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Protecting critical infrastructure of water supply in interests of consumer safety

Keywords

water supply system, reliability and safety of water supply, critical infrastructure

Abstract

Given the status as an element of Critical Infrastructure, the operation of a water-supply system is an issue of importance that demands detailed analysis. There are in fact a range of crisis situations that may arise (e.g. floods, droughts, earthquakes, breakdowns, technical disasters, etc.) in which a ubiquitous common problem may relate to the supply of the population in drinking water. The lack of any such supply is fully capable of ensuring that serious disease and even epidemics arise, hence the need for emergency plans to be drawn up as regards the supply of drinking water under various crisis situations. The trigger for analysis and safety assessment in regard to a water-supply system is then the introduction of procedures in regard to safety management that minimise the impacts of incidental undesirable events, as well as the health and sanitary risks posed to water consumers, while introducing procedures appropriate in the context of the supply of water under crisis conditions.

1. Introduction

General strategy to ensure the protection of the so-called Critical Infrastructure (CI) was developed by the European Council in 2004, with the Commission of the European Communities two years later presenting a draft Directive on the identification and designation of European critical infrastructure and the assessment of needs in terms of its protection. This came under the European Programme for Critical Infrastructure Protection, EP-CIP and Critical Infrastructure Warning Information Networks.

Council Directive 2008/114/EC establishes procedures for the identification and designation of items of European Critical Infrastructure (ECI), and there is to be a common approach to assessing the need to enhance the protection of such infrastructure in order to protect people. The definition of such Critical Infrastructure as arrived at by the Poland's Act on Crisis Management is as follows (of course in translation): CI should be understood as systems and assets relating to them functionally, including constructions, devices, installations and services of key importance to the security of the state and its citizens or to ensuring the efficient functioning of bodies in the public administration as well as entrepreneurs (2008/114/EC; Tchórzewska-Cieślak, 2017; Żuber, 2014).

Where the supply of water is concerned, reliability can be seen to lie in the safeguarding of stable conditions that can provide for the meeting of current and future demand for water, in the right

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quantity, of the required quality, at any time convenient for consumers, and at an acceptable price (Rak, 2004; 98/83/EC). The random nature of failures makes the research in this area complex, while ensuring that is based primarily on the analysis of operational data and expert opinions (Eid, 2010; Eid et al., 2015; Rak, 2005; Sun et al., 2020). The effects of failure in a water-supply system give rise to inadvertent supply disruptions, or else to a supply that is of inadequate quality (AL-Washali et al, 2019; Rak, 2009a,b; Tchórzewska-Cieślak, 2006, 2007a).

Crisis management of critical infrastructure is clearly an important issue and requires case-by-case analysis for each type thereof, including the drinking water systems (Rak et al., 2019).

In the event that crisis situations arise, it does not really matter whether it is floods, droughts, earthquakes, breakdowns, technical disasters, etc. As there is always likely to be a problem with supplying the population in drinking water (Arai et al, 2010; Rak & Tchórzewska-Cieślak, 2013; Taeho et al., 2014). Furthermore, it is more or less universally typical that the lack of such supplies will cause (or certainly has the potential to give rise) serious diseases and even epidemics (Mays, 2005).

Naturally, a water-supply system may of itself generate a crisis situation. Then, various adverse event scenarios may result in an unreliable functioning and a consequent losses of safety for water consumers (Directive (EU) 2020/2184; Kroll, 2006; Rak & Tchórzewska-Cieślak, 2006).

Under the EU's new Drinking Water Directive, four areas were identified as offering scope for improvement, namely: "the list of quality-based parametric values, the limited reliance on a risk-based approach, the imprecise provisions on consumer information, and the disparities between approval systems for materials that come into contact with water intended for human consumption and the implications such disparities have for human health. In addition, the ***Right2Water*** initiative identified as a distinct problem the fact that part of the population, in particular marginalised groups, has no access to water intended for human consumption, and providing such access is a commitment under Goal 6 of the Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda for Sustainable Development (United Nations 2015)".

For these reasons it is important that emergency plans should be developed for the supply of drinking water in various crisis situations, along with a detailed risk analysis regarding the possible occurrence of undesirable events in a water-supply system, in order that a comprehensive safety management programme for such a system might be developed.

2. Crisis response plans

Poland's Government Center for Security is responsible for the preparation of the National Critical Infrastructure Protection Programme. The goals are to create conditions under which the security of critical infrastructure can be improved, in particular in the field of:

- the prevention of disruptions of critical infrastructure,
- the preparation for crisis situations that may affect critical infrastructure adversely,
- the response in situations of destruction or the disrupted functioning of critical infrastructure,
- the reconstruction of critical infrastructure.

The Water Framework Directive addresses the following points when it comes to safety and protection of water resources:

- water is not a commercial product like any other, but rather an inherited good that must be protected, defended and treated as such,
- water supply is a service of general interest,
- there is a need to prevent or limit the impact of incidents by which waters are accidentally polluted,
- the participation of the general public, including end-users,
- the sustainable use of water ought to be promoted by virtue of the long-term protection of available water resources.

In the EU Member States, the European Commission recommends that EN 15975-1:2009 and EN 15975-2: *Security of drinking water supply* be implemented. These relate further to Guidelines for Risk and Crisis Management. Part 1 and 2: Crisis management (EN 15975-1-2).

In the case of a water-supply system, a CI protection programme should include, in particular (after Tchórzewska-Cieślak, 2009a):

- the recognition of functionally significant objects,
- the identification, selection and prioritisation of countermeasures, as divided into: permanent

security measures (defining the necessary investments and measures in the field of security, access control, security and preventative measures, procedures for reporting threats to crisis management, raising public awareness, training and security information systems) and *ad hoc* security measures activated in line with a changing level of risk of threats,
- a developed risk-alert network (e.g. a multi-barrier system),
- contingency plans, e.g. alternative sources of supply of water to the population, water delivery by carts or in the form of bottled water,
- risk analysis based on major threat scenarios, with weaknesses identified and potential impacts analysed,
- the securing of funds and appointing of groups of experts to coordinate the implementation of individual procedures.

In accordance with Article 3, point 1 of Poland's Act on Crisis Management, a crisis situation is one exerting a negative impact on the level of the safety of people, the property to a large extent, or the environment. It is causing significant restrictions in the operation of the competent bodies in public administration, given the inadequacy of the available resources.

Crisis response plans are developed at the national, voivodship, poviat (county) and gmina (local-authority) levels. After (Rak et al., 2013; and Tchórzewska-Cieślak, 2018), the plan includes such elements as:

- main plan: risk characterisation and assessment of occurrence, including via risk maps and flood-hazard maps, characterisations of forces and resources and possibilities for them to be used, analysis of the functioning and possibilities of public administration in crisis situations, the envisaged variants of action and the mode of updating the plan and its annexes,
- crisis-response procedures defining a set of measures in the event of crisis situations under states of emergency: tasks in the field of threat monitoring, balance and mode of mobilising forces, and measures necessary to remove the impacts of threats, principles of cooperation and methods of reducing levels of loss and mitigating the impacts of the threat,
- functional annexes to the main plan specifying standard operating procedures, describing the methods of operation of entities performing tasks in the field of crisis management, organisation of communication between entities and the system of monitoring threats, warning and alerting, principles of informing the public about threats, organisation of evacuation, as well as social and medical care.

3. Water supply in crisis situations

Water contamination is understood as denoting unfavourable changes in physical, chemical and bacteriological properties that make it difficult or impossible to use it for human consumption. The appearance of contaminated water in the distribution subsystem may be caused by contamination of the water source, ineffective treatment processes or secondary water contamination in the supply network (Tchórzewska-Cieślak, 2009). Consumers are threatened by contaminants whose removal requires adjustment by conventional water treatment, those that can be removed after the initiation of alternative treatment technology, and those that the treatment process is unable to remove. The occurrence of microbiological contamination and pathogenic organisms is particularly dangerous (Tchórzewska-Cieślak, 2007b).

The main causes of pollution of water sources include (Pietrucha-Urbanik & Tchórzewska-Cieślak, 2018; Rak & Tchórzewska-Cieślak, 2005a):

- events with the features of a serious accident and serious failures, the register of which is kept by Poland's Chief Inspectorate for Environmental Protection, e.g. contamination of a river with petroleum substances caused by an accident involving land traffic,
- uncontrolled leakage of untreated sewage from wastewater treatment plants,
- deliberate action by third parties: acts of war, terrorist or cyber-terrorist attacks, psychopathic attack or acts of vandalism,
- extreme weather phenomena, droughts and floods.

Under Poland's Environmental Protection Act, a serious breakdown is an event occurring during an industrial process, storage or transport in which a release of one or more hazardous substances occurs, leading to an immediate threat to human life or health or to the environment, or to such a threat with a delay.

Water intakes may also prove potential targets for terrorists attack due to the very large range of impact that can be exerted on a water supply system and the direct impact of the supplied water on the health of consumers (Tchórzewska-Cieślak, 2011). However, it should be recalled that the introduction of a poisonous substance to treated water in a distribution subsystem is definitely more dangerous to consumers than the poisoning of river water, because the poisonous substance is significantly diluted in surface water (U.S. EPA. 2006; Roeger & Tavares, 2018).

However, an attack on a water-supply system does not have to be carried out physically. Cybercrimes and cyberterrorism, i.e. a type of terrorism that uses the achievements of information technology, poses an increasing threat in the modern world (Rak & Tchórzewska-Cieślak, 2006; Rodrigues et al., 2020). Currently, more and more large water-supply systems make use of modern SCADA or GIS software. It is frequent for water-treatment processes to be fully automated. Communication between individual subsystems included in a water-supply system usually takes place using GPRS data transmission. Therefore, disruption of remote-control components by third parties may lead to disruptions in the functioning of the water-supply system and, as a result, to the need for water supplies to a city to be suspended (Tchórzewska-Cieślak & Pietrucha-Urbanik, 2013, 2014).

The effects of emergency events and crisis situations occurring in a water-supply system take in supply companies, individual consumers and industry (Rak & Tchórzewska-Cieślak, 2007).

In the event of a crisis situation, drinking water should be supplied to the supply system in the required amounts (Tchórzewska-Cieślak & Rak, 2005b; Rak & Tchórzewska-Cieślak, 2010). There therefore needs to be:

- a balance of water demand under normal conditions and in a period of limited supplies,
- a list of functionally significant water-supply devices and their technical characteristics, as well as a compilation of data on equipment with power generators,
- an analysis of shortages in terms of the quantity and efficiency of water intakes, and the quantity and power of generating sets,
- a characterisation of water-supply devices that will be able to operate under special conditions,
- a list of activities whose pursuit is necessary should there be contamination, as provided separately for each type of contamination, along with the sizes of doses to be applied and the dosing method, as well as analysis of the risk to health,
- qualitative and quantitative characterisations of the water services necessary for a fully operational service, including the organisation of fully operational communications for notification purposes,
- a schedule for the delivery of water in the event of a supply-system failure,
- a list of people (operational positions) responsible for different activities.

Methods to reduce the consequences of emergency events in a water-supply system that arise include:

- the development of emergency response plans, not least in regard to people being supplied with drinking water from alternative sources,
- the development of alternative water-treatment technologies, in the context of the possibility that incidental events may arise,
- the development of an information system, as well as preventative measures,
- ongoing monitoring of the subsystem by carrying out systematic inspections, cable renovation and modernisation work in regard to the entire subsystem,
- an increase in reserve margins (alternative water sources, emergency capacities in network reservoirs).

Crisis situations and failures can be prevented by ensuring the protection of critical elements of a water-supply system, by remote monitoring of that system, by the planning of maintenance services, and by the development of a water safety plan based on risk analysis resulting from the possibility of undesirable events.

4. Minimising health risks

The World Health Organization (WHO) recommends the development of the so-called water safety plans – WSPs, with a view to so-called health risks resulting from the possibility of consumption of contaminated water by consumers being minimised (Oluwasanya, 2017; WHO 2011; Tchórzewska-Cieślak, 2011).

Examples of drinking-water contamination and proposed WSP remedial measures are as follows:

- microbiological contamination:
  - protection of the intake against cattle and human clusters (protective zones of water intakes),
  - use of early warning systems (e.g. screening stations) to stop water abstraction during periods of high contamination. e.g. after thunderstorms,
  - increasing the reliability of treatment by introducing back-up (alternative) systems,
  - automatic closure systems preventing the supply of improperly treated water,
  - anti-backflow devices,
- chemical contamination:
  - optimization of chlorine dosing to reduce trichloromethane,
  - isolation of the system from potential leaks,
  - risk assessment for suppliers of chemicals,
  - physical contamination:
  - rinsing the water supply network,
  - new standard maintenance procedures to prevent re-suspension of sludge,
  - measures to prevent backflow.

Risk management under WSP should include (WHO 2011; Tchórzewska-Cieślak, 2018) among others:

- to carry on hazard assessment and risk prioritization for each subsystem from source to consumer,
- to analysis the identified risk (selection of events that may trigger a sequence of adverse events, the so-called domino effect, development of models of emergency scenarios, development of functional and system models of sequences of events: event trees and failure trees, analysis of operator errors, estimation of the probability of occurrence of threats and probable causes and health effects for consumers),
- to perform quantitative health risk assessments and assess the safety level of water consumers,
- to identify pathways through which threats can be passed on to consumers,
- to identify critical control points,
- to define the method of monitoring and the control procedures for each identified risk, including the definition of the scope and frequency of monitoring (acceptance limits),
- to prepare recommendations for the decision-making process (proposing those risk control options which, according to experts, are the most effective in terms of expected benefits and incurred costs),
- to develop procedures for informing water consumers about threats and risks, taking into account terrorist threats (including cyber and bioterrorist threats).

5. Analysis and assessment of threats of water consumers safety

First of all, risk assessment should cover: hazard identification and the development of scenarios of adverse events (Tchórzewska-Cieślak, 2018).

The purpose of hazard identification is to indicate the type of substance in drinking water, while the assessment of the level of risk should be based on indicating its effect on human health and classifying the substance on the basis of all available data. The impact of individual substances on human health is determined by appropriate specialists (doctors, chemists, biochemists, microbiologists) based clinical and long-term laboratory tests.

In the context of the health risk analysis, one should also consider substances that are not currently standardized, but the conducted research indicates that they may pose a potential health risk (e.g. genotoxic and carcinogenic), e.g. PAHs, xenobits.

Developed by U.S. Environmental Protection Agency (U.S. EPA) Integrated Risk Information System – IRIS is an electronic database containing information on health effects for humans from exposure to various chemicals in the environment. The IRIS database is a tool that provides information on hazard identification and dose response data estimation. The problems associated with the chemicals in water are mainly due to their ability to cause adverse health effects after prolonged consumption of contaminated water (Damikouka et al, 2007; Huggett, 2001; Hulebak & Schlosser, 2002; ISO, 2015a, 2015b, 2018; MacDonald, 2002; Marriott, & Gravani, 2005; Schmidt & Rodrick, 2003; Tchórzewska-Cieślak, 2018).

According to the European Union directive, the following stages of the procedure are distinguished in the process of health risk assessment through hazard identification and assessment based on:

- the physicochemical properties (physical state, boiling point, melting point, specific density, vapor pressure, solubility in water and organic solvents),

- the absorption routes (inhalation, dermal, digestive),
- the type of exposure (occasional, continuous, intermittent),
- the biotransformation (whether a more or less toxic substance is formed as a result of transformations).

The hazard analysis can also be performed using the HACCP method (Hazard Analysis Critical Control Points). The HACCP method is a procedure aimed at ensuring the safety of drinking water by identifying and estimating the scale of threats from the point of view of health quality and the risk of hazards during all stages of the drinking water production process.

The main HACCP procedures include: the identification of possible biological, chemical and physical hazards and the methods of identification. Potential hazards categories are: biological, chemical, physical. The system is also intended to identify methods of risk reduction and to establish corrective actions (Rak et al, 2008; Rak & Pietrucha, 2008; WHO, 2005).

6. Matrix method for analyzing and assessing safety of water consumers

The risk matrices are built up in function of the specificity of the system and the purpose of the risk analysis. For the analysis of the failure risk of the water supply network, the parameters characterizing the type of network and the failure frequencies are considered.

In the analysis of the water supply network safety, two types of risk can be considered: the production disruption risk (producer standpoint) and the health-related risk (consumer standpoint). The overall consumer risk is the result of both types of risk. A greater rank is assigned to the health-related risk (Tchórzewska-Cieślak, 2011).

Health-related risk is a function of the following parameters (Tchórzewska-Cieślak, 2011):

- the probability P or frequency f of the adverse events in SZZW as directly perceived by the consumers,
- the Cost C (e.g. purchase of bottled water, possible costs of medical treatment after consuming non-potable water or other non-measurable costs related to the loss of comfort, health, or life),
- the consumer's vulnerability V or resilience R to the adverse events.

Evaluation criteria for the loss parameter can concern in varying degree (Tchórzewska-Cieślak, 2018):

- water pressure offsets (over-pressure and under-pressure),
- organoleptic changes in water,
- consumer complaints,
- announcements in public media,
- health risk for consumers,
- secondary water contamination in individual parts of the water supply network,

While, evaluation criteria for the vulnerability parameter can concern (Tchórzewska-Cieślak, 2011):

- closed-loop network, emergency section separation (for repair),
- possibility of avoiding interruptions in water supply for consumers, full monitoring of the water supply network,
- a comprehensive emergency warning and response system covering the city's needs for at least 24 hours, full possibility of using alternative water sources.

7. Water supply system management using RCM procedure

Water supply system management using the Reliability Centered Maintenance (RCM) technique. The RCM is a method used to develop a management (maintenance) program, the process of functioning or operation of a system or its subsystems, in order to achieve the required level of reliability and safety (Anderson & Neril, 1990; Moubray, 1997; Nowlan & Heap, 1978; PN-IEC 60300-3-11; Smith, 1993; Yssaad & Abene, 2015).

The RCM method was developed in the 1970s, initially in the aviation industry, and later, inter alia, in energy, land and sea transport, heavy industry, automotive, oil and gas (Afefy, 2010; Deshpande & Modak, 2002; Emovon & Okwu, 2018; Ramli & Arffin, 2012; Ribeiro & Pinto, 2004; Sawatdee et al., 2007; Tarar, 2014; Vera-García, 2020; Wang & Majid, 2000).

Four basic assumptions of the method can be distinguished (Tchórzewska-Cieślak, 2018):

- maintain the required level of system functioning (priority given to the system operator),
- define system failures (important in terms of functionality) and the causes of failures that prevent the performance of the required functions,

- determine the risk level of the possible causes of damage; select the appropriate and most effective preventive procedures for the causes of damage with an unacceptable level of risk of occurrence,
- implement initial and dynamic handlers.

The Initial Maintenance Program should be developed at the system design stage as a preventive maintenance program. The program should include (Tchórzewska-Cieślak, 2018):

- data on: functions, operating conditions, environmental conditions, etc.),
- operating methods,
- operating tools,
- training plan.

The program should include: actual operating data, actual damage data, new techniques, new materials, new tools and operating techniques.

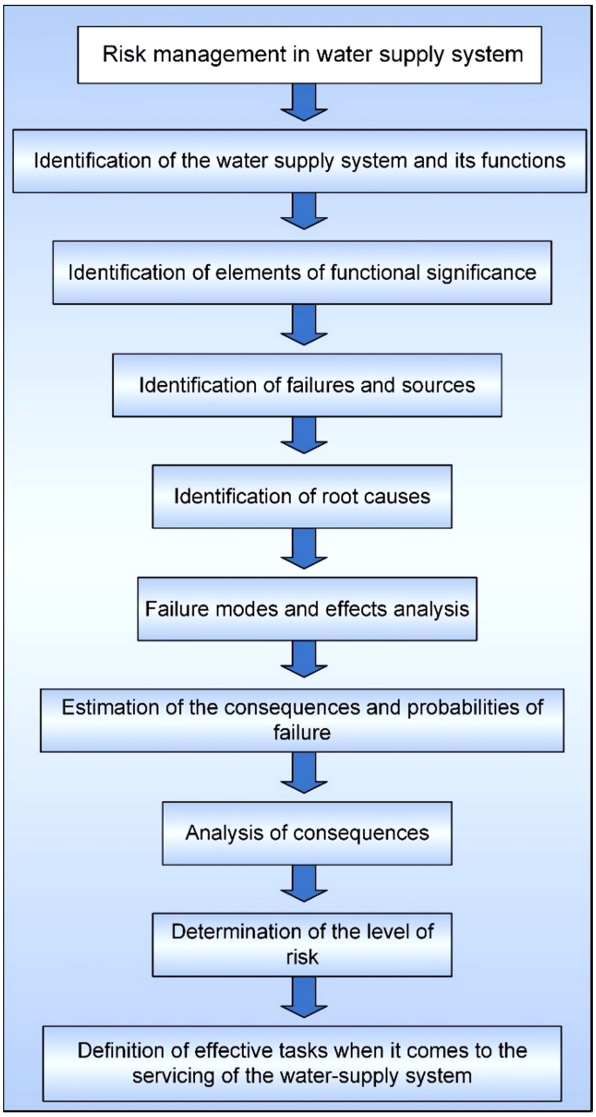

Figure 1. Procedures for managing the functioning of a water-supply system.

The required level of reliability and safety is the one that is built into the system and forms an integral part of it. This is the highest level of reliability and safety that can be expected from a water supply system if it receives effective maintenance service. Reaching higher levels requires modification of the management of the water supply system.

The basic procedures of the RCM method for the management of risks relating to the functioning of a water-supply system are as follows (Tchórzewska-Cieślak 2018), (Figure 1):

- identification of the supply system and its functions:
  - online (so-called regular) functions, i.e. basic operations of the system, with the operator possessing current information on elements of the system and the status of their required functions,
  - irregular (non-standard) functions not monitored constantly, and therefore relating to possible hidden damage.
- identification of elements of functional significance – a functional (block-structure) diagram of the system and a block reliability diagram should be developed, in order to depict the interrelated nature of individual system components in terms of the proper functioning of the entire system, with critical (functionally important) elements distinguished in this way,
- identification of failures and sources to determine how the system may prove unable to perform its functions (analysis in this case should identify failures that have already occurred in the system, on the basis of historical data, as well as failures that are probable, not yet occurring in the system, but capable of having serious consequences (the assumption here is that all failure conditions relating to a given system function should be identified),
- identification of root causes, again with all possible causes identified (possibly through the use of something like an Ishikawa chart),
- a Failure Modes and Effects Analysis (FMEA) in line with PN-IEC 812, so as to identify failures having a significant impact on the effectiveness of a water-supply system (again performed for each critical element of the system),
- estimation of the consequences and probabilities of failure,
- analysis of consequences,

- determination of the level of risk relating to the possible occurrence of causes of damage of a specific type, and – on this basis – assignment to the programmes of initial or dynamic maintenance,
- definition of effective tasks when it comes to the servicing of the water-supply system (developing a service programme that accounts for the possibility of risk transfer).

The RCM analysis method has been used in numerous complex production systems. It can also form part of a comprehensive risk-management program for a water-supply system, and would seem particularly useful in the planning of preventative actions relating to the prevention of damage, elimination of causes, and development of rescue scenarios.

For the method to be comprehensive, it should be implemented at every stage of the system life cycle, i.e. at the design stage, the execution stage and throughout the entire period of operation.

8. Conclusion

The risk-management process should start by establishing an integrated ranking list (identifying priority issues). The next step is the formulation of principles of risk management. In this regard, the adopted technical solutions should be optimised on the basis of the expected results and the invested funds. The selected solution should be implemented and its functioning monitored. This will allow for verification of the method used and a determination of the extent to which risk has been limited. Enterprises to which the operational supervision of the water supply system belongs should be able to manage risk, inform users about its size, take appropriate actions to minimize that risk, and initiate actions that must be taken in the face of the risk.

One of the basic elements of risk management should be the assessment of the diversification of the water supply with a view to the safety of ponds being improved.

The current standards for safety analysis in water management as broadly conceived (including the safety of a supply of drinking water) should cover the entire cycle of water circulation in the municipal catchment area. Such procedures are extensions of the WSP from the Water Cycle Safety Plan.

These plans include an analysis of the risk of threats at each stage of the water cycle in the municipal catchment area, analysis of the operation of sewage disposal and treatment systems, as well as risk assessment relating to areal pollution. In this aspect, a risk involves the so-called micropollutants, which are often not regulated, but may pose a threat to the health of consumers, as well as to the natural environment.

In the face of growing tensions in the international arena, including via projected conflicts over water, as well as climate change, it would seem necessary to have an efficient system of threat detection, as well as rapid crisis-response systems should a threat of water shortage arise.

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