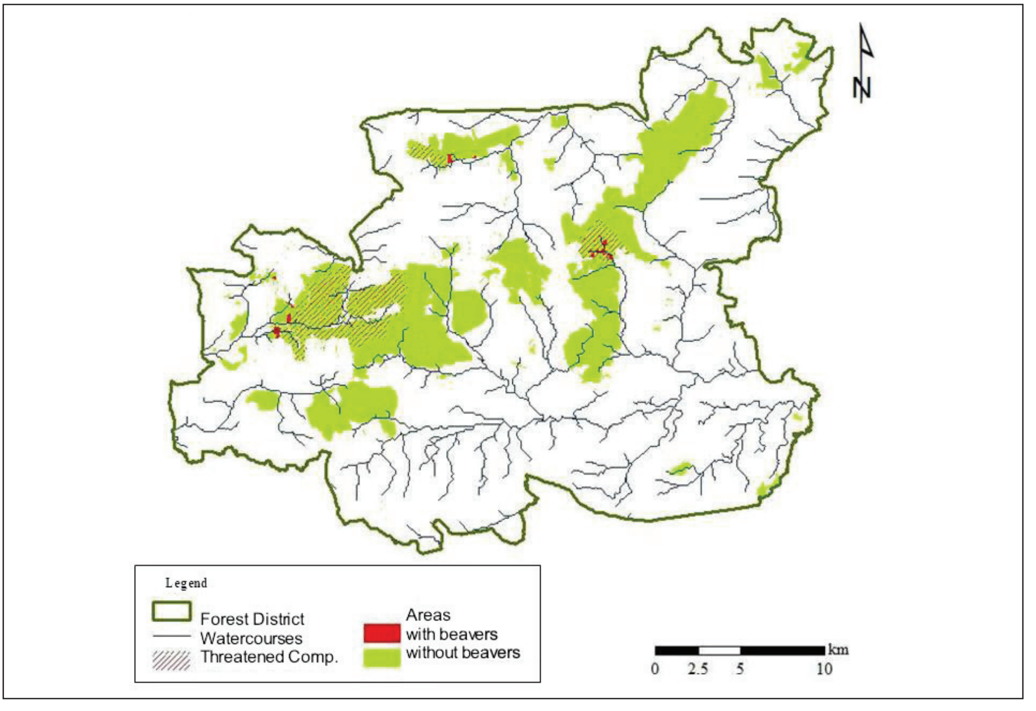

Fig. 5. The map of compartments threatened by the results of beavers' foraging

Taking into account the areas threatened by flooding in the Forest District (Figure 6), only in the area of the basin of Tuszymka, the dams are directly at the main stream (in its upper part). The other two are in some distance from main streams – on the rivers of Kłapówka (basin of Młynówka) and Gołębiówka (basin of Wisłok), just at the borders of the basins, thus in the upper course of the rivers.

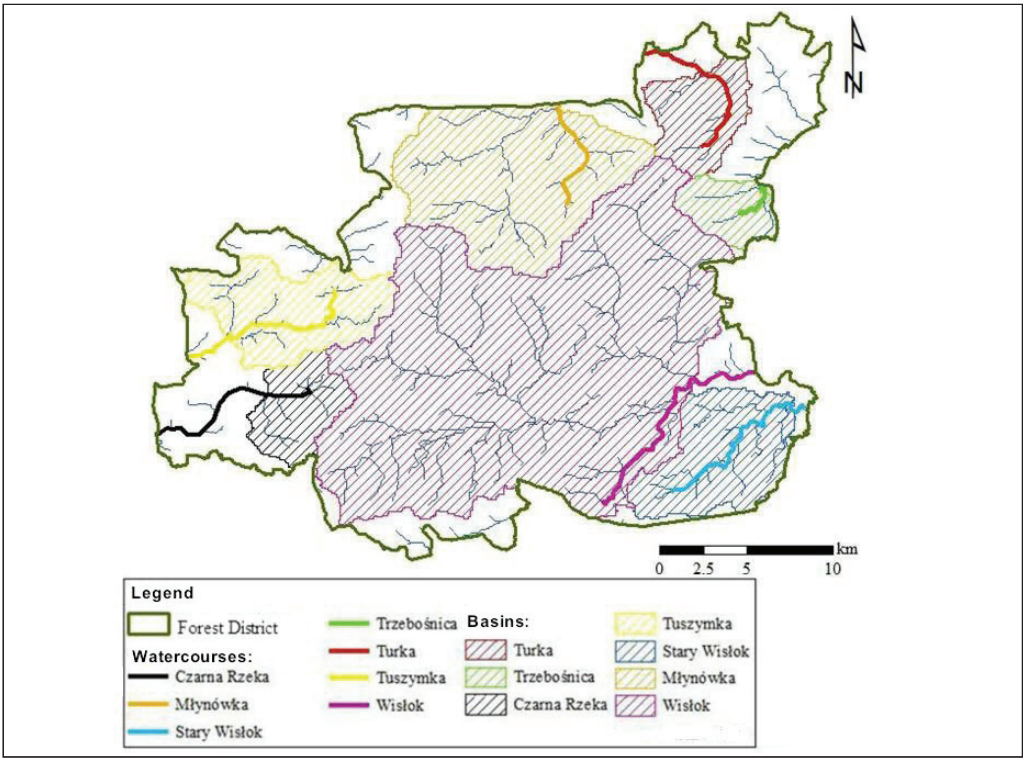

Fig. 6. The areas threatened by flooding against the background of the main watercourses and their basins

5. Conclusions

Defining the results of the beavers' activities is an ambiguous issue, depending on the subject for which the survey is carried out – taking into account the interests of the State Forest Holding, these activities cause damage (flooding of the compartments, depreciation of the resources and the destruction of the road surfaces), however, from the point of view of agricultural and business activities of the local community it is a positive activity – water is withheld by dams and the flooding of residential and agricultural areas is not that intense.

In this paper marking the areas threatened by flooding had a purely model character, because no forest co-efficients of retention were taken into account, which would be necessary to full reliable flood analysis. This model is suitable in the initial definition of the flooded areas. Reading this, one has to take into account the fact that the areas in the direct vicinity with compartments are most threatened, where the construction activities of beavers were observed. At the borders of the marked area the effects of damming are unnoticeable.

After carrying out the hydrological analyses, one can notice that their accuracy depends on the resolution of the Digital Terrain Model and the precision of the determined course of watercourses. For more detail analyses one should apply a more accurate DTM e.g. obtained as the effect of processing data from the airborne laser scanning, carried out within the ISOK project (*pl. Informatyczny System Osłony Kraju* – Information System of Protecting the Country from the most serious danger). The amount and the course of the defined watercourses is also influenced by the border value of the amount of coupled cells, where the determination of the stream begins. The higher the number the smaller number of streams is marked by the algorithm, which consequently is decisive in the course of further analyses, such as determining elementary and coupled basins. The fragmentation of the network of river streams causes the increase of the number of basins, which influences more accurate marking of the areas threatened by flooding, but at the same time it makes the categorization of main watercourses more difficult. The categorization of main watercourses is more efficient at the analysis of larger area than the Forest District itself, because it covers a small area, not fully able to effective and full representation of the whole river basins of the main streams in Poland.

In the Forest District Głogów Małopolski the threat with flooding takes place near the river of Tuszymka, due to the area of the marked terrains and the category of the river, on which the damming occurs. The remaining two areas (in the basin of Wisłok and Młynówka) do not have such a great significance, because beavers live in the area of the rivers of third and fourth category – Kłapówka and Gołębiówka, at the border of basins (watersheds), which also mitigates the effects of flooding. Habitats taken by beavers are mainly fertile, fresh and humid areas, mostly fulfilling the protective function (also in the reserve). Their stay in the nature reserves limits the damage caused by their activities to the commercial forest, because the reserves take the retention function and mitigate the effects of floods in the neighbouring compartments.

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