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Systemic Approach to Risk Measurement of Drainage Systems in Urban Areas

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***Abstract*—**The work delineates the threats of maladjustment of the capacity of rain canals, designed and built in the early 20th century, in connection to heavy rainfall, especially in summer. This is the cause of the so called 'urban floods.' It directly relates to fierce raise of paving in the cities. Resolving this problem requires a change in philosophy of draining the rainfall by wider use of retention, infiltration and usage of rainwater.

In systemic approach to managing the safety of urban drainage systems the risk, which is directly connected to safety failures, has been accepted as a measure. The risk level defines the probability of occurrence of losses greater than the ones forecast for a given time frame. The procedure of risk modelling, enabling its numeric analysis by using appropriate weights, is a significant issue in this paper.

***Keywords*—**Drainage system, urban areas, risk measurement.

I. INTRODUCTION

THROUGHOUT years rainwater drainage system was the basic way of draining urban areas. It was made of a net of covered pipes along with special devices and objects. Designed in accord with the engineering art it usually functioned without many difficulties. Nowadays, rainwater drainage should be understood as just an element of urban drainage areas, tightly connected with the recipient.

Sewage system is developing in uncertainty and risk nowadays. There must be a balanced way of managing rainwater as well as surface waters.

The problem of managing rainwater from urban drainage basins is an important and complex issue with which a number of Polish cities have been struggling since a couple of years. It is worth to be treated with attention.

II. THREATS AND PROBLEMS RESULTING FROM FUNCTIONING OF RAINWATER DRAINAGE SYSTEMS NOWADAYS

One of the most common problems for rainwater drainage systems is their hydraulic overflow or the hydraulic overflow of the floating waters (urban rivers). Heavy rainfalls which intensity often outstands the capacity of urban sewage systems are a major flood threat (the so called 'urban floods'). Number of catastrophes caused by extreme hydrological and weather conditions is unfortunately increasing. Main problems with urban floods do not appear in the riverbed but in the drainage basin. Sealing up the drainage basin increases the threat of urban flood. Rapid increase in creating rain-tight surfaces (e.g. pavements, streets, parking places) seriously distracts the natural water cycle, eliminating the places of natural retention and infiltration. There are areas where in the last couple of decades twice as much surface has been rain-tightened as in the entire history of settlement. Rainwater from hardened surfaces is transported fast to the sewage systems and equally fast dropped to the watercourses.

Environmental effects of such a drainage system are following [1], [2], [7]:

- lower level of underground water in the water-bearing level directly contacting the surface and the disruption of natural water conditions,
- soil degradation in urban areas due to drought,
- hydro-morphological changes of watercourses, e.g. disappearance of surface waters or decrease in the low flow waters as well as its ecosystem degradation and floods,
- limiting of usage of rainwater by city flora and decrease in air humidity which has a negative impact on our mood, mainly during the heat period,

Rainwater, which in the last century was treated as 'clean', is nowadays highly variable and the load of pollution carried by rainwater is comparable with the load of pollution carried by the sewage system. Sometimes even to industrial sewage. Therefore, those waters, carried by closed canals, are considered as sewage, which has another negative impact on the water environment which they are polluting.

Pollution from rainwater can influence the recipient differently depending on time scale. Heavy metals which have accumulated in sediments may influence the environment for many years. Specific quality parameters of river water sections may change due to rainwater drop in a period varying from one hour till more than a year. Such a long changes of sewage quality are caused by release of sewage from sediments, dropped to the recipient and sedimenting partially on its bottom. The most important measure of rainfall pollution is the suspension concentration. The problem is not only with the suspension itself but also with pollution connected to it, e.g.: organic compounds, heavy metals, bacteria, large part of oil pollution as well as the phenomena appearing on the surface of suspensions, such as: ion exchange, catalysis with enzymes and mineral catalysts participation.

Features influencing the rainfall composition disposed of by closed canals are as follows [1], [2], [8]:

- Type of river basin

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- River basin use and its cleanness as well as the cleanness of air masses above it.
- Road types and traffic concentration
- Frequency and way of cleaning the basin (roads, markets)
- Ways of glazed frost prevention
- Rainfall parameters (as a pollution carrier)
  - Rainfall rinsing capacity which depends on rainfall intensity, its height and time scale
  - Length of break between rainfalls which determines the amount of pollution slimed on the surface of the basin.
- Season of the year
- Hydraulics and construction of the canal systems transporting the sewage as well as the type and number of its objects (separators, tanks, keys)
- Way of using the canal system
- Percentage of green areas on the surface

The general quality parameters of rainfall sewage (results of research) are shown in the next three tables.

TABLE I
APPROXIMATE SEDIMENT OF POLLUTION IN RAINWATER SEWAGE [8]

Pollution indicators	**Pollution values in rainfall sewage**	
	Minimum and maximum values	**Average values range**
pH	3,9 – 8,7	5 – 8
General sediment [g/m^3]	5 – 40000	80 – 17000
BOD [g/m^3]	1 – 1100	7 – 83
COD [g/m^3]	5 – 3100	40 – 50
Chlorides [g/m^3]	5 – 428	12
General nitrogen [g/m^3]	0,3 – 12,7	3 – 10
lead [g/m^3]	0,9 – 12,6	-

TABLE II
FEATURES OF RAINWATER SEWAGE FROM DIFFERENT URBAN BASINS [9]

Pollution indicator	**Basin type**					
	City centres		**Residential districts**		**Roads**	
	range	**Average sediment**	**range**	**Average sediment**	**range**	**Average sediment**
Average sediment [mg/l]	20 - 20000	300 - 2000	10 – 40000	100 – 3000	30 – 5000	300 – 1000
COD [mgO$_2$/l]	50 1000	70 300	20 – 1500	50 – 400	20 – 3500	100 – 500
BOD [mgO$_2$/l]	till 500	10 – 100	till 300	20 – 50	till 100	0,5 – 3,0
General nitrogen [mg/l]	1 – 15	5 – 10	1 – 15	5 – 10	0,5 – 8,0	0,5 – 3,0
General phosphorus [mg/l]	0,5 – 10	0,5 – 3	0,1 – 4,0	0,2 – 1,0	0,2 – 7,0	30 – 70
Ether extract [mg/l]	till 100	30 – 50	till 100	30 – 40	till 250	10 – 50
Chlorides [mg/l]	till 25000	10 – 50	till 10000	10 – 50	till 46000	0,3 – 0,6
Lead [mg/l]	till 2,0	0,2 – 0,4	till 1,0	0,1 – 0,3	till 2,0	0,5 – 0,7
Zinc [mg/l]	till 5,0	0,3 – 0,8	till 5,0	0,2 – 0,6	till 6,0	0,002 – 0,006
Cadmium [mg/l]	till 0,008	0,002 – 0,003	till 0,007	0,002 – 0,003	till 0,02	0,2 – 0,5
Copper [mg/l]	till 0,4	0,1 – 0,2	till 0,3	0,05 – 0,1	till 0,8	0,01 – 0,1
Chrome [mg/l]	till 0,1	0,02 – 0,06	till 0,1	0,01 – 0,03	till 0,6	0,02 – 0,04
Nickel [mg/l]	till 0,06	0,02 – 0,04	till 0,07	0,01 – 0,03	till 0,08	

TABLE III
POLLUTION ACCUMULATED IN THE SEDIMENT [9]

Pollution	**Percentage of pollution connected to the sediment**
COD	**83-92 %**
BOD	**90-95%**
General nitrogen	**65-80%**
Hydrocarbons	**82-99%**
Lead	**97-99%**

Majority of rainwater sewage stopped on street tank keys which can be further divided into:

- High working load keys which maintain basins with highly intense circular flow, in the city centre and intensely populated districts with many buildings, collecting sewage from car parks near shopping malls
- Low working load keys, situated mainly in the suburbs, in the low traffic streets.

Table IV shows quality features of major pollution in sediments.

TABLE IV
RANGE OF MAJOR POLLUTION IN SEDIMENTS [9]

Pollution indicator	**Range of observed values**	
	High working load keys	**Low working load keys**
Substances extracting by paraffin ether [mg/kg]	0,19 – 2,67	0,03 - ,055
General chrome [mg/kg]	4,1 – 20,2	3,2 – 9,4
Zinc [mg/kg]	30,0 – 429,0	28,1 – 167,0
Copper [mg/kg]	2,6 – 44,6	2,5 – 22,2
Lead [mg/kg]	0,02 – 76,6	0,029 – 32,5
Oil derivatives [g/kh]	0,1 – 17,5	0,021 – 0,68

Rainwater canal pipes are inhabited by various living organisms (bacteria, viruses, nematodes), mainly in the sediment layer. Their metabolism is high due to participating in biodegradation of organic pollution included in the sediment. Part of those organisms may cause illnesses. Microbiological and parasitological features of sediments from street tank keys and devices cleaning the rainwater have been presented in the work which based on research carried out a few years ago [9].

One of the recent issues is the issue of designing the load of rainfall taken by the drainage system. Due to economical reasons rainwater drainage systems cannot be designed to fully prevent pour outs for every heavy rainfall in the decade. Socially acceptable level of pour outs that guarantees good drainage level needs to be established.

Lack of quality and quantity monitoring hydraulic tools prevents water companies from managing an integrated water supply system.

Delivering rainwater to the sewage treatment plants using the general sewage system during heavy rainfall may result in poor outcome of the plants' work. The amount of sand and pollution removed from sewage during heavy rainfall is 5 up to 10 times greater than during the rainless period. This causes functional difficulties for the sewage treatment plant. Those are mainly disruption in removing nitrogen and phosphorus; the costs of usage also increase due to the increased amount of treated sewage. Because of the above mentioned reasons one should not drain rainwater to the small sewage systems. A solution protecting the sewage treatment plants is creation of storm overflows, however they become a threat to the recipient and its usage is regulated by Ministry of the Environment [2].

It also needs to be established who should cover the costs of running and maintenance of the sewage systems, and water treatment plants as well as the objects connected to rainwater treatment, e.g. clarifiers and pumps for increased water levels.

The atmosphere of uncertainty and risk concerns not only the negative weather conditions but also the fact that the existing systems do not cope with growth of the urban areas. There are no defined models for designing the rainwater drainage systems and the current ones are often used inadequately.

The consequences of bad selection and low functional efficiency of the rainwater drainage systems often lead to catastrophes. Frequently, even small rainfall paralyses the city. Roads are flooded and rivers damaging the road surface float through the city.

Lack of efficient drainage system of the road surface causes damages, e.g. cracks and potholes. Those damages have a great impact on safety and are often the cause of road accidents. There have been catastrophes when part of the street collapsed along with the car. Ditches are also an example of badly functioning drainage systems. Lack of systematic maintenance of ditches (gross mowing and waste removal) causes the ditch to stuff and prevents drainage. The depth of the ditch may also be a problem.

III. SYSTEMIC SAFETY MANAGEMENT OF DRAINAGE SYSTEMS IN URBAN AREAS

Considering the above, the main target of safe and rational drainage system should be lowering of quantity and speed of water drained from the urban areas as well as water treatment.

That is why the new as well as the existing canal systems are being complemented with objects responsible for infiltration and retention (porous surfaces, drain wells, retention boxes, green roofs or plant passages). They can be additional solutions to the traditional systems of rainwater treatment.

Such solutions are not only environmental friendly (better water balance of urban areas and lowering the flood threat by decreasing the flow speed) but they also improve the quality of urban life and bring economical benefits.

Alternative rainwater treatment should be described in economical, ecological and technical perspective. It must be followed by the description of reliability and safety of the existing canal system. Ecological perspective is mainly keeping the water resources balanced, improvement of local climate conditions and water treatment. Economical perspective is crucial for choosing the best technical solution and its later usage. Alternative solutions for managing rainwater should limit the technical actions and costs (also the ones which are difficult to estimate) connected to extension of traditional rainwater drainage systems.

Measuring reliability of the canal system is a consequence of the need to point to technical and organizational means which ensure that the system will work in a satisfactory manner. It also needs to justify the economical effectiveness as well as include the reliability criteria on the level of designing, to limit the negative effects of system failure.

Interaction between devices and objects included in the urban drainage system results from their ability of quantity and quality waste water treatment in time and space, conditioned by health, environmental protection and economical reasons.

Reliability of object functioning creates safety. The measure defining safety (safety level) is risk directly connected to safety failures [3]–[6]. It is defined by the value of probability of unfavourable event occurrence in a specific time along with its consequences. Risk measurement, i.e. analysing risk coming from a particular threat or group of threats to the system as well as defining the ways of decreasing risk is an important act for safety improvement.

Risk model crucial for risk analysis must include the following:

- threat model capable of determining threat measures,
- reliability model capable of determining the value of probability of unfavourable events including the probability of primarily dangerous events,
- relationships between these two models.

Risk analysis procedure includes:

- threat identification,
- setting the value of probability of unfavourable (dangerous) events,

- defining the negative consequences of unfavourable events,
- risk estimation,
- risk evaluation.

The most important information about the risk level is the probability of occurrence of losses higher than expected for a given time frame in a specific system. Negative results of failures in the rainwater drainage system can occur on technical, economical, environmental and social level, for example: flooding of buildings and areas, damages to municipal infrastructure, environmental pollution, decrease of life standard among the citizens, vulnerability to environmental pollution diseases, compensation.

Therefore, risk is a function of variables characterised by the probability of creating a loss as well as variables characterising the amount of loss.

$$\text{Risk} = P(Z) \text{ x } S(Z) \qquad (1)$$

where,

$P(Z)$ – the probability of occurrence of an unfavourable event Z

$S(Z)$ – results (loss) caused by event Z

For measuring risk level (risk estimation) one can use risk matrices. Risk matrix is a risk map divided on 9, 16, 25 or more fields merging the probability of occurrence of an unexpected, unfavourable event (e.g. heavy rainfall) exceeding the system capacity with a scale of consequences (e.g. damages to municipal structure). By defining the probability of occurrence of each event and assigning it a corresponding category a threat hierarchy is created. Categories are defined descriptively (not too precisely). For failure probability scenarios the following labels are assigned: improbable, not too probable, occasional. The consequences of results are defined as: negligible, marginal, serious, disastrous.

In order to determine a numeric value of technical risk specific categories of probability of an unexpected event occurrence have a frequency weight value assigned (W_1) whereas the consequences of these events are described by a numeric scale of weight results (W_2). Hence the mathematical interpretation of risk as a function of probability of unexpected events occurrence and their consequences can be presented in the following way:

$$\text{Risk} = W_1 \text{ x } W_2 \qquad (2)$$

Risk can be lowered by decreasing the probability of occurrence of an unexpected event or by decreasing the consequences of such an event, if it happens at all, so by lowering the threat. A perfectly reliable and safe rainwater drainage and canal system cannot be created due to random value of rainfall. Additionally, the systems are large, created from many separate parts organizing subsystems and nets.

Classification of results has been shown in Table V and the probability description of an unfavourable event occurrence in Table VI.

TABLE V
CLASSIFICATION OF RESULTS AND ITS CHARACTER

Weight	Consequences	Category	Description
1	Negligible	Z	No casualties or wounded.
		M	Almost without damages. Low or none financial losses.
		Ś	Unmeasurable effect for the natural environment.
2	Small	Z	No casualties or wounded. Psychological trauma occurs for a short amount of time.
		M	Some damages, local difficulties, small financial losses.
		Ś	Small, short impact on natural environment.
3	Medium	Z	Wounded can occur, large social losses.
		M	Big damages, society unable to function, considerable financial losses.
		Ś	Noticeable results in natural environment.
4	Large	Z	Wounded occur frequently, occasional casualties
		M	Paralysis of functioning of the urban area, big finnacial losses.
		Ś	Long-lasting effects on the natural environment.
5	Disastrous	Z	Casualties and wounded occur
		M	Huge damages, Paralysis of functioning of the urban area, huge financial losses.
		Ś	Irreparable losses in natural environment.

TABLE VI
PROBABILITY DESCRIPTION OF AN UNFAVOURABLE EVENT OCCURRENCE

Weight	Probability	Description
1	Very rare	It can occur only in exceptional circumstances once every 500 years or rarer
2	Rare	It is not expected to happen, not documented at all. It can occur once every 100 years or rarer.
3	Possible	It can occur in a certain time, rarely documented, usually preserved in oral stories, It can occur once every 50 years..
4	Probable	It is probable that it will happen, documented. Happens once in about 5 years.
5	Highly probable	It is expected to happen and is very well documented. Happens approximately once a year.

Very important feature in risk and safety analysis is the human factor, controlling element of the system, highly unreliable, cannot be omitted in risk analysis. Human factor in safety analysis comes down to modelling human abilities to function correctly in every circumstance, i.e. before occurrence of unfavourable events as well as after them (extreme state).

IV. CONCLUSION

Storms, even very intensive, have always occurred during summer. Specific micro-climate of huge, concrete cities which form the so called 'warmth islands' generating great pollution on small amount of space has always been a favourable condition for rapid, intensive storms. Considering climatic changes urban floods can be expected more and more often.

Nowadays one cannot just collect and drain rainwater. It also needs to be efficiently managed. Systemic approach is a complex view of the problem or a specific situation including urbanization level, laying of pipes and sewers, soil and water conditions, local area limitations, ecological, etc. Only in this way the centre of the problem can be seen and solutions proposed.

The problem cannot be defined without analysis including the impact of surroundings and changes which occur there. Functioning of drainage system in urban areas must be closely connected with the recipient of these waters.

Extension of a considerable number of devices used for drainage and rainwater taking, implementing costly relieving elements and adjusting the containers to taking more water are necessary actions which have to be taken in order to fulfil the growing needs. Creating rainwater sewage systems generates great costs which need to paid from local resources and the new legal regulation system for managing rainwater.

Reasonable management of flow, transport and quality of rainwater directed to the recipient is necessary. Rainwater management problem cannot be resolved using simple, conventional methods. Systemic actions leading to creation of an appropriate drainage basin in the next few years are crucial. Engagement and co-operation of many institutions as well as gaining social support for such actions is essential. In order to create a correct rainwater management system a sequence of works, enabling the city to crate the rainwater management model, needs to be carried out. For designing such a model the analysis of the current status including the following points has to be prepared: description of situation concerning surface flows, evaluation of the possibility of infiltrating rainwater, state of the rainwater sewage system, description of the net of surface watercourses, legal analysis concerning the management of the net and retention tanks as well as legal analysis connected to the possibilities of gaining additional funds for the rainwater management system.

The main aim of this work is to outline the problem of mentioning risk directly connected to safety failures and to present the procedure for modelling risk process enabling its numeric analysis by using an appropriate system of weights – frequency and results.

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