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THE ROLE OF SPATIAL PLANNING IN FLOOD PROTECTION

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Summary

The paper presents the evaluation of flood risk in the watershed of the Serafa River – the right tributary of the Vistula. The assessment involved the hydrological calculation and hydrodynamic modeling of wave transformation in the riverbed. The final risk assessment was based on the determination of critical areas, where the largest flood losses occur. It has been shown that proper spatial planning plays an important role in reducing flood-related losses. Moreover, it is necessary to take sustainable actions consisting in delaying the runoff from the watershed by the application of different forms of small retention and infiltration methods.

Keywords

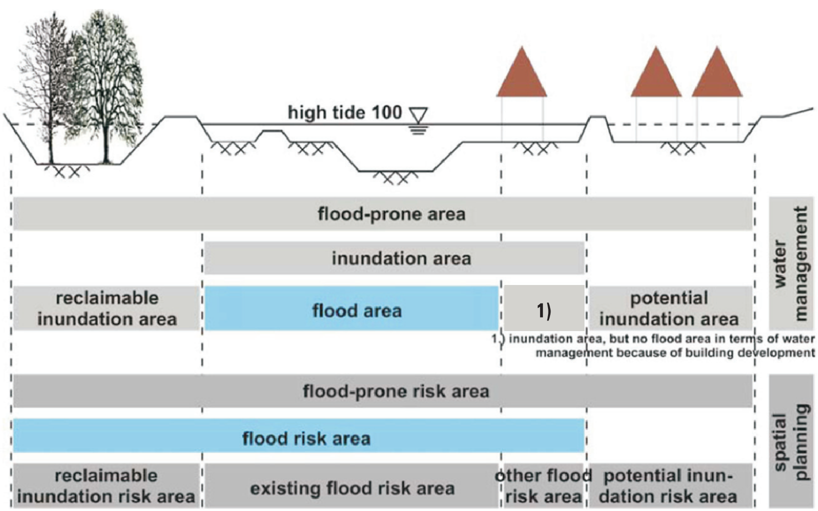
flood risk • flood risk assessment • hydrodynamic modeling • flood areas

1. Introduction

The increased of flood risk and losses caused by this disaster has originated with the development of settlements. As the availability of water for human consumption was a key factor in the settlement location, river valleys have always been the preferred places to live. The floodplains of river valleys have always been valuable agricultural lands due to periodic floods, their soils are some of the most fertile. Due to changes in the land use of floodplains, overflowing river waters increased the risk of significant material and human losses. According to Zevenberger and colleagues in 1900 [Zevenbergen et al. 2011], 13% of the global population lived in urban areas. In 2007, this value increased to 49.4% and this population was distributed in only 2.8% of the global area. According to forecasts, 69.6% of the world population in 2050 will live in cities. This a rapid rise in population density in a small area, leads to increased susceptibility to flooding and will result in significant losses caused by this disaster. This problem is of particularly concern to developing countries, where due to improper land use planning, the areas which are accounted as natural floodplains, are inhabited by humans, which has lead to their degradation. This process is particularly intensified in Latin America where 77% of the population lives in cities (this is 47.2% of the world population) [Tucci 2007]. It needs to be remembered that flooding is a natural phenomenon and a consequence of the natural hydrological cycle. The risk of flood losses increases as a result of flood plain land development. The reasons for this are as follows:

- the lack of local development plans that regulate the land development (according to the flood protection needs),
- failure to comply with the restrictions contained in land use planning, leading to the issuance of decisions on land development in areas threatened by flooding,
- location of settlements in areas with medium flood risk –floods are relatively rare in these areas, but if they do occur they cause significant losses.

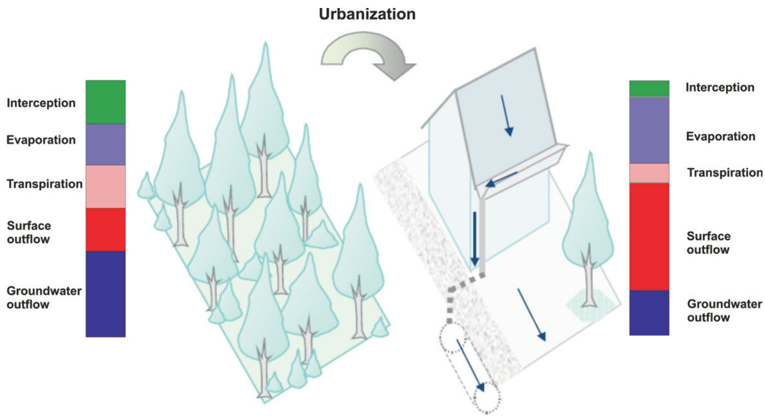
Hence the need for designation of areas along watercourses, which will ban the from establishment of settlements – i.e. the areas directly threatened by flooding. Areas of direct flood risk should be included in the natural valley retention of watersheds. In turn, flood risk zones, comprise inundation areas, usually determined by the so-called "high tide 100", not secured by protective constructions with buildings located inside (Figure 1). The flood risk areas should also refer to the potential inundation risk areas, due to e.g. failure of protective constructions.



Source: Flood… 2006

Fig. 1. Summary of different types of flood risk areas applicable in Germany

As a result of severe land sealing (the increase in the proportion of impervious areas: roads, parking lots, roofs etc.), the ability of infiltration reduces, which in the case of extreme rainfall leads to the occurrence of the so-called pluvial flooding [Urban… 2008, Zevenbergen et al. 2011]. Figure 2 presents the impact of watershed sealing on the water balance. Due to the watershed sealing, the share of runoff increases in the total water balance at the expense of interception, transpiration and soil drainage. This leads to an increase in the frequency of extreme flows. In urbanized watersheds maximum flow rate can be raised even up to seven times.



Source: modified after Miguez and de Magalhaes 2010

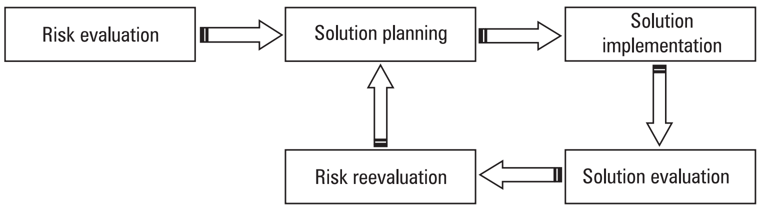
Fig. 2. The impact of urbanization on water balance components

In extreme situations, urban flooding can cause massive destruction that could result in regression of the development level by years or even decades. Current data show that economic losses caused by urban floods are still increasing [Urban… 2008, after: MunichRe 2005]. This is also due to incorrect urban policy, leading to an increase in the spiral of flood protection needs [Januchta-Szostak 2010, Kowalczak 2007].

There is another important factor contributing to the current high flood risk, namely the one-sided approach to flood protection. Too often, flood management in urban areas are mainly concerns by the hydraulic and engineering flood protection aspects only. At the same time, they ignore the spatial, ecological, political and socio-economic causes of risk.

In order to reduce flood risk in cities, it is necessary to use an integrated flood risk management plan, whose aim is to minimize the social and economic losses to an acceptable level. Conducting such analyses is dictated by the provisions of the (so-called) Directive of the European Parliament and Council of October 23rd 2007 on the assessment and management of floods (2007/60/EC) and the Water Law of July 18th 2001 (No. 115, item 1229, amended) [Ustawa Prawo Wodne… 2001]. The stages of flood risk management are shown in Figure 3.

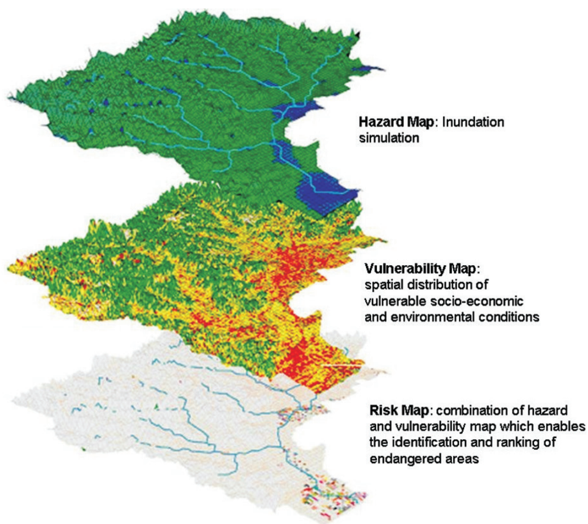
Flood risk management plans in cities, should be started from an assessment of current and future risks. Flood risk is defined as the probability of loss and is dependent on three elements: the scale of the threat, the threat of area exposure and sensitivity [Crichton 1999]. The risk assessment must be carried out in an integrated manner, i.e., by identifying all potential flood-associated hazards, including the prediction of future urbanization-related risk. Hydrological and hydraulic modeling of flood events in different hydro-meteorological variants, taking into account the impact of land use, climate variability, etc. is an important element in the flood risk assessment. Such an assessment should provide answers on the probability of the risk and magnitude of losses that may be generated by flooding. Therefore, the quantification of risk must begin with an analysis of hydrometeorological data and hydraulic calculations. The results of the hydrological and hydraulic modeling provide information on the expected frequency of floods and their characteristics (range, depth of water table in the floodplain, duration and flow rate) in different types of built-up areas. These analyses result in the creation of flood risk maps, which form the basis for the identification of areas with the highest flood risk and the proposed solutions to reduce the risk.



Source: Urban… 2008

Fig. 3. Stages of flood risk management

Figure 4 illustrates the steps involved in creating flood risk maps.



Source: Urban… 2008

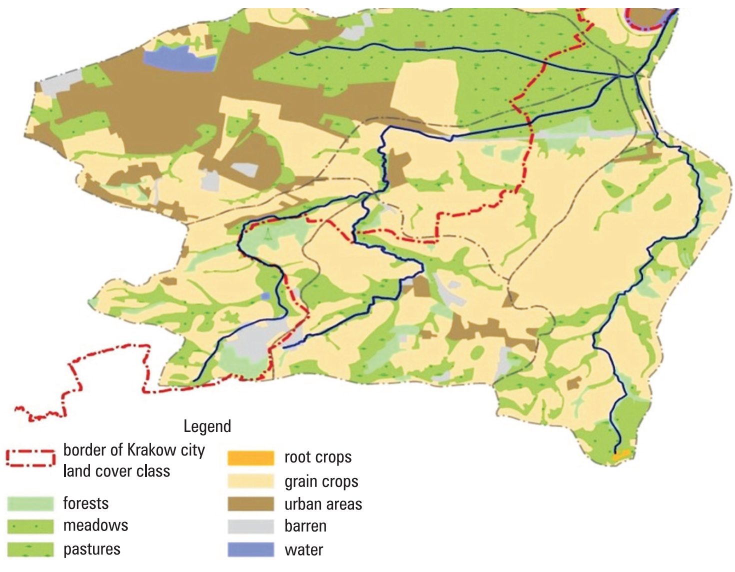
Fig. 4. Steps to creating flood risk maps

The development of flood risk management plans is based on information obtained from the flood risk analysis.

The aim of this study was to assess the flood risk in the watershed of the Serafa River, located in the agglomeration of Kraków, being the first component of the risk analysis. The analysis was conducted on the Serafa River, because it has been creating a very serious problems, in the area of Kraków with the event of heavy rains for many years. The essential elements of flood risk analysis of the studied area, come from the "Concept of drainage and flood safety for improving the city of Kraków" [Koncepcja… 2011].

2. Characteristics of the watershed and the Serafa River

The Serafa River, located in the Lesser Poland Voivodeship, is a second order right tributary of the Vistula. The river is 12.7 km long and the area of its watershed is 72.39 km². It begins as the Srawa in Wieliczka, near the pond in the Mickiewicza Park, while nearby the Winnie the Pooh Street it connects with the Grabówka, inflowing from the left. From this site it flows out of Wieliczka as the Serafa. In the vicinity of the A4 motorway and the Nad Serafą Street in Krakow it takes its left tributary – the Malinówka, which begins in Barycz together with its many small tributaries from the vicinity of Kosocice, Rajsko, Rżąka and Soboniowice. The Serafa takes another left tributary – the Drwina, with flows into the Vistula River in Brzegi, right behind the Przewóz barrage. Figure 5 presents land use forms of the studied watershed.



Source: Koncepcja… 2011

Fig. 5. Land use structure in the watershed of the Serafa River

The Serafa watershed is dominated by arable land, although strong human pressure can be seen in the form of built-up areas, particularly in the watershed of the Drwina Długa tributary (north-western part of the watershed). The sealing degree of the watershed (the share of precipitation-impermeable land in relation to the entire watershed) ranges from 20 to 65%. This is a very large proportion of such an areas and greatly exceeds the level of 10%, at which adverse environmental changes of the watershed, resulting from human activity, are intensified [Wałęga 2010].

3. Material and methods

Flood risk assessment was carried out for maximum flows with probability of exceedance equal to 1%. Due to the fact that the Serafa is an uncontrolled river, the calculations of maximum flow with the probability of exceedance equal to 1%, with the determination of hypothetical waves were completed using a mathematical rainfall-runoff model based on a cascade of linear Nash reservoirs. Total daily precipitation data with the probability of exceedance equal to 1% was derived from the Institute of Meteorology and Water Management, National Research Institute, branch in Kraków for the Botanical Garden meteorological station is located in the city center. In order to convert point rainfall into areal rainfall, the reduction factors, given by Lambor [1971], were applied. Based on research conducted by Kaczor and Wałęga [Kaczor and Wałęga 2011], on the temporal distribution of precipitation events in the agglomeration of Kraków, beta distribution function was applied in order to create synthetic rainfall hietograms. Effective precipitation was calculated according to the NRCS-CN method [Banasik 2009], including the impact of land use, soil type, plant cover and soil moisture on the value of peak flow rate. The second soil moisture level was included in the calculations. The share of impermeable area was determined based on the orthophoto maps by identifying the percentage of a given watershed occupied by sealed areas. The soil type and land use classes were identified based on the soil-agricultural map on a reference scale 1 : 25.000 developed in 2011 at the Institute of Soil Science and Plant Cultivation in Puławy.

A one-dimensional unsteady motion model, based on the hydraulic method known as "dynamic wave method", was used to determine the range of flood risk zones. The dynamic wave method is described by a full one-dimensional Saint-Venant equations in the form of a mass conservation equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial (A + A_0)}{\partial t} - q = 0 \tag{1}$$

and momentum conservation equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (\beta Q^2 / A)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f + S_e\right) + L = 0 \tag{2}$$

where: Q – flow, h – water table elevation (water level), A – active cross-sectional area, A_0 – inactive cross-sectional flow, x – distance, t – time, q – side inflow or outflow per length unit, β – moment coefficient for the velocity distribution, g – gravitational acceleration, S_f – friction slope of channel or floodplain, Sc – slope of the watercourse bottom, L – effect of side flow moment.

The value of friction slope S_f was calculated by using the Manning equation for steady flow:

$$S_f = \frac{n^2 \left|Q\right| Q}{A^2 R^{4/3}} \tag{3}$$

In this equation, the "n" is the coefficient of resistance by Manning and the "R" is the hydraulic radius.

In order to properly map the shape and course of the river network, in the section covered by the model, the digital terrain model (DTM) derived from The Main Geodetic and Cartographic Documentation Centre resources (validity – 2009) was used. The watercourse axes were generated based on the above. The data obtained from the DTM were verified based on topographic maps on a scale of 1 : 10.000 and orthophoto map on a scale of 1 : 5.000. In order to fully reflect the flow conditions of high water, cross-sections in sites with insufficient length were extended to the valley, cross-sections based on the DTM. The values of roughness coefficient by Manning were determined in each of the cross-sections – separately for the main channel, the left and the right floodplain. Hydraulic parameters of all engineering structures, significantly affect the flow conditions of flood water and were mapped in the hydraulic model. The available technical documentation, cartographic material (master maps) and inventory data available from surveying of these objects were used for this purpose.

Due to the fact that the relevant calculations were preceded by the so-called initiating calculations ("hot start"), whose purpose was to stabilize the model in the initial period of operation, the following global initial conditions were adopted: 5 cm – water level and 0.5 $m^{-3} \cdot s^{-1}$ – flow. Adoption of such small initial values and the creation of the initialization file allowed for avoidance of flow oscillations and enabled the extend of the time step in the relevant calculations. The designation of flood risk zone range was based on an analysis of the intersection of the digital model of water surface (DMWS) with the digital terrain model (DTM). Hydrodynamic modeling of flood wave transformation in the riverbed was conducted using the MIKE 11 program developed at the Danish Hydraulic Institute, Denmark.

4. Analysis of results

Table 1 summarizes the values of sub-watershed surface areas and the CN parameter characterizing the watershed's retention capacity.

Table 1. Summary of the CN parameter values for each sub-watershed

Watershed	Surface area [km^2]	CN
Serafa to Malinówka	11.14	78.53
Malinówka	8.68	76.50
from Malinówka to Drwina Długa	10.25	74.21
Drwina Długa	24.61	81.25
from Drwiny to Zabawka	0.37	79.14
Zabawka	13.86	76.87
from Zabawka to the mouth	3.47	83.49

As follows from the data presented in Table 1, there are very high values of the CN parameter in the Serafa watershed. This indicates the reduced capacity of precipitation retention of this watershed. This can induce an increased volume of surface runoff to watercourses as a result of heavy rainfall, which in turn leads to significant flows. This poses a threat to investments located in the river valley.

The Nash model is commonly used for the transformation of effective precipitation into direct runoff in watersheds with limited information on the actual hydrological regime. This is due to the simplicity of determining its parameters and high efficiency in the practical application [Banasik et al. 2008, Sheng 2000, Sahoo et al. 2006]. Furthermore, the Nash model parameters (retention parameter "k" and number of cascade reservoirs) are estimated using fixed relationships for urban watersheds. The usefulness of the Nash model to simulate floods in urban watersheds was verified among others by Banasik and Pham [2010] in Warsaw. Taking into consideration the availability of input data and positive verification of the applied model given in literature, it was decided to use the Nash model to simulate precipitation floods in uncontrolled watersheds in Kraków. The Nash model parameters were calculated based on the relations given by Banasik [2009]. Table 2 summarizes parameter values of the Nash model together with the calculated maximum flows with p = 1% for each sub-watershed.

The values of maximum flows and direct runoff hydrographs were the boundary conditions in the hydrodynamic model.

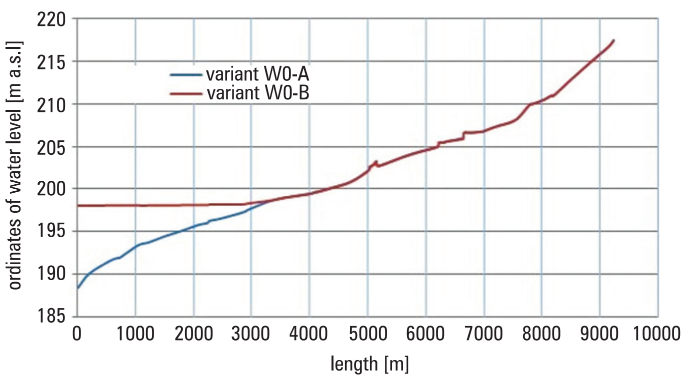
Another step of the analysis was to perform the hydrodynamic modeling of the river Serafa. These actions helped to identify critical areas (areas of concern), i.e. those in which flood water threats the infrastructure and buildings.

In Kraków, the problems occur particularly in the estuary sections of the Vistula tributaries, with simultaneous long-term high water levels in the Vistula. When the water level in the Vistula exceeds 520 cm in the Bielany section, the shaft sluices on the tributaries are closed. A backwater is formed as a result of prolonged precipitation and inability of water drainage to the Vistula, leading to inundation of the floodplains. For instance, during the high water level in the Vistula River, the level exceeding 520 cm lasted 6.5 days. As a result of further intensive rainfall, stream waters outpoured in their estuary sections into the Vistula, which in turn led to flooding of more than 70 streets [Wojciechowski 2010]. Also, under this research a variant in which water level in the Vistula River, corresponding to the flow with the probability p = 1% remains for a long time and shaft sluices are locked, was analyzed. Figure 6, shows the water table elevations in the Serafa River, in the case of unobstructed water runoff to the Vistula River (WO-A variant) and closed shaft sluices (WO-B variant). The performed calculations indicate a significant effect of backwater on the elevation of water level at about 3 km from the mouth of the Serafa River. In an extreme case, in the estuary section of the Serafa, the difference in water table elevations between the variants equals 967 cm. As a solution to this problem Pumping stations for high water levels and construction or modernization of backwater embankments may be applied in the discussed area.

Table 2. Summary of the Nash model parameters for each sub-watershed

Watershed	p = 1%				
	D [h]	LAG [h]	k [h]	N [-]	Q_{max} [$m^{-3} \cdot s^{-1}$]
Serafa to Malinówka	20	1.82	1.33	1.36	10.596
Malinówka	20	2.62	1.45	1.81	7.721
Serafa from Malinówka to Drwina	20	2.71	1.52	1.78	8.517
Drwina Długa	20	2.73	1.84	1.48	24.057
Serafa from Drwina to Zabawka	20	0.80	0.47	1.72	0.364
Zabawka	20	2.68	1.62	1.66	12.392
Serafa from Zabawka to ujścia	20	1.75	1.02	1.72	3.707

D – duration of the effective precipitation, LAG – lag time, k – retention coefficient of the reservoir, N – number of cascade reservoirs, Q_{max} – maximum flow value with p = 1%

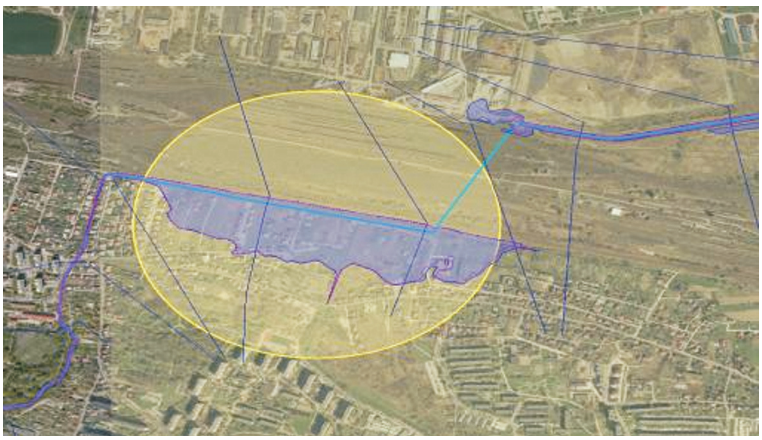


Source: author's study

Fig. 6. Water table elevations with p = 1% on the Serafa River under the conditions of undisturbed water runoff to the Vistula (WO-A variant) and closed shaft sluices (WO-B variant)

Limited capacity of riverbeds located within the analyzed watershed is also a major problem. It is assumed [Wojciechowski 2010], that the four-day total precipitation greater than 140 mm causes flooding and overflows of rivers in the upper parts of Kraków, located at a considerable distance from the Vistula. For example, during the flood in 2010, the four-day total precipitation (May 15th–18th) recorded at the Koźmice Wielkie station, that represents the southern part of Kraków equaled 231.1 mm. The two-day total precipitation recorded at this some station (May 15th–16th) reached 147.4 mm. In the described situation, the Serafa River and other rivers in the southern part of the City (Wilga, Sidzinka, Kostrzecki Stream) had already began to overflow on May 16th in the afternoon. Water levels at the water gauge in Bielany were then about 400 cm.

The conducted evaluation of the capacity of the Serafa River and its main tributaries, being also rainwater receivers, indicates the need for increasing the capacity of most of these watercourses. The most serious problems include improperly maintained river channels and obstructions of culverts or bridges, which limits the capacity of watercourses. Figures 7 and 8 present the critical regions due to obstruction of the culvert and channel capacity loss.



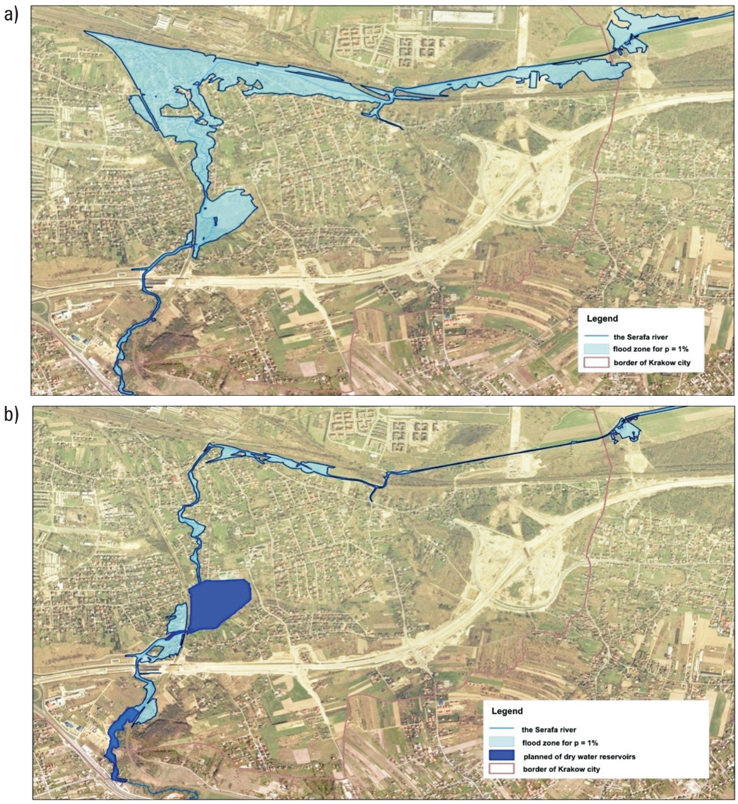
Source: Koncepcja… 2011

Fig. 7. The danger zone on the river Drwinka due to the culvert obstruction

To improve this situation, it is necessary to take measures to increase the channel capacity, e.g. through clearing of channels, increasing valley retention or considering the construction of dry storage reservoirs in the upper parts of their watershed. The reduction of precipitation wastewater discharge from the new stormwater drainage systems and implementation of the "system" (watershed) management of precipitation wastewater runoff seems to be an important measure. As mentioned above, the construction of dry storage reservoirs is one way to increase the capacity of stream channels. Figures 9 a and b present the flood zone coverage for the Serafa River in the current situation and after the planned construction of two dry reservoirs.

Source: Koncepcja… 2011

Fig. 8. The danger zone on the river Serafa due to the loss of channel capacity



Source: Koncepcja… 2011

Fig. 9. The flood zone coverage for the flow with p = 1% for the Serafa River, a) in the current situation, b) after the construction of two dry storage reservoirs

Also it should be also remembered that the designated critical areas should be taken into consideration when preparing local land development plans. Where the location of new investments are in a floodplain, they should be prohibited, as they constitute the so-called area of imminent flooding.

The calculations showed that losses in the Sarafa watershed, due to the potential risk of flooding with the probability p = 1%, can affect nearly 69 buildings and farms. It needs to be remembered that, in the case of urban floods, the major problems occur not only in the river channel (where the majority of funds for flood protection are donated), but most of all in the watershed. This is mainly due to uncontrolled sealing of the watershed, which disrupts the natural water balance. This is leads to increased runoff to watercourses as a result of heavy rainfalls and consequently leads to a reduction in their capacity. In order to prevent the effects of incorrect watershed's development, a sustainable approach that consists in delaying runoff from the watershed should be promoted due to the use of various forms of small retention such as seminatural water retention and infiltration solutions at the site of precipitation [EPA… 2007, Tucci 2007, Wałęga 2010] or the use of legal restrictions on the issuance of decisions on water usage.

5. Summary

Implementation of the provisions of the (so-called) Flood Directives requires the member states to carry out flood risk analyses, as a result of which flood risk management plans will be developed. This is particularly important in the case of urban watersheds, where due to high population density and a robust infrastructure, the occurrence of floods generates significant losses. This paper addresses the problem of assessing the risk of flooding in the area of the Kraków agglomeration, which is the first element of the risk assessment. The analysis was carried out, on the example of the Serafa watershed, which creates very serious problems following the occurrence of heavy rainfall. Hydrological calculations and hydrodynamic modeling of wave transformation in the river channel were performed to conduct this assessment. The final risk assessment consisted in determining the critical areas where the greatest flood losses occur. Finally, based on the conducted research, the most important conclusions about the flood protection of the city could be drawn:

- Proper planning plays an important role in reducing flood losses. The lack of a local land development plan or its relation to water management in Kraków causes uncontrolled sealing of subsequent watershed areas without providing adequate retention and capacity of the current system.
- Tasks related to the ongoing maintenance of the existing flood infrastructure and natural watercourses should be properly implemented. Given the current state of the aforementioned objects, the lack of proper maintenance and current repairs increases the flood risk, as confirmed by calculations performed on the Serafa River. It is necessary to continue providing the full capacity of watercourse channels. Failure to perform logging of wicker shoots, not carrying out desilting or liquidation of

escarpment slides or obstructions may reduce the capacity by up to several dozen percent.

- It is necessary to take sustainable actions involving the delay of discharge from the watershed area due to the use of various forms of small retention and infiltration. Small measures, primarily undertaken in the watershed will reduce the amount of runoffs supplying surface streams and reduce losses due to the occurrence of inundation or floods.

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