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Information technology for forecasting epidemiological threats based on the telegraphic equation

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ABSTRACT

Based on the analysis, it is established that traditional approaches, such as the SIR (Susceptible-Infectious-Covered) and SEIR (Susceptible-Exposed-Infectious-Covered) models, do not provide sufficient forecasting accuracy and do not take into account the complex dynamics of the spread of infectious diseases. The need to develop a method that will improve forecasting accuracy and provide support for managerial decision-making to predict the spread of epidemiological threats based on the telegraphic equation is substantiated. The developed system allows for making effective management decisions aimed at reducing the negative impact of the epidemic on the population and medical infrastructure. The use of the telegraphic level allows us to predict the wave spread of infection, spatial and temporal delays, as well as sources of new infections, which ensures accurate forecasting of peak periods, the duration of the epidemic, and the workload of medical facilities. The developed method integrates the classical SIR model with the telegraphic level, which allows the modelling the dynamics of infection spread in a spatio-temporal environment. This method provides forecasting of the spatial and temporal dynamics of infection spread, taking into account wave effects, delays, and the influence of external factors. It provides an opportunity to accurately analyze key epidemic indicators, such as the peak of the disease, its duration, and the distribution of the burden on hospitals. The developed method and mathematical model based on the telegraphic level provided an appropriate level of accuracy in predicting the spatial and temporal dynamics of the spread of epidemiological threats. Testing the model on historical COVID-19 data showed that the average forecast error was 5...10%. This indicates the model's adequacy. In the case of high population mobility, the model accurately described the wave dynamics of the infection. The proposed decision support system includes a user-friendly interface with four tabs for entering model parameters, analyzing results, visualizing them, and generating recommendations. It allows to improve the accuracy of estimating the duration of the epidemic, peak loads, and some resources. The developed system is a tool for managers to support the adoption of governmental decisions aimed at predicting the infection of the population of regions and optimizing the use of medical resources. The results of the study can be used to plan epidemic response measures at the local, regional, and global levels. The proposed system ensures efficiency, flexibility, and accuracy, which are key to managing epidemiological situations in the face of modern challenges.

Keywords: Information technology; model; telegraphic equation; epidemiological threats; forecasting, modeling

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INTRODUCTION

Epidemiological threats, including infectious diseases, remain a significant challenge in the healthcare system, affecting all aspects of life and activities of the community population [1, 2]. The COVID-19 pandemic has demonstrated that timely forecasting of the spread of infection is important. This allows us to justify preventive measures and minimize the negative consequences for the population. The main problem in addressing this issue is the complexity of modeling the spread of the epidemic in real-time, taking into account many factors, such as geographical features, social contacts, immunization rates and the nature of the transmission of the infection [3, 4]. In this case, using mathematical models involving computational intelligence becomes a prerequisite for effectively managing epidemiological threats.

Predicting the spread of epidemiological threats requires substantiation of theoretical foundations based on differential levels. In particular, SIR (Susceptible-Infectious-Covered), SEIR (Susceptible-Exposed-Infectious-Covered), and their modifications can be used for this purpose. However, most of these models are focused on describing processes under deterministic conditions, which makes it difficult to adapt them to the real conditions of the project environment with a high degree of uncertainty and spatial and temporal variability.

In practice, forecasting is often limited to statistical approaches or simulation modeling. These methods do not always take into account the dynamic nature of the spread of infection. At the same time, current research shows that the use of the telegraphic equation to model wave processes in the spread of epidemics is a promising area [5, 6]. The telegraphic equation allows us to describe not only the rate of infection spread but also its spatial patterns, which is quite important for decision-making in a crisis.

The use of the telegraphic level in decision support systems provides a qualitatively new approach to modeling epidemiological processes. This equation allows for wave and delay effects that traditional models do not provide. In addition, the integration of this mathematical framework with modern computational intelligence and big data methods allows for adaptive models that take into account real-world conditions and are quickly updated based on new data.

Today, there are no practical tools for predicting the spread of epidemiological threats based on the telegraphic equation. Therefore, there is a need to develop an appropriate method and decision support system that will improve the efficiency of forecasting the spread of epidemiological threats based on the telegraphic equation.

LITERATURE ANALYSIS

Effective management decision-making in the face of epidemiological threats largely depends on the integration of mathematical modeling, computational intelligence, and real-time data processing [7], [8], [9]. We have analyzed modern methods and approaches related to forecasting the spread of infectious diseases, focusing on their theoretical foundations, practical implementation, and limitations.

Mathematical models in epidemiology deserve special attention. Epidemiological modeling traditionally involves the use of deterministic approaches. They are the basis for such models as SIR and SEIR. They describe the dynamics of disease transmission using systems of ordinary differential equations [10, 11], [12]. These models have been widely used to estimate infection rates and predict disease trajectories under various scenarios. However, they often assume a homogeneous mixing of populations and neglect spatial and temporal variations, which limits their application in real-world settings.

To address these limitations, stochastic models and network approaches have been developed [13, 14], [15]. These models take into account the randomness and complexity of the interaction network, capturing the heterogeneity of population dynamics. Despite their improvements, computational complexity and data availability remain serious challenges for their effective deployment.

At the same time, modern methods of epidemic forecasting are now being used. The use of partial differential equations has become popular in modeling the spatial and temporal dynamics of disease spread [16]. In particular, it has been proposed to use telegraphic equations, such as hyperbolic partial differential equations, to account for wave-like spread and delay effects in the spread of an epidemic [17]. These equations offer the advantage of describing more realistic dynamics than traditional parabolic models such as reaction-diffusion equations.

Decision support systems (DSS) are increasingly being used to improve the accuracy and speed up management decision-making [18], [19]. These systems combine predictive models with optimization algorithms to improve the efficiency of vaccination, quarantine, and resource allocation. However, most existing DSSs lack the functionality to use mathematical models such as telegraphic equations, which limits their ability to capture complex spatial and temporal dynamics. In addition, many systems are designed for specific diseases or areas, which reduces the possibility of using them for management decisions [20], [21], [22].

Thus, there are several gaps in existing research. Although scientists have made significant progress in epidemiological modeling and DSS development, there are still several unresolved scientific and applied problems [23], [24], [25]. In particular, many approaches do not take into account the dynamic interaction between the spatial distribution and temporal development of epidemics, which is essential for accurate forecasts. There is also limited integration of telegraphic equations. Telegraphic equations are not used in practical DSS implementations. In addition, existing systems are in most cases unable to adapt to the rapidly changing design environment.

Taking into account the identified gaps, our study proposes a method and DSS that use telegraphic equations to predict the spread of epidemiological threats. By integrating spatio-temporal modelling capabilities with computational intelligence, the proposed approach aims to overcome the limitations of existing systems, providing accurate results for management decision-making.

FORMULATION OF THE PROBLEM

Effective management of epidemiological threats requires accurate forecasting of their spread, taking into account spatial and temporal characteristics and a variety of factors that affect the dynamics of infection. Traditional models, such as SIR and SEIR, are unable to account for wave effects, delays in infection transmission and uneven spatial distribution, which limits their practical application. To solve these problems, it is necessary to develop a new approach that will improve the accuracy of forecasting and increase the efficiency of management decision-making.

Our study solves a scientific and applied problem, which is to develop a method and DSS for predicting the spread of epidemiological threats based on the telegraphic equation. This ensures that the spatial and temporal dynamics of the spread of infections are taken into account and allows us to develop effective response strategies based on real data.

The object of our research is the process of spreading epidemiological threats in the spatio-temporal design environment, which reflects the dynamics of infectious diseases due to their wave propagation, transmission delays, and the influence of external factors. The subject of the study is the method and tools for forecasting the spread of epidemiological threats using the telegraphic level, as well as the development of a decision support system for managing epidemiological processes based on this method.

THE PURPOSE AND THE OBJECTIVES OF THE STUDY

The study aims to develop a method and a decision support system for predicting the spread of epidemiological threats based on the telegraphic level. This allows to ensure the efficiency and reliability of epidemiological situation management at all levels - from local to global.

To achieve this goal, the following tasks should be performed:

– develop a method based on the telegraphic equation for forecasting the spatial and temporal dynamics of the spread of epidemiological threats, taking into account wave effects, delays, and the impact of external factors of the project environment;

– to create a DSS that integrates the developed method with real data for prompt forecasting of the epidemiological situation and providing recommendations for making effective management decisions.

RESEARCH METHODS

The study uses systematic approaches that combine mathematical modeling, numerical methods, computational intelligence tools, and data analysis methods. To describe the spatial and temporal dynamics of the spread of epidemiological threats, the telegraphic equation was used [5]. This is a hyperbolic partial differential equation that allows modeling wave processes, delays, and the interdependence between spatial and temporal parameters.

Numerical methods are used to solve the telegraphic level and obtain forecasts. In particular, the finite difference method for approximating derivatives, as well as iterative solution methods for computing numerical solutions in complex conditions with high dimensionality [6]. We also verify numerical methods by comparing them with analytical solutions for simplified scenarios.

We also use statistical methods to analyze historical data on epidemiological threats, including correlation analysis and hypothesis testing of the relationship between changes.

The DSS is created by integrating a mathematical model with computational intelligence algorithms and a user interface.

The main functionalities include:

1. Real-time collection and processing of real data.

2. Visualisation of the spatial and temporal dynamics of infection spread.

3. Providing recommendations for management decision-making.

A METHOD FOR PREDICTING THE SPREAD OF EPIDEMIOLOGICAL THREATS BASED ON THE TELEGRAPHIC EQUATION

The proposed method for predicting the spread of epidemiological threats with regard to spatial and temporal dynamics involves their description using the telegraphic equation. The telegraphic equation is a mathematical model used to describe wave processes. When solving the management task of predicting the spread of epidemiological threats, this equation allows for modeling the spatial and temporal dynamics of the spread of infections.

In general, the telegraphic equation has the form:

$$\frac{\partial^2 u(x,t)}{\partial t^2} + 2\alpha \frac{\partial u(x,t)}{\partial t} = c^2 \frac{\partial^2 u(x,t)}{\partial x^2} + f(x,t), \quad (1)$$

where $u(x,t)$ is a function that describes the number of objects (infected population) in space x and time t; α is the attenuation coefficient (characterizes losses or extinction in the process of infection spread); c is the rate of infection spread in space (analogous to wave speed); $f(x,t)$ is the source of new infections or external influences that lead to the emergence of additional infected people in the region.

When predicting the spread of epidemiological threats, the telegraphic equation is proposed to be used
to model the wave-like spread of epidemics. Unlike diffusion models (which are based on equations such as heat conduction and describe the gradual spread of infections), the telegraphic equation has its characteristics and allows for several components of the project environment to be taken into account (Fig. 1).

In particular, the spatial and temporal delay in the spread of the infection. The infection does not spread instantly. That is, it takes time for the wave to reach new territories or regions. The model also takes into account the presence of a spreading wave. During an epidemic, waves of infections can be observed when the first outbreak is followed by a wave of decreasing numbers of patients and then a new outbreak. This is due to repeated contact or other factors in the project environment.

The telegraphic equation describes such oscillatory processes well. In addition, the proposed method takes into account the rate of spread of the infection.

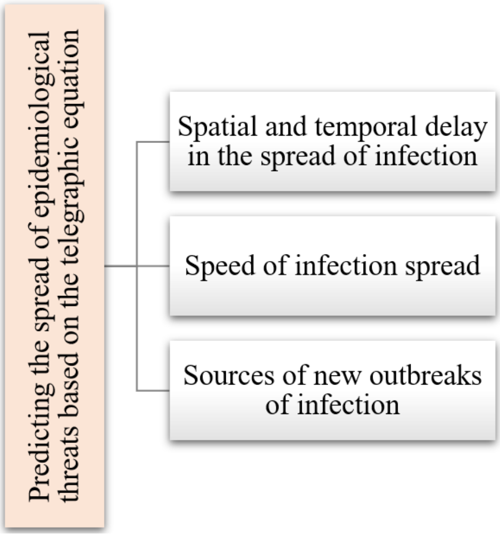

Fig. 1. **Components of the telegraphic equation used to predict epidemiological threats**
***Source*: compiled by the authors**

The rate of spread of infection varies depending on the mobility of the population, quarantine measures, etc. This method also takes into account the source of new infections. The function $f(x,t)$ describes the emergence of new outbreaks of infection in different places or at different times. This allows modeling situations where an epidemic may break out in remote regions with a delay.

The telegraphic equation assumes that the infection spreads in waves with a speed of c. These waves are damped by attenuation α, which describes the natural processes of epidemic decay or the measures implemented (e.g. quarantine). At the beginning of the epidemic, the function $u(x,t)$ describes a sharp outbreak, when the number of infected people increases sharply in the center of the epidemic and gradually spreads to other regions. For example, if the epidemic started at point x_0, then the wave of infection will spread from this point at a rate of c. After a certain time, the infected will appear at points $x_1, x_2, \ldots x_n$. The change in the intensity of infection of the population with infectious diseases in different regions depends on the attenuation coefficient α.

When predicting epidemiological threats, the initial number of infected people at a point x_0, time $t = 0$, level of population mobility and the impact of quarantine are set. Quarantine or vaccination affects

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the parameter α, increasing or decreasing the rate of epidemic decay. This makes it possible to simulate the spread of the infection in different regions with given initial conditions, as well as to assess how the infection spreads in the hospital district.

Knowing $u(0,x)$ and $u(l,x)$ – functions that describe the process of the epidemic at two points x in time, according to the differential-symbolic method [6], it is possible to find a solution to this problem, i.e. a function that analytically describes the process of epidemic spread at any point and at any time. At the same time, $u(0,x)$ is a function that describes the number of infected people (or other related quantities) at time $t=0$ for a certain point in space x. At the same time, $u(l,x)$ is a function that describes the number of infected people (or other related quantities) at time $t=l$ for a certain point in space x. In the case of $f(x,t)=0$, there are no sources of new infections or external influences that lead to the emergence of additional infected people in the region, equation (1) is homogeneous and the finding of its analytical solutions is shown in [5].

In general, the telegraphic equation allows us to accurately describe the wave-like dynamics of the spread of infections in a given region, taking into account time delays, the rate of infection spread and the sources of new outbreaks. The proposed method is used to predict peaks in population morbidity, the spread of infection to new territories, and to estimate the total burden on medical institutions in an epidemic.

The algorithm of the proposed method for predicting the spread of epidemiological threats based on the telegraphic equation is shown in Fig. 2.

To take into account the spread of infection not only in time but also in space, it is proposed to slightly adapt the telegraphic equation (1) to the problem of forecasting the spread of epidemiological threats with regard to spatial and temporal dynamics:

$$\frac{\partial^2 I(x,t)}{\partial t^2}+2\alpha\frac{\partial I(x,t)}{\partial t}=c^2\frac{\partial^2 I(x,t)}{\partial x^2}+f(x,t), \quad (2)$$

where $I(x,t)$ is a function that defines the dependence of the number of infected persons at a point in space x at a given time t; α is the attenuation coefficient; c is the rate of infection spread; $f(x,t)$ is external sources of infection, including new outbreaks in other regions or other influences.

Subsequently, the telegraphic equation is linked to the classical SIR model. This makes it possible to expand the spatial and temporal approach to modelling the spread of epidemiological threats. The combination of these two approaches allows us to simultaneously take into account both the dynamics of infectious disease infection in a region of a given population and the spatial distribution of infection.

The classical SIR model describes the dynamics of an infectious disease in a population, dividing the population into three groups:

S (susceptible) – the population of the region that may be infected;

I (infected) – the population of the region that is infected and can transmit the infection to others;

R (recovered) – the population of the region that has recovered or become immune, i.e. can no longer transmit the disease.

The model is described by the system of differential equations:

$$\frac{dS}{dt}=-\beta\frac{SI}{N},\quad \frac{dI}{dt}=\beta\frac{SI}{N}-\gamma I,\quad \frac{dR}{dt}=\gamma I, \quad (3)$$

where $S(t)$ is the number of vulnerable persons over time; $I(t)$ is the number of infected persons over time; $R(t)$ is the number of recovered persons; β is the rate of infection of the region's population; γ is the rate of recovery of the region's population; N is the total population living in the region.

Model (3) is the basic model for calculating the dynamics of infectious diseases. However, it does not take into account spatial features, such as changes in different regions, migration of people or delays in the spread of infection. Combining it with the telegraphic equation makes it possible to overcome these shortcomings.

The SIR model is good at describing the overall dynamics of infection within a population, but it does not take into account the spatial aspect of infection spread. To model not only the temporal but also the spatial and temporal dynamics of the infection, the telegraphic equation (2) is introduced. This equation allows us to model the spread of infection in the form of waves that propagate at a certain speed c in space x and time t.

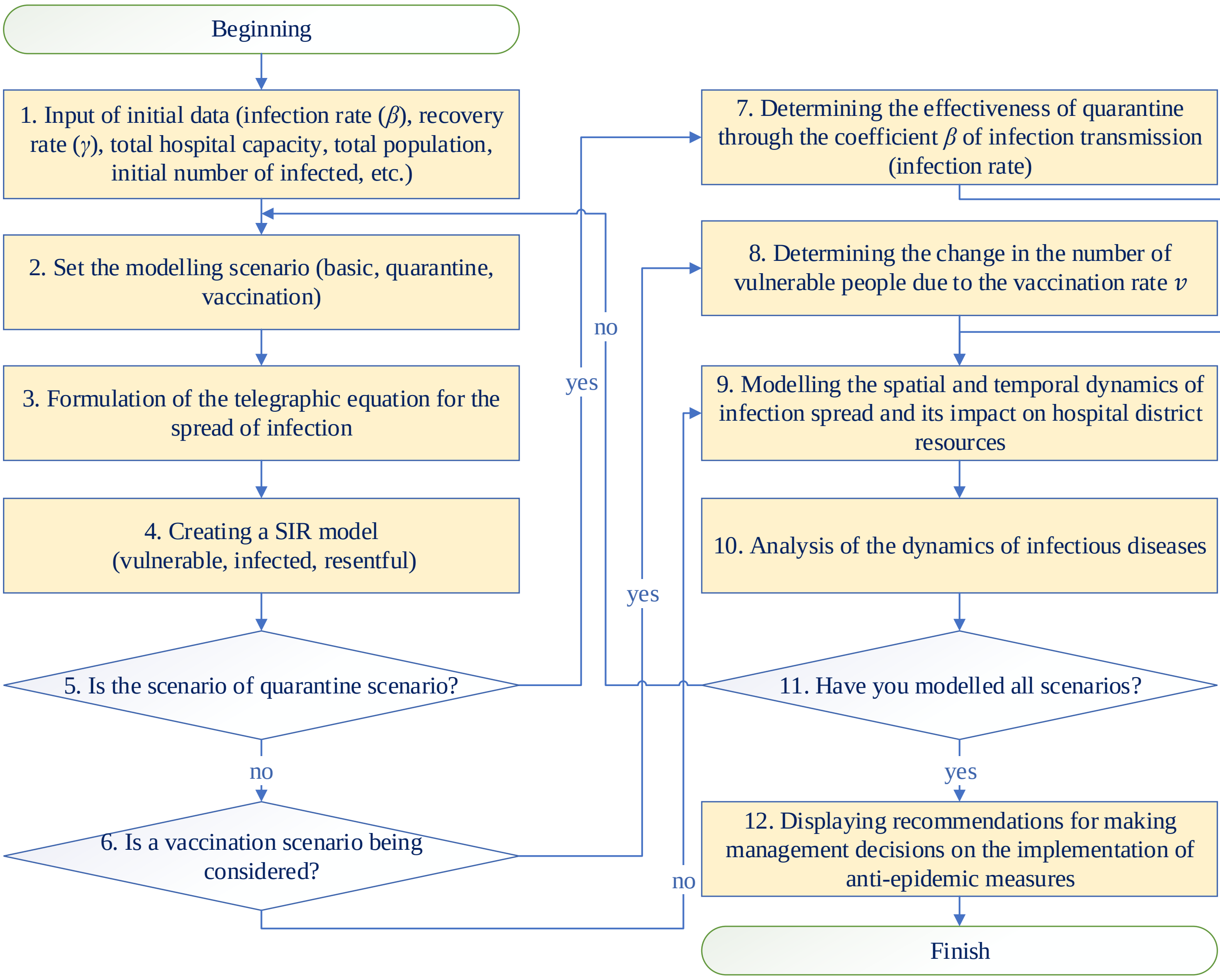

Fig.2. **Flowchart of the algorithm of the proposed method for predicting the spread of epidemiological threats based on the telegraphic equation**
***Source*: compiled by the authors**

Let us consider the connections between the models. The telegraphic equation (2) for spatial propagation is improved as follows. The SIR model is extended by introducing a dependence on spatial coordinates x. For this purpose, the telegraphic equation is used to describe the processes of how an infection spreads from one region to another at a rate (the rate of spread).

Thus, for each of the parameters $S(x,t)$, $I(x,t)$, and $R(x,t)$, it is proposed to use the telegraphic equation (2) to describe the spatial and temporal dynamics.

The classical SIR model assumes that the infection spreads instantaneously throughout the population. In practice, however, the infection spreads in stages, invading new regions. The telegraphic equation (2) describes this spatial spread c at a certain rate, which corresponds to real-world conditions.

In real-life situations, the infection spreads with a certain time delay as the wave of infection spreads from the initial epicentre of the epidemic to other regions. The telegraphic equation (2) takes this delay into account by means of the second time t derivative.

The proposed method allows to take into account the movement of people between regions, due to which the infection spreads to new territories, which is very important for modelling epidemiological threats in large hospital districts.

Spatial differentiation makes it possible to obtain more accurate forecasts, as the infection spreads in different regions and this will affect the resources of hospitals and medical institutions. Based on this method, it is possible to predict the burden on hospitals in different regions and ensure their even distribution. The telegraphic equation allows you to predict disease waves and periods of decay, which will help determine when to expect new outbreaks and how to respond to them in a timely manner. Using the source function $f(x,t)$, it takes into account the emergence of new outbreaks in different regions or interventions (e.g. vaccination or quarantine), which allows for better planning of preventive measures.

The combination of the classical SIR model with the telegraphic equation makes it possible to model not only the dynamics of population infection over time t, but also the spatial spread x of the infection. This makes it possible to create a more accurate and efficient decision support system for predicting epidemiological threats and planning the resources of medical institutions in hospital districts.

It is also important to take into account possible scenarios of actions during the spread of infections related to quarantine and vaccination. Our method provides for the implementation of such scenarios when modeling the dynamics of the epidemic spread, which relates to the introduction of anti-epidemic measures for quarantine or vaccination.

The introduction of quarantine affects the parameter β, reducing it by the quarantine efficiency coefficient ε:

$$\beta_n = \beta \times (1-\varepsilon), \quad (4)$$

Vaccination provides an additional period of time to change the number of susceptible individuals to infectious diseases through the vaccination rate, which leads to changes in equations (3):

$$\frac{dS}{dt} = -\beta \frac{SI}{N} - vS, \quad \frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I, \quad \frac{dR}{dt} = \gamma I + vS, \quad (5)$$

where v is the vaccination rate, which directly reduces the number of susceptible persons S to infectious diseases and adds them to the recovered ones R.

Based on the modeling of spatio-temporal dynamics, the impact of the spread of infectious diseases in the population of the region on the resources of hospital districts is estimated. To take into account the workload of hospital districts, we introduce a variable $H(t)$ that reflects the workload of hospitals over time t. The maximum hospital utilization over time can be expressed as the double integral of the number of infected people in a given hospital district. This allows us to take into account how the number of infected people varies depending on the spatial and temporal dynamics of the spread of infections within the district:

$$H(t) = \iint_{\Omega} I(x,t)\,dS, \quad (6)$$

where Ω – is the boundary of the hospital district.

Hospital utilization depends on the number of people infected with the disease in a given area. If the number $I(t)$ of infected persons exceeds the hospital's capacity over time t, this leads to a critical overload of hospitals $H_{\max}$.

The proposed forecasting model the spread of epidemiological threats, taking into account spatial and temporal dynamics, allows us to predict the following indicators (Fig. 3):

1. the peak period of morbidity, which accounts for the maximum number of infected persons $I_{\max}$, is defined as the maximum $I(x,t)$ for all values of t;

2. the duration of the epidemic, defined as the time during which the number of infected persons becomes less than 1;

3. the burden on hospitals, which is determined from the forecast $H(t)$ of the burden on hospitals and its compliance with the maximum number of hospital beds $H_{\max}$.

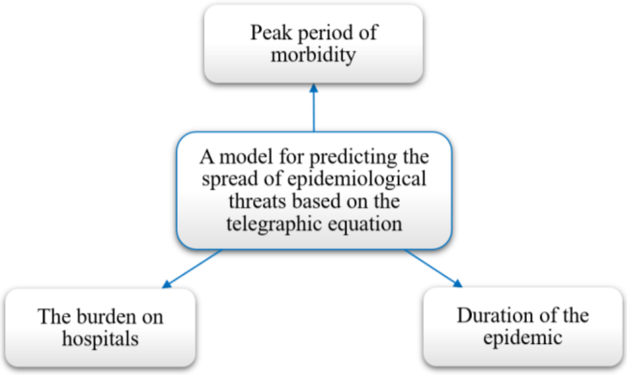

Fig. 3. **Scheme of indicators that can be quantified on the basis of the proposed method of forecasting the spread of epidemiological threats**
***Source*: compiled by the authors**

The proposed method for predicting the spread of epidemiological threats based on the telegraphic equation allows for taking into account both the temporal and spatial dynamics of the spread of infection, which is important for assessing the workload of hospitals and making appropriate management decisions by project managers.

DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR FORECASTING THE SPREAD OF EPIDEMIOLOGICAL THREATS

Based on the proposed method and mathematical model, a decision support system for predicting the spread of epidemiological threats in hospital districts based on the telegraphic equation has been developed. The system is based on a combination of the classical SIR model and the telegraphic equation to take into account the spatial and temporal dynamics of infection spread. The system integrates a four-tab interface for easy parameter input, analysis of results, and generation of recommendations.

Let us consider the architecture and functionality of a decision support system for predicting the spread of epidemiological threats based on the telegraphic equation. The system is implemented in Python using Tkinter libraries for building a graphical interface, Matplotlib for visualising graphs of epidemic dynamics, Scipy (odeint) for the numerical solution of the system of differential equations describing the dynamics of the SIR model, and PIL (Python Imaging Library) for working with images.

The proposed decision support system for predicting the spread of epidemiological threats based on the telegraphic equation consists of four main tabs: “Model Parameters”, “Results”, “Model Parameters” and “Recommendations”.

The “Model Parameters” tab of a DSS for predicting the spread of epidemiological threats allows the user to enter all the necessary input data for modeling an epidemic. It includes several fields for entering values, a drop-down list for selecting scenarios, and function buttons for running the model, clearing fields, and saving the results to a file (Fig. 4). The key elements of the “Model Parameters” tab are described below.

The start tab “Model Parameters” contains fields for entering initial data. They include:

1) recovery rate (γ) – a field for entering the recovery rate, which shows how long it takes for infected people to recover;

2) total hospital capacity – a field for entering the maximum load on medical institutions, i.e. how many patients can be admitted to hospitals in the hospital district at the same time;

3) total population (N) – a field for entering the total population of the region for which the forecast is made (for example, it can be the number of people in a particular hospital district);

4) initial number of infected (I_0) – a field for entering the number of infected people at the beginning of the epidemic. This allows you to determine the starting point of the disease spread;

5) number of simulation days – this field defines the duration of the simulation in days. The user specifies the number of days for simulating the spread of the epidemic;

6) number of hospitals – this field defines the number of medical facilities available to provide care to patients during an epidemic. The more hospitals there are, the greater the capacity of the healthcare system to provide care to the infected;

7) efficiency of hospitals (0-1) – this field allows you to indicate the efficiency of hospitals in providing medical services during the epidemic. The value is measured in the range from 0 to 1, where 0 means complete inefficiency (hospitals cannot cope with the load) and 1 means maximum efficiency (hospitals are fully capable of handling all cases);

8) quarantine effectiveness (0-1) – this field determines how effective quarantine measures are in containing the spread of infection. The value is also indicated from 0 to 1: 0 means that quarantine is ineffective and does not affect the spread of the virus, and 1 means full effectiveness when quarantine practically stops the transmission of the virus;

9) vaccination rate (% per day) – this field sets the rate of vaccination of the population as a percentage per day. The parameter indicates how many percent of the vulnerable population is vaccinated daily, which reduces their vulnerability to infection. This allows you to model the impact of mass vaccination on slowing the spread of the epidemic.

In addition, there is a drop-down list that allows you to select one of the possible epidemic scenarios:

1. “Base” – a scenario in which no additional measures are envisaged;
2. “Quarantine” – a scenario in which the infection rate is reduced through restrictive measures;
3. “Vaccination” – a scenario that takes into account mass vaccination of the population and a decrease in the number of vulnerable people.

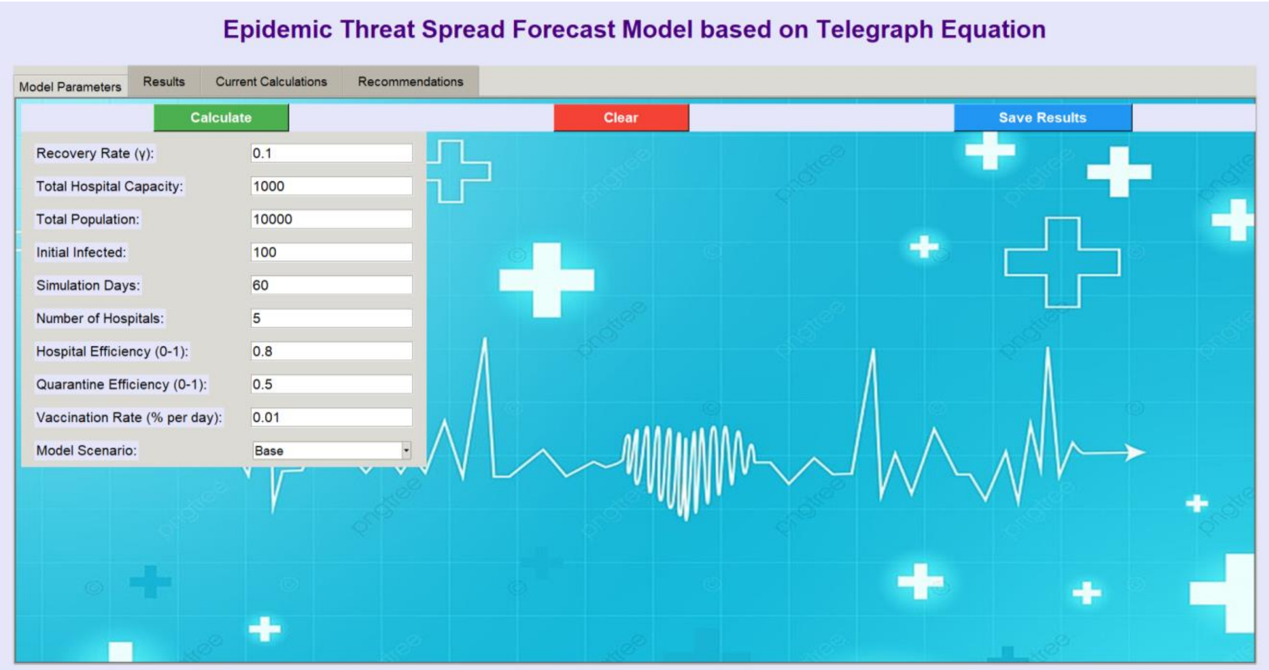

Fig.4. **On-screen form of a decision support system for predicting the spread of epidemiological threats based on the telegraphic equation**
***Source*: compiled by the authors**

The "Models parametrs" tab contains the function buttons "Calculate", "Clear" and "Save results". The Calculate button is used to start calculations based on the entered data. By clicking it, the user initiates the process of numerical solution of differential equations and receives the results in the Results, "Model Parameters", and Recommendations tabs. The Clear button allows you to quickly reset all input fields to their initial values. This is useful for running new simulations with different data. The "Save Results" button allows you to save the entered parameters to a file for further use or analysis. This is useful for comparing several scenarios.

All the elements of the "Model Parameters" tab are made using the Tkinter library for convenient and intuitive use. The input fields are aligned symmetrically, with labels that clearly explain each parameter. Buttons are located at the top of the tab for easy access.

The "Results" tab in the decision support system for predicting the spread of epidemiological threats is the key to visualizing the modeling results (Fig. 5). It is designed to view and analyze the dynamics of the epidemic based on selected parameters.

In the "Results" tab, the user can set the time frame for displaying the simulation results. The choice is to set the start and end dates of the simulation to get data only for a specific period. This is useful when you need to focus on certain stages of the epidemic, such as the initial outbreak or the peak period.

There is a field for selecting the administrative district or hospital region where the simulation takes place. This allows you to track the spread of the epidemic and its impact in a particular county. The "Apply Filter" button is used after setting the parameters (date and county). The user clicks the "Apply Filter" button, which allows you to update the display of graphs and results according to the selected filters. This helps to fine-tune the display of results and adapt them to the specific needs of the analysis.

The graphical representation of the epidemic dynamics (Fig. 5) shows the dynamics of changes in the number of people in three categories (vulnerable, infected, and recovered) on the Y-axis during the simulation period (X-axis). The graph also shows a line representing the maximum utilization of hospitals. It allows you to visually assess whether the epidemic is exceeding the capacity of the healthcare system.

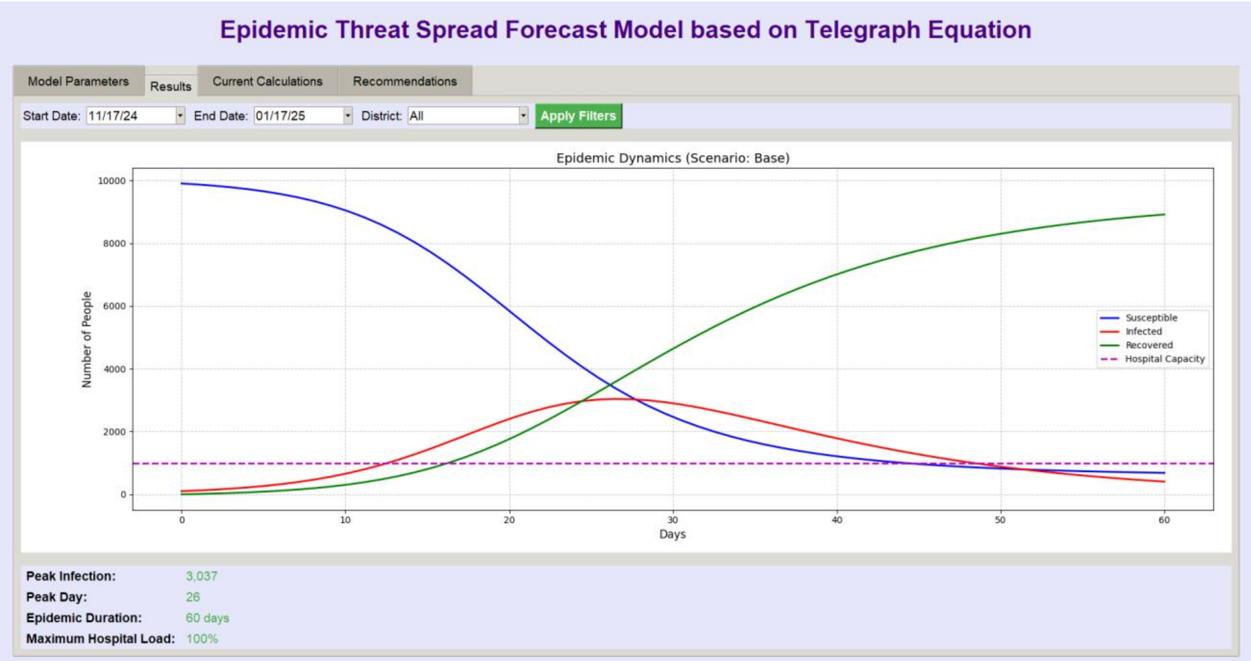

Fig.5. **On-screen form of a decision support system for predicting the spread of epidemiological threats based on the telegraphic equation with the Results tab active**

***Source*: compiled by the authors**

Below the graph are fields displaying the main modeling results, which allow for a quick assessment of the key indicators of epidemic spread:

– “Peak Infection” the highest number of infected individuals during the simulation;

– “Peak Day” The specific day on which the peak infection occurs;

– “Epidemic Duration” the total length of time the epidemic lasts, from the start to the end of the simulation.

– “Maximum Hospital Load” the highest demand on hospital resources during the epidemic.

The “Results” tab of the decision support system helps visualize the dynamics of the epidemic and allows you to make informed decisions about medical planning and resource management in crisis situations.

The “Model Parameters” tab is the main component for analyzing the results of modeling the spread of an epidemic based on the telegraphic equation It provides users with detailed data on the daily dynamics of the epidemic spread in the form of a table and provides an additional graph to assess the impact of measures on the spread of the epidemiological threat.

The “Model Parameters” tab helps project managers and medical professionals make management decisions based on detailed information about daily changes in the epidemiological situation, allowing them to quickly adapt strategies to combat the epidemic and improve the management of medical resources.

In the “Recommendations” tab, based on the modeling results, the system generates recommendations for quarantine measures, vaccination, or other measures to control the epidemic. The recommendations are based on the predicted peak values of infection rates and the possibility of exceeding hospital capacity.

The “Save Results” button allows users to save the results of forecasting the spread of epidemiological threats based on the telegraphic equation in JSON format. The obtained results in separate files allow project managers to store them and share information with other stakeholders.

The following algorithm is used to generate results in DSS:

1. Initial data input – the user enters data on the number of infected persons, population mobility, available health care resources, and infection rates;

2. Modeling process – based on the input data, the system applies telegraphic-level equations to model the spread of the epidemic in time and space;

3. Generating results – DSS generates key results such as peak infection, peak day, duration of the epidemic, and maximum hospital utilization.

4. Generating recommendations – DSS generates recommendations based on the analysis of the current spread of the epidemic, the availability of resources, and potential measures. For example, it suggests optimizing hospital capacity or adjusting vaccination strategies based on projected infection rates and available resources.

Recommendations are made based on a comparison of the projected spread of infections and available resources (hospital beds) to minimize the risk of overloading healthcare facilities. Key parameters that influence recommendations include infection rates, available medical resources, and the effectiveness of various interventions.

The developed decision support system for predicting the spread of epidemiological threats based on the telegraphic equation allows one to effectively predict the spread of epidemics in a given region, taking into account various scenarios. It provides basic information for project managers to make management decisions based on the projected spread of infection, as well as quarantine and vaccination scenarios. This makes it an important tool for project managers as well as for regional governments and healthcare facilities during crisis situations such as pandemics.

DISCUSSION OF THE RESULTS

The results of the study confirm the feasibility of using the telegraphic level to model the spatial and temporal dynamics of the spread of epidemiological threats. The developed method and DSS provided forecasting accuracy, flexibility in changing conditions, and the ability to integrate with real data.

The developed method and mathematical model based on the telegraphic level provided an appropriate level of accuracy in predicting the spatial and temporal dynamics of the spread of epidemiological threats.

Testing the model on historical data, such as COVID-19 data, showed an average forecasting error of 5-10%. This result was obtained by comparing the predicted values of the dynamics of the spread of the infection with actual data, using the root mean square error (RMSE) method and other statistical indicators to assess the accuracy of the forecasts. The comparison showed that the model is able to adequately reflect the dynamics of the spread of the infection, in particular in conditions of high population mobility, which is confirmed by an accurate description of the wave dynamics of the infection. In the case of high population mobility, the model accurately described the wave dynamics of the infection spread.

To compare the effectiveness of the developed DSS with existing systems, such as EpiEstim and COVID-19Sim, an analysis was conducted according to certain criteria: forecast accuracy, spatial and temporal detail, and flexibility. The developed DSS showed an average forecast error of 5...10%, while for traditional models the error varied within 10...15%. The telegraphic level-based DSS ensured that the wave processes of the epidemic spread were taken into account, while most analogs use simplified deterministic approaches. The developed DSS adapts to changes in data, which is not provided by the above-mentioned traditional systems.

The developed DSS can be used to predict the spread of new infections, develop epidemic management strategies at the regional and national levels, and optimize the use of medical resources, such as the number of beds, vaccines, and personnel.

At the same time, there are limitations to the use of the developed DSS. In particular, the accuracy of the forecasts depends on the quality and volume of input data. Integrating the model with big data in real-time requires significant computing resources. There is a need to accurately calibrate the telegraphic level coefficients for each scenario and regional conditions.

Further research should improve the DSS by integrating machine learning models for automatic parameter calibration. Expand the scope of the model to take into account the impact of new strains of infections. Optimize computing resources to ensure the speed of the DSS.

The results demonstrate that the use of the telegraphic level is a promising approach to modeling epidemiological threats. The proposed decision support system can improve the efficiency of epidemic management, ensuring the accuracy of forecasts and the practical usefulness of recommendations.

CONCLUSIONS

The improved method for predicting the spread of epidemiological threats taking into account spatial and temporal dynamics involves their description by using the telegraphic equation to model the wave-like spread of epidemics, which, unlike existing models, has its own characteristics and allows taking into account a number of components of the project environment, in particular, the spatial and temporal delay in the spread of infection, sources of new infections, the presence of an epidemic wave, which underlies the accurate prediction of the peak period of morbidity, the duration of the

The developed decision support system for predicting the spread of epidemiological threats based on the telegraphic equation is based on an improved method that combines the classical SIR model and the telegraphic equation to take into account the spatial and temporal dynamics of the spread of infection, integrates an interface with four tabs for convenient parameter input, which is the basis for effective analysis of results and the formation of recommendations for project managers.

FUTURE WORK

Further research, is planned to improve the developed decision support system by integrating more complex mathematical models based on the telegraphic equation. This will ensure that more factors of the project environment regarding epidemiological infection of the population are taken into account. Computational intelligence methods will also be applied to automatically calibrate system parameters. Particular attention will be paid to expanding the functionality of the system, its validation based on data on other epidemiological threats, and adaptation to the global level of epidemic management.

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Інформаційна технологія прогнозування епідеміологічних загроз на основі телеграфного рівняння

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АНОТАЦІЯ

На підставі проведеного аналізу встановлено, що традиційні підходи, такі як моделі SIR та SEIR, не забезпечують достатньої точності прогнозування та не враховують комплексну динаміку поширення інфекційних захворювань. Обгрунтовано потребу в розробці методу, який дозволить підвищити точність прогнозування та забезпечить підтримку прийняття управлінських рішень для прогнозування розповсюдження епідеміологічних загроз на основі телеграфного рівняння. Розроблена система дозволяє приймати ефективні управлінські рішення, спрямовані на зменшення негативного впливу епідемії на населення та медичну інфраструктуру. Використання телеграфного рівня дозволяє передбачити хвильове розповсюдження інфекції, просторово-часові затримки, а також джерела нових інфекцій, що забезпечує точне прогнозування пікових періодів, тривалості епідемії та завантаження медичних закладів. Розроблений метод інтегрує класичну SIR-модель із телеграфним рівнем, що дозволяє моделювати динаміку поширення інфекції в просторово-часовому середовищі. Цей метод забезпечує прогнозування просторово-часової динаміки розповсюдження інфекції, враховуючи хвильові ефекти, затримки та вплив зовнішніх факторів. Він забезпечує можливість точного аналізу ключових показників епідемії, таких як пік захворюваності, її тривалість та розподіл навантаження на лікарні. Розроблені метод та математична модель на основі телеграфного рівня забезпечили належний рівень точності в прогнозуванні просторово-часової динаміки поширення епідеміологічних загроз. Перевірка моделі на історичних даних про COVID-19 показала, що середня похибка прогнозу склала 5…10%. Це свідчить продостатню адекватність моделі. У випадку високої мобільності населення модель точно описувала хвильову динаміку поширення інфекції. Запропонована система підтримки прийняття рішень включає зручний інтерфейс із чотирма вкладками для введення параметрів моделі, аналізу результатів, їх візуалізації та формування рекомендацій. Вона дозволяє підвищити точність оцінки тривалості епідемії, пікових навантажень та деяких ресурсів. Розроблена система є інструментом для менеджерів, що забезпечує підтримку прийняття упарвлінських рішень, спрямованих на прогнозування зараження анселення регіонів інфекцією та оптимізацію використання медичних ресурсів. Результати дослідження можуть бути використані для планування заходів реагування на епідемії на локальному, регіональному та глобальному рівнях. Запропонована система забезпечує оперативність, гнучкість та точність, що є ключовими для управління епідеміологічними ситуаціями в умовах сучасних викликів.

Ключові слова: інформаційна технологія; модель; телеграфне рівняння; епідеміологічні загрози; прогнозування; моделювання

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