ORIGINAL ARTICLE

Determination of retention value using Mike She model in the area of young glacial catchments

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Abstract

The aim of the paper is the identification of the kinds and conditions of retention occurring in the selected of young glacial catchment (the Potok Oliwski) in natural and anthropogenic conditions by means of the mathematic model of Mike She. As a result of the performed calculations it has been possible to determine that the studied area, thanks to the nature-shaped factors, has a high retention potential, which refers to the ground water storage. The conditions of surface retention, in which a great role is played by blind drainage, have been analysed as well.

Keywords Retention · Catchment · Edge zone · Area without outflow · Depression

Introduction

To approach the problem of water resources in detail, it is necessary to study them from a macro and systematic perspective (Wang et al. 2016). First, new places should be sought, where humans they could tap new resources or apply some technological measures to recover substantial amounts of water that have so far figured as losses in the total balance. One of the latter is employing natural retention to store and then recover water. This can involve not only the surface water cycle, but also the sub-surface one. Among the natural objects that can be employed to store precipitation water and then be used for household and economic purposes are basins without outlets, both of the absorptive and the evapotranspiration type (Major and Cieśliński 2010). All kinds of practices, both technological (small water reservoirs, weirs, gates, etc.) and non-technological (afforestation, tree planting, protective vegetation belts, protection of kettle ponds, country ponds, marshes, etc.)—can help to slow down or stop water while restoring the natural landscape. However, to be able to employ the various forms of retention correctly, one should first identify the conditions that will affect small water cycles and the magnitude of retention in the catchments (Quinton

et al. 2003; Brooks 2005). Today, to assess changes in hydrological and climatic conditions considered in global, regional and local level are used all kinds of mathematical models. One of the better models involving different elements of the natural environment of water circulation, including the retention model is Mike She. This model is used, among other things Larsen et al. (2014) for a Danish catchment, Wang et al. (2012) who performed the analysis multi-site calibration, validation and sensitivity of the MIKE SHE Model for a large watershed in northern China, Prucha et al. (2016) who performed a variety of hydrological simulation scenarios for dry areas, Doummar et al. (2012) who made simulation of flow processes in a large scale, Rahim et al. (2012) who made application of MIKE SHE modelling system to set up a detailed water balance computation, or Bosson et al. (2013) who developed exchange and pathways of deep and shallow groundwater in different climate on example catchment in Sweden. For countries where long dry seasons are observed, it is important to know the base flow indicator (BFI) (Kelly et al. 2019). Base flow index originally was developed as a parameter to index the ability of a catchment to store and release water (Beck et al. 2013). BFI is calculated as the ratio of the flow under the baseflow hydrograph (the baseflow volume) to the flow under the river hydrograph (total flow volume) (Kelly et al. 2019). BFI is applied in hydrology and hydrogeology where it is used as a catchment descriptor in low flow studies (Tallaksen and Van Lanen 2004), and a groundwater availability

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indicator (Ngongondo 2006). In turn, according to Rai et al. (2017) analysis of morphometric parameters with the help of geographic information system (GIS) would prove a viable method of characterizing the hydrological response behaviour of the watershed.

Poland's water resources are modest when compared with other European countries (Kallis and Butler 2001). WEI water exploitation index is 20% for Poland, whereas in countries such as Cyprus, Belgium or Spain over 30% (maximum above 60%). Do not forget at the same time that water resources will be reduced as a result of climate change (Arnell 2004; Christensen et al. 2004; IPCC 2019), which may cause flooding (Hattermann et al. 2013) or water deficit (Tokarczyk 2013). The amount of water at our disposal largely depends on precipitation. This implies the possibility of retention of rainwater from built-up areas.

In the introduction to the paper, a hypothesis was assumed that an improvement in the condition of water circulation in the catchment area of the river selected for analysis could result from the use of natural endorheic hollows of the morainic plateau zone for precipitation water retention from built-up areas. On the basis of this thesis, the main goal of the paper was established, namely the determination of types and conditions of retention occurring in the catchment, especially in its headwater part in natural conditions as well as in changed conditions accounting for human impact in terms of building development and manner of precipitation water discharge.

The aim of the study is an analysis of the dynamics of the hydrological system located within a young Scandinavian glacier accumulation and finding the relationship between the variables characterizing the components of the water balance. In the result, is found a mathematical model of the system dynamics.

Methods

The main work consisted in a survey of source materials obtained from the Municipal Council in Gdansk, database of "Akwedukt" and Hydrogeological Modelling Laboratory and using the computer program Mike She for mathematical modelling.

The work scope included the determination of the boundaries of the surface catchment of the Potok Oliwski and localisation of natural endorheic absorptive and evapotranspirative hollows within its area. For the establishment of morphometric parameters of the endorheic hollows, the area calculated in Mapinfo determined by the isohypse constituting the edge of the hollow, was used. The volume was calculated for the assumed maximum depth of 1 m, using the formula for the cone volume with a base equal to the area of the hollow:

$$V = 1/3 \cdot P \cdot h, \tag{1}$$

where V cone volume, P base area field, h cone height (here: hollow depth).

Additionally, the capacity of the reservoirs (hollows) was estimated using cartographic information, bathymetry and a numerical terrain model (Fig. 1). Such calculations were made using ArcGIS—3D Analyst tools. In order to determine the volume of water in the reservoirs, the contours of the area under study were created. The volume represents the area between the surface and the space above or below the polygon elements based on a selection made in the Reference Plane-Calculate above/below the plane.

As a result, it was determined that the results obtained with the two methods did not differ much from each other.

The subsequent work was related to the use of the computer program Mike She designed for mathematical modelling of the processes occurring in nature in the scope of the phenomena related to water circulation. The author of the program is Dansk Hydraulisk Institut.

The preparatory work consisted in digitalisation of the hydrographic network, areas of various types of use, as well as data on the geological construction and levels of underground water table. The choice of data concerning precipitation was conducted in such a way to reflect the actual course of precipitation. The calculations were based on precipitation data from the years 1997–2019 measured at 30-min intervals in the automatic measurement station of the Gdansk Refinery.

This was followed by an analysis of the results of model calculations for the balance components in natural conditions with respect to the correctness of the balance. The balance error for the whole of calculations was close to zero, which confirmed its correct calculation.

The subsequent stage of the work was the introduction of changes in the boundary conditions in the form of a definite area of building development, giving the outflow coefficient and directing precipitation waters from this area into the Potok Oliwski. The proportion between infiltration and surface runoff in the built-up area was presented too. The duration of the impact of building development on the conditions of water circulation in the catchment started with the beginning of the balance period from a value of zero. Then the elements of the balance in natural conditions and in anthropogenic conditions were compared, and there was an attempt at indicating causes and effects of the observed changes.

During the work, it was necessary to determine the value of the intensity of the filtration discharge on the basis of the formula by Darcy:
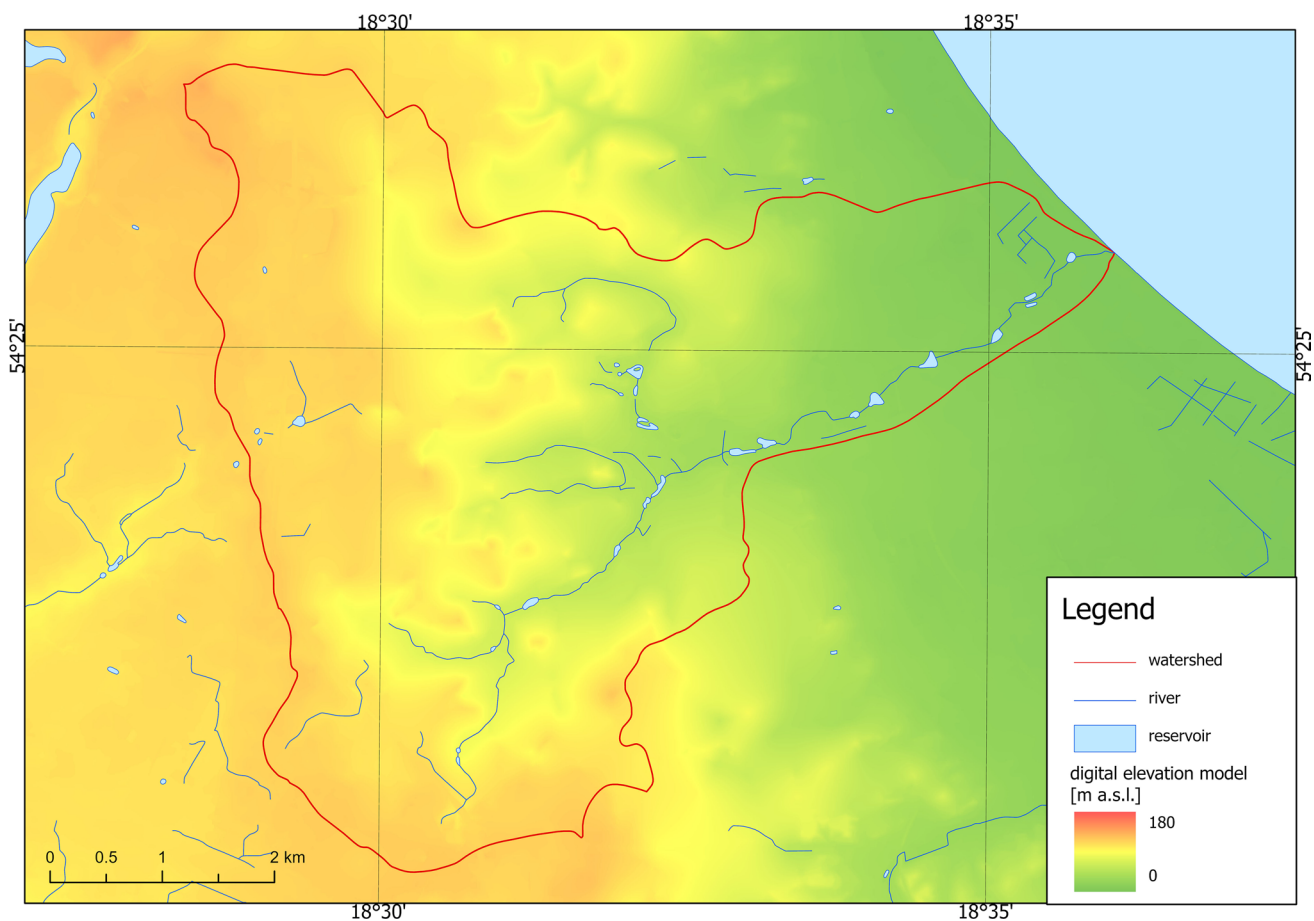
Fig. 1 Numerical terrain model of the Potok Oliwski catchment

$$Q = k \cdot J \cdot F \qquad (2)$$

where Q intensity of filtration discharge, k filtration coefficient ($k = 0.001$ m s$^{-1} = 3.6$ m h^{-1}), J hydraulic gradient (1 m—assumed hollow depth), F cross-section area.

The constant elements, constituting the input data to the model include: land relief, hydrographic network, including surface streams, water reservoirs, site of storm drainage discharge, type of area use, geological profiles, data on levels of underground water table on the basis of which water-bearing horizons are localised, aeration and saturation zones. On the other hand, elements variable in time, forming temporal sequences of changes of these parameters, which are measured and entered into calculations as boundary conditions include: precipitation intensity, temperature, atmospheric pressure, wind strength, snow cover, evaporation, types of vegetation and many more, whose number and reliability influence the accuracy of the obtained calculation results. If some of the data are unavailable, on the basis of the general hydrological knowledge, initial assumptions are entered and then appropriately modified by the system.

Thanks to the model calculations, complex information on the dynamics of surface and underground waters in the studied area is obtained with an optimally selected time step, whose significant feature is adaptation to changes in particular parameters. In the case of calculations which run parallel for many processes, this means such a way of reacting to changes in one parameter so that they were captured in others related to it as soon as possible.

Area of investigations

The area selected for research is the catchment of the Potok Oliwski, especially its headwater part situated in the area of the city of Gdansk and its vicinity, in Northern Poland (Fig. 2).

Due to natural factors, the retention potential in the headwater part was distinguished by its value and significance. Hence, it received special attention in the discussion of certain issues. For the purposes of the paper, it is called the plateau part of the catchment: from the east separated by the line marked on the border of morainic relief and the relief of valley cuts of the edge zone. However, for calculation
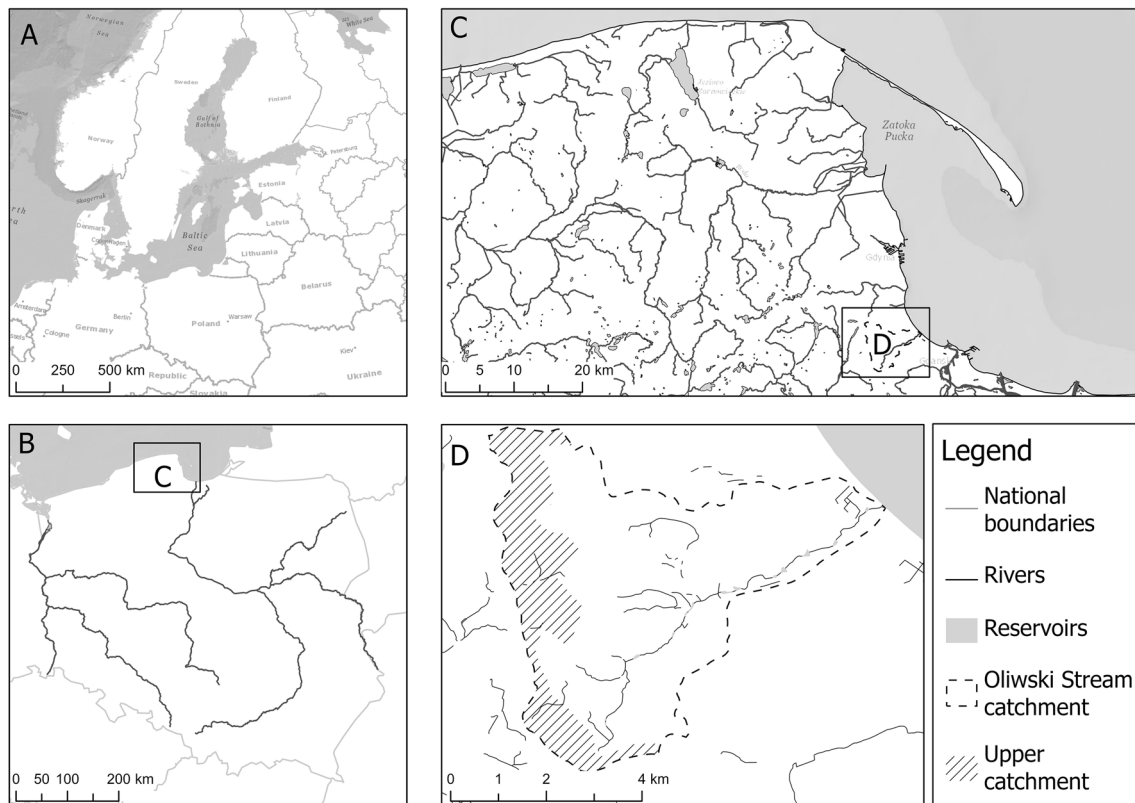
Fig. 2 Catchment of Potok Oliwski with plateau part

purposes, the whole catchment of the Potok Oliwski in its surface extent was taken into consideration, which is more appropriate in terms of balance and gives a more complete view of the situation.

The plateau part of the catchment of the Potok Oliwski covers an area of 7.25 km^2. The largest part of its area is covered by forests (2.71 km^2), then agricultural areas (2.03 km^2), building development in the form of housing estates and industrial and service buildings (1.45 km^2). This is an area with a small quantity of high vegetation, parks, green squares, areas with a diverse cover. Due to levelling works, the natural undulating of the area is disappearing as well, and numerous hollows are being dried out or filled up. The building development of the plateau is often accompanied by a poor development of infrastructure in the form of appropriate for the area and unobstructed storm drainage system and retention reservoirs. A very characteristic element of the development in the stream catchment (Fig. 3) is the Tri-city ring road leading from the north to the south. It forms a certain border in the manner of use of the catchment area, dividing it into the western part, heavily anthropogenically transformed and the eastern natural part.

The plateau part of the Potok Oliwski catchment does not have an organised network of surface waters. Surface hydrographic elements are represented here by marshes, lakes,

kettle ponds and the most characteristic numerous endorheic areas. The drainage of this part of the catchment occurs through streams of the edge zone. Some valleys of this zone remain dry, constituting a way for potential precipitation and melt waters.

The Potok Oliwski together with its tributaries (Fig. 4) is characterised by a high mean unit gradient reaching up to 12.5‰, and in the edge zone this parameter is even over 20‰. The discharge intensity in the river in the years 1996–2019 ranged from 0.011 to 0.42 m^3 s^{-1}. A tendency of discharge increase year by year was also observed. It can be attributed to the growing quantity of water reaching the streams of the catchment from the storm drainage system embracing the built-up areas. The Potok Oliwski in its lower course is completely regulated and accompanied by a number of retention reservoirs and ponds. The stream receives precipitation water from nearby housing districts.

Underground waters in the catchment of the Potok Oliwski occur in three regional water-bearing horizons: Cretaceous, Tertiary and Quaternary. The analysis of cartographic materials reveals that the directions of local flow of underground water are dependent here on the land relief and layout of rock layers. In the Quaternary cover for altitudes from about 170–100 m above the sea level, underground water flows take various directions, resulting
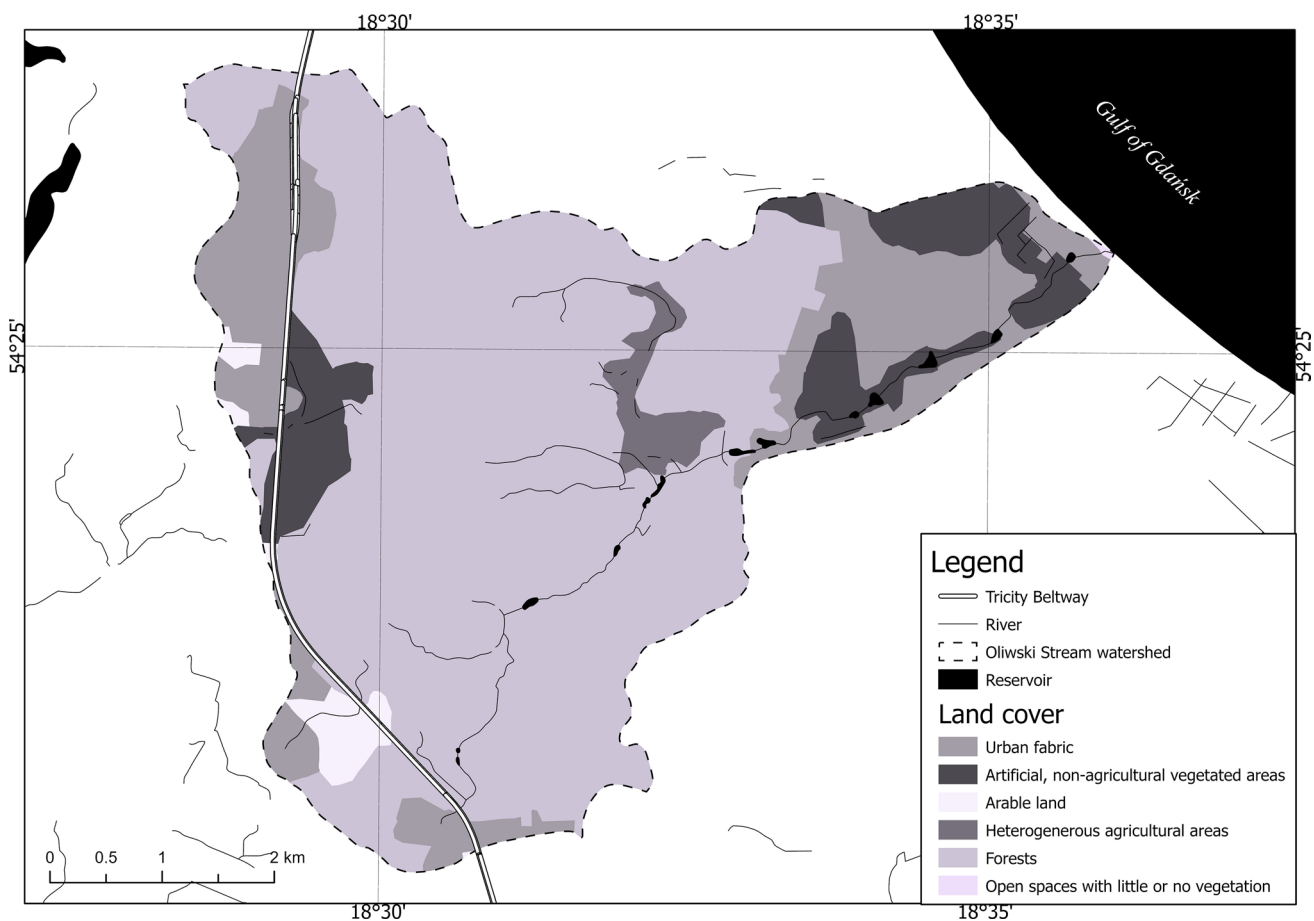
Fig. 3 Structure of use of area in Potok Oliwski catchment (Major and Cieśliński 2015)

from adjustment to local higher morainic elevations and alternating rock layers of better and poorer permeability. For altitudes from about 100 m above the sea level to the base of the Quaternary layers, occurring at various altitudes, underground waters have already a uniform northeastern direction of flow. In the Tertiary and Cretaceous levels, the direction is consistent with the regional flow of underground water to the recipient, i.e. the Baltic Sea.

Thanks to the knowledge of these facts it can be assumed that irrespective of the surface border of the catchment, infiltrating precipitation waters supply water-bearing layers in accordance with the underground watersheds. However, already at a level of about 100 m above the sea level and still within the Quaternary formations, they join the regional direction of underground waters flow leading from the south west to the north east to the basic drainage base.

On the plateau the level of the underground water table occurs at various depths: in the area of some evapotranspirative hollows it is the highest, reaching 1–2 m below the ground level, and within the slopes of erosion valleys the level of underground waters occurs at a depth from 5 to 25 m

below the ground level, while at the bottom it rises up to the ground level or 2 m below.

A lack of organised surface outflow and the postglacial geological structure of the ground results in the occurrence of two types of endorheic hollows—absorptive and evapotranspirative (Fig. 5), with a domination of the former. The depth of absorptive hollows does not exceed 1.25 m, while the area of the largest ones reaches over 12 thousand m^2 with a volume of 4000 m^3. Most hollows have an area of about several hundred square metres and a similar volume.

Results

Components of water balance in natural conditions

Fall and evaporation

The amount of precipitation in the catchment area of the Potok Oliwski is highly diversified. Until 2000, they ranged from 400 to 500 mm. After this time, an increase
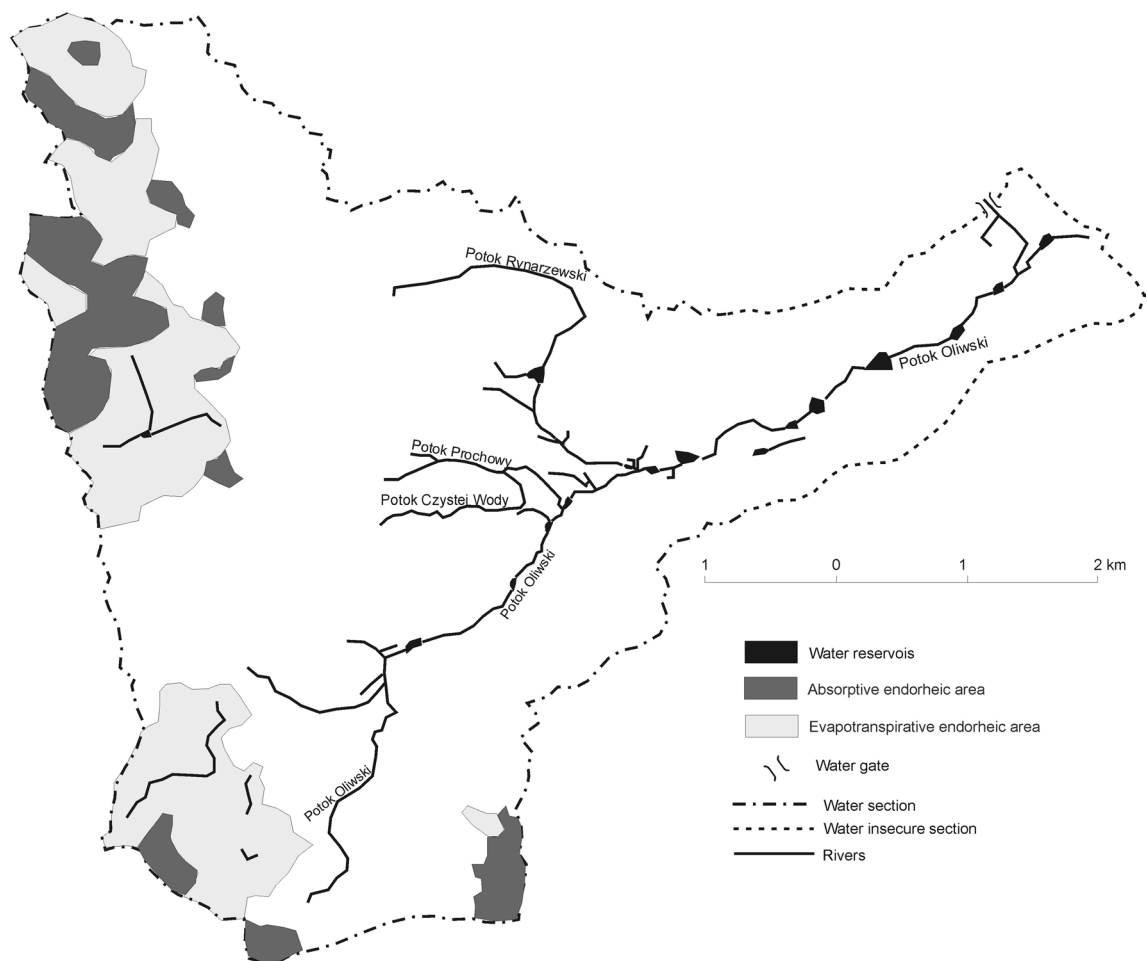
**Fig. 4** Potok Oliwski catchment (Major and Cieśliński 2015)

in rainfall to the level of 600–650 mm can be seen, and in recent years it has exceeded 700 mm. You can also find years with annual rainfall exceeding 900 mm (2017).

Averaged data concerning atmospheric precipitation do not account for maximum or minimum values; they do not allow for determination of other parameters, such as duration or intensity of precipitation either. In many cases, the values of actual precipitation are many times higher or lower than the mean value calculated for a given period. Measurements with averaged values for a few days are presented below to demonstrate how much they differ from each other in various time spans (Fig. 6).

Thanks to a detailed record of actual precipitation distribution, it is possible to determine the quantity of water which appears on the surface of the catchment due to precipitation in any time period and which undergoes further processes of water circulation in nature. Table 1 contains a list of water volumes calculated for chosen days with various precipitation intensities. During torrential precipitation, the volume can exceeds the values of ordinary precipitation by over 26 times.

Evaporation is a process which, in the conditions of temperate climate, lasts continuously, and its value is influenced by numerous factors: temperature, air pressure, vegetation, wind power and direction, land relief, occurrence of marshes, etc. According to Valipour (2017), the most important weather parameters are temperature, relative humidity and wind speed for evapotranspiration models. Since they are very diverse in the catchment area, and there are no detailed data concerning these parameters, for the purposes of model calculations it was assumed that 20% of the precipitation value is the loss for evaporation. The remaining 80% of the precipitation value enters further calculation within the scope of water circulation (Bedient et al. 2007).
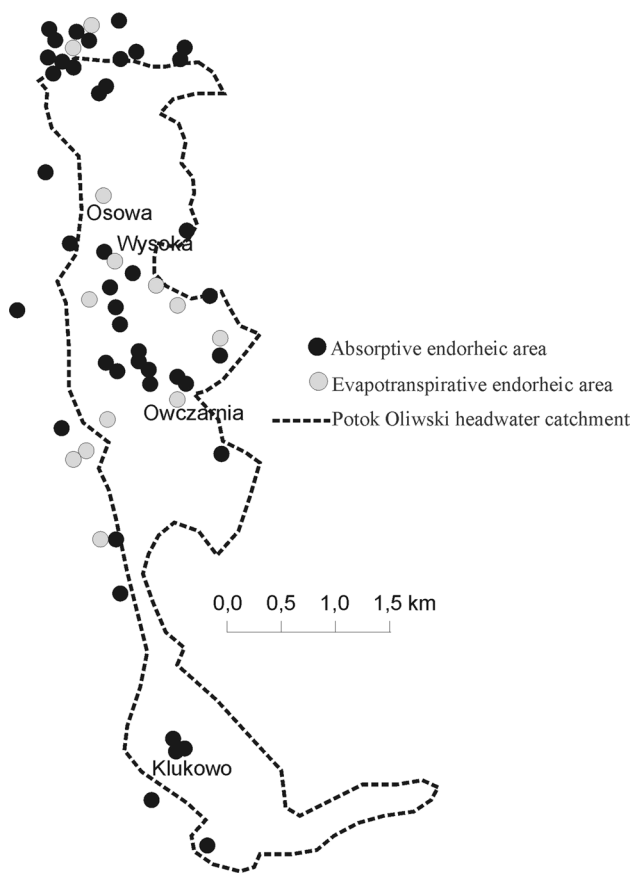
Fig. 5 Endorheic hollows of the plateau part of the Potok Oliwski

Surface retention

The first stage of surface retention is interception. Water losses for interception of mixed forests reach 18–26% of annual precipitation (Bedient et al. 2007), whereas moistening of the surface of arable fields absorbs 0.2–2.0 mm of each precipitation episode. After reaching the ground, water is held in small terrain hollows (depression retention) and in the topsoil. Surface retention includes also water gathered in natural absorptive and evapotranspirative endorheic hollows and water-logged areas.

The obtained model results reveal a clear relationship between values reached by surface retention and precipitation at the same time (Fig. 7). What is also characteristic is an instant reaction to precipitation phenomena and a high similarity of lines representing both elements. In the investigated period, the values of surface retention ranged from 61,720 to 780,000 m^3.

The highest values of surface retention were recorded in 2016 and 2017, when heavy rains were recorded (the highest in the last 70 years). In general, there is a tendency to increase retention and precipitation over the years.

Retentionin in the areation zone

Reaching under the ground surface, water is held in the aeration zone. The thickness of this zone for the whole catchment varies and is determined from the side of the base by the level of ground water table which in the area taken into consideration in the calculations reaches from several tens of metres below the ground level in the plateau to natural outflows on the surface in the edge zone and water-logged areas in the outlet section of the river (Hidalgo and Cruz-Sanjulián 2001).

In the analysis of the balance calculations, the gentle curve representing retention should be noticed as it indicates a slow reaction to precipitation and a lack of rapid fluctuations (Fig. 8). After larger precipitation, a gentle rise in the retention value is noticed, and after it stops, a long-lasting high level indicating a large quantity of water held in the aeration zone. For better readability, Fig. 8 is limited to the 1997–2002 time segment.

Retention in saturation zone

Despite its constant filling with water it also enables retention. The indicator showing the occurrence of underground retention is assumed to be the fluctuations in the underground water table: raising indicates a periodic holding of water, decrease indicates loss (Bedient et al. 2007).

The fluctuations of underground waters in the examined balance period are presented below. What is noteworthy are the vertical movements of underground water table. In the plateau point, the underground water table did not rise above 38.05 m and did not fall below 48.64 m below the ground level. The fluctuation amplitude over the twenty-three balance years was 10.59 m, and the thickness of the zone exceeded thirty metres, which show a great retention potential occurring in the plateau and stability of underground waters. All the changes: increases and decreases occurred very slowly without rapid shifts.

In the edge zone, the amplitude of underground water table fluctuations was 7.55 m, and the values ranged from a minimum of 3.34 m below the ground level to a maximum of 10.89 m below the ground level. The aeration zone in the edge part of the catchment has a much smaller thickness, and thus retention potential, which is on average 2.4 m.

Surface outflow

In natural conditions, surface outflow forms after the forms of surface retention are filled. Its characteristic feature is a quick reaction to precipitation phenomena, which is the more rapid the higher the rain intensity, the lower the ground permeability coefficient, larger slope of the terrain and ground over-desiccation (Bartolini et al. 2011). The rate
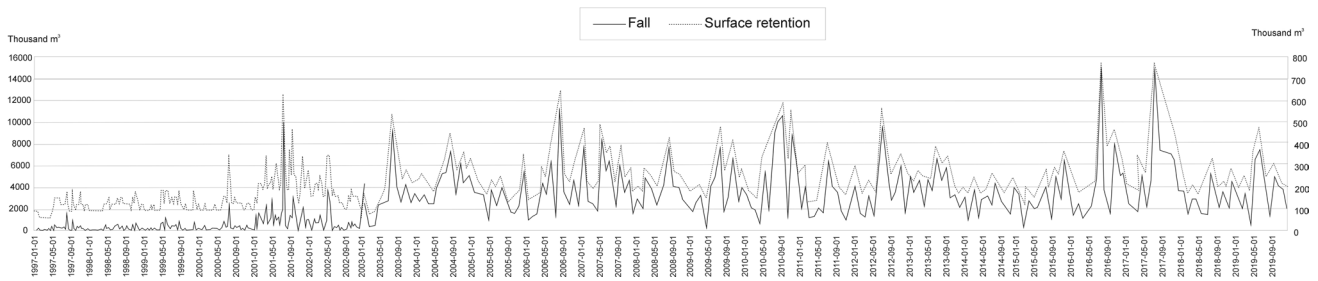
Fig. 6 Falls in day 18.02., 12.03. and 9.07. 2001 year
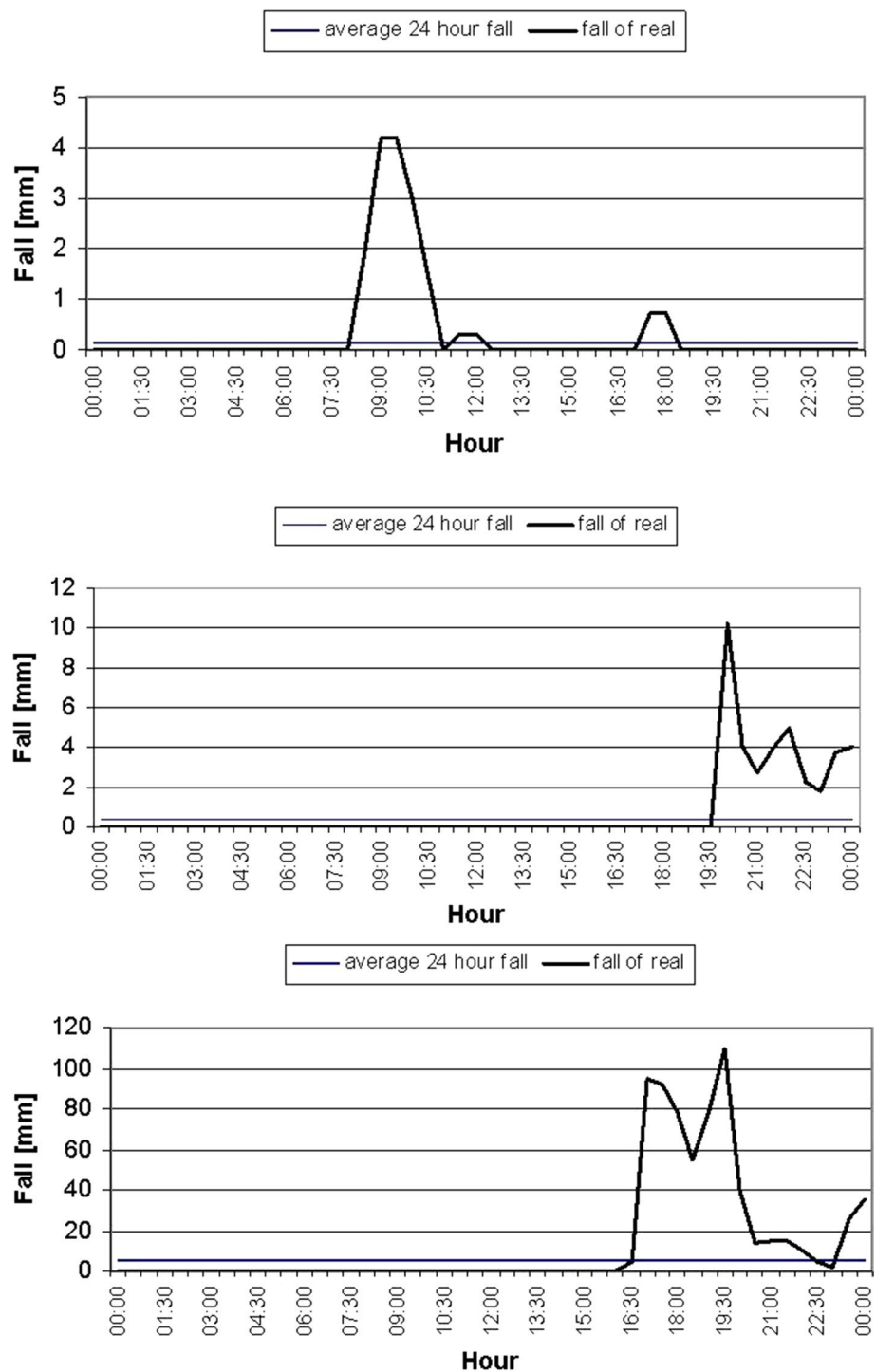
Table 1 Water quantity in plateau part of catchment depending on precipitation intensity

| Precipitation type	Water volume (m³)	Sum of daily precipitation (mm)	Max intensity (mm/h)	Mean daily precipitation (mm)
Usual 18 II 2001	30,450	4.05	4.2	0.17
Intense 12 III 2001	73,950	8.25	10.2	0.34
Tempestuous 9 VII 2001	804,750	143.7	111.0	5.99

Fig. 7 Value of precipitation and surface retention for the Potok Oliwski catchment (Major and Cieśliński 2017, supplemented)

Fig. 8 Retention in aeration zone in the Potok Oliwski catchment
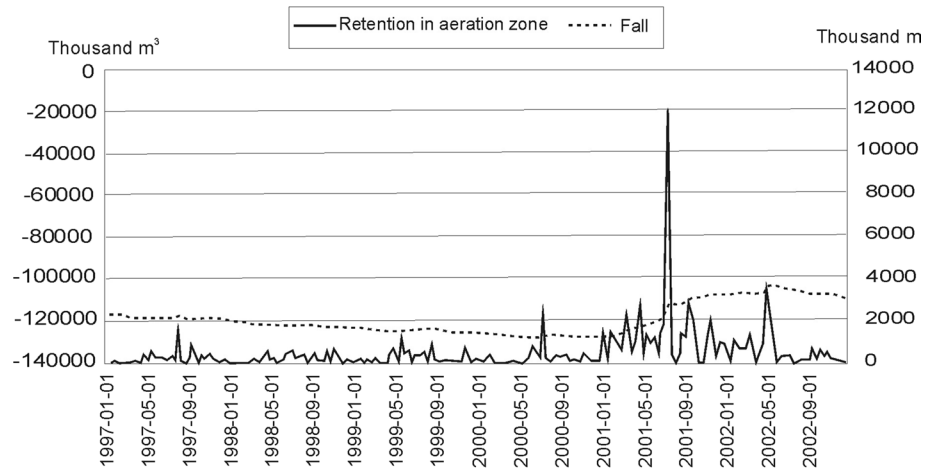
Fig. 9 Surface outflow in Potok Oliwski catchment
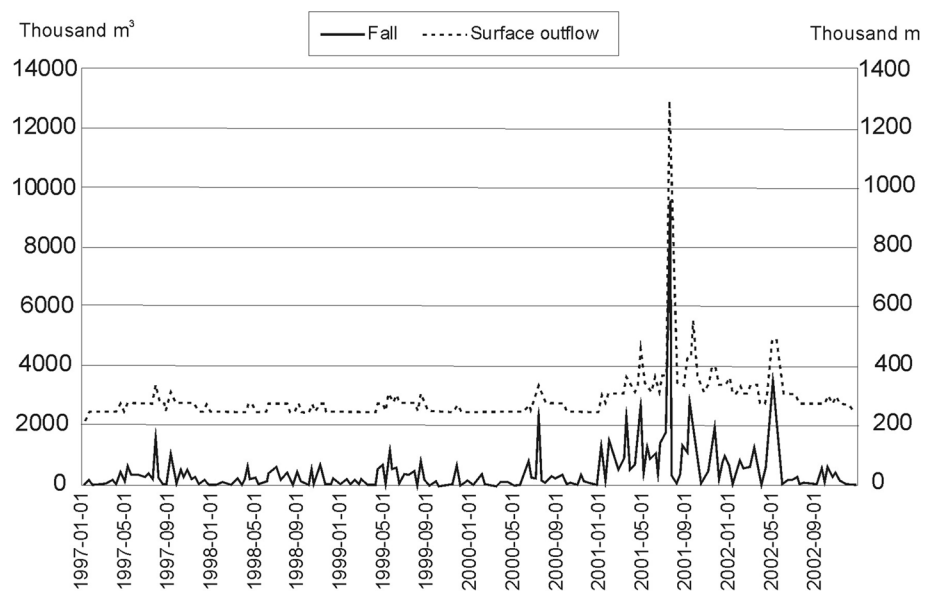
of water movement in this way is many times higher than in the underground outflow. The close relationships between surface outflow and precipitation volume are confirmed by model calculations (Fig. 9). For better readability, Fig. 9 shows only the period 1997–2002. The subsequent period did not differ in the course of rainfall and surface outflow

in time, but only in their size, which increased in the last measurement period.

The shape of the curve showing the outflow volume is almost identical to the shape of the precipitation curve, thus the changes occurred at the same time, without delay between the precipitation and its result in the form of surface

outflow. The increase and decrease in the volume of precipitation resulted in outflow increase and decrease, respectively. The values in the study period ranged from 246 and 1 697 thousand m³.

River outflow

The components of river outflow include surface alimentation, which as being dependent on precipitation and melt waters occurs periodically and episodically, and underground alimentation of a stable character. The proportion of underground waters in alimenting river outflow in the catchment of the Potok Oliwski in the study period on the average was 39.36%, which is a value typical of catchment of a mountainous character of land relief—for Carpathian rivers it is 40–50%. The proportion of surface outflow in the river outflow of the study area is on average 60.64%, however its values reached even 98% in calculations, during torrential rains in July 2001, 2016 and 2017.

With such features of alimentation of surface streams in the catchment, the relationship between the mean daily precipitation intensity and value of discharge in the Potok Oliwski is clearly noticeable both in a multi-year as well as short-term perspective.

During the whole balance period, the increase in precipitation caused a fast increase in discharge value, yet a small (up to 24 h) time shift between these phenomena is observed. The maximum values of discharges in the Potok Oliwski reach 7.151 m³·s⁻¹ and occurred two days after the highest precipitation (Fig. 10).

Components of water balance in conditions of anthropogenic development

The basic change, introduced to calculations with regard to anthropogenic development, is the determination of the size and localisation of building development. The analysis of the spatial development of the total catchment reveals that the building development covers 8.7 km², which constitutes 28.56% of the whole area (Fig. 11). Thus, local parameters of surface outflow from these areas and areas of potential infiltration changed. It was assumed that the coefficient of surface outflow is on average 0.6, as it ranges from 0.9 for compact building development to 0.3 for villa-type housing. Thus, the quantity of precipitation water which falls on the built-up area is discharged into storm drainage system in 60%, and the remaining 40% infiltrates taking part in further circulation.

Surface retention

After introducing building development, together with its canalised outflow of a part of precipitation water, into model calculations, it was observed that the retention potential
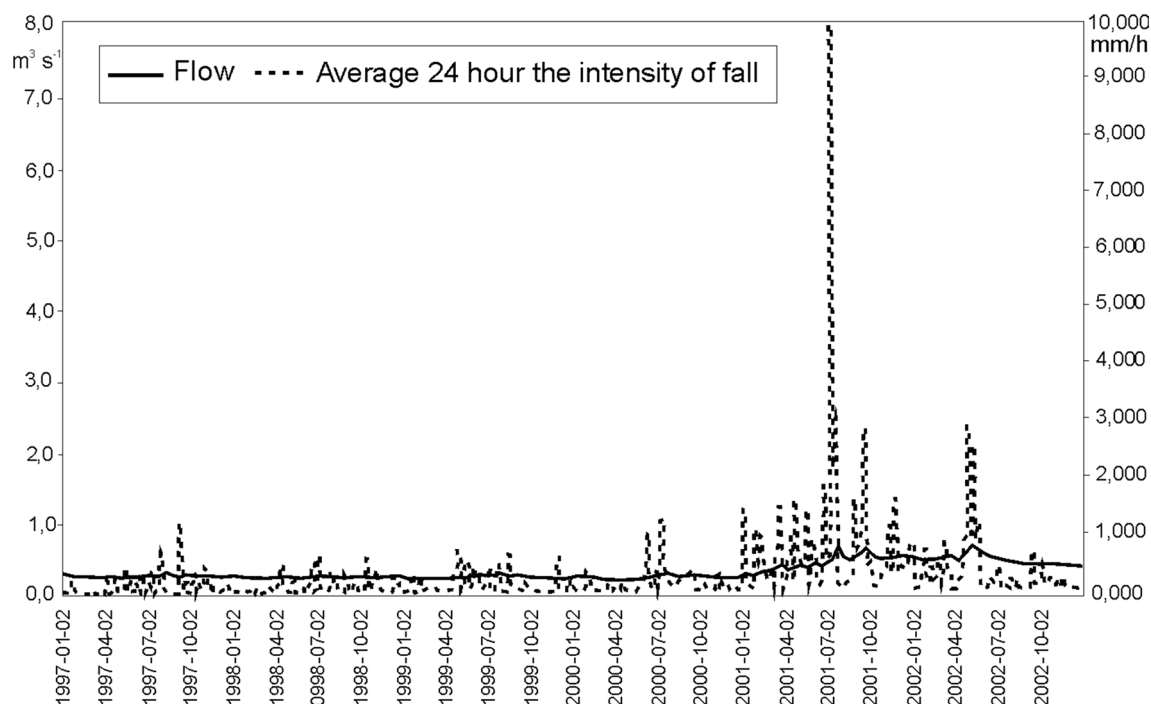
Fig. 10 Relationship between mean daily precipitation intensity and volume of discharges in the outlet section of the Potok Oliwski in balance period
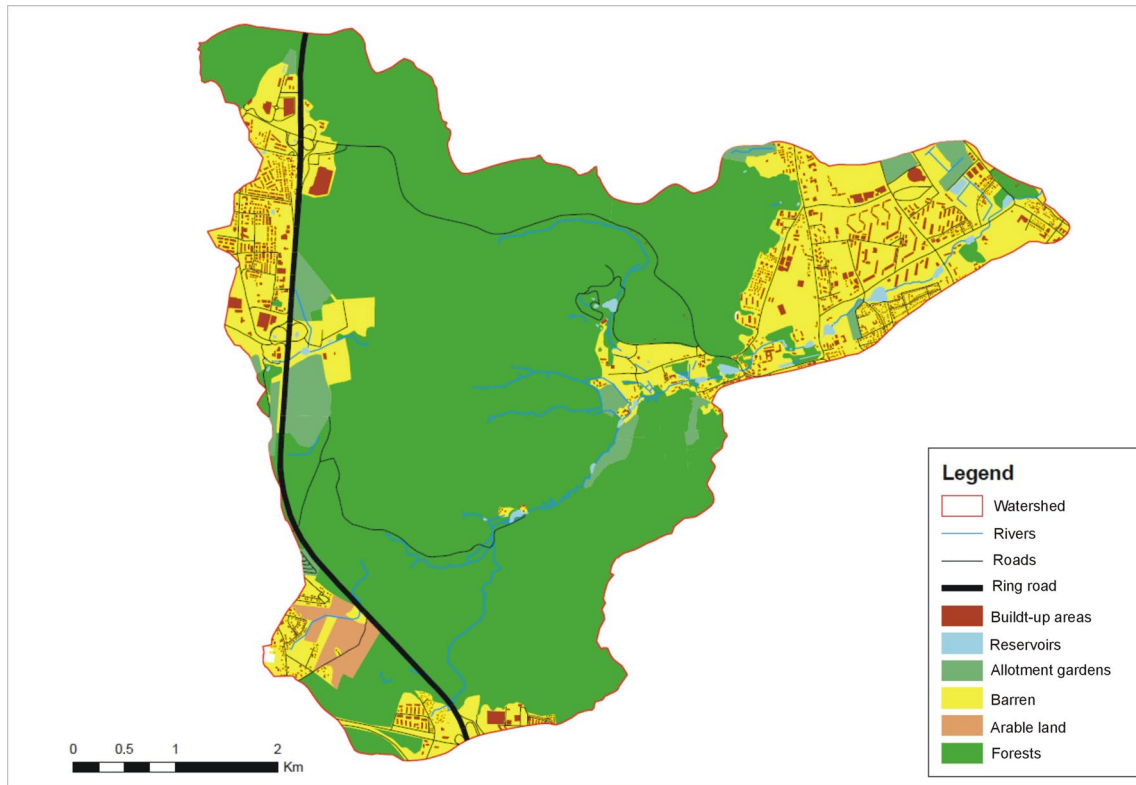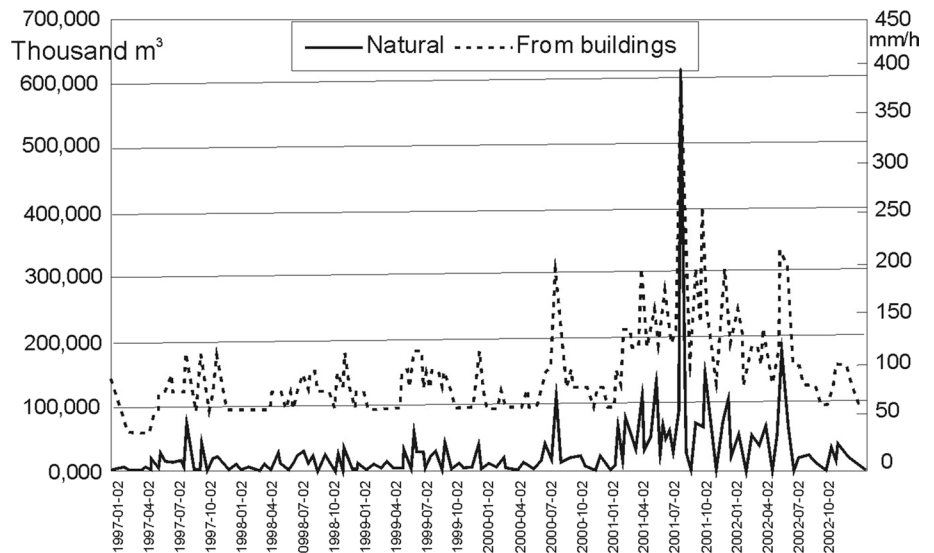
Fig. 11 Structure of land use in the Potok Oliwski catchment in 2018

Fig. 12 Surface retention in natural conditions and with building development in catchment of the Potok Oliwski

diminished or periodically equalled natural conditions in response to the changed surface features, but never exceeded them (Fig. 12). For the sake of clarity, it has been decided to present only a fragment of the measurement period (1997–2002) in Fig. 12.

The close relationship between an increase in precipitation and in retention volume on the surface of the area still occurred. Its mean value for the whole balance period decreased with respect to the natural one by 7.4% and did not correspond to the percentage proportion of built-up area in the catchment. Thus it can be assumed that the capacities of water retention in the surface part of the catchment were not changed significantly.

Retention in aeration zone

This type of retention has undergone a gradual change. As time passed the introduced building development had a growing impact on the retention in this zone (Fig. 13). A lowering of the line representing the retention value after building development in comparison with natural conditions can be observed. This means that the retention potential in this zone increased with its thickness, whose lower limit is determined by the ground water table.

Retention in saturation zone

Changes in the ground water level in the conditions of building development became noticeable in the plateau and edge zones of the catchment with a clear gradual and persistent lowering. In the plateau during the balance period, the ground water table decreased in comparison with natural conditions, and the difference between them grew in time. The lowest occurrence of ground waters was at a depth of 50.64 m below the ground level and the highest at 42.43 m, hence the amplitude was up to 8.21 m.

In the edge zone, the water table dropped as well, and the difference between the curves was maximally 0.37 m. The highest occurrence of ground waters was at a depth of 4.07 m, i.e. 0.32 m deeper than in natural conditions, while the lowest at 10.76 m. The amplitude of fluctuations was 5.69 m, i.e. over 1 m less than in natural conditions, which indicates a decrease in retention volume in the saturation zone.

Surface outflow

The change in the manner of the use of the area, by the introduction to calculations of building development of 60% proportion of surface outflow, brought about significant results in this element in the whole balance period. Its values diminished in comparison with the natural conditions or had the same value. The difference between them ranged from 0 to 45.6% of the value of natural outflow, and the highest disproportions occurred in periods of intense precipitation, and outside them the decrease in surface outflow was most frequently 13%.

River outflow

Alimentation in the conditions of building development was, in the whole balance period, lower than alimentation in natural conditions. The biggest differences occurred in periods of higher precipitation quantity, which is reflected by the growing distance between the curves. The percentage proportion of the underground alimentation did not change, and was still 38% on average, which leaves the remaining 62% to surface alimentation. Probable reasons for this phenomenon could be seen in the successively lowering underground water table both in the plateau and in the edge zone, which is a place of underground water drainage. Their lowering could have caused a decrease in the efficiency of springs or their periodic disappearance, and thus a decrease in the contribution in the alimentation of streams.

The preformed calculations revealed that the discharges in the Potok Oliwski, like in the case of natural conditions, responded with an increase to increased atmospheric precipitation and with a decrease after it ceased. However, the

Fig. 13 Retention in aeration zone in natural conditions and with building development
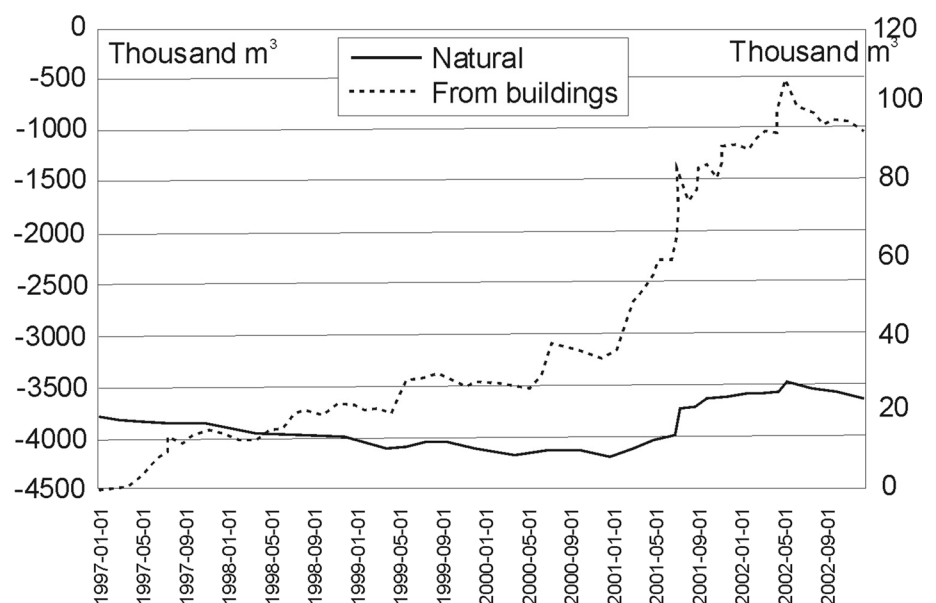
volume of the discharges, after a part of precipitation water was discharged to surface waters, changed substantially. The minimum value in both cases is the same: 0.1 m³ s⁻¹, while the maximum from 7.15 0.1 m³ s⁻¹ for natural conditions rose to as much as 27.61 0.1 m³ s⁻¹ (383%). Mean values from 0.3 to 0.39 0.1 m³ s⁻¹ (130%), respectively. One of the causes of the many times increased discharges is the storm drainage system, which in accordance with boundary conditions, discharges precipitation waters from built-up areas.

Retention of precipitation waters by natural endorheic hollows

Depending on the rain intensity (Table 2), different quantities of water can occur on the plateau area (7.25 km²) during one hour. Some of the water from built-up areas gets into the storm drainage system according to the following proportions.

The alternative way of using thus estimated precipitation was based on the permeability potential of surface formations, and consequently on water infiltration, using three

Table 2 Quantity of precipitation water discharged into storm drainage system depending on precipitation intensity

Ordinary rain 18.02.2001	Heavy rain 12.03.2001	Torrential rain 9.07.2001
Water quantity in built-up area		
6090 m³	14,790 m³	160,950 m³
Water quantity discharged into storm drainage system		
3654 m³	8874 m³	96,570 ³

retention stages: from surface to underground. Taking into consideration absorptive hollows, which would receive precipitation waters, a good or medium character of permeability of the formations which make them was assumed. After checking the voluminal intensity of filtration discharge and thus water infiltration capacity in hollows, using the formula by Darcy, the necessary area of hollows which would infiltrate rain of various intensities was established. It ranges from 1015 m² for ordinary rain to 26,825 m² for torrential rain. It should be highlighted that the indicated range of areas of hollows is adapted to the current size of building development of the plateau part of the catchment and can be adjusted to the needs with respect to both precipitation intensity and size of built-up area which it is to concern by using e.g. several smaller hollows clustered together or by a small deepening (0.5 m) of one larger hollow.

The selected, as an example, hollows of areas: 12,300 m², 4900 m², 4500 m², constituting recipients for the whole built-up part of the catchment meet the above requirements in terms of the size of infiltration surface (Fig. 14). Only in the case of a one-hour torrential rain would it be necessary to deepen one of them or divide this volume of precipitation water into an additional hollow.

In order to verify the effectiveness of retention in the hollows in the course of 24-h infiltration, three hollows with a total area of 21700 m² and volume of 7230 m³ were selected. For an ordinary rain, the water quantity which gathered in the hollows during this period as a result of precipitation underwent infiltration without delay (Fig. 15). The infiltration value equalled precipitation value. The infiltration value reached on that day was 1865.81 m³/30 min, which constituted only 4.8% of the potential value. It was similar in the case of a heavy rain (12.03.2001) where infiltration values

Fig. 14 Infiltration compared with precipitation on 18.02.2001(Major and Cieśliński 2015)
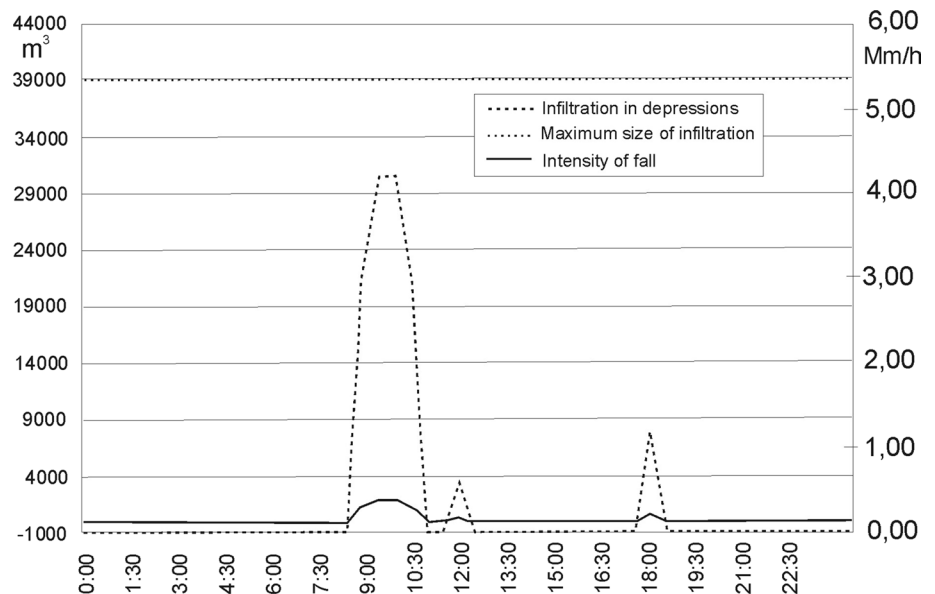
**Fig. 15** Infiltration compared with precipitation on 12.03.2001 (Major and Cieśliński 2015)
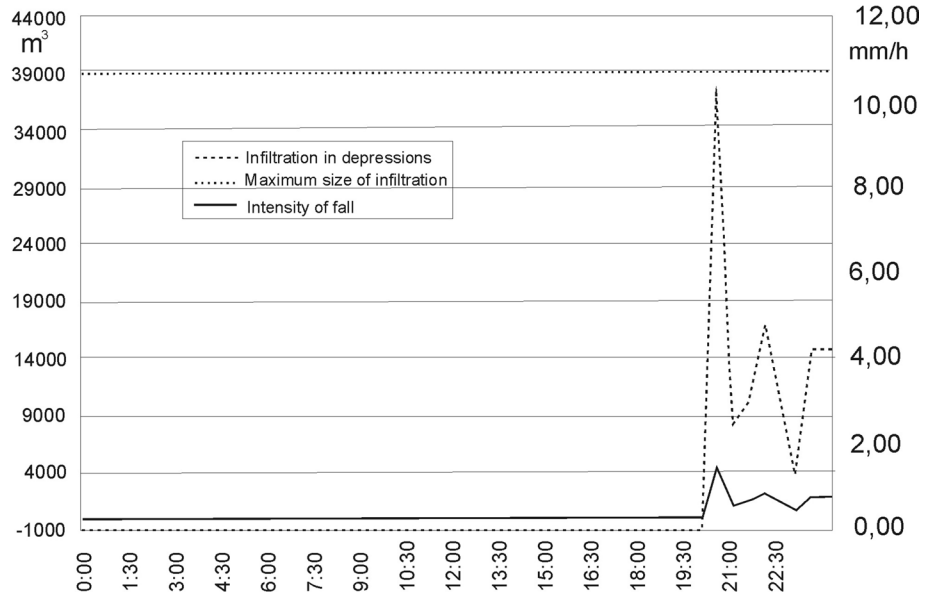
corresponded to the quantity of water gathered in the hollows and did not even come close to the maximum value. They reached a value of 4531.25 m^3, which is 11.6% of the potential (Fig. 16).

The last day selected for analysis was 9.07.2001 with an especially high precipitation intensity, which resulted in flooding in the area of Gdansk. The analysis of infiltration value and volume of water gathered in the hollows showed that on this day the maximum infiltration value was reached three times and lasted for 1.5 h, and in the remaining period it was lower. The water quantity which did not

manage to infiltrate for the study area was 3587.04 m^3 at 5 p.m., 5574.82 m^3 at 5:30 p.m. and 10,250.64 m^3 at 7 p.m.. However, already half an hour after the occurrence of this excess, it was completely infiltrated.

Taking into consideration the parameters of selected hollows and precipitation conditions characteristic of the study area, the above calculations reveal that the infiltration conditions are sufficient to receive precipitation from built-up areas, which would enable preventing intrusion in the system of surface streams in the form of discharges from the storm drainage system.

Fig. 16 Infiltration compared with precipitation on 9.07.2001 (Major and Cieśliński 2015)

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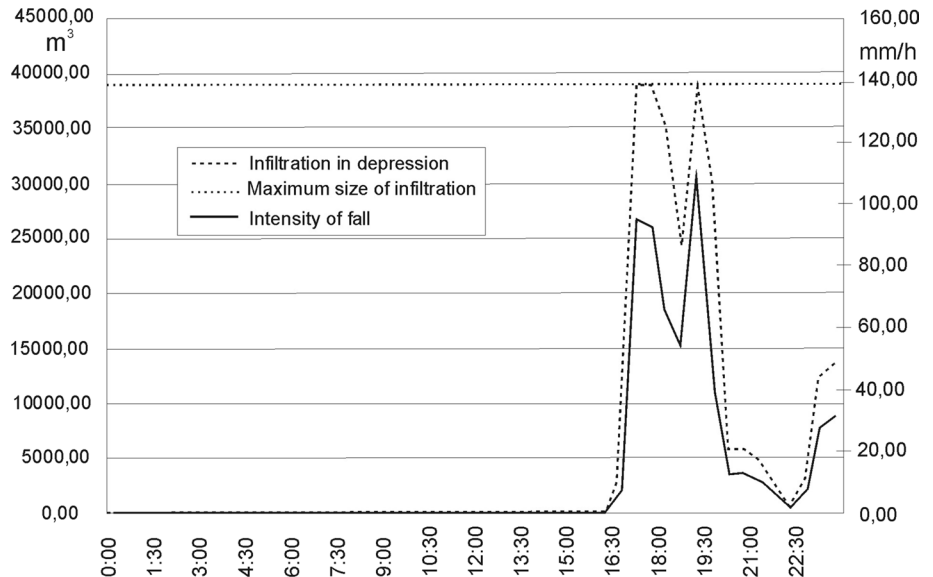
Discussion

One of the common facilities of the hydrographic network landscape lake districts are small reservoirs, so-called. ponds or kettles, whose number is very large and estimated for the Polish for a few hundred thousand. They are extremely important objects in geographical space, as a result of their ability reservoirs, hydrological numerous functions and primarily biological values (Oertli et al. 2005). Ponds because of its morphometry, the specific ecological conditions (Davis et al. 2008; Oertli et al. 2009) and often no connection with rivers (Gerke et al. 2010) are highly susceptible to external influences. Location in a specific type of basin entails a number of consequences of their functioning. Till recently the opinion that, with its catchment areas, they form outflow, which are not included in the main hydrographic system. Recent studies show that periodically they can transform into objects drainage, which carries the consequences of changes in the water cycle and water resources in the basin. This applies in particular periods of flooding (Solin 2008). That is particularly important because according to the classification Dettinger (2013) analysed river is a atmospheric river. Atmospheric rivers have, in recent years, been recognised as the cause of the large majority of major floods. Ponds are nowadays a significant impact on the nature of the circulation of water in the basin, because they are a natural form of retention of rainwater. According to Tiner (2003), they form isolated areas in the geographical space. At the same time due to natural or anthropogenic changes may, in conjunction with other hydrographic facilities situated in their neighbourhood to create a whole hydrographic systems.

Hydrological changes ponds should be related to the replacement of the vertical, that is, atmospheric precipitation and evaporation and replacement of horizontal, i.e. inflow and outflow of ground water. particularly difficult to assess the evapotranspiration, because it is linked a critical water, energy and climate variable (Badgley et al. 2015). In certain periods of the year following the supply surface, which results from changes in water level in the basin. Ponds are different power supply, but the fact is that only two sources of feeding outweigh i.e. precipitation and inflow of groundwater. According Lisched and Kalettka (2012), who studied the pond in northern Germany, these conditions account for 90% of the variance.

The presence of the ponds is connected with the replacement of the vertical, in particular the power atmospheric evaporation (Lehsten et al. 2011) so that the amount of water in the pond depends on the flow of air exchange with the water, although the correlation between indices of climate change and the change of the water level have a delayed reaction on one year. These effects correspond to an increased evaporation in summer and increase in winter precipitation. However, many hydrologists states that the ponds are also in contact with groundwater (Chernet et al. 2001). As a result, the circulation of water in the pond is more complicated than would be expected. Since the ponds have often surface contact with the entire hydrographic system their hydrological conditions depend on the exchange of a vertical, and preferably from precipitation (Sobel et al. 2003). On the other hand, Lischeid and Kalettka (2012) indicate that a retention time of water in the pond and the road exchange determine the stability of the hydrological ponds. An important aspect is to determine the effect of the amount and intensity of precipitation on changes in hydrological conditions. In the case of torrential rains, closed basins are very often incapable of retaining the whole of the rainwater, therefore the water 'escapes' from a depression, in this postglacial area largely via underground flow (Chernet et al. 2001; Lowenstein et al. 2003), partially to return later with overland flow. Confirmation of this statement is Kalettka and Rudat (2006) research, who showed that some of the moraine ponds in the north-eastern part of Germany tend to overflow during high water levels. Importantly, this phenomenon is not only the nature of the local. Downing (2010) and Liu et al. (2016) demonstrated for the small bodies of water play an important role in the water cycle, not only in the region but also on a global scale.

In summer, the rapid evaporation from the free surface of the water can lead to a reduction in the amount of water. According to Young and Abnizova (2011) extremely important for ponds is a positive water balance and various hydrological linkages. Power and water loss in the ponds is mainly determined by morphometry, the structure of land use, soil conditions in the basin and seasonal climatic and hydrological conditions. The more power sources of ponds, the greater the degree of ponds stability. In the case of the domination of power by underground or precipitation is observed limited hydrological life of ponds.

Blind drainage is elements of the hydrographic network highly significant for human management. They perform many functions, the most important being hydrological, ecological, geomorphological and economic ones (Sun et al. 2010). They are chiefly potential natural retention reservoirs (a hydrological function) that can be used to offset the increasingly frequent deficits of water resources. In effect, they can receive substantial quantities of precipitation that are otherwise irretrievably lost, especially during torrential rain events.

Calculations made in the work indicate that filtration conditions for the basins are sufficient to they serve as receptacles for rainwater from built-up areas. Consequently, it reduces the risk of flooding during heavy rains, that threaten

the built-up areas in the zone of the abrasion platform. It also gives you the opportunity to obtain reserve water resources that can be used for various purposes. However, a constant and unsolved problem remains are removing large areas of forests (Mincey et al. 2013) or construction urban infrastructure (Kaushal and Belt 2012).

Conclusions

In order to have a detailed knowledge of the retention conditions in the headwater part of the catchment of the Potok Oliwski, it would be necessary to perform numerous systematic and long-lasting investigations of a broad scope of subjects. As they have not been done yet, for the purposes of the goal undertaken in this paper, it was decided to use a modern tool, i.e. the Mike She program for mathematical modelling, thanks to which it is possible to reproduce, almost life-size, all the processes of water circulation in various conditions of natural environment and for any time period. The use of the program in this paper is just a modest example of the possibilities offered by it for analysing various issues, forecasting and predicting phenomena with a high significance to the catchment, where negative effects of the human impact are accompanied by the necessity for rational management of precipitation waters. The usability and a wide application of the program is reflected in the fact that it is successfully used in numerous projects in Greece, USA, Slovenia, Bangladesh or Botswana.

The performed calculations revealed that the study area, thanks to factors shaped by nature, possesses a high retention potential, mainly with regard to the aeration and saturation zones. The conditions of surface retention, to which endorheic hollows greatly contribute, have been investigated as well.

The introduction to calculations of the anthropogenic factor reduced the use of retention in the headwater part of the catchment with an increase in outflow of surface waters caused by the discharge of waters of surface runoff from built-up areas. An important phenomenon is the lowering of the ground water table in the area of the plateau and the edge zone, changing the structure of streams' alimentation, in which the proportion of the surface component has risen. In some cases this can result in a change of character of some streams from permanent to intermittent or episodic, due to the loss of hydraulic contact of surface and underground waters in the headwater areas found in the drainage zone. Another alarming phenomenon observed thanks to the calculations, was an increase in the volume of discharge in streams. The increased proportion of surface alimentation resulted from the discharge of precipitation waters into streams from the built-up areas of the plateau. In the light of the awareness of the currently advancing process of building

development and covering of the catchment surface with impermeable materials with a high outflow coefficient, it can be expected that the discharge values will increase too, unless the manner of water discharge from these areas is changed. The highest values of this phenomenon were observed for the conditions of the torrential rains, which in July 2001, 2016 and 2017 was one of the causes of the flood in Gdańsk. It seems that in the case of further development of the Potok Oliwski catchment area, its retention capacity will decrease.

Compliance with ethical standards

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