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DAMAGE EVALUATION OF A TOWN'S SEWAGE SYSTEM IN SOUTHERN POLAND BY THE PRELIMINARY HAZARD ANALYSIS METHOD

In the paper, the technical risk has been evaluated for the sewage network of a city in Southern Poland. The basis for calculations were field studies concerning operation of the said network, with the focus on technical data (network type, length, materials, size) and the failure rate information (type and duration of failure, unwanted event frequency). A two-dimensional matrix for failure risk in the pipelines was prepared with consideration to the type of pipeline and the material, as well as a risk map for pipeline malfunction. Obviously, the number of factors may be extended. In order to perform such analyses and add new factors, an appropriate database is needed, while in the case of sewage systems there is still little data collected. The evaluated risk of failure for the studied network was discovered to be in the tolerated and controlled-risk groups. The matrices and technical risk maps can prove to be useful in the process of optimizing the operation of the sewage network, e.g. in planning and executing repair works.

1. INTRODUCTION

Sewerage systems can pose a potential danger to the natural environment, the system's users and their immediate surroundings. Analysis of these systems should include evaluation both of the system's functional reliability as well as its safety. Increasing breakdowns, often with catastrophic consequences and external operating conditions impose such an approach in the evaluation and management of these systems.

The evaluation of functional reliability usually boils down to the question of the failure frequency and the removal of the failure's cause. Reliability generates system safety, but does not directly define its value. Expanding studies into functional reliability by incorporating research into the impact of failures on the environment and surroundings, including the community leads us to safety [1, 2]. Thus, safety, viewed

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from an engineering perspective, i.e. technological safety, replaces reliability. Safety (reliability of safety) on a macro scale, in the scope of a sewerage system, can be defined by analogy to water supply systems [3–6] as a state of sewage management which allows collecting, removal and treatment of both current and forecast volumes of domestic (communal) sewage and rainwater, keeping to the requirements of sanitary regulations, environmental protection and public order. The following are directly connected to safety:

- undesirable events,
- dangers,
- losses.

Undesirable events are associated with the unreliability of the system's safety, posing threats to the assets which translates into losses due to its negative consequences. These losses may be financial, human, ecological or emotional. Assuming that failures within gravitational sewerage systems are difficult to detect, the losses borne by the natural environment (ecological losses) may be significant and therefore should not be excluded from the safety analysis. Undesirable events generally relate to individual components of a sewerage system, i.e. to pipes, pumps, manholes, etc. but they can also affect entire subsystems, e.g. sewage drainage or sewage treatment subsystems. Superimposing multiple failures, the so-called domino effect, may result in total system failure. Risk is often used to determine the level of safety. It is intuitively seen as opposing safety and defines the probability of a threat with its associated losses.

Failures in sewerage systems cannot be entirely eliminated. These systems are extensive, comprising many separate parts grouped to form subsystems and systems. There is a dependence between the devices and structures embracing the system which is a result of their capability to process the sewage by volume and quality over time and distance, qualified by health, environmental and economic issues. During their operation, sewerage systems are exposed to a number of adverse factors, most of which are random, practically impossible to control in a planned manner, but assessable statistically. Therefore, it is impossible to precisely predict, and more so, fully eliminate their detrimental effects. The risk of their appearance is a normal phenomenon, and in the field of safety there is no "safe condition".

However, awareness of this risk and its management allows us to significantly reduce the frequency of undesirable events, and limit their undesirable consequences, which is an important activity in improving safety and as a safety management tool.

2. RISK EVALUATION

Risk evaluation (assigning a probability value to a risk) is a stage in the risk management process preceded by gathering information on threats relating to the given

system. The available information forms the basis for estimating the risk (Fig. 1). According to the above definition, risk is a function of:

- variables characterising the probability of losses occurring (measure of unreliability),
- variables characterising the magnitude of the loss (measure of threat).

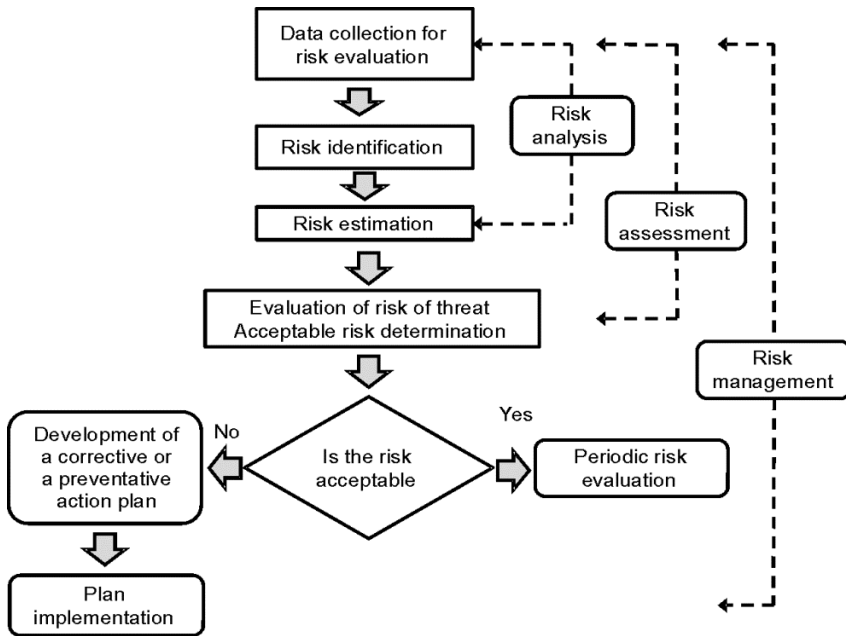


Fig. 1. Algorithm for a risk modelling (management) process

The relationship between the measure of risk, and the measures of failure and threat can be written as follows:

$$\left(\begin{matrix} \text{measure} \\ \text{of risk} \end{matrix} \right) = \left(\begin{matrix} \text{measure} \\ \text{of failure} \end{matrix} \right) \cdot \left(\begin{matrix} \text{measure} \\ \text{of threat} \end{matrix} \right) \quad (1)$$

The measure (level) of failure is usually expressed by the probability (or intensity) of an undesired event happening, while the level of threat is expressed in terms of the expected losses, i.e. consequences of the event. Thus

$$\text{Risk} = P(Z) \cdot S(Z) \quad (2)$$

where: $P(Z)$ is the probability of undesired event Z happening, $S(Z)$ – the consequences (losses) due to the undesired event Z .

Equation (2) implies that the risk can be reduced by minimizing the probability of an undesired event happening and/or limiting the consequences of the undesired event, i.e. minimizing the threat. Risk evaluation should be performed independently for each

of the identified threats. Risk analysis can be performed either by means of a quantitative method, or a qualitative method using matrices, graphs and calculations.

Quantitative methods allow more rational evaluation and promote better safety than qualitative methods. They are, however, more difficult to use and require a larger amount of initial data. To perform a quantitative risk analysis, it is essential to use the appropriate model – a probability risk model, which should include:

- model of threats, enabling determination of the probability of threat occurring,
- reliability model, enabling determination of the correct probability of the undesired event including the probability of the initial hazardous events,
- relations between these models [1]

Qualitative methods are approximate methods of risk analysis. Qualitative risk evaluation is usually a subjective estimate, based on best practices and experience. These estimates result in lists of threats together with the related risk ranked. In qualitative methods each risk and its potential consequences are presented descriptively. The preliminary hazard analysis (PHA) method is an example of a qualitative method of risk evaluation which will be discussed later in this paper. This method can be successfully applied as an initial risk assessment during the preparation of a detailed risk evaluation. It was used to estimate and evaluate the risk of damage to the sewerage network in the city of Cracow.

3. GENERAL INFORMATION ON THE REASONS AND CONSEQUENCES OF FAILURES OF THE SEWERAGE SYSTEM

The current discussion concerns a gravitational sewerage network, whose characteristic feature is inability to identify system outage during operation whilst the state of awaiting repair is usually discrete, since network inspections are carried out at set frequencies [7]. This is why an indicator of its condition based on accepted breakdowns (unreliability) within a sewerage system is not always accurate. Situations exist in which a given network is highly reliable but its condition is essentially poor.

A failure can be defined as a set of conditions and causes for its occurrence, forces destructive to the subsystem components and soil subsidence towards the sewer, as well as post failure consequences [8]. Factors affecting the natural aging process of the sewer and the likelihood of damage to the sewerage network include the following:

- factors related to the sewer construction technology (e.g. inappropriate and consolidated soil surrounding the sewer),
- potential hydraulic overload of the sewer (e.g. flood, unplanned development),
- global power shortage,
- uncontrolled inflow of harmful substances into the sewer network,
- rheological phenomena in the ground (e.g. mining subsidence, earth tremors),
- erosive impact of the groundwater environment,

- reactive substances present in the sewage or formed during its flow (e.g. sulfate corrosion),
- sewer abrasion,
- external factors (road traffic),
- acts of vandalism and terrorism.

The most frequent phenomena occurring within the gravitational sewerage system are unsealed sewers and the infiltration of groundwater containing soil particles into the sewer [9, 10]. Voids then form which may cause the ground directly above the sewer to collapse. Infiltration of groundwater with soil particles into the sewer may even lead to a catastrophic failure. The scale of these phenomena is determined by the size of the unsealed area, type of ground, as well as the particle size distribution curve and concentration in the area of the sewer's orientation. If the problem occurs, smaller particles are washed away as long as a filter composed of bigger particles exists above the unsealed area. In the case of sewer backflow or during the sewer's operation under pressure, the filter becomes damaged. This process eventually leads to subsidence directly above the sewer. As a result, this leads to the ground at the surface collapsing in addition to the foundations located directly above the sewer. In the case of rigid surfaces (e.g. roads) on unconsolidated ground, voids form locally directly under the road surface. When these voids reach large dimensions, the ground then settles or cracks, followed by the collapse of the road surface.

On consolidated ground voids appear above the areas where the fragments are missing in the upper part of the sewer structure. These voids can reach large dimensions with heights attaining several meters. Voids are predominantly found above concrete sewers built during the 1950s and 1960s as the quality of the concrete in these sewers is very poor. Studies undertaken by researchers at Kielce University of Technology [11] have shown that the concrete classification was often below B10.

The greatest and most frequent problems in the operation of gravitational sewage systems are blockages or silting and sliming (obstructions in the sewers, lateral sewers and manholes). Sewers require unblocking. More commonly it is the lateral sewers which become blocked due to improper usage. Silting and sliming in addition to sedimentation in sewers occurs in sections where the rate of flow is insufficient to transport the suspended particles (is not self-cleansing). The silting of suspended particles in sewers increases the resistance to flow, causing foulness in the sewer. Under such conditions, the normal rate of flow may be reduced by as much as 70%. Foulness in sewers may also be caused by an uneven gradient and by specific sewage composition (e.g. sewage from a dairy containing a lot of fats). Root penetration is also a frequent phenomenon. Sewage, due to a higher temperature and high mineral contents are a perfect feeding medium for tree roots and therefore, after infiltrating the sewer they expand rapidly, and in time block the sewer stopping the flow.

A significant percentage of sewer damage consists of cracking, deformations, cave-ins, dislocation of pipes at joints, cradles (counterslopes), as well as corrosion

and abrasion caused by a number of reasons including ground subsidence, external and internal loading, careless construction work, or the abovementioned root infiltration. Corrosion, on the other hand, is caused by reactive substances found in sewage, or ones formed via chemical or biological reactions in the sewer during sewage flow. Sulfate corrosion is most common due to the release of hydrogen sulfide under anaerobic conditions during the decomposition of pollutants in sewage at relatively high temperatures and slow sewage flow. It has been noted recently that this problem affects both old and relatively new sewer sections alike.

Table 1 presents the failure frequency of sewerage networks in Poland based on long-term surveys carried out by various authors [12].

Table 1

General failure frequency based on population size [12]

Population size	Below 10 000	From 10 000 to 20 000	From 20 000 to 50 000	From 50 000 to 100 000	From 100 000 to 200 000	More than 200 000	Total
Mean value of all failures [No./km-year]	0.51	2.11	3.53	2.29	3.26	2.00	2.6
Median of all failures [No./km-year]	0.37	1.42	2.14	2.14	3.10	0.82	1.56
Number of water companies analysed	11	21	40	40	14	9	135

The presented damages and failures, taking into account their consequences, can be of two types. The former, visible on the surface, usually in the form of flooded structures, roads collapsing, equipment failure (e.g. pumps), no inflow into sewage treatment works (vacuum systems) are removed as they occur. The other, invisible on the surface, often remain undetected for long periods of time. It is these failures that pose a greater threat to the environment and may cause sewer catastrophes. They cause contaminations in groundwater and subterranean water due to sewage leaking from damaged sewers. This process is uncontrolled and may be long lasting. They may also cause water infiltration into the sewers, lowering the groundwater level, and thereby may increase the cost of sewage treatment. Losses caused by undesired events may be viewed on three levels: technical, economic, and socio-environmental which may include:

- environmental pollution,
- lowering of the standard of living,
- infrastructure flooding,
- flooding of the terrain,

- ill health caused by diseases linked to environmental pollution,
- compensation payments,
- environmental charges.

In gravitational sewerage systems, damage detection is very small, due to the general lack of continuous monitoring of these networks. Usually these damages affect the natural environment and are difficult to assess. When considering reliability, the following need to be taken into account: the main collectors, intercepting sewers, critical network components, e.g. pumping stations, holding tanks with associated anti-siphonage pipes which generate significant consequences.

4. PROCEDURE OF RISK EVALUATION IN THE PRELIMINARY HAZARD ANALYSIS

The PHA technique does not take into account a numerical value for the probability of a risk occurring but enables specification of only its severity and sets the acceptable risk level, usually by means of a risk matrix (mathematical interpretation of risk). The risk matrix is an excellent and convenient tool for illustrating ranking risk. The ranking of risk is in itself an important part of its analysis [1, 2, 13]. The risk matrix is a risk map divided into 9, 16, 25 or more cells, depending on the accepted scale of risk evaluation. It links the probability of an undesired risk occurring (e.g. sewer damage) with its consequence level (severity) according to Eq. (2). Frequency values (W_1) are assigned to individual probability categories for undesired events, while categories for the consequences of these events are described using a weighted numeric scale for the consequences (W_2) [14].

$$r = W_1 W_2 \quad (3)$$

Thus, each risk is assigned to coordinates in the matrix (combinations of accepted probability levels for undesired events and the consequences of these events). The division of the risk map into cells is related more to the risk indicators expressed in points (value ranges) than numbers (continuous scales). Risk evaluation can be performed on a grading scale of three or more. The matrix can be constructed as required, usually in the form of a chart or table. The scales refer equally to the severity of the consequences in failure scenarios (undesired events) as well as to the probability (frequency) of their occurrence, allocating them to an appropriate category, based on expert opinions. By assigning a probability to each defined event, an ordered list of threats is created. Categories (levels) are presented as a qualitative description – one could say, imprecise. The number of categories is selected independently for each analysis and matched to the potential size of the consequences. The probability for failure scenarios (random events) is described by categories, e.g. unlikely, quite likely, likely, etc., and consequences are described as, e.g. negligible, marginal, serious or

catastrophic, alternatively, small medium and large. Table 2 presents a sample risk matrix of failures (undesired events) relating to a given threat.

Table 2

Numeric values for a risk occurring in a given failure scenario
– two parameter risk matrix (developed by the author)

Event occurrence	The effects of consequences		
	Small $W_2 = 1$	Medium $W_2 = 2$	Large $W_2 = 3$
Not very likely, $W_1 = 1$	1	2	3
Quite likely, $W_1 = 2$	2	4	6
Most likely, $W_1 = 3$	3	6	9

The evaluated risk should be allocated to the accepted risk category. This is known as evaluating the risk of the likelihood of an undesired event occurring. If the risk severity lies outside the acceptable range, preventive and prompt actions must be defined, in particular actions such as the preparation of the means allowing reduction of the risk of the event potentially occurring. As a general rule, small losses occur relatively frequently whilst big losses do occasionally.

5. RISK EVALUATION FOR A GIVEN TYPE OF DAMAGE IN THE ANALYSED SEWERAGE NETWORK

The sewerage network under examination consists of two separate subnetworks, each with its own separate sewage treatment works. Both networks are gravitational. However, in areas where the gravitational draining of the sewage into the central network is impossible for height reasons, local sewerage networks exist with their own sewage treatment works. In central parts of the city, the sewerage network is a combined system, whilst on the outskirts it is a separate system where foul sewage is drained into the central system and storm water into the local watercourses. The main sewer collectors, despite having been constructed in the early 20th century, still possess spare capacity and are capable of operating efficiently without the need for implementing significant changes. This allows new urban areas which are in the immediate neighbourhood of existing sewers to be connected to the central sewerage network. The total length of the network (lateral sewers including the external network) is 1780 kilometres, built from concrete, stone, reinforced concrete, cast iron, PVC, steel and PE.

In the period of the network's operation, sometimes over a century, the operating conditions changed, the amount of sewage increased, the load bearing capacity of the sewers decreased as their condition deteriorated, and the dynamic load increased due to road traffic. There followed a gradual deterioration of the pipelines, the flow conditions changed mainly due to silting and badly laid sewers, potential conditions were

created for the formation of hydrogen sulfide and sulfate corrosion. Figure 2 shows the number of failures over a 10 year period.

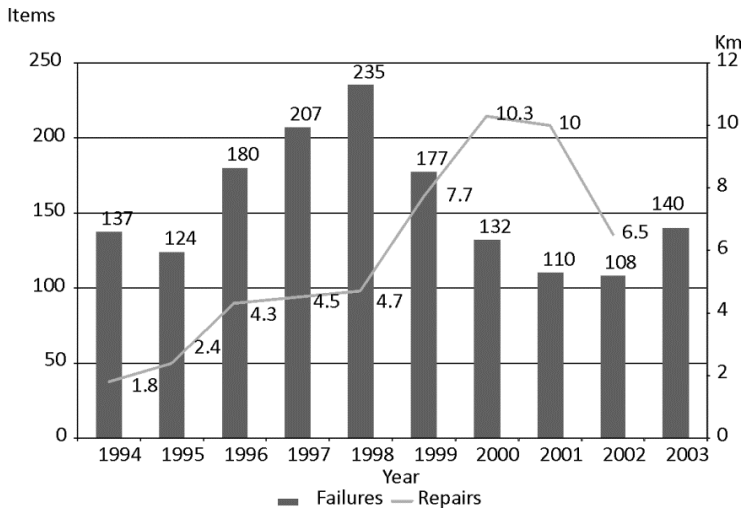


Fig. 2. Failures and repairs in the sewerage system of a town in Southern Poland [15]

A failure was defined as an event where some (or all) of the sewage failed to reach the sewage treatment works, seeped into the ground or was transported directly to the receiver. Such events include loss of network seals, cave-ins, deformation, cracks in the sewer, manhole damage and others. Since 2003 the average failure count has remained steady at around 150. This is possible due to gradual renovation and replacement of damaged sewers – annually around 10 km of pipeline undergo a general overhaul. If possible, work is undertaken using trenchless technologies. In recent years, thanks to the availability of modern technologies, new sewers are being constructed in a similar manner. A risk evaluation for a given type of damage in the analyzed sewerage system was performed based on detailed data on those failures which occurred in 2003 (Fig. 3).

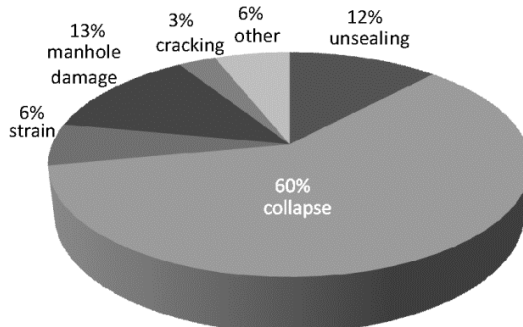


Fig. 3. Failure types by percentage on the analysed sewerage network in 2003 [15]

The sewer unit failure rate indicator λ [$\text{a}^{-1}\cdot\text{km}^{-1}$] was adopted as a criterion for the probability of sewer damage. The choice of this criterion made the evaluation of the risk of damage to the sewer not too difficult, although the availability of data on the number of failures in sewerage systems is worse than for example, in water supply systems. This is due to the fact that damage to a sewer is detected long after its occurrence, the detection often being incidental.

The adoption of a probability category (estimated probability level) is no longer unequivocal. The size of the network, the number of repair crew and technical backup play decisive roles. After analysing an analogous indicator for a water supply system, the characteristic sum of the individual estimated probability levels (probability categories) of the failure scenarios was related to an assumed, limiting failure rate value of $\lambda = 0.03$ [$\text{a}^{-1}\cdot\text{km}^{-1}$]. It is a limiting value for properly functioning sewerage network.

On a grading scale, the following three probability categories were adopted:

- low (not likely); $\lambda \leq 0.03 \text{ a}^{-1}\cdot\text{km}^{-1}$, $W_1 = 1$,
- moderate (quite probable); $0.03 < \lambda \leq 0.3 \text{ a}^{-1}\cdot\text{km}^{-1}$, $W_1 = 2$,
- high (probable); $\lambda > 0.3 \text{ a}^{-1}\cdot\text{km}^{-1}$, $W_1 = 3$

The value of the total system sewer unit failure rate indicator was $\lambda = 0.102436 \text{ a}^{-1}\cdot\text{km}^{-1}$ (for the network length of 1367 km and 140 failures). The values of the individual sewer unit failure rates (frequency) classified by type of event and the probability category of these damages are specified in Table 3.

Table 3

Summary of unit failure rates indicator, probability categories and categories of consequences of damage (by the author)

Failure rate indicator [$\text{a}^{-1}\cdot\text{km}^{-1}$]	Probability category	Consequence category
0.012292	1	1
0.061461	2	2
0.006146	1	1
0.013316	1	2
0.003073	1	2
0.006146	1	1

Each event carried a clearly defined consequence. Unsealing, sewer cracks, manhole damage contributed to a drop in the load bearing capacity of the sewer, they were followed by the ground subsiding around the sewer, manhole (damage caused by vehicles), polluting the groundwater. Problems were also noted, relating to the odour emanating from the damaged sewer. Sewer deformation, silted and slimy sewers, blocked manholes resulted in sewage flooding street properties.

Weighting the consequences of a given damage is very difficult. The size of the consequences for a given damage depends at least on the place where it occurred, the

effectiveness of the repair crews, access to the failure location, the time taken to detect the failure, the extent of the damage to the sewer (e.g. crack).

Individual evaluation levels of undesired events in a sewerage network are characterized according to a three category grading scale:

- low – failures in lateral and branch sewers which are simple to fix, and do not cause flow problems (deformation, insignificant unsealing, cracking), $W_2 = 1$,
- moderate – failures relating to collecting pipes and collectors (may cause disruption to road traffic, also incurs environmental costs, discharge sewers, combined sewers (collapsed sewers, infrastructure, sewer cracks, collapsed manholes) $W_2 = 2$,
- high – failures relating to the main and intercepting sewers, significantly affecting the road traffic, road damage, high environmental costs, combined sewers (significant sewer damage, disturbed ground, seepage of toxic substances into the sewer, e.g. ammonia) $W_2 = 3$. To evaluate risk, to a greater accuracy, 5 levels of risk were defined (Table 4).

Table 4

Categories and numeric values assigned to risk (by the author)

Risk likelihood	Value	Category of accepted risk
Very small	1	tolerated
Small	2	
Moderate	3 and 4	controlled
Large	6	unacceptable
Very large	9	

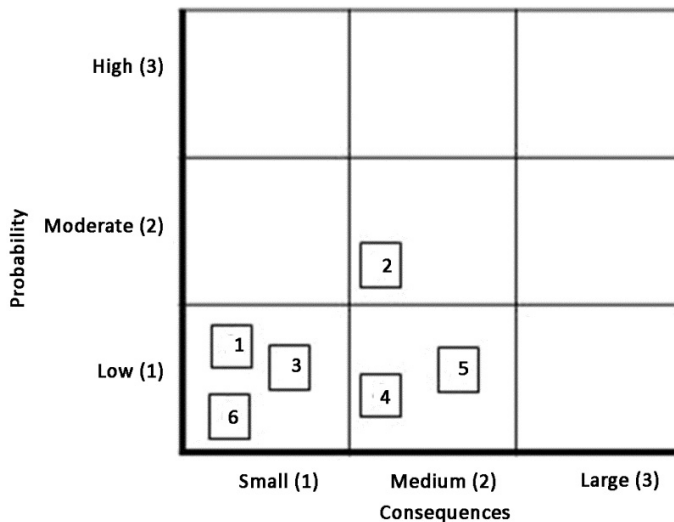


Fig. 4. Risk damage map of the analysed sewage system (by the author)

The likelihood of failure in the analysed sewerage network taking into account the type of failure is presented in the form of a risk map in Fig. 4.

6. SUMMARY

The evaluated risk of damage of the analysed sewerage system, using the PHA method, discussed in this paper, is a point for further discussion. This assessment was preceded by a characteristic of the evaluation of reliability and safety of the discussed system as necessary actions to evaluate risk and required information on the causes and consequences of sewerage system failures. After describing the PHA technique by means of the risk matrix, the risk of certain types of damage (unsealing of sewers, collapsed sewers, sewer deformation, manhole damage, sewer cracks and others) was assessed using the unit failure rate indicator, on the basis of proposed probability category values and consequence categories. These results cannot be compared with any previously published ones due to lack of such data relating to sewerage systems.

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