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STUDY OF OPERATIONAL CONDITIONS OF HYDROTECHNICAL STRUCTURES IN THE AREA OF PIASKI – DOLNY TARAS IN BYDGOSZCZ WITH THE USE OF EPA SWMM

ANDRZEJ POPOW, RADOSŁAW PASIOK

Institute of Geotechnics and Hydrotechnics,
Wrocław University of Technology,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

Abstract: The article presents expected influence of constructing Czyżkówko dam, planned to raise water of the river Brda in Bydgoszcz, on operational conditions of the system draining adjacent area. Using EPA's Storm Water Management Model a dynamic runoff model has been built for Piaski housing estate with the use of the available rain gage data. The paper gives a short theoretical basis for various component models (infiltration, evaporation, conduit and groundwater flow) and the conclusions from the operational analysis of the networked drainage system during a heavy rain. It also presents some aspects of using such dynamic rainfall-runoff model for inspecting and designing an urban drainage system.

1. INTRODUCTION

A new Czyżkówko dam is planned at km 15+946 of the Brda River. Raising the water in the river to the level 41.00 m asl will change the operational condition of the neighboring areas. To constrain the flow area on the lower valley terrace on the left side of the river, a lateral dam is planned in the km 15+950÷18+290 together with a draining channel.

The planned lateral dam decreases the reservoir area along the length of 2,340 meters above the main dam. At the same time, it prevents surface runoff to the river and it forces a change of the direction of groundwater flow. Between the side dam and the slope of the upper valley terrace the flood plains were allotted for the housing development. Drainage of the lower terrace of the Brda valley in this region takes place with the use of a ditch system, which will not ensure proper conditions for the land use after rising the water level at the main dam. That is why the existing ditches will be modernized and connected with the new channels, ensuring effective drainage of the land allotted to housing development. Thus a hydraulic structure will come into existence which will serve as: a receiver of surface runoff from the upper valley terrace and waters filtrating just below the terrain surface as well as a sewage receiver from the rainwater drainage system.

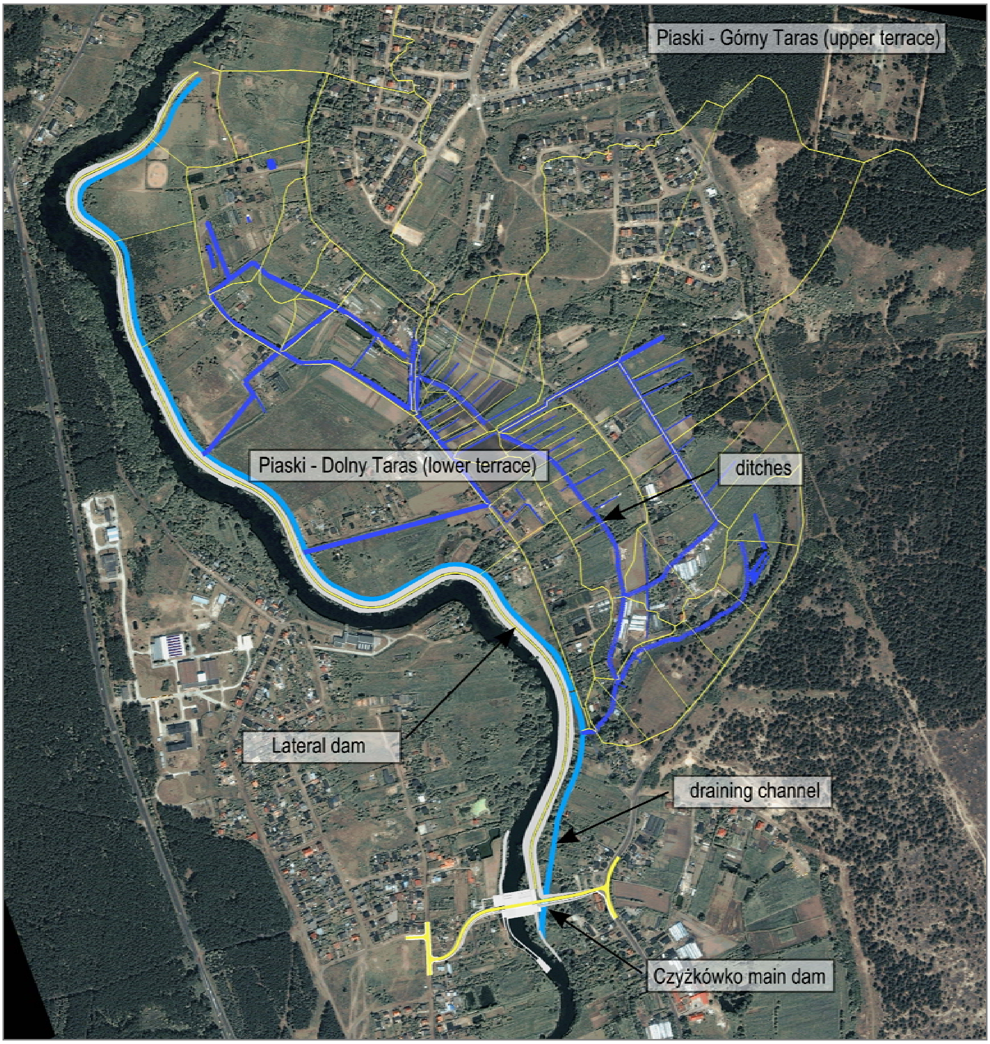

Fig. 1. Imagery of "Piaski – Dolny Taras" in Bydgoszcz
(source: Town Planning Office in Bydgoszcz [6]). The location of the planned dam.
Drainage system of the area on the left river overbank and the division of the land into subcatchments

In the new exploitation system, the drainage of the dam will constitute a vital element in the rainwater drainage and maintaining the right groundwater level in the area of the lower terrace of the Brda river valley. It is assumed that the rainwater will be conveyed by the ditches to the channel, situated just below the slope of the lateral dam. The present concept of the dam construction meets the requirements of the local development plan for the estates of "Piaski – Dolny Taras" and "Czyżkówko" as well as "Jachcice" in Bydgoszcz. For the structures encompassed in the plans the analysis of the environmental impact has been made. In order to do that model research has been conducted, which allowed an estimation of outflow from “Piaski – Dolny Taras” in Bydgoszcz after the construction of the “Czyżkówko” dam, in stormy conditions. The reason why such simulation can be vital to the estimation of the outflow is the location of the planned estates below the upper terrace (figure 2). Flow from the catchment of this terrace of an area of 278.1 ha will have significant impact on the drainage system of the built-up areas on the lower terrace, the catchment area of which is 113.6 ha only.

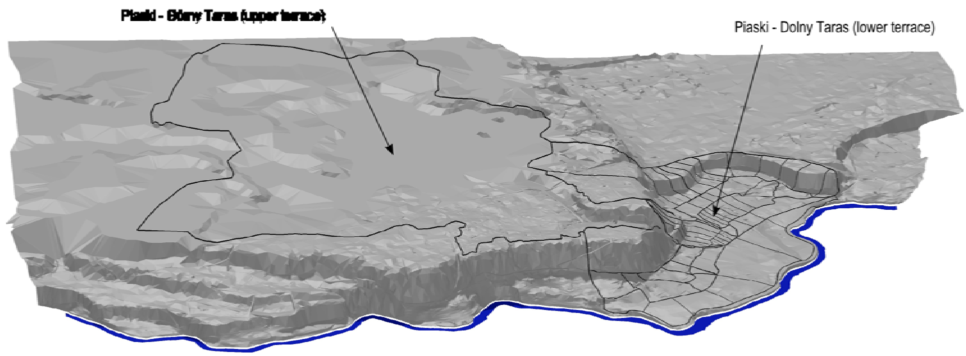

Fig. 2. The surface of the catchment axonometry; the vertical scale is 5 times the horizontal

Hydraulic calculations of the draining conduits consist in establishing the design storm intensity and the discharge in the channels. The intensity of rainfall, depending on the probability and duration, is established on the basis of empirical relations, e.g. Lambor, Błaszczyk [1], designing directives [13], and the IMWM analysis. Duration of the design storm determines the time of flow from the catchment border to the computational cross-section. The intensity and the duration define the design storm on the assumption that no backwater will take place. The basic criterion in the determination of the probability of rainfall occurring are economic reasons. It is recommended [13] to estimate rainfall intensity while designing a drainage channel system according to the equation

$$q = A / t_r^{0.667} \quad \text{(1/s·ha)} \tag{1}$$

where:

t_r – rainfall duration (min),

A – a value depending on a probability p%, average yearly rainfall depth H (mm), for p = 10% and yearly rainfall depth below 800 mm is 1013.

Maximum discharge can be estimated with the following equation

$$Q = \varphi \cdot \psi \cdot q \cdot F \quad \text{(1/s)} \tag{2}$$

where:

q – design rainfall intensity (l/s·ha),
F – catchment area (ha),
φ – time lag coefficient,
ψ – runoff coefficient.

The discharge is calculated with time lag φ and runoff coefficient ψ, on the basis of empirical formulas and values depending on the physical properties of the catchment. The time lag coefficient is most often based on a simplified equation $\varphi = 1/F^{(1/6)}$ [1].

The present method of channel designing does not allow us to take into consideration many phenomena that take place in the process of creating a runoff, which occur in the catchments of a complex structure. First of all, it does not enable us to describe the runoff during the rainfall. It requires many simplifications which, in turn, can lead to the false or ineffective solutions. Moreover, it does not offer a possibility of determining an impact of the planned hydraulic structure on environment. In the case discussed, the individual ditches will cause retention and some culverts will cause backwater. There is an interaction between groundwater and waters infiltrating from the land surface as well as from the channels to the soil. That is why in estimating the runoff from the area of the Piaski – Dolny Taras estate dynamic hydrology computational methods have been used.

In traditional hydraulic calculations of ditches, the unsteadiness of rainfall intensity is not taken into consideration. A constant rainfall intensity is assumed and these conditions have been adopted in the calculation of draining conduits. However, having at our disposal currently available computational tools, the way the draining system functions during a real unsteady rainfall can be determined. This in turn allows us to optimize the network and the dimensions of conduits of the whole drainage system.

Table 1

Rainfall intensity as a function of its duration for probability $p = 10\%$

Rainfall duration	Rainfall intensity for $p = 10\%$			
	IMWM [3]		Equation (1)	
min.	mm/hr	mm/min.	mm/hr	mm/min.
5	134.4	2.52	124.2	2.07
10	**93.0**	**1.55**	**77.4**	**1.29**
15	74.0	1.23	59.9	0.99
30	47.2	0.78	47.4	0.47
60	34,8	0.58	18	0.29
120	20.8	0.34	11.1	0.18

The basic rainfall data from the meteorological stations in Piła, Bydgoszcz–Szwederowo and Chrząstowo has been made available by the Institute of Meteorology and Water Management (IMWM) in Poznań [3] and from the meteorological station IMWM Bydgoszcz – by IMWM, Maritime Branch in Gdynia [2]. While making this analysis the usefulness of formula (1) for the rainfall intensity could be checked. The results are presented in table 1.

2. HYDRAULIC CALCULATIONS

The calculations have been made with the EPA's (Environmental Protection Agency, United States) Storm Water Management Model (version 5, March 2008). The program, its source code, the description and examples of application as well as the results of the accuracy analysis are available on the EPA website: http://www.epa.gov (Urban Watershed Management Research). The descriptions of the flow models quoted below will not allow us to present the whole range of calculation possibilities of the SWMM program. The authors' aim was to pay attention to issues which influence the way and quality of the solution of the problem of runoff from catchment encompassing the built-up areas.

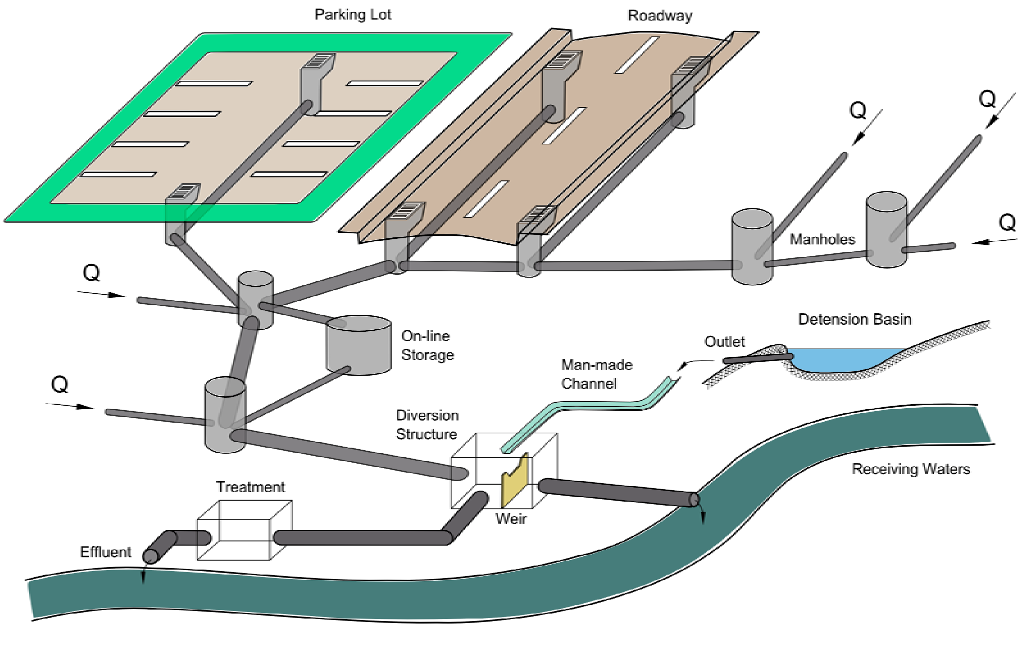

Fig. 3. Outline of the model of a drainage system in SWMM program

The drainage system in SWMM [11] allows the water flows between several environmental compartments. These are:

• The *Atmosphere* represented by rain gages,

• The *Land Surface* of the catchment receiving precipitation and sending outflow to the transport and groundwater compartments,

• The *Groundwater* – receiving waters infiltrating from the Land Surface – transports part of it to the Transport compartment,

• The *Transport* compartment (figure 3) – a network of channels, conduits, reservoirs and regulators, transporting water to its destination.

The basic facility of the description of hydrological parameters is the catchment. Values connected with the rainfall, outflow, infiltration and evaporation are attributed to the areas of subcatchments (figure 4).

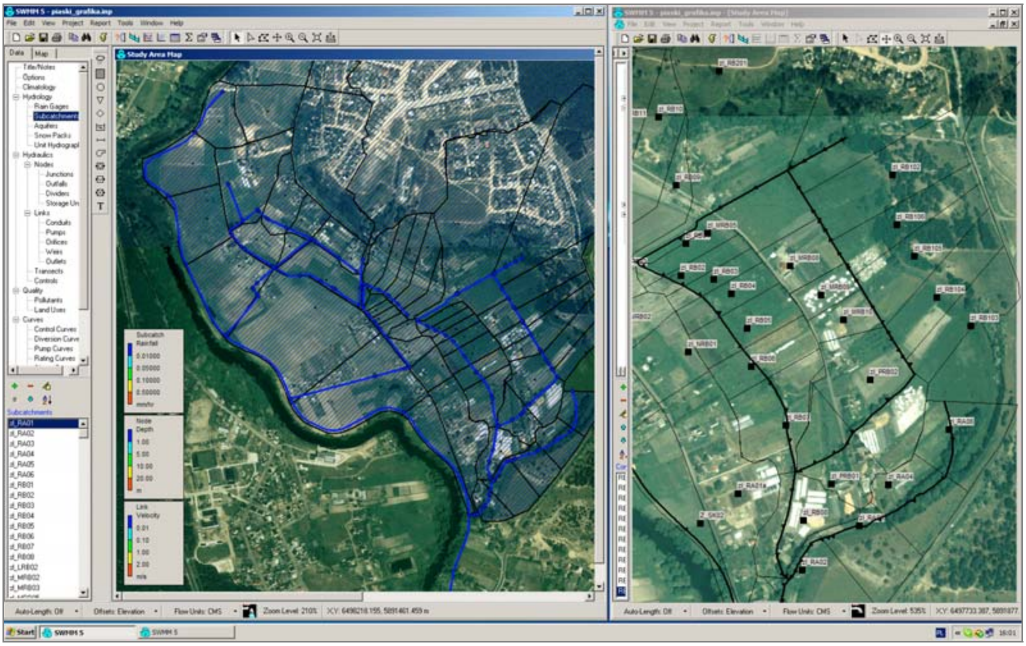

Fig. 4. Edition of parameters of subcatchments in SWMM program

3. MODEL OF SURFACE RUNOFF

Each subcatchment constitutes a model of nonlinear reservoir [9], it receives rainfalls and outflows from other subcatchments. The capacity of the reservoir depends on the size of the depression storage. The outflow from the catchment in time t is obtained through a continuous numerical solution of the equation of the net inflow to reservoir, including evaporation and infiltration (3), (4). Figure 5 illustrates the model of the surface runoff.

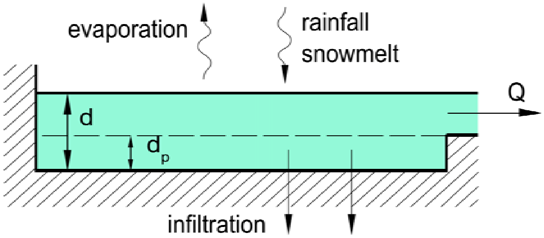

Fig. 5. Surface runoff model in SWMM program

$$\frac{\mathrm{d}V}{\mathrm{d}t} = A\frac{\mathrm{d}d}{\mathrm{d}t} = A \cdot i^* - Q\,, \tag{3}$$

$$Q = W\frac{1}{n}(d - d_p)^{5/3}S^{1/2}\,, \tag{4}$$

where:

- V – water volume (m^3) in the subcatchment,
- t – time (s) ,
- A – surface area of the subcatchment (m^2),
- d – depth of water (m),
- i^* – rainfall excess (m/s) (rainfall intensity minus evaporation and infiltration),
- d_p – depth of the depression storage (m),
- W – subcatchment width (m),
- n – Manning's roughness coefficient,
- S – subcatchment slope (m/m).

3.1. INFILTRATION MODEL

Infiltration, i.e. inflow to the unsaturated groundwater zone from the land surface, can be calculated with the following methods: Horton, Green–Ampt and SCS [9]. Horton's method uses observations showing that the infiltration intensity declines exponentially during the prolonged rainfall. The parameters of this model are: maximum and minimum infiltration intensity, decay coefficient, indicating the speed of the intensity decay in time as well as the time necessary for the soil which is fully saturated to be completely dried. The other method, which derives its name from the names of its creators: Green and Ampt [12], is based on the assumption of the existence of the sharp wetting front, separating the lower unsaturated soil layer from the higher saturated one. The equation which describes the sharp wetting front is as follows:

$$\int_{0}^{F(t)} \frac{1-\psi\Delta\theta}{F+\psi\Delta\theta} \mathrm{d}F = \int_{0}^{t} K \mathrm{d}t \,, \tag{5}$$

where:

F – total infiltrated volume (m^3),
K – hydraulic conductivity of the soil (mm/hr),
θ – moisture of an unsaturated soil layer,
ψ – suction head at the wetting front (mm).

In the SCS method there is an empirical parameter characterizing the catchment, called a curve number [10]. It depends on the group to which the soil characterizing the catchment has been qualified and on the land use.

3.2. GROUNDWATER MODEL

The aquifer is the volume of a soil capable of gathering and conducting water. The model enables vertical movement of water infiltrating from the land surface into the deeper layers of the soil, from where it can also exfiltrate into the drainage system. Depending on the existing hydraulic gradients water can be exchanged between the drainage system, e.g. the channels and the soil.

Aquifers are described with the use of soil porosity, hydraulic conductivity, evapotranspiration depth, bottom elevation and the loss rate to the deep groundwater. Figure 6 presents a diagram of the groundwater, with its saturated (lower) and unsaturated layers. The model takes into consideration the following flow directions: infiltration from the surface (f_I), evapotraspiration in both zones (f_{EU} and f_{EL}), water percolation from the unsaturated zone to the saturated one (f_U) and further to the deeper layers of the soil (f_L). On these grounds, in each time step, the current levels and the quantities of water in individual layers are calculated.

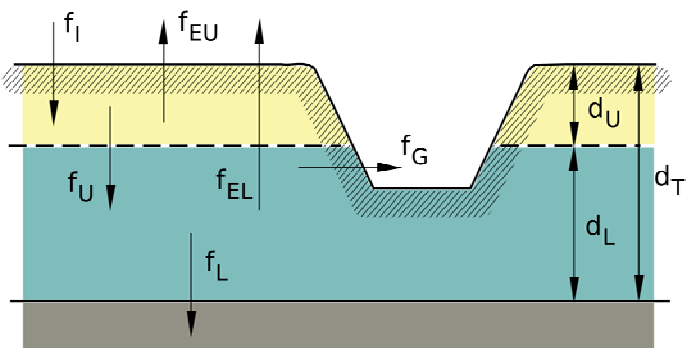

Fig. 6. Groundwater model in the SWMM program

3.3. FLOW MODEL

The calculations can be made for the stationary flow or with the use of St. Venant's equations. In the first case it is assumed that in a given time step the flow in channels and conduits is steady, i.e. the inflow to the given conduit occurs without any transformation or delay on its end. In case of unsteady flow, the mass and momentum equations can be of two forms: kinematic or dynamic wave. A simplified model of the kinematic wave (uniform unsteady flow solution), in which gravity forces are counterbalanced with the friction, does not allow us to take into consideration the influence of the creation of backwater, pressurized flow nor the flow reversal. This model is suitable only to calculate dendritic networks. The solution of full St. Venant's equations (6), (7) allows us to make calculations in the networks containing loops or lateral channels and enables calculation of reversal flow as well as flooding when the water depth exceeds the maximum available depth.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 , \tag{6}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \tag{7}$$

where:

Q – flow discharge (m^3/s),
A – flow area (m^2),
V – flow velocity (m/s),
H – hydraulic head (m),
S_f – friction slope,
h_L – local energy loss per unit length of conduit (m).

SWMM 5.0, contrary to the older versions of the program, uses the successive under-relaxation method [8] to solve equations of the dynamic wave.

4. RUNOFF FROM PIASKI – DOLNY TARAS AREA

Outflow from the catchment area has been estimated with the use of morphological analysis of the conditions of surface runoff, taking into consideration the infiltration in bigger catchments. In small subcatchments the infiltration has been neglected due to the impossibility to estimate the land use and terrain slope in the whole area of the planned estate, as well as the change of directions of the groundwater filtration and surface detention in new conditions. The subcatchment of the upper terrace is developed, and in the built-up part outflow has been directed to the natural receivers and the city sewage system. Partial or total soil saturation has been assumed also in the catchments of RA ditch (figure 7), because of the constant inflow to the ditch from the slope of the upper terrace.

The filtration parameters have been assumed on the basis of the land use map [5]. In the context of data verification and the assumptions the outflow model is subjective. The methods of the dynamic hydrology are not yet commonly used to the analysis of the surface runoff in small catchments and that is why no comparative materials are available. In general, simplified methods are applied.

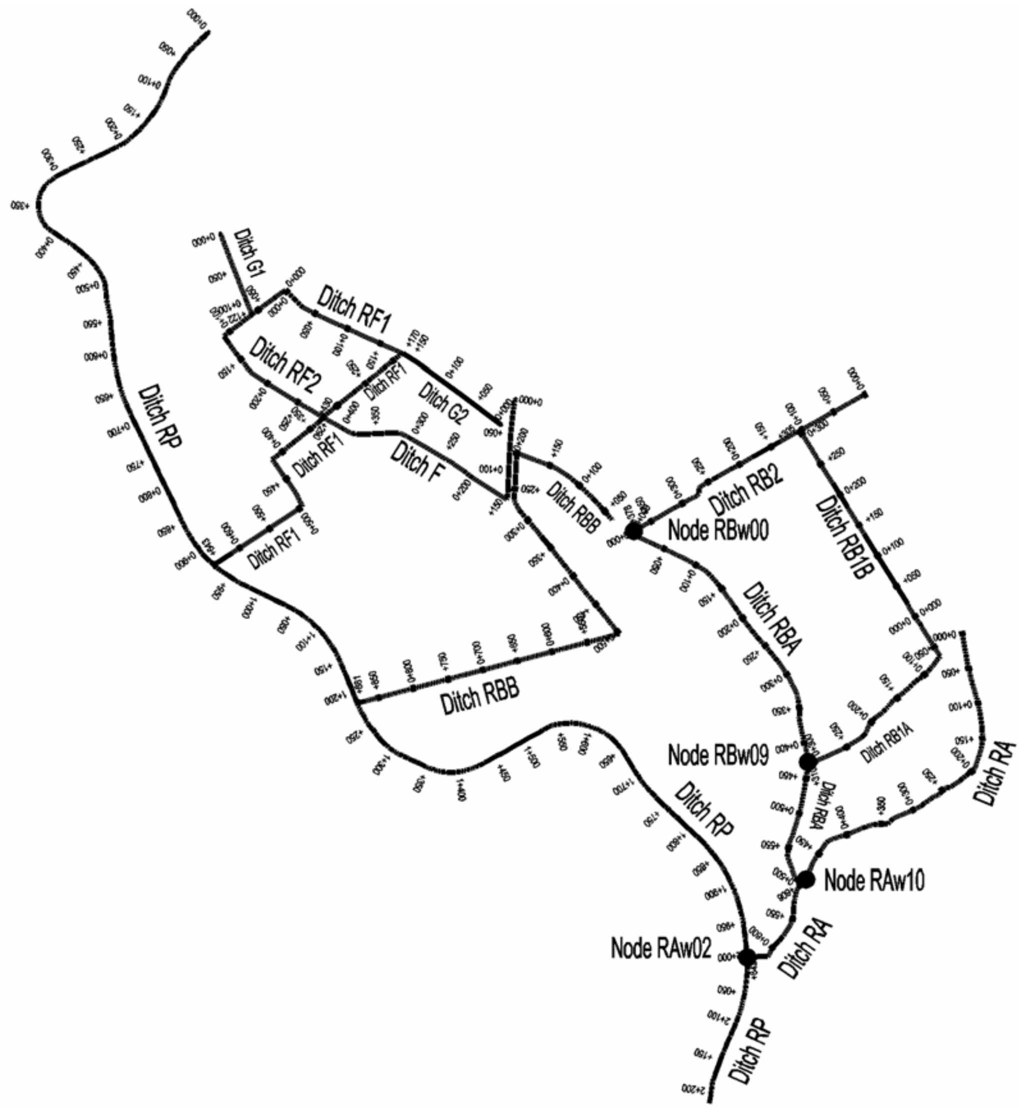

Fig. 7. The ideogram of the main conduits of Piaski – Dolny Taras estate;
the names of ditches and junctions

The hydrographs of the outflow from the individual subcatchments are constructed in the junctions of the channels and ditches. The amount of junctions results from the division of the conduits to sections of constant shape and slope. Additional junctions are established at the inflows from the surface of the subcatchment.

The analyzed area includes 58 subcatchments of 391.7 ha (including the catchment of the upper terrace of 278.1 ha), 11 channels with 118 inflow junctions, of the total length of 6.8 km. In the channels 24 culverts have been located. The simulation results can be presented and graphically edited based on values calculated for the subcatchments, junctions and channels. Figure 8 presents diagrams of the calculated discharges of the flow in the ditches, for the rainfalls that last less than 10 minutes. It was established that assuming longer lasting rainfalls (15 and 30 minutes) does not provide new information on how the drainage system operates.

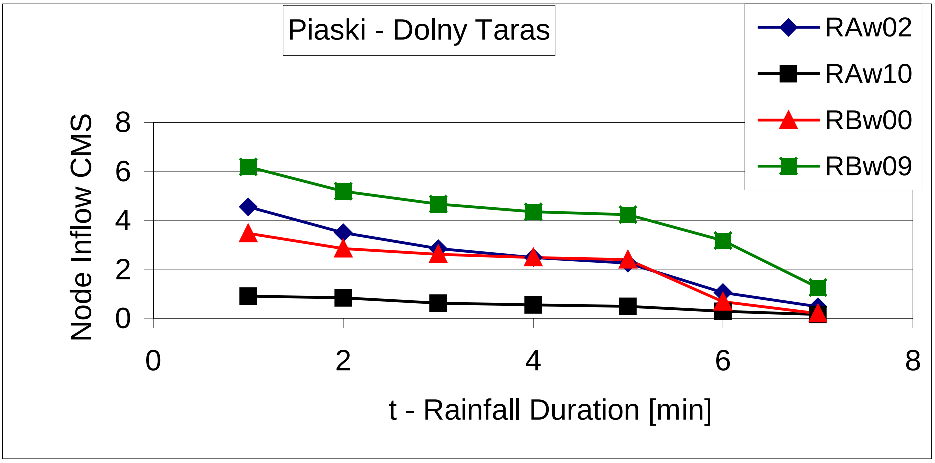

Fig. 8. Results of the flow simulation depending on the duration of the rainfall ($t < 10$ min), at selected points of RA and RB ditches. Rainfall intensity calculated for $p = 10\%$

The results of the calculation suggest that drainage of the areas allotted for development, in the southern part of Piaski – Dolny Taras estate, is controlled by the RBA and RA ditches (figure 7). This is due to the location, the size of the catchment, and the technical parameters of the hydraulic structures. In the whole flow range, culverts situated on the RBA ditch cause a fivefold discharge reduction, that is, a great channel retention. The sample simulation results of the water flow in the ditches are presented in figures 9 and 10. The enlargement of the culverts dimensions mentioned above will enable one to convey waters without retention which causes flooding of the adjacent areas. The RA ditch protects the area planned for development from the runoff from the upper terrace and collects waters from its slope. Due to the considerable soil saturation in this region the surface retention does not occur and the runoff from the area starts together with the rainfall. The highest water levels occur after 15 minutes from the start of the rainfall. The simulation results are depicted in figure 11.

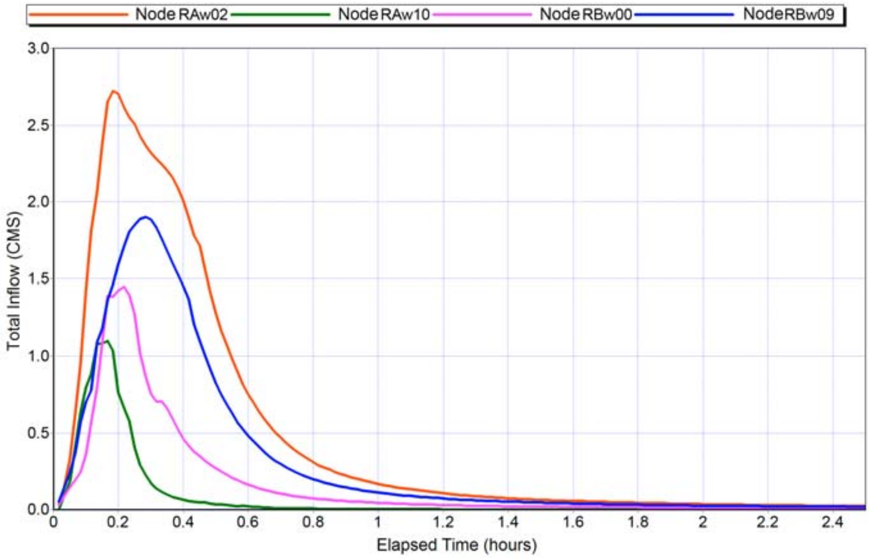

Fig. 9. Simulation results of the outflow from Piaski – Dolny Taras catchment.
Discharges in the junctions. Rainfall 77.4 mm/h, lasting 10 min; p = 10%

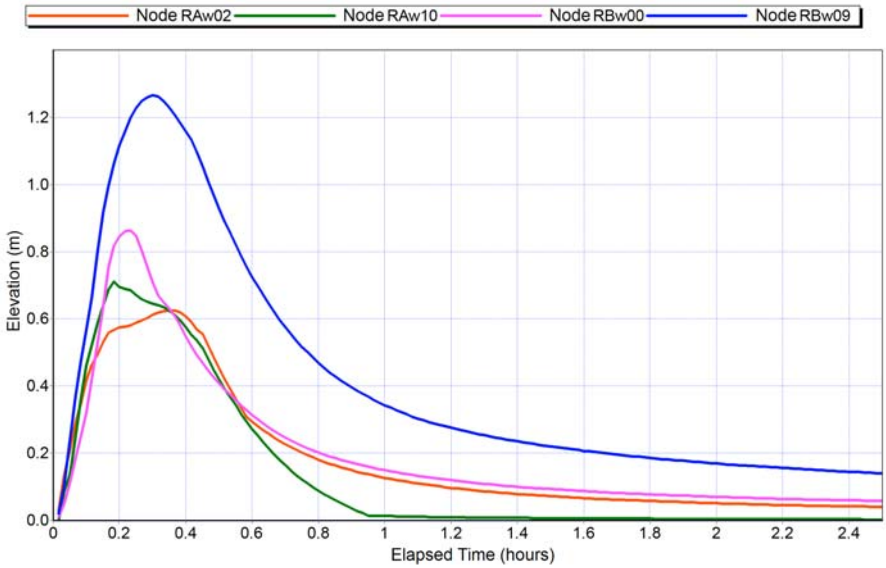

Fig. 10. Simulation results of the outflow from Piaski – Dolny Taras catchment.
Water levels in the junctions. Rainfall 77.4 mm/h, lasting 10 min; p = 10%

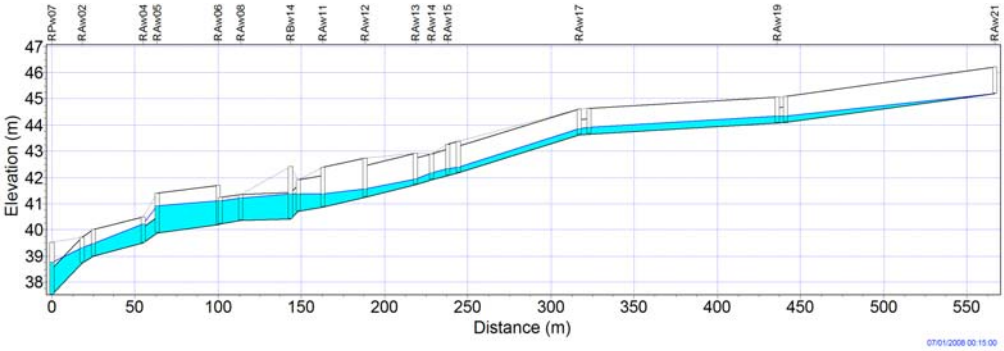

Fig. 11. Simulation results of the outflow from Piaski – Dolny Taras catchment. The profile of water levels in RA ditch after 15 minutes from the start of the rainfall. Rainfall 77.4 mm/h, lasting 10 min; $p = 10\%$

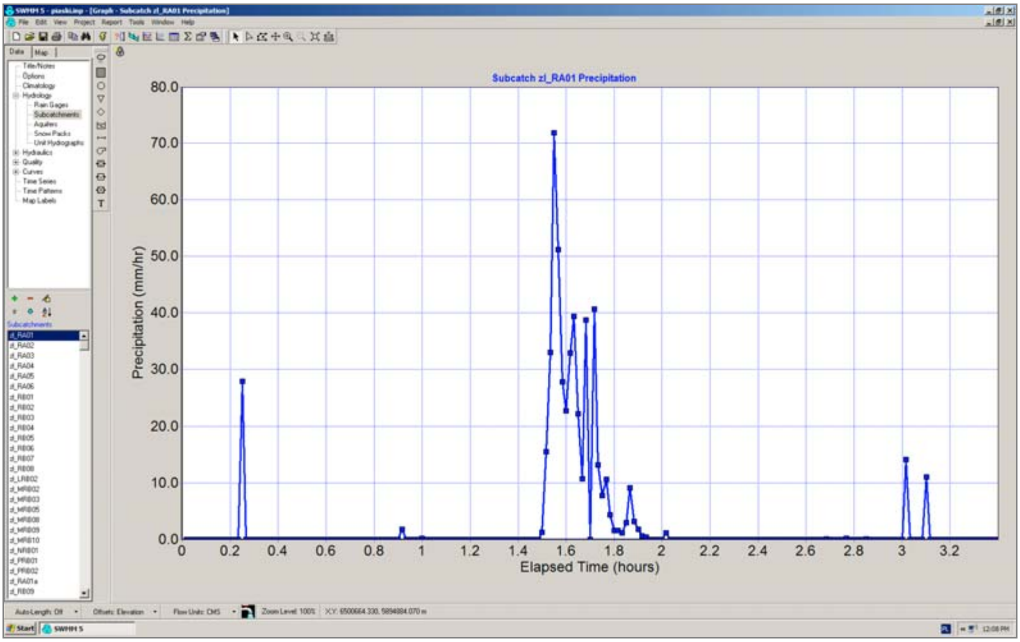

Fig. 12. Rainfall hyetograph based on the rainfall registered on 17 June 2007 at Climatological Station in Chrząstowo

In figure 12, an excerpt of the hydraulic calculation results is presented, in which the outflow has been defined based on the registered rainfall event. Rainfall intensity vs. time has been based on the data registered during the rainfall on 17 June 2007. The maximum value of the of rainfall intensity was 71.9 mm/h. From the chart, three rainfall events can be determined. A short rainfall, lasting 6 minutes, then, after

1 hour 28 minutes – heavy rainfall lasting 13 minutes, and the last one with a similar characteristic but smaller intensity and the same duration. In World Meteorological Organization classification a rainfall with the intensity above 50 mm/hr is described as *heavy rainfall.*

The rainfall–runoff simulation results in Piaski – Dolny Taras catchment for the measured rainfall (figure 12) are presented in figures 14 and 15 for selected elements of the drainage network (figure 7). The total rainfall was 8.72 mm (13.25 mln liters); infiltration loss – 5.45 mm (2.9 mln liters). The outflow from the catchment area was 3.21 mm (10.28 mln liters) and the surface retention – 0.063 mm (0.06 mln liters). Due to the channels retention, caused by the existing culverts, maximum water levels do not correspond to the maximum discharges, since they occur at different times. The maximum water level in the RA and RB ditches, based on the rainfall data of 17th July 2007, is depicted in figure 13.

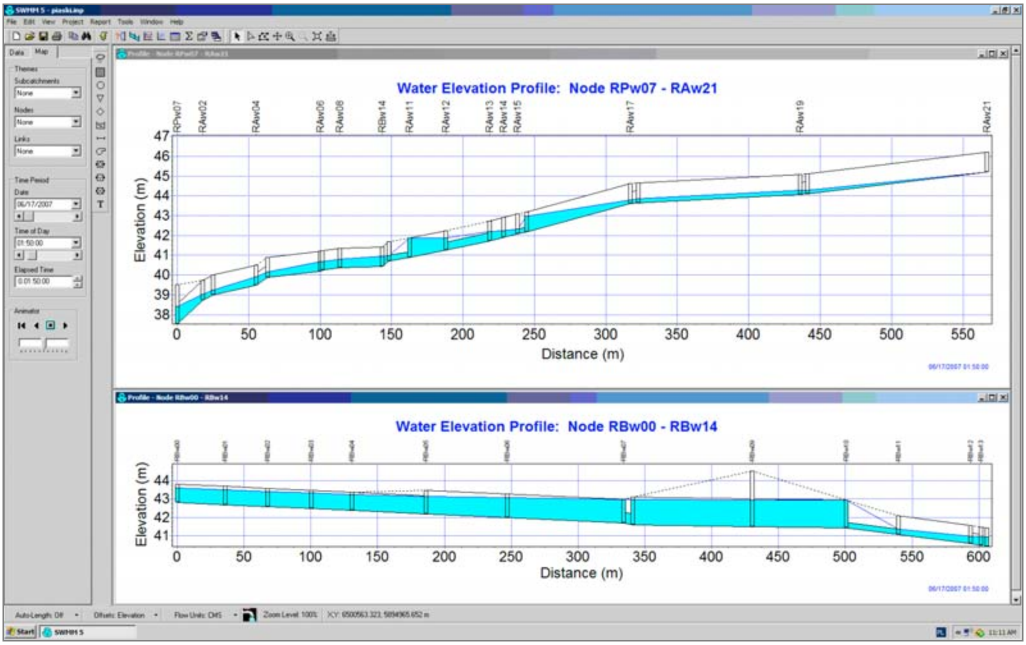

Fig. 13. Simulation results of the outflow from Piaski – Dolny Taras catchment. The profiles of RA and RB ditches. Water levels after 1 hour 50 min from the start of the simulation. The rainfall according to the IMWM hyetograph of 17th June 2007

In the calculation of the channels, there are assumed the shortest duration of the design rainfall t_{dm} = 10 minutes and the maximum rainfall intensity, depending on the assumed probability [1]. In the case examined it is the value of 1.29 mm/min (chart 1). The total rainfall will then be 12.9 mm (77.4 mm/h).

Considering the character of these calculations it can be assumed that the rainfall–runoff process simulation presented above has been made for conditions usually taken into consideration while designing a drainage system.

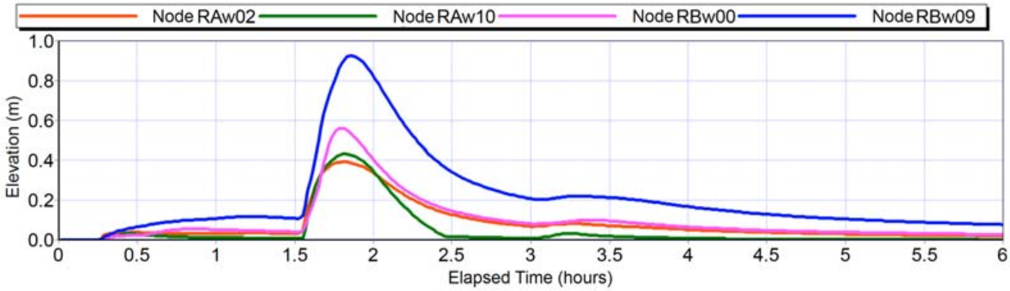

Fig. 14. Simulation results of the outflow from Piaski – Dolny Taras catchment.
The rainfall according to the IMWM hyetograph of 17th June 2007.
Water levels at selected points of RA and RB ditches

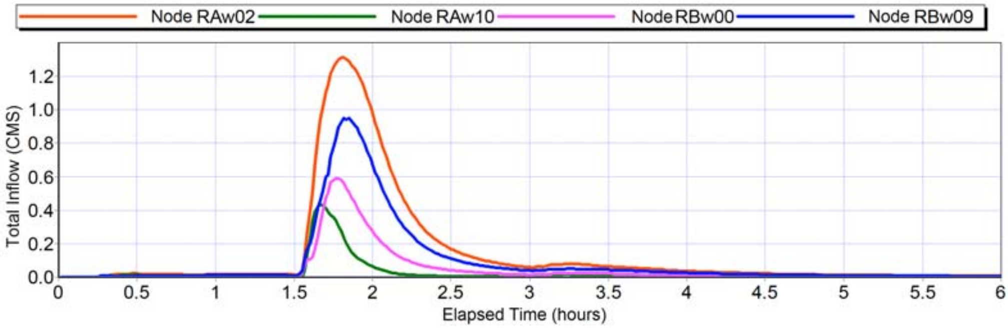

Fig. 15. Simulation results of the outflow from Piaski – Dolny Taras catchment.
The rainfall according to the IMWM hyetograph of 17th June 2007.
Discharges at selected points of RA and RB ditches

Based on the above calculation it can be observed that the existing system of ditches is able to convey the runoff from the Piaski – Dolny Taras catchment. The existing culverts will cause backwater in the ditches, their total filling and the flooding of the adjacent area. Reconstructing the culverts will improve the outflow conditions, but it will not enable the flow control. Each heavy rain will cause the flooding of the local drainage systems. After all the necessary modernization works the outflow from the Piaski – Dolny Taras catchment will be conveyed to the Brda river with the use of the existing ditches (as well as the planned *RBB*) and the planned *Czyżkówko* lateral dam gutter (*RP*). The ditches will be able to convey waters from heavy rainfalls after reconstruction of the culverts increasing the flow velocities in the ditches.

5. FINAL REMARKS

Preparing the SWMM model is very laborious, both at the data insertion stage and in the calibration process. However, the benefits of using such kind of software seem to exceed the amount of work necessary to get a working model. Operational models (EPA SWMM, HEC-HMS) are more and more widely applied despite the lack of the rainfall data. The data, however, can be acquired with the tools installed and used for one's own needs, for example, with a weather station installed in a suitable location inside a catchment. The cost of a professional weather station does not exceed 1000 € [14]. Such stations are able to continuously register barometric pressure, temperature, humidity and the rainfall intensity. The data can be easily transmitted to a computer and analyzed. Thus, installing a weather station solves the problem of evaluating the current runoff conditions in a catchment which depend on the rainfall history on the preceding days. It therefore seems that nothing stands in the way of the practical use of the computational methods presented in the paper and help land users accurately develop and operate their local drainage system.

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