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Smart City: Cyber-Physical Systems Modeling Features

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Abstract This chapter presents an approach to modeling smart city subsystems based on the principle of their cyber-physical integration into a single infrastructure. The uniqueness of the approach is the provision of the smart city topology as a set of cyber-physical clusters that ensure the functioning of the city. Unlike existing solutions, the proposed approach allows to consider the relationship of the information flows between different levels of smart city systems. Considered features of modeling of the cyber-physical water supply system (including active control system models, resource allocation models, scenario modeling) were put into practice by the smart city infrastructure in Saint Petersburg, Russia. The analysis of the functioning of the megalopolis water supply enterprise revealed significant vulnerabilities in ensuring the strategic security of the Leningrad Region, Russia. A basic list of recommendations for reducing the probability of water shortage has been developed based on scenario modeling of disabling of the main water supply source. These results are the basis for creating simulation models of interrupting the main source of smart city water supply and considering issues of improving the efficiency of water supply cyber-physical systems control in the smart city.

Keywords Cyber-physical systems · Management systems modeling · Smart city · Water supply systems · Improvement of control models · Digital water utility

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1 Introduction

The problem of resource management in modern cities is particularly relevant. Urbanization imposes certain requirements on the development of models of resource management. In the modern world, the issue of improving the efficiency of water resources management in modern cities is an important task. Cities are evolving, becoming more technological and smart while facing serious challenges-in addition to water scarcity due to climate change, the scarcity also occurs due to the degradation of water sources, anthropogenic impact on sources, an increase in the number of urban residents, which leads to significant problems of reducing the quality of life of urban residents, and deterioration of health. In December 2016, the United Nations General Assembly unanimously adopted the resolution "International Decade (2018–2028) for Action—Water for Sustainable Development" to help put a greater focus on the water during ten years [1], confirming the international importance of the issue of security water.

Modeling and management of environmental systems is an important aspect of ensuring the strategic development of cities, of which the quality of management of urban water supply systems plays a special role. Urbanization of the modern world, the dynamic development of society, due to the need to provide residents of modern cities with clean fresh water. At the same time, public water supply systems face a number of problems, including outdated infrastructure, growing regulatory requirements, problems of water quantity and quality, and lack of resources. According to [2], the United States will have to spend up to $ 200 billion on water systems over the next 20 years to upgrade transmission and distribution systems. Of this amount, $ 97 billion (29%) is estimated to be needed to control water losses. The average loss of water in systems is 16%—up to 75% of this can be recovered.

A similar situation is typical in most countries, which gives this topic of international significance. Anthropogenic impact on the environment, degradation of water resources, climate change increases the risk of water scarcity of cities, the occurrence of threats to water security of agglomerations. The potential of using modern technologies, including complex adaptive systems for controlling water supply in a modern city, allows minimizing risks and improving the quality of water provided to residents of cities.

The technological development of modern cities has certainly affected cities that are evolving into smart cities. The modern city is an abundance of systems that carry potential threats. Monitoring and security of critical water supply infrastructure systems in modern cities is an integral part of the security of vital support systems. At the same time, the possibility of integrated monitoring of systems increases the efficiency of using both the systems themselves in terms of maintenance and increasing the operating life, including involving robotic systems and systems and improves the quality of consumed water resources [3].

An important direction in ensuring the strategic security of cities is modeling potential threats and adjusting management based on the identified shortcomings. An integrated approach will increase the level of strategic security of modern cities.

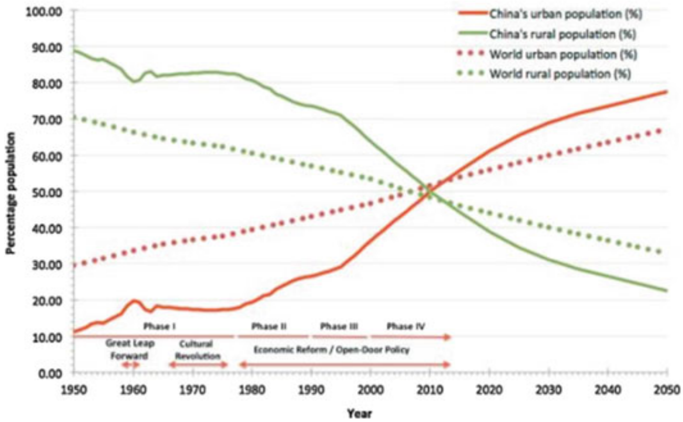

Fig. 1 Temporal dynamics of the urbanization levels (% urban population) for China and the world

Urbanization trends place higher demands on water quality. Often, previously designed water supply systems cannot provide a quantitative indicator of the increase in the volume of water consumed. The dependence on water is increasing at times, provided that additional external anthropogenic impacts on the environment are affected by the degradation of water resources and, as a result, the risk of lowering the quality of water provided to the urban population is realized Population growth combined with economic growth has fueled recent urban land expansion in North America. Between 1970 and 2000, the urban land area expanded at a rate of 3.31% creating unique challenges for conserving biodiversity and maintaining regional and local ecosystem services [4]. This trend also confirms [5], demonstrating the dynamics of the urbanization levels for China and the world (Fig. 1).

An audit of water supply systems (WSSs) in the United States, Netherlands и United States [6] shows that in the Netherlands, at least half of the water distribution pipes have been replaced since the 1970s; as a result, pipe networks are, on average, 33–37 years old. Although there are regional differences, an estimated 22% of the pipes in the United States are more than 50 years old; the average age of pipe at failure is 47 years, and only 43% of pipes are considered to be in good or excellent condition. In the United Kingdom, as much as 60% of pipe inventory does not have a record of pipe age, and estimates of average pipe age are on the order of 75–80 years overall.

Also, the aquatic environment acts as a major pool for antibiotics and antibiotic-resistant genes (ARGs). Antibiotics in the aquatic environment generally originate from effluents of wastewater treatment plants, industrial sites, hospitals, and livestock farms. It was estimated that in 2013 the total usage of 36 antibiotics reached 92,700 tons in China, making it the world's largest producer and user of antibiotics [7]. This allows concluding that, in addition to the level of deterioration of water supply systems, dividing by climatic zones, in the future, the model should include parameters for a technical assessment of the state of WSS in cities, as well as the quality of water supply sources as an integral part of assessing the level of water security in cities.

Based on the problems, we formulate the goal of the study—to identify the features of modeling the CP WSS of the Smart City.

Research Objectives:

1. To analyze the systems of a smart city as a combination of CPS and classifying systems.
2. Identify the features of CPS of a smart city by the example of water supply systems.
3. Build practical basic models for managing the cyber-physical water supply system in Saint Petersburg, Russia.

2 CPSs Within the Smart City

2.1 Concept Overview

To solve the first task, it is necessary to form a comprehensive view of the specifics, determine the concepts used in the study. The basic concepts are CPSs and smart cities. According to [8], cyber-physical systems (CPS) are complex systems with organic integration and deep interaction of computing, communication, and control (3C) technologies. Currently [9], CPS are managed, reliable, and extensible networked physical systems that are further integrated with computing, communication, and control capabilities that can interact with people through many new modalities. CPS are the foundation and core of Industry 4.0 and the Industrial Internet. As we see, the obligatory criterion of CPSs is the presence of functions and human participation in the performance of a certain function. The classification of CPSs in a smart city will be considered in more detail below.

According to [10] assert that a smart city has six main dimensions: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. The authors propose replenishing the concept, namely: smart city—is a set of systems operating in the digital ecosystem of the city, with the aim of increasing the efficiency of the use of city resources, ensuring safety, improving the quality of life and health of the city residents.

In the Russian Federation, for example, the term Safe City is used along with the term Smart City. The functionality of Safe City systems in the Russian Federation is a set of systems aimed at coordinating the interaction of services responsible for maintaining law and order, preserving the life and health of city residents, increasing the efficiency of management of administrative and administrative authorities, and improving interagency cooperation.

2.2 Classification of CPS of the Smart City

The next stage of the study is to consider the Smart City as a set of CPS and, based on this set, divide CPS into directions, creating a basic classification. At the same time, the classification requires a more advanced division and not just the creation of the main and supporting clusters.

The city is a holistic management object that operates according to certain rules and depends, in terms of management theory, on management decisions, managerial impact, quality, and timeliness. At the same time, the city can be represented as a holistic distributed active management mechanism in which there is a plentiful amount of active elements, for example, providing services, residents, enterprises. In turn, they have a mechanism for influencing the functioning of the governing body, and managerial influences depend on the preferences of the active elements.

Existing approaches to decomposing smart cities into cyber-physical systems do not allow a comprehensive assessment of the interaction between different cyber-physical systems. The approach to classification is either very superficial [9]. Only the basic functions of the city and the division into main and supporting clusters are taken into account. Or there is no classification at all [19], which does not allow us to form a consolidated topology of cyber-physical systems of a smart city.

In this chapter, we propose to consider a smart city as a set of basic cyber-physical systems. These systems include a set of modern tools for protecting and processing the received information using basic Analytics technologies for making the best management decisions. The procedure for decomposing a smart city into cyber-physical systems is fundamental in the approach proposed by the authors. The extended classification requires a comprehensive infrastructure audit to identify cyber-physical systems. Each of these complexes includes a wide range of modern tools and interfaces that ensure the processing of various types of data and the provision of digital services and services, methods of automated processing, recognition, and ensuring all the properties of information security (confidentiality, integrity, availability of data).

In contrast to analogs, this approach allows us to take into account the peculiarity of the disparity and diversity of cyber-physical systems. Classification involves the decomposition of a smart city into cyber-physical systems and the division into categories (clusters). The classification is based on active system management functions. This makes it possible to comprehensively form the topology of cyber-physical smart city systems and evaluate their interaction. The basic classification of smart city cyber-physical systems developed by the authors is presented in Table 1.

The “Security” cluster can be interpreted both as “Providing” and “Supporting”. In turn, the authors decided to separate this function into a separate cluster, due to the potential increase in the number of threats to the functioning of the Smart City, especially cyber threats.

Table 1 CPS classification of smart city

Cluster	Description	Example CPS
Control	It is aimed at ensuring timely decision-making on the basis of reliable data obtained from CPS	Support and decision-making system, secure management, analytical systems
Control	Supervision of compliance with established requirements. Often presented as a subsystem of the cluster "management" or "safety"	Monitoring systems and condition, environment, traffic congestion, equipment condition
Safety	It is aimed at identifying potential threats to the security of both city residents and their property, as well as city infrastructure, enterprises	CCTV, video surveillance, warning systems, intrusion detection
Providing	Ensuring the functioning of the city	Water supply, gas supply, electricity supply, telecommunication, logistics
Supporting	Supporting systems responsible for maintaining the functioning of the city	Smart manufacturing, smart buildings

3 Modeling the Cyber-Physical Water Supply System of the Smart City

3.1 Analysis of the Specificity of the Subject

Based on the classification of Smart city CPS described in Chap. 2, let's look in more detail at the water supply system as an example of a CPS. To evaluate the features of modeling, it is necessary to analyze the principle of operation of the system.

The system is based on the principle of resource allocation using the infrastructure of the water supply enterprise. The supply function is the basic one for the enterprise and the supplied water (resource) must meet the established parameters (characteristics) approved in this particular locality (city, country). The characteristics are the quality and guarantees of quantitative indicators of providing residents in case of compliance with the established requirements, often contractual relations and pricing policy [11].

The system consists of a set of water supply sources (resources), a management body (water supply enterprise), and water supply infrastructure (main and local communications).

Let's imagine the functioning of a water supply company as a basic business process (Fig. 2).

A distinctive feature of digital Vodokanal as a CPS of a Smart city from an "analog" Vodokanal is the availability of specialized equipment, sensors, for example, based on IoT and IIoT, data centralization and Analytics that allow you to quickly monitor the state of systems, optimize maintenance costs, and indirectly increase the service life of the infrastructure.

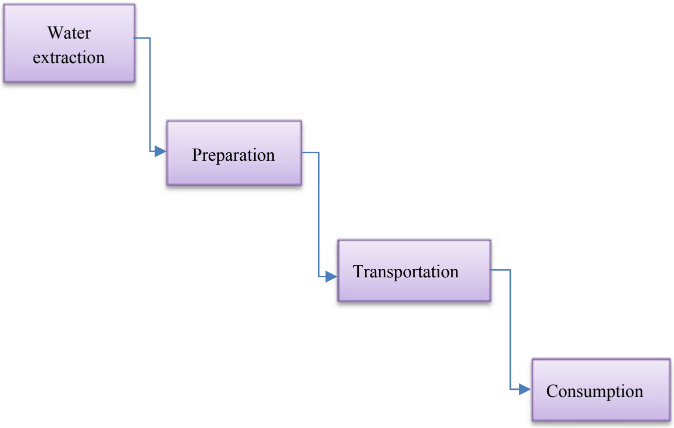

Fig. 2 The Basic business process of functioning of a water supply company

If we consider the water supply system as an active system, then with the appearance of additional intelligence of the system, increasing the active elements of the system, the complexity of managing the system increases. In this case, part of the control becomes automated or automatic, thereby reducing the human factor, but there are additional potential threats that can affect the system's control mechanism.

3.2 Building Basic Models of a Cyber-Physical Water Supply System

Based on the study of the specifics of the cyber-physical water supply system of a Smart city, we will build basic models. A cyber-physical water supply system is a multi-link active resource distribution system, the resource is water. The system is managed by the management body. In control theory, active and passive systems are distinguished. In addition to being able to select a state, the AC elements have their interests and preferences, that is, they select the state purposefully (otherwise their behavior could be considered passive).

The General formulation of the task of managing an active system is as follows: The state of the system that belongs to some valid set A, is represented by the variable (1):

$$y \in A \tag{1}$$

The state of the system depends on control actions (2):

$$\eta \in U : y = G(\eta) \tag{2}$$

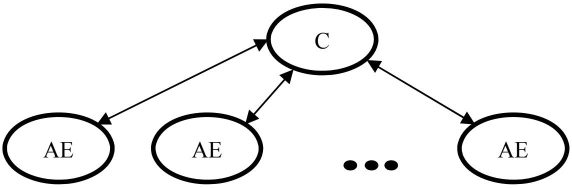

Fig. 3 Two-level automated fan-type system

Value $K(\eta) = \Phi(\eta, G\ (\eta))$ it is called control efficiency, where $\eta \in U$—control the action.

The task of the governing body is to choose such an acceptable control that maximizes the value of efficiency, provided that the reaction of $G(\eta)$ of the system to the control actions is known (3):

$$K(\eta) \to \max_{\eta \in U} \tag{3}$$

Accordingly, the management task is reduced to the need to choose the optimal control (4):

$$\eta^* = \tilde{\eta}\ (y) \in U, \tilde{\eta}: A \to U \tag{4}$$

Let's imagine a two-level active fan-type system (Fig. 3).

The AU structure is a set of information, management, and other relationships between AU participants, including relationships of subordination and distribution of decision-making rights. The governing body, active elements are members of the system, and resources are distributed according to the specified rules [12].

In turn, the section of contract theory is also applicable to modeling the functioning of water supply CPS. Contract theory-studies incentive mechanisms in active systems operating under conditions of external probabilistic uncertainty are also discussed in Sect. 3.4.

Consider the following approach based on the resource allocation mechanism. When distributing a resource between n active elements центр. The resource value of the i—element is determined by its utility function (5), where x_i—is the amount of resource it receives, a r_i—is the type of active element.

$$\varphi_i(x_i, r_i) \tag{5}$$

In turn, the main task of the center will be to distribute the resource itself with a given goal, for example, to maximize the utility of all elements (6)

$$\sum_{i \in I} \varphi_i(x_i, r_i) \to \max_{x \geq 0} \tag{6}$$

When modeling CPS, it is necessary to take into account the feature of the multi-links of the active system, which affects the system control model.

3.3 Consideration of the Features of Modeling Integrations of the Cyber-Physical Water Supply System of a Smart City

Modeling integrations of the cyber-physical water supply system of a Smart City has certain features. Integration refers to the process of combining disparate system elements into a single unit or dividing them into secure segments in order to improve the efficiency of system management. In our case, we will consider the process of integrating the integration of a cyber-physical water supply system with the management center of Smart city systems. Which is often a hardware and software platform that meets the security requirements for data storage and processing.

Integration in order to centralize data, improve the management and control mechanism, should be considered as additional potential threats to the functioning of the system.

To evaluate the performance of the CPS modeling integration of water Smart city model underlying the data exchange between the elements of the active system as a "Digital water supply system" (DWSS) and "Analog water supply system" (AWSS), it will also give an initial expert assessment of changes in the number of parts of the system, additional potential vulnerabilities.

Figure 4 simulates the functioning of an "analog" water utility, i.e. a water

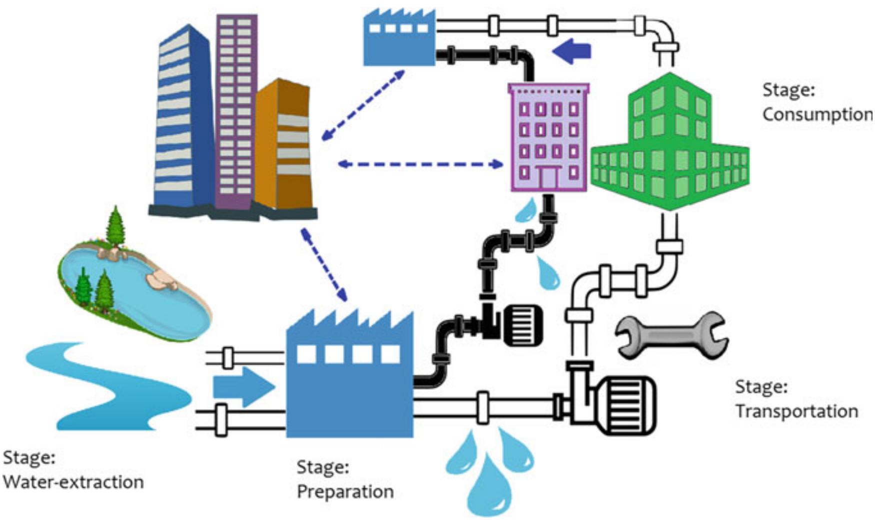

Fig. 4 Modeling of the operation of the "analog water supply system"

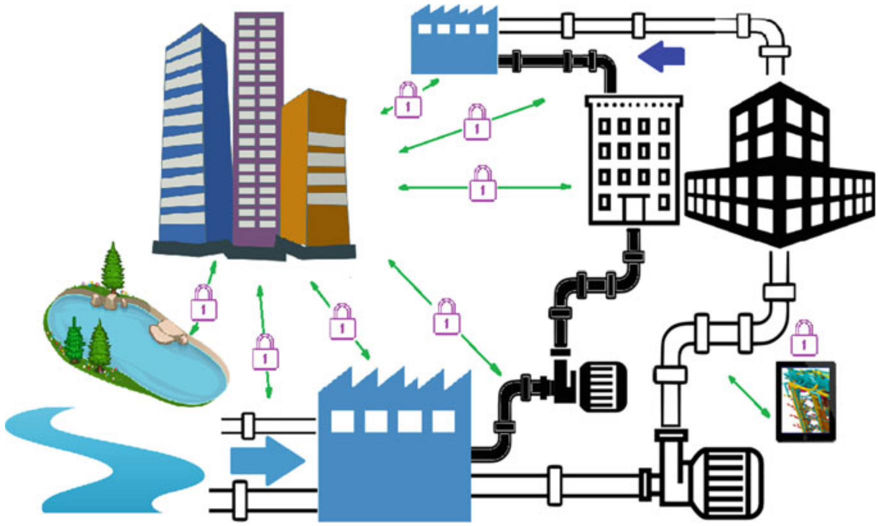

Fig. 5 Modeling of the operation of the "digital water supply system"

supply company that does not use centralized systems for accounting and monitoring resources, equipment condition, operational monitoring of resource losses, and predictive Analytics. Often, the information provided to the management body is unreliable, untimely, and incomplete, which leads to the inability to form an objective full-fledged situation for the water supply enterprise, the quality of the resource, equipment wear, planned and actual costs for repairs, and to ensure the level of safety.

Figure 5 simulates the functioning of the "Digital water supply system" as a complete CPS. Data is exchanged in a secure, centralized, and automated way at each production stage, according to the business process Fig. 2—from source to consumer. It analyzes the chemical and biological composition and resource losses, the condition of equipment and its level of wear, and quantitative indicators of consumption. Innovative technologies become a tool to improve the control efficiency of water supply systems of a modern city [13]. By automating the operation of the "digital water channel", the potential number of security threats increases, which, as already mentioned, must be taken into account in the management models of the CPS of water supply in a smart city [14].

Based on the analysis, we compare the advantages and disadvantages of the two types of water utilities (Table 2).

The digital water channel control model is different from the analog water channel management model. Digitalization of the industry has a positive impact on the level of development of water utilities, centralizes the exchange of data over secure communication channels, provides the opportunity to build models of both deterministic and stochastic, the result of which is to optimize costs [13] and improve the quality of services provided to consumers. Often, the main problem of the transition to the

Table 2 Comparison of advantages and disadvantages of the operation of "analog water supply system" and "digital water supply system"

	The analog water supply system	The digital water supply system
Advantages	Less qualified personnel to maintain systems "Used" to manage this way and unwillingness to change the strategy	Improving the quality of delivered water Increasing the level of security Loss reduction Cost optimization
Disadvantages	Additional threat The lack of systems for monitoring the quality of the resource There is no reliable operational information about losses	Increasing the number of threats Additional infrastructure maintenance costs

management of a "digital water channel" is the lack of funding even to maintain the existence of an "analog water channel". The authors believe that this problem is a serious test and challenge for the modern world in the period of transition to digital format, and it is important that the technological solutions of Smart cities also meet the security requirements, including in the field of CPS water supply for Smart cities.

3.4 Practical Implementation

Let's take a practical example of the created basic models and analyze their applicability. One of the largest cities in the Russian Federation – Saint Petersburg with a population of more than 5 million people-was taken for the study. Vodokanal St. Petersburg, Russia's oldest and one of the biggest suppliers and sewage operators in Russia. Vodokanal of Saint Petersburg is one of the best water supply and sanitation companies in Russia. The installed technological equipment allows us to provide high-quality water to consumers, while the negative factors of the company's operation for environmental pollution are minimal and meet the requirements of international standards. Water in the Baltic Sea in the area of Saint Petersburg has a low level of anthropogenic pollution, which allows us to conclude about the effectiveness of measures and technologies used to ensure the management of the functioning of the cyber-physical water supply system.

Build two almost basic models, as applied to St. Petersburg:

1. Resource allocation model, according to the theory of contracts.
2. Scenario modeling of failure of the main water supply source (degradation, infection).

A. *Resource allocation Model, according to contract theory.*
An active element, such as a consumer, selects an action $y \in A$, which under the influence of the external environment leads to the implementation of the result of the i-th active element (7), where где A—is the set of feasible actions of the

active element, A_0—is the set of valid results of activity of the active element [12].

$$z \in A_0 \tag{7}$$

Suppose that on the available set of possible actions of the active element is finite and has the form

$$A = \{y_1 \ldots, y_n\}, A_0 = \{z_1 \ldots, z_n\} \tag{8}$$

Set formula

$$\sigma_i = \sigma(y_i), c_i = c(y_i), p_{ij} = p(z_j, y_i) \tag{9}$$

At the first stage, you need to define a set of actions to be implemented: for each possible action

$$y_k, k = \overline{1, n} \tag{10}$$

We are looking for an incentive system σ_j^k, that satisfies the constraints of (11) and implements it.

$$0 \le \sigma_j^k \le C, \quad j = \overline{1, n} \tag{11}$$

Looks like:

$$\begin{cases} \sum_{j=1}^{n} \sigma_j^k p_{kj} - c_k \ge \sum_{j=1}^{n} \sigma_j^k p_{ij} - c_i, A_i = \overline{1, n} \\ 0 \le \sigma_j^k \le C, j = \overline{1, n} \end{cases} \tag{12}$$

Conclusion: this basic approach allows us to conclude that contract theory can also be applied to modeling the functioning of water supply CPS.
After analyzing the basic theoretical mechanism of resource allocation, according to the theory of contracts, let's move on to a practical assessment of the resources themselves, namely the sources of water supply in St. Petersburg.

B. *Scenario modeling of failure of the main water supply source (degradation, infection).*

During the study, it was revealed that according to the approved state scheme of water supply and sanitation of the city of Saint Petersburg [15], the main source of water supply in the city is the Neva river (98% of the total amount of water consumed; the remaining 2% are underground sources). The proportional ratio makes it possible to consider that it is actually the main and only one.

In case of contamination/degradation of the main source of water supply, it is necessary to promptly ensure the transition to a backup source of water supply, if there is one. It often happens that in many settlements there are no redundant sources for a variety of reasons—from natural to economic [1].

Reservation of water supply sources dates back to antiquity, for example, in the Byzantine period in Istanbul, one of the great creations in the field of water supply reservation was built, combining with a special architectural monument-the Big Basilica Cistern [16]. CIS tank was about 100,000 tons. The 4.80 m thick exterior walls were made waterproof by covering them with a 3.5 cm thick brick dust solution.

According to the Russian legislation [17], the reservation of sources of drinking and household water supply in the event of an emergency is carried out on the basis of underground water bodies protected from contamination and clogging. At the same time, such sources should be provided with special protection zones, the regime of which corresponds to the regime of zones of sanitary protection of underground sources of drinking and household water supply.

Source redundancy can be implemented with the help of additional wells, backup protected storage (open and closed), rapid transportation of the resource by transport, and storage of large-size reserves at enterprises (Fig. 6). Switching to a backup is also possible in an automated way, similar to the power supply when in case of disconnection of the main power source, the backup power is switched on either by

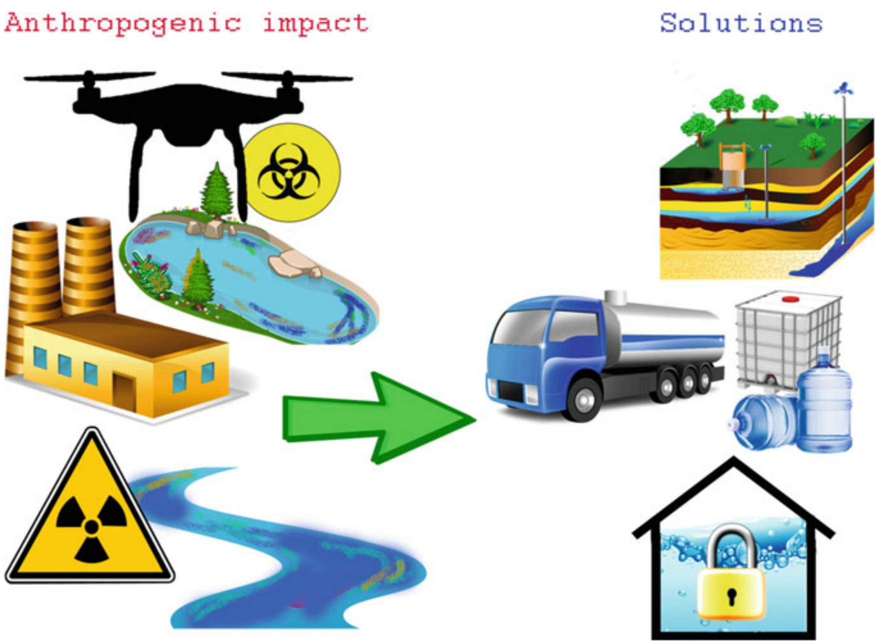

Fig. 6 Modeling potential water degradation scenarios

switching to an independent backup power line or by using a specialized installation like a fuel generator or solar/wind power and battery-stored backup power.

At the same time, it is often problematic for many cities to consider the possibility of quickly entering a backup water supply, especially if management systems do not provide for such a possibility. Unfortunately, many cities face this situation, which leads them to disrupt the stable functioning of systems and increase the risk of threats to water security. Active chemical and biological contamination, deliberate anthropogenic contamination of water sources for the purpose of terrorist and extremist activities, including sabotage [18], which are displayed in this scenario modeling, are potentially possible. Such studies allow us to justify the feasibility of modeling the functioning of CPS and the introduction of reservation systems in order to increase the level of strategic security of a modern city, improve the level of water resources control.

Recommendations based on scenario modeling:

1. Saint Petersburg is one of many cities that has a "single" source of water supply. Very often, cities are not provided with backup sources of water supply and in case of emergency situations-epidemics, biological infections, anthropogenic pollution, can cause significant economic and social damage. When building smart cities, it is necessary to take into account the fact of a "single" source and to forecast and analyze the scenario in the models in order to improve the strategic security of cities.
2. The presence of virtually the only source of water supply for the city of Saint Petersburg with more than 5 million inhabitants is unacceptable. The largest freshwater lake in Europe-Lake Ladoga, which is the source of the Neva River, is located near Saint Petersburg. This can potentially increase the security level to ensure water security of the region requires an increase in monitoring of compliance with measures of the purity of lake Ladoga, equipping CPS water for the purpose of operational monitoring of the chemical and biological status of the water body.
3. Consider the possibility of building closed protected freshwater storage facilities in Saint Petersburg.
4. Further research will include additional simulation modeling of various scenarios for the functioning of the cyber-physical water supply system in Saint Petersburg, taking into account the identified threats, trends, and the level of equipment wear, as well as integration with Smart city systems. Special attention should be paid to improving the level of security of both the functioning of systems and assessing the potential consequences due to the failure of supporting CPS.

4 Conclusion

Advanced technologies of smart city governance (including water resources management) are based on the use of cyber-physical systems. At the same time, the existing global challenge of improving water resources management is particularly acute in the context of water source degradation, water shortages, and continuing population growth. This area of research is a pressing issue. The analysis of the theory and practice of smart city functioning as a set of cyber-physical systems allowed to conclude that it is advisable to refine the methods of classification of smart city cyber-physical systems. In particular, the application of the clustering approach of the cyber-physical systems of the smart city became the basis for the developed taxonomy of cyber-physical systems. This classification implies the decomposition of cyber-physical systems on the basis of control functions, providing consolidated construction of the cyber-physical system's topology and assessment of their interaction.

The authors created the basic models of functioning of cyber-physical water supply systems in a modern city and considered the specifics and features of the modeling process. When modeling cyber-physical systems of a smart city, it is necessary to take into account that these systems are multi-link active ones. By building models, it is possible to improve water management and reduce potential risks [20]. The development of integrated models of cyber-physical water supply systems functioning in a modern city requires additional research. The basic models of cyber-physical water supply systems simulated by the authors have been practically tested. Conducted scenario modeling implied disabling of the main water source in a city with more than 5 million inhabitants - on the example of the city of Saint Petersburg, Russia. In order to increase the strategic security of the region, a list of measures has been compiled to reduce the likelihood of water scarcity, including the creation of reserve protected closed-type freshwater storage facilities and equipping Lake Ladoga with cyber-physical water supply systems. These results are the basis for considering the improvement of smart city water supply management and the creation of simulation models for the scenario of the smart city's main water source disabling.

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