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INFLUENCE OF CHANGES IN LAND USE ON THE VALUES OF MAXIMAL PEAK FLOWS ON EXAMPLE OF WINNA GÓRA IN THE NEIGHBOURHOOD OF MŚCIWOJÓW RESERVOIR

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Summary

In the paper the evaluation of influence of changes in water catchment area land use on the size of peak outflow was conducted. The investigations were conducted in Winna Góra catchment area located in Mściwojów, Lower Silesian voivodeship. The catchment area is 11.78 hectares. At present, the catchment is used as arable land, forest and meadows. In the future the area of sealed surfaces such as: roofs, roads and car parks will increase. This can contribute to the change of water balance components. Analyses has shown, that changes in the use of a catchment area lead to reduction of surface flow time from the catchment (less resistance to motion) – in effect it causes increase of the outflow volume at about 28%. The increase of the water outflow volume may have significant influence on the Winna Góra development. To counteract the results of adverse changes caused by the catchment sealing – it is recommended for the investigated area to apply a balanced approach. This would consist of retaining precipitation water in its place of origin.

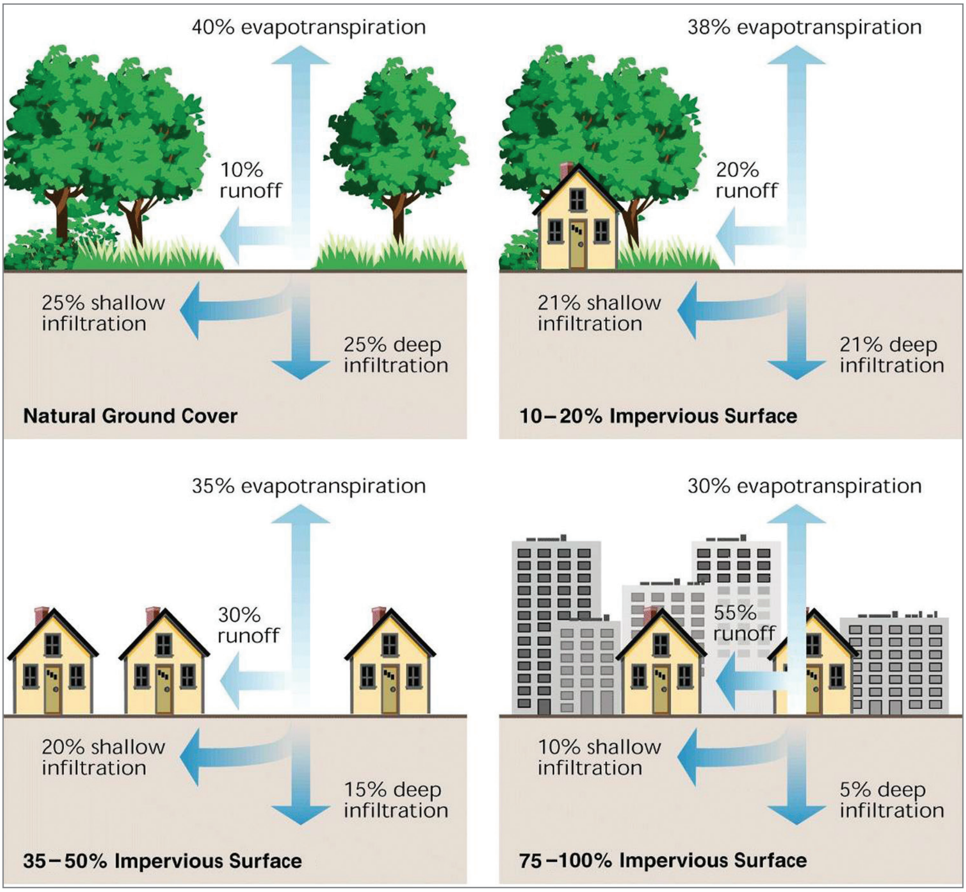
Keywords

catchment sealing • concentration time • rational method • balanced catchment development

1. Introduction

Floods are natural and seasonal phenomena, which play an important role in the environment. The problem occurs when flooding appears on man heavily invested areas, which results in the growing risk of substantial loss of life and property.

The growing degree of urbanisation leads to the increase of the number of impermeable surfaces in the catchment basin. Consequently often occurring tempestuous rain falls in spring are the main cause of rising violent surface water flows. This results in local flooding of the lowest located areas. It is estimated that in undisturbed grounds nonsealed and covered by natural plants surfaces the outflow amounts approximately to 10% of the rain fall. The rest is subject to evapotranspiration (40%)



Source: Wałęga et al. 2013, modified after: Zevenbergen et al. 2011

Fig. 1. Changes of water circulation components as a result of catchment urbanisation

As a direct result of the process of urbanization, adverse effects in hydrological processes in the catchment take place. They manifest themselves in the increased incidence of extreme hydrological events (floods and streamflow droughts). For example, the research associated with the occurrence of a flood risk on the Kielce agglomeration area revealed, that in the highly urbanized Silnica catchment (as a result of flows which occur on average once every 100 years), the flood area will be nearly 150 hectares and will cover heavily invested areas [Ślizewski et al. 2012]. The correct estimation of the parameters which characterize the degree of risk of the occurrence of floods, as a result of catchment land use changes, is very important. Knowledge of the magnitude of the risk will allow actions to be taken, which will mitigate the adverse effects in the spatial management of the catchment. For example, in the aforementioned catchment area of the Silnica river, the reduction of the maximum flow on the outlets of the rainwater drainage due to water retention enlargement, will cause a decrease in the average depth of the flooding from a few to several cm and a reduction of the maximum depth of flooding from 30 cm to 70 cm. Smaller depths and the lessen extent of flooding will have the impact on reducing the negative consequences and reduction of overall losses caused by flooding [Woźniak--Vecchie et al. 2012].

The aim of the work is to determine the influence of changes in use of Winna Góra on the maximum amount of water runoff as a result of torrential rainfall. The paper presents the results of the work carried out under the project: "Valorisation and Sustainable Development of Cultural Landscapes using Innovative Participation and Visualisation Techniques", implemented within the Central Europe Programe.

2. Characteristics of the Winna Góra development

Area of Winna Góra is situated in the vicinity of Mściwojów village, Lower-Silesian Voivodship and neighbours directly with the Mściwojów reservoir [Brożek et al. 2013]. Its area is 11.87 hectares. In Table 1 fundamental morphometric characteristics of investigated area are presented.

Table 1. Morphometric characteristics of Winna Góra area

Parameter	Value
Area [ha]	11.78
Maximum height H_{max} [m a.s.l.]	209.20
Minimum height H_{min} [m a.s.l.]	193.70
Length of the drop line from the top of the mountain to the reservoir L [m]	165.0
Average slope $J_{śr}$ [%]	9.40

Analysis of the present status of development of the Winna Góra area was performed based on information included in The Topographic Objects Base (TBD), in scale 1 : 10 000 and in topographic maps in scale 1 : 10 000. In the investigated area at present, there are grasslands, arable land and forest. Grassland do not have a large value from an economic point of view. The composition of the existing vegetation is: fescue, common quaking grass, herbs and weeds: wild thyme, spurges. Because of the very deep level of the ground waters table, vegetation of plants in this zone have adapted first of all by the amount of precipitation and the conditions of their infiltration to the subsoil. Planned development of Winna Góra from the side of Mściwojów reservoir takes the following form:

- number of new designed buildings – 2,
- real area of roofs of designed buildings – 2783 m^2,

- area of designed car park – 840 m^2,
- area of designed playground and tennis courts – 1157 m^2,
- length of roadway (bitumen roads) – 941 m,
- area of roadway (bitumen roads) – 5175 m^2,
- length of planned pathways – 1230 m,
- area of planned pathways – 3690 m^2,
- area of planned vineyard – 22966 m^2.

The remaining area constitute grasslands. Below Figure 2 presents the visualisation of the planned development of Winna Góra.

Source: Visualisation made by Bartosz Mitka and Paweł Szelest

Fig. 2. Visualisation of concept of Winna Góra in Msciwojów development

3. Methodology of calculations

In view of the planned investments in the changing of Winna Góra land use, the question arises – how will the planned revision of the housing stock, particularly an increase sealing of the part of the catchment, will influence the formation of the outflow? To answer this question, it is necessary to assess the size of the outflow, in terms of current and planned future land use. Due to the complex circulation of water in the catchment, with a high degree of sealing, the answer is burdened with a high degree of difficulty and the results can be regarded as estimates. In order to determine the influence of buildings on the size of the outflow from Winna Góra, two-step hydrological calculations were conducted. In the first stage the size of the outflow in terms of current land use was estimated, in the second stage – in terms of the planned land use. In both stages, the same input data concerning rainfalls were adopted. Due to the small size of the catchment (equal 11.78 hectares), the size of the outflow was calculated using the method of flow time, also known in the literature as the rational method. The size of the outflow according to the rational method in $m^3 \cdot s^{-1}$, is calculated from the formula listed [Maidment 1993]:

$$Q = 0.278 \cdot q_m \cdot C \cdot A \quad (1)$$

where: q_m – meaningful rainfall intensity [$mm \cdot h^{-1}$], C – dimensionless outflow coefficient, A – catchment area [km^2].

It is a formula based on the so called block precipitation of rain, with a constant intensity for a given duration of time and frequency of appearance. In view of the considerable simplification used in this method, it is assumed that the rational formula may be used to calculate the flow of the peak flow in a small urbanized and rural catchments, representing an area of 2.5 km^2. In practice, for the calculation of runoff from the catchment, the rainfall of a certain probability of occurrence is taken. In the formula, flow coefficient C is allowed to include in the calculation: precipitation loss on interception, infiltration, surface retention, evapotranspiration and terrain evaporation and rising wave flattening. Its values are dependent of the catchment management, its slope and rainfall intensity. In practice, the runoff coefficient values are determined according to the land use [Ponce 1989].

Due to the different land cover for a proposed building the weighted average runoff coefficient formula was determined:

$$C_Z = \frac{C_1A_1 + C_2A_2 + \ldots + C_iA_i}{A_1 + A_2 + \ldots + A_i} \quad (2)$$

where: C_i – weighted average runoff coefficient for the i-th partial surface [–],
A_i – the value of the i-th partial catchment area [km^2].

The intensity of meaningful rain is the second parameter next to runoff coefficient, which significantly affects the size of the outflow. Precipitation characteristics, which have to be established before carrying out actual calculations, is the duration time (t) and the probability of the occurrence (p). In the case of a small catchments, it can be assumed that the precipitation is evenly distributed and that it has a constant intensity over the whole catchment area. Thus maximum outflow in the tested cross-section will occur in the situation, when the whole catchment will take part in the formation of runoff [Shaw et al. 2011]. Critical duration of rain, where there occurs the maximum outflow is named the time of concentration. In the absence of a clear draining stream in the analyzed area, there is only the surface runoff to estimate the characteristics, so the method based on solving the kinematic wave equation was used in the following form [USDA 1986]:

$$t_{c1} = 6, \frac{92}{I^{0}}, 4 \cdot \left(\frac{n \cdot L}{\sqrt{S}}\right)^{0}, 6 \qquad (3)$$

where: n – Manning roughness coefficient depending on the kind of the surface [–] – see Table 2, L – the flow path length [m], I – intensity of rain [$mm \cdot h^{-1}$], S – slope of the flow path [$m \cdot m^{-1}$].

Table 2. Values of land roughness factor n [USDA1986]

Description of surface	n
Concrete, asphalt, flat land with no vegetation	0.011
Gravel, terrain with varying topography	0.02
Cultivated land	
vegetation ground cover < 20%	0.06
vegetation ground cover > 20%	0.17
crops (mature crops)	0.3
fallow	0.5
Grass	
short and sparse vegetation	0.15
dense turf	0.24
very dense grass, tall, flat surface	0.41
pastures	0.20
Forests	
poor brushwood	0.40
dense brushwood	0.80

In view of the fact that occurring in the formula above rainfall intensity "I" depends on its duration, time of the surface flow must be calculated using iterative methods. In the first stage of the calculation, the concentration time is assumed and then the intensity of rain is calculated for the taken time period and probability of occurrence. Knowing "I" we calculate t_{c1}. Calculations are run until the moment when assumed time of concentration is similar to that obtained from the formula above. The calculation of the intensity of the rain were performed for the duration "t" equal to concentration time (for current and prospective development) and for probabilities of precipitation equal p = 1, 5, 10, 20 i 50%. The amount of precipitation for a specified time period and probability and next its intensity "I", in $[mm \cdot h^{-1}]$, were calculated from the formula of Bogdanowicz-Stachy [Bogdanowicz and Stachy 1998]:

$$P_{max(t,\, p)} = 1.42 \cdot t^{0.32} + \alpha(-\ln p)^{0.548}$$

where: t – the duration of the rain [min], p – probability, α – the location and scale parameter [mm].

Parameter "α" is determined on the basis of the location of the object in question and the precipitation duration time "t". Taking into account location of the analyzed catchment, parameter "α" has been set for the South region.

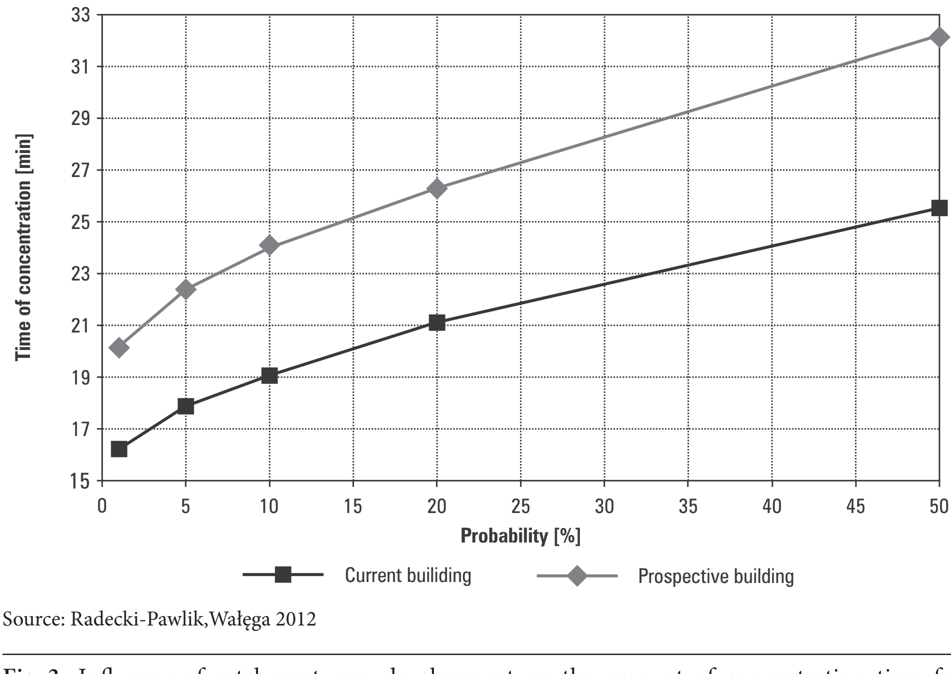
4. The results of the investigations

The basic parameter occurring in the rational formula is the intensity of rain. Its' calculated values are summarized in Table 3. It depends on the probability and duration of rain. "C", the duration of the rain, has been established based on the time of concentration. This characterizes the duration of water runoff from the farthest point of the catchment to the runoff cross-section. One of the reasons for the decision on the kinematic wave method adoption, is to determine the time of concentration and a willingness to take into account the type of flow surface and precipitation kind. Calculations of the time of concentration made for the runoff surface slope $s = 0.094\ m \cdot m^{-1}$, length of runoff path L = 165 m, roughness coefficient of the runoff surface equal n = 0.24 (the current land management – wasteland, grasslands) and n = 0.18 (for the prospective development – roof surfaces, roads, car parks, vineyards). The increase in the degree of the catchment sealing will result in a faster runoff (shorter times of concentration), which will lead to an increase in the intensity of rain for the same probabilities (see Table 3 and Figure 4). As a result, runoff larger values will be observed.

Table 3. Rainfall intensity of duration "t" equal to concentration time for different probabilities

Probability	Rainfall intensity $[mm \cdot h^{-1}]$	
	Current building	Prospective building
1	101.8	113.14
5	77.7	88.7
10	64.85	75.74
20	52.2	58.41
50	31.61	36.44

As a result of increased catchment sealing times of concentration became shortened from 4 minutes for the rain with p = 1% to 7 minutes for the rain with p = 50%. In case of rains with a very heavy intensity (in case of low probabilities), within a short period of time falls on a catchment a large amount of water what leads to the situation in which the catchment's ability of retension is rapidly lost, regardless of its use. This explains the situation, that by the precipitation of a higher intensity, the change of the time of concentration as a result of differences in the use of catchment is smaller, than by less intense rainfall. Time of concentration increases with increasing probability of rain. This is because with a higher probabilities, rainfall intensity is lower and therefore less water reaches the given surface, hence the rate of outflow will be smaller. Thus, precipitation characteristics play an important role in calculating the time of concentration. The conclusion is that hydraulic methods for calculating the time of concentration produce more accurate results than the empirical methods (for example, methods of Kirpich or Kerba), as they take into account the whole complexity of the runoff process [Weinerowska-Borys 2010].



Source: Radecki-Pawlik,Wałęga 2012

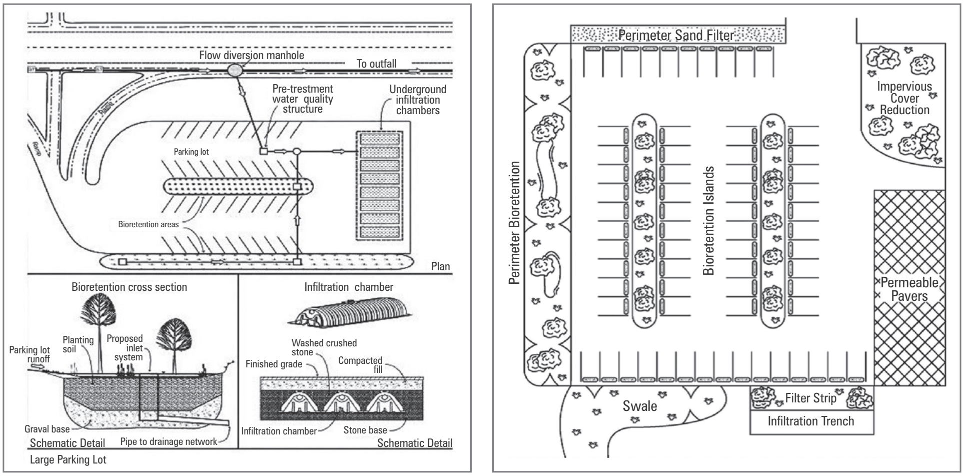
Fig. 3. Influence of catchment area development on the amount of concentration time for rains of with different probabilities

Table 4 summarizes the results of calculations of the size of surface outflow from the Winna Góra area for current building and prospective building and different probabilities of rain.

Table 4. The values of the maximum probable flow in Winna Góra catchment for various development

Probability	Maximum flow [$m^3 \cdot s^{-1}$]	
	Current building; C = 0.36	Prospective building; C = 0.44
1	1.200	1.630
5	0.916	1.278
10	0.764	1.091
20	0.615	0.842
50	0.373	0.524

Assuming that the volume of runoff coefficient for the current building will be c = 0.36 (as for uncultivated and arable land), size Q_{max} will vary from 1.20 $m^3 \cdot s^{-1}$ for p = 1% to 0.373 $m^3 \cdot s^{-1}$ for p = 50%. With an increase of the degree of catchment sealing (weighted average runoff coefficient c = 0.44), the volume of maximum flow will increase on average about 28% in relation to the current building. As a result of the catchment area development with parking lots and roads, this diminishes the amount of rainwater which may infiltrate into the ground which leads to an increase in the volume of outflow. This increase could have a significant impact on the development of the Winna Góra (for example, the potential intesification of the erosion processes) but little effect on the Mściwojów water reservoir. In order to reduce the impact of catchment sealing on the volume of runoff, solutions on the rapid draining of excess water are applied (traditional rain water drainage channels in the open and closed form) or a balanced approach. Using the first approach, it is possible to get rid of the problem in a place which is at risk. As a result of changes in the water circulation, the problem moves to the lower parts of the catchment, often causing a much more serious threat, than before the drainage was made [Tucci 2007]. A balanced approach would consist in the application of the planning and technical methods in the whole catchment. This consists in delaying the outflow and increasing the catchment water storage capacity. Delaying the outflow by increasing the time of concentration will reduce water runoff and relieve water reservoirs from excessive runoffs caused by tempestuous rainfalls, and may reduce the effects of water erosion [Miguez and de Magalhaes 2010]. In this approach rain will be restrained at the place of its occurrence in such solutions retention basins, permeable pavements, retention and infiltration reservoirs, etc. Taking into account the characteristics of the investigated area, to stop the precipitation in the space of origin it is possible to use the complete solution to the management of precipitation like from a car park (see Figure 4), in which there are several different systems (bio-retention, underground systems of drainage boxes, permeable pavement, etc.). In the case of roofs areas, specially in newly designed buildings, green roofs can be used or rainwaters can be used for the needs of the household. This contributes to a significant reduction in the consumption of tap water. In addition these solutions to the retention function for rainwater runoff also affect the retention of significant amounts of impurities contained in the run-off from the polluted surfaces like roads or car parks.



Source: Wałęga 2010, after: EPA 2007, Wałęga et al. 2013, after: EPA 2007

Fig. 4. Examples of complex development of rainwater from the car park

5. Conclusions

This paper assesses the impact of catchment area use and changes on the size of the maximum outflow. The study was carried out within the project "Valorisation and Sustainable Development of Cultural Landscapes using Innovative Participation and Visualisation Techniques", implemented within the framework of the Central Europe program. Analyses were carried out in the area of Winna Góra, located in the village of Mściwojów in the vicinity of the Mściwojów reservoir. Currently, the area is mainly used for agriculture. In the future, it is planned to increase the area sealing through the construction of roads, car parks and buildings. The influence of the catchment sealing on the runoff volume was determined using the indirect method of calculation in two versions, current and prospective development. Analyses showed that increasing catchment sealing leads to a reduction of surface runoff time from the catchment (less resistance to motion) which will lead to an average of 28% increase in volume of the outflow. This increase of the water volume of the outflow can have a significant impact on the development of Winna Góra (for example, the potential intensification of the erosion processes). In order to counteract the effects of these adverse changes, as a result of the catchment sealing, it is recommended that the balanced approach involving the retention of the precipitation in the place of origin for the investigated area be used. For this purpose it is also recommended that, the devices for retention and infiltration of precipitation from the different kinds of building should be used.

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