UDC 519.2, 519.8
DOI: 10.20535/SRIT.2308-8893.2022.2.07

SIMULATIONS OF NEW COVID-19 PANDEMIC WAVES IN UKRAINE AND IN THE WORLD BY GENERALIZED SIR MODEL

I. NESTERUK

Abstract. New waves of the COVID-19 pandemic in Ukraine, which began in the summer of 2021, and after holidays in the middle of October 2021, were characterized by the almost exponential growth of smoothed daily numbers of new cases. This is a matter of great concern and the need to immediately predict the epidemic dynamics in order to assess the maximum possible values of new cases, the risk of infection, and the number of deaths. The generalized SIR-model and corresponding parameter identification procedure were used to simulate and predict the dynamics of two new epidemic waves in Ukraine and one worldwide. Results of calculations show that new cases in Ukraine will not stop appearing before November 2022. The pandemic can continue for another ten years if the global situation with vaccination, testing, and treatment does not change.

Keywords: COVID-19 pandemic, epidemic waves, epidemic dynamics in Ukraine, global pandemic dynamic, mathematical modeling of infection diseases, SIR model, parameter identification, statistical methods..

INTRODUCTION

The COVID-19 pandemic dynamics in Ukraine was discussed in [1–14]. To predict the first wave of the pandemic, the classical SIR model [15–17] and the statistics-based method of its parameter identification [18] were used. To simulate new epidemic waves, a numerical method of their detection [4, 19], a generalized SIR-model [20], and a corresponding parameter identification procedure [21] were developed. In particular, eleven epidemic waves were simulated for Ukraine [5, 8–11] and five pandemic waves for the whole world [5].

The calculations of the 11th pandemic wave (based on the accumulated numbers cases reported by Ukrainian national statistics [22, 23] in the period May 23 – June 5, 2021) predicted the end of this wave on August 25, 2021 with the number of cases 2,226,797 (see [11]). As of August 25, 2021 the real number of cases accumulated in Ukraine was 2,278,171 (see Table 1). It means that the predicted saturation level was exceeded only 2,26% (after 81 days of observation). The obtained high accuracy of the method allows us to hope for a fairly accurate forecast for next pandemic waves in Ukraine (12th and 13th) and in the whole world (6th), to which this study is devoted. Some results concerning the 12th epidemic wave in Ukraine are already available in [13].

DATA

We will use the data set regarding the accumulated numbers of laboratory-confirmed COVID-19 cases and deaths in Ukraine from national sources [22, 23].

The corresponding numbers V_j, d_j and moments of time t_j (measured in days) are shown in Table 1 for the period of July to November 2021. The values V_j, corresponding to the previous moments of time, can be found in [4, 8–10]. The period T_{c11}: May 23 – June 5, 2021 has been used in [10] for SIR simulations of the eleventh epidemic wave in Ukraine. Here we use the datasets, corresponding to the period T_{c12}: September 29 – October 12, 2021 to simulate the 12th wave and the period T_{c13}: October 28 – November 10, 2021 for the 13th wave. Other V_j and t_j values will be used to control the accuracy of predictions.

T a b l e 1. Cumulative numbers of laboratory-confirmed COVID-19 cases and deaths in Ukraine in the summer and autumn of 2021 according to the national statistics [22, 23]

Day in corresponding month of 2021	Number of cases in July, V_j	Number of cases in August, V_j	Number of cases in September, V_j	Number of cases in October, V_j	Number of cases in November, V_j	Number of deaths in October, d_j	Number of deaths in November, d_j
1	2236497	2253534	2290848	2447222	2955693	56649	68727
2	2237202	2254361	2293541	2455189	2979086	56775	69447
3	2237579	2255345	2296155	2460010	3006463	56889	70146
4	2237823	2256397	2297534	2469856	3032951	57206	70842
5	2238364	2257478	2298307	2482518	3058014	57526	71635
6	2238974	2258532	2300504	2497643	3075433	57840	72084
7	2239591	2259151	2303276	2514005	3088501	58081	72557
8	2240246	2259451	2306939	2529913	3107489	58331	73390
9	2240753	2260232	2310554	2541257	3130772	58463	74206
10	2241043	2261354	2314423	2550089	3155519	58700	74857
11	2241217	2262601	2316619	2562085	3179577	59052	75601
12	2241698	2263864	2317824	2578394	3203149	59523	76302
13	2242245	2265217	2321156	2597275	3217639	59935	76705
14	2242868	2265912	2325796	2610899	3228441	60137	77147
15	2243605	2266329	2331540	2623882	3244749	60414	78085
16	2244196	2267219	2338164	2635170	3263417	60633	78754
17	2244495	2268666	2344398	2644694	3284008	60810	79506
18	2244677	2270226	2348381	2660273	–	61348	–
19	2245275	2271826	2350646	2679185	–	61843	–
20	2245930	2273558	2355805	2701600	–	62389	–
21	2246656	2274561	2362559	2725385	–	63003	–
22	2247419	2275171	2370425	2748614	–	63486	–
23	2248164	2275863	2379483	2769405	–	63872	–
24	2248450	2276590	2387750	2784039	–	64202	–
25	2248663	2278171	2392397	2803159	–	64936	–
26	2249344	2280203	2395404	2825733	–	65628	–
27	2250061	2282285	2401956	2851804	–	66204	–
28	2250907	2284191	2411622	2878674	–	66852	–
29	2251869	2284940	2423379	2904872	–	67393	–
30	2252785	2286296	2435413	2922302	–	67729	–
31	2253269	2288371	–	2936238	–	68027	–

To estimate the mortality rate in Ukraine (ratio of accumulated number of deaths d_j to accumulated number of cases V_j), let us take figures d_j corresponding different days: 52,286 (June 26, 2021); 52,665 (July 13, 2021); 52,981 (August 2, 2021); 53,789 (August 30, 2021); 54,550 (September 15, 2021); 57,526 (October 5, 2021); 59,052 (October 11, 2021), [22, 23]. Taking corresponding V_j values we can calculate the mortality rates $m_i = d_j * 1000 / V_j$ (per thousand of cases) for the listed days: 23,40; 23,49; 23,50; 23,52; 23,40; 23,17; 23,05. Thus, the mortality rate is rather stable (its variation during June to October 2021 is only 0,47). We will use the average value $m = 23{,}36$ to predict the number of deaths in Ukraine during the new 12th and 13th pandemic waves.

We will use the data set regarding the accumulated numbers of laboratory-confirmed COVID-19 cases in the whole world from the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU) [24]. The numbers V_j and moments of time t_j (measured in days) corresponding to the version of JHU data available on November 18, 2021 are shown in Table 2 for the period of May to November 2021. The period T_{c6}: September 29 – October 12, 2021 will be used for SIR simulations of the sixth pandemic wave in the whole world. Other V_j and t_j values will be used to control the accuracy of predictions.

T a b l e 2. Cumulative numbers of laboratory-confirmed COVID-19 cases in the whole world in the summer and autumn of 2021 according to the JHU datasets [24]

Day in corresponding month of 2021	Number of casesin May, V_j	Number of cases in June, V_j	Number of cases in July, V_j	Number of cases in August, V_j	Number of cases in September V_j	Number of cases in October, V_j	Number of cases in November, V_j
1	152276590	171272898	182726434	198444595	218595466	234356127	247171157
2	152951570	171758996	183167695	199022653	219272430	234701054	247599693
3	153630578	172248309	183544382	199660021	219990395	235008467	248117984
4	154438256	172667912	183872893	200335410	220474967	235452671	248643609
5	155280720	173067049	184242453	201024324	220914961	235872200	249157004
6	156150815	173390272	184695883	201846052	221355380	236384642	249569269
7	156983904	173710775	185159327	202397022	222080699	236816997	249914970
8	157770675	174077854	185639668	202838586	222712220	237290992	250391584
9	158412936	174497701	186147179	203492405	223349675	237622759	250871092
10	159031606	174947362	186574219	204141032	223983497	237937441	251442851
11	159770619	175368288	186944737	204869528	224439880	238319075	251956201
12	160530984	175741060	187381421	205580294	224808018	238751674	252542169
13	161256546	176044679	187901397	206385979	225409164	239214456	252974728
14	161974329	176352002	188442853	206919889	225960250	239658510	253318827
15	162603295	176723278	189014972	207383880	226527940	240115116	253860137
16	163152581	177121944	189613250	208062469	227104401	240449869	254382438
17	163691215	177514452	190087192	208745487	227697551	240764659	–
18	164313944	177921297	190518240	209473681	228234315	241178794	–
19	164986139	178270695	191014762	210189272	228594983	241619751	–
20	165265741	178573040	191544693	210979353	229128857	242090131	–
21	165892200	178866758	192103503	211519485	229597662	242546214	–
22	166471396	179238527	192667887	211965954	230135505	243030920	–
23	166948481	179676298	193357870	212670361	230646900	243390258	–

Continued Table 2

Day in corres-ponding month of 2021	Number of casesin May, V_j	Number of cases in June, V_j	Number of cases in July, V_j	Number of cases in August, V_j	Number of cases in September V_j	Number of cases in October, V_j	Number of cases in November, V_j
24	167400782	180081192	193829848	213357235	231194181	243705625	–
25	167933373	180503102	194275173	214087524	231560977	244135761	–
26	168502846	180869106	194815533	214823164	231909080	244576866	–
27	169057033	181180563	195425745	215568802	232381444	245088017	–
28	169557476	181508885	196070028	216116120	232830308	245545805	–
29	170039483	181888509	196722877	216562642	233332705	246049111	–
30	170431363	182285486	197453162	217249144	233817106	246429566	–
31	170810073	–	197963310	217868234	–	246749382	–

GENERALIZED SIR MODEL AND DATA SMOOTHING PROCEDURE

The generalized SIR-model relates the number of susceptible S, infectious I and removed persons R for a particular epidemic wave i, [9, 20]. The exact solution of the set of non-linear differential equations uses the function

$$V(t) = I(t) + R(t), \tag{1}$$

corresponding to the number of victims or the cumulative laboratory-confirmed number of cases versus time t [9, 20]. Its derivative:

$$\frac{dV}{dt} = \alpha_i SI \tag{2}$$

yields the estimation of the average daily number of new cases. When the registered number of victims V_j is a random realization of its theoretical dependence (1), the exact solution presented in [9, 20] depends on five parameters (α_i is one of them). The details of the optimization procedure for their identification can be found in [21].

Since daily numbers of new cases are random and characterized by some weekly periodicity, we will use the smoothed daily number of accumulated cases:

$$\overline{V}_i = \frac{1}{7}\sum_{j=i-3}^{j=i+3} V_j ,$$

and its numerical derivative:

$$\left.\frac{d\overline{V}}{dt}\right|_{t=t_i} \approx \frac{1}{2}(\overline{V}_{i+1} - \overline{V}_{i-1}) \tag{3}$$

to estimate the smoothed number of new daily cases [4, 5, 10, 19].

RESULTS AND DISCUSSION

The optimal values of SIR-model parameters and other characteristics of the 12th and 13th pandemic waves in Ukraine and the 6th wave in the whole world are calculated and listed in Table 3. The corresponding SIR curves are shown in

Figs. 1 and 2 by blue and brown lines for Ukraine and green lines for the world. Black lines illustrate the results of SIR simulation of the eleventh epidemic wave in Ukraine published in [11]. It can be seen that the optimal values of SIR parameters are very different (even for 12th and 13th epidemic waves in Ukraine). Close values were obtained only for the average times of spreading the infection $1/\rho_i$. The assessments of the pandemic wave durations (corresponding the moment when the number of infectious persons becomes less that unit) are very pessimistic (November, 2022 for Ukraine and December 2031 for the whole world). A similar long epidemic wave was also predicted for India [25].

Table 3. Optimal values of parameters and other characteristics of the 12th and 13th COVID-19 pandemic waves in Ukraine and the 6th wave in the whole world

Characteristics	**12th epidemic wave in Ukraine, i=12, [13]**	**13th epidemic wave in Ukraine, i=13**	**6th pandemic wave in the whole world, i=6**
Time period taken for calculations T_{ci}	September 29 – October 12, 2021	October 28 – November 10, 2021	September 29 – October 12, 2021
I_i	25,261.4089164122	73,492.9652436053	1,550,494.67573132
R_i	2,399,050.73394073	2,801,190.17761354	231,782,051.609983
N_i	3,790,400	7,237,600	334,411,200
ν_i	1,137,541.61656928	4,252,588.61675970	101736415.543763
α_i	2.63670321714285e-07	6.7868529452959e-08	2.84345358576434e-09
ρ_i	0.299935964004210	0.288616935787874	0.289282775580724
$1/\rho_i$	3.33404499630449	3.46480014164856	3.45682523956893
r_i	0.997536473683354	0.998339758268927	0.999305866880929
$S_{i\infty}$	845,264	3,503,575	84,981,994
$V_{i\infty}$	2,945,136	3,734,025	249,429,206
Final day of the epidemic wave	June 16, 2022	November 13, 2022	December 2031

The saturation levels (final sizes) $V_{i\infty}$ of the 12th wave in Ukraine and 6th global wave are already exceeded (compare corresponding values in Tables 1–3). As of November 17, 2021 the real accumulated number of deaths – 79,506 – registered in Ukraine (see Table 1) has already exceeded the figure 68,764 predicted in [13] for the end of 2021 with the use of *V(t)* curve for 12th epidemic wave. This discrepancy can be explained by the sharp increase in the daily number of new cases which occurred after long holidays October 14–17, 2021 (see red "crosses" in Figs. 1 and 2). These changes in the epidemic dynamics indicate the beginning of a new (13th) wave in Ukraine. The calculations allow us to estimate the new saturation level $V_{13\infty}$ = 3,734,025 (see Table 3) and the expected accumulated number of deaths 3,734,025*0,02336=87,227 by November 2022. Registered numbers of deaths in Ukraine agree with the theoretical estimation for 13th wave (compare the magenta "triangles" and the dashed magenta line in Fig. 2).

According to the predictions for the 12th wave (posted in [13]], the numbers of infectious persons and average daily new cases will stop to increase around 17 and 14 October 2021, respectively (see blue dashed and dotted lines in Fig. 2). The registered smoothed daily number of new cases in Ukraine really achieved a local maximum on October 10, 2021, but started to increase very rapid after October 17, 2022 (see the red "crosses" in Figs. 1 and 2).

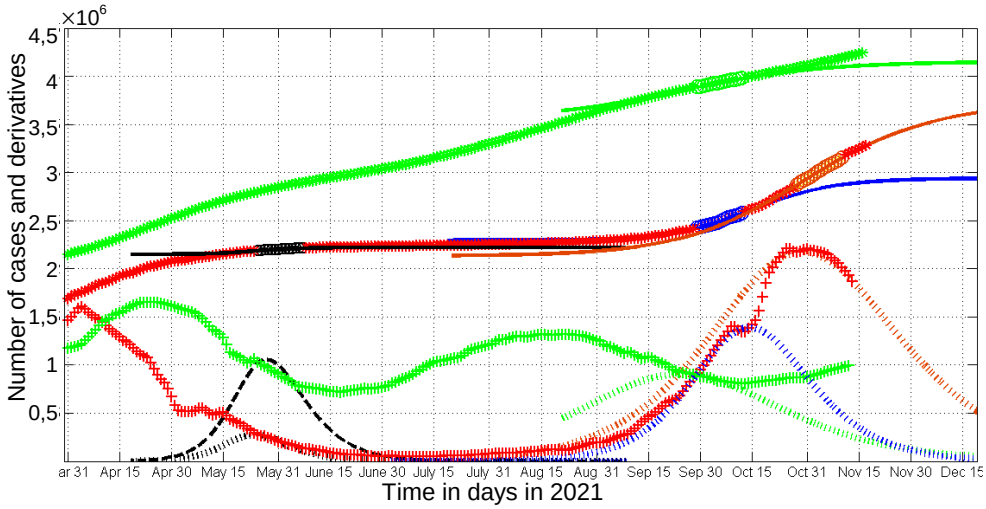

Fig. 1. The COVID-19 pandemic waves in Ukraine and in the whole world in the summer and autumn of 2021

The results of SIR simulations of the 11th (see [11]), 12th, and 13th waves in Ukraine are shown by black, blue, and brown lines, respectively. Green lines represent the 6th pandemic wave in the whole world. Numbers of victims $V(t) = I(t) + R(t)$ — solid lines (for the world divided by 60); numbers of infected and spreading $I(t)$ multiplied by 5 – dashed; derivatives dV/dt (eq. (2), multiplied by 100 for Ukraine and by 2 for the world) — dotted. "Circles" correspond to the accumulated numbers of cases registered during the periods of time taken for SIR simulations (for the world divided by 60). "Stars" corresponds to V_j values beyond these time periods (for the world divided by 60). "Crosses" show the first derivative (3) multiplied by 100 for Ukraine and by 2 for the world.

Unfortunately, the general SIR model cannot predict the emergence of new epidemic waves. It simulates the dynamics for only the period with constant epidemic conditions. Therefore, permanent monitoring of the number of new cases is needed to determine changes in the epidemic dynamics. After that it is possible to do new simulations by means of the generalized SIR model with calculation and use of new values of its parameters.

We can only point out the three possible reasons for the new 13th wave in Ukraine:

1. The long weekend of October 14–17, 2021 without significant quarantine restrictions led to a significant increase in travels and contacts. This period accounted for the maximum number of infected (see the blue dashed curve in Fig. 2). We observed a similar situation in Ukraine in May 2020, when the lockdown was lifted during the period of the maximum number of infectious people, which led to the emergence of the second epidemic wave before the end of the first one [5, 10]. An increase in contacts during the holidays in early May 2021

also led to an increase in the number of infectious persons (see the black dashed line in Fig. 1). But during this period there was a tendency to reduce the daily number of new cases, so the increase in contacts only slowed down this trend (see red "crosses" in Fig. 1).

2. Due to a large number of asymptomatic patients, many COVID-19 cases are not detected and registered [26–31]. The ratio of real to detected cases in Ukraine was estimated to be between 4 and 20 for different periods of time [9, 11]. Such large numbers of undetected cases may suddenly change the number of reported cases, if the population frightened by the increase in mortality begins to seek medical care more often.

3. Appearance of new coronavirus strains.

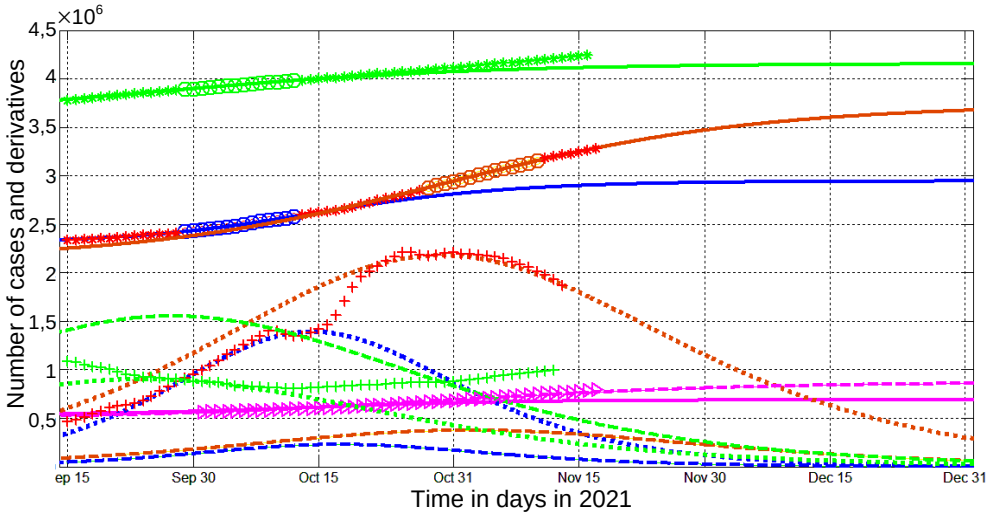

Fig. 2. The COVID-19 pandemic waves in Ukraine and in the whole world in the autumn of 2021

The results of SIR simulations of the 12th and 13th waves in Ukraine are shown by blue and brown lines, respectively. Green lines represent the 6th pandemic wave in the whole world. Numbers of victims $V(t) = I(t) + R(t)$ — solid lines (for the world divided by 60); numbers of infected and spreading $I(t)$ (multiplied by 5 for Ukraine) – dashed; derivatives dV/dt (eq. (2), multiplied by 100 for Ukraine and by 2 for the world) — dotted. The magenta lines represent the estimation of the accumulated number of deaths during the 12th (solid) and 13th (dashed) epidemic waves in Ukraine multiplied by 10. Magenta "triangles" represent the accumulated numbers of death in Ukraine form Table 1 multiplied by 10. "Circles" correspond to the accumulated numbers of cases registered during the periods of time taken for SIR simulations (for the world divided by 60). "Stars" corresponds to V_j values beyond these time periods (for the world divided by 60). "Crosses" show the first derivative (3) multiplied by 100 for Ukraine and by 2 for the world.

"Stars" and "crosses" in Figs. 1 and 2 illustrate the accuracy of simulations for the accumulated number of cases and the averaged daily numbers of new cases (eq. (3)). Comparisons with corresponding blue solid and dotted lines in Fig. 2 show that the theoretical estimations for 12th wave in Ukraine were consistent with observations before October 15, 2021. After October 18 the results of observations are very close to the theoretical estimations for the 13th wave (see brown solid and dotted lines in Fig. 2). As of November 17, 2021 the

number of infectious persons (the brown dashed line) and the daily number of new cases were decreasing. Premature lifting of quarantine restrictions, a significant increase in contacts during the New Year and Christmas holidays or/and the appearance of a new coronavirus strain could disrupt these positive trends.

Unfortunately, the general SIR model cannot predict the emergence of new epidemic waves. It simulates the dynamics for only the period with constant epidemic conditions. Therefore, permanent monitoring of the number of new cases is needed to determine changes in the epidemic dynamics. After that it is possible to do new simulations by means of the generalized SIR model with calculation and use of new values of its parameters.

The global number of new cases is also characterized by wave-like behavior (see green "crosses" in Fig. 1). But unlike Ukraine and many other countries, the difference between the minimum and maximum values of the derivative (3) is much smaller for the world dynamics. The minima of new global cases also do not go to zero (compare green and red "crosses" in Figs. 1 and 2). All this limits the use of the SIR model for the long-term predictions. In particular, the increase in daily number of new cases (see green "crosses" in Figs. 1 and 2) indicate the beginning of a new global wave after October 15, 2021 (this fact makes the predictions for the 6th wave no more relevant). It should be noted that the COVID-19 pandemic is characterized by a very slow decline in the number of infectious $I(t)$. In particular, according to the results of modeling of the 6th world wave (shown in Table 3), the number of infectious persons worldwide may be less than 100 in May 2021. This small number is enough to continue the pandemic for almost 10 years.

CONCLUSIONS

The generalized SIR-model and corresponding parameter identification procedure was used to simulate and predict the dynamics of two new epidemic waves in Ukraine and one in the whole world. Results of calculations show that new cases in Ukraine will not stop to appear before November 2022. If the global situation with vaccination, testing and treatment will not change, the pandemic could continue for another ten years.

Acknowledgements. The author is grateful to Oleksii Rodionov for his help in collecting and processing data.

REFERENCES

1. I. Nesteruk, I.Kudybyn, and G. Demelmair, "Global stabilization trends of COVID-19 pandemic", *KPI Science News*, no. 2, pp. 55–62, 2020. doi: 10.20535/kpi-sn.2020.2.205124.
2. I. Nesteruk, "Simulations and predictions of COVID-19 pandemic with the use of SIR model", Innov Biosyst Bioeng, vol. 4, no. 2, pp. 110–121, 2020. doi: 10.20535/ibb.2020.4.2.204274. Available: http://ibb.kpi.ua/article/view/204274
3. Yu.N. Kyrychko, K.B. Blyuss, and I. Brovchenko, "Mathematical modelling of the dynamics and containment of COVID-19 in Ukraine", *Scientific Reports*, 10:19662, 2020. Available: https://doi.org/10.1038/s41598-020-76710-1
4. I. Nesteruk, *Coronasummer in Ukraine and Austria. [Preprint]*. ResearchGate, June 2020. doi: 10.13140/RG.2.2.32738.56002.

5. I. Nesteruk, *COVID-19 pandemic dynamics.* Springer Nature, 2021. doi: 10.1007/978-981-33-6416-5. Available: https://link.springer.com/book/10.1007/978-981-33-6416-5
6. S. Pardhan and N. Drydakis, "Associating the Change in New COVID-19 Cases to GDP per Capita in 38 European Countries in the First Wave of the Pandemic", *Front Public Health*, 8:582140, 2021. doi: 10.3389/fpubh.2020.582140.
7. S. Chintala, R. Dutta, and D. Tadmor, "COVID-19 spatiotemporal research with workflow-based data analysis", *Infect Genet Evol.*, 88:104701, 2021. doi: 10.1016/j.meegid.2020.104701.
8. I. Nesteruk and N. Benlagha, "Predictions of COVID-19 pandemic dynamics in Ukraine and Qatar based on generalized SIR model", *Innov. Biosyst. Bioeng.*, vol. 5, no. 1, pp. 37–46, 2021. doi: 10.20535/ibb.2021.5.2.230487. Available: http://ibb.kpi.ua/article/view/230487
9. I. Nesteruk, "Visible and real sizes of new COVID-19 pandemic waves in Ukraine", *Innov. Biosyst. Bioeng.*, vol. 5, no. 2, pp. 85–96, 2021. doi: 10.20535/ibb.2021.5.2.230487. Available: http://ibb.kpi.ua/article/view/230487
10. I. Nesteruk, "Detections and SIR simulations of the COVID-19 pandemic waves in Ukraine", *Comput. Math. Biophys.*, 9, pp. 46–65, 2021. Available: https://doi.org/10.1515/cmb-2020-0117
11. I. Nesteruk, "Influence of Possible Natural and Artificial Collective Immunity on New COVID-19 Pandemic Waves in Ukraine and Israel", *Explor. Res. Hypothesis. Med*., 2021. doi: 10.14218/ERHM.2021.00044.
12. I. Nesteruk, O. Rodionov, A.V. Nikitin, and S. Walczak, "Influences of seasonal and demographic factors on the COVID-19 pandemic dynamics", *EAI Endorsed Transactions on Bioengineering and Bioinformatics*, 2021. doi: 10.4108/eai.8-12-2021.172364.
13. I. Nesteruk, *Simulation and predictions of a new COVID-19 pandemic wave in Ukraine with the use of generalized SIR model*. Medrxiv, 2021. Available: https://doi.org/10.1101/2021.10.13.21264949
14. I. Nesteruk and O. Rodionov, "New COVID-19 Pandemic Waves Caused by Omicron and Efficiency of Vaccinations", *J. Biomed. Res. Environ. Sci.*, 3(1), pp. 114–139, 2022. doi: 10.37871/jbres1410. Available: https://www.jelsciences.com/ articles/jbres1410.pdf
15. W.O. Kermack and A.G. McKendrick, "A Contribution to the mathematical theory of epidemics", *J. Royal. Stat. Soc., Ser A.*,vol. 115, issue 700, 1927, 21 p.
16. J.D. Murray, *Mathematical Biology I/II*. New York: Springer, 2002.
17. D. Langemann, I. Nesteruk, and J. Prestin, "Comparison of mathematical models for the dynamics of the Chernivtsi children disease", *Mathematics in Computers and Simulation*, vol. 123, pp. 68–79. 2016. doi: 10.1016/j.matcom.2016.01.003.
18. I. Nesteruk, "Statistics based models for the dynamics of Chernivtsi children disease", *Naukovi Visti NTUU KPI*, no. 5, pp. 26–34, 2017. doi: 10.20535/1810-0546.2017.5.108577.
19. I. Nesteruk, "Identification of the New Waves of the COVID-19 Pandemic", in book *COVID-19 Pandemic Dynamics*. Springer Nature, 2021. doi: 10.1007/978-981-33-6416-5_8. Available: https://link.springer.com/chapter/10.1007/978-981-33-6416-5_8
20. I. Nesteruk, "General SIR Model and Its Exact Solution", in book *COVID-19 Pandemic Dynamics*. Springer Nature, 2021. doi: 10.1007/978-981-33-6416-5_9. Available: https://link.springer.com/content/pdf/10.1007%2F978-981-33-6416-5_9.pdf
21. I. Nesteruk, "Procedures of Parameter Identification for the Waves of Epidemics", in book *COVID-19 Pandemic Dynamics*. Springer Nature, 2021. doi: 10.1007/978-981-33-6416-5_10. Available: https://link.springer.com/chapter/10.1007%2F978-981-33-6416-5_10

22. *Coronavirus in Ukraine - Statistics - Map of infections, graphs*. [Internet]. 2021. Available: https://index.minfin.com.ua/ua/reference/coronavirus/ukraine/
23. *Cabinet of Ministers of Ukraine – Home.* [Internet]. Available: https://www.kmu.gov.ua/
24. *COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU)*. Available: https://github.com/owid/covid-19-data/tree/master/public/data
25. I. Nesteruk, "The COVID-19 pandemic dynamic in India in the spring and summer of 2021", J. Bio. Med.: Open Access, vol.2, issue 2, pp. 1–13, 2021. Available: https://gnoscience.com/uploads/journals/articles/856271132747.pdf
26. "Coronavirus: 'strange pneumonia' seen in Lombardy in November, leading Italian doctor says", *South China Morning Post.* Available: https://www.scmp.com/news/china/society/article/3076334/coronavirus-strange-pneumonia-seen-lombardy-november-leading
27. "Wir sind alle erkrankt", *Frankfurter Allgemeine.* Available: https://m.faz.net/ aktuell/sport/mehr-sport/militaerweltspiele-2019-in-wuhan-damals-schon-corona-faelle-16758894.html
28. D.M. Weinberger et al., *Estimating the early death toll of COVID-19 in the United States. [Preprint.]*. MEDRXIV, 2020. Available: https://doi.org/10.1101/2020.04.15.2006643
29. "Slovakia tested most of the country in two days. Here's how they did it and what they found", *CNN*. Available: https://edition.cnn.com/2020/11/02/europe/slovakia-mass-coronavirus-test-intl/index.html
30. "Slovakia's Second Round of Coronavirus Tests Draws Large Crowds", *Reuters*. Available: https://www.voanews.com/covid-19-pandemic/slovakias-second-round-coronavirus-tests-draws-large-crowds
31. "An experiment with mass testing for COVID-19 was conducted in Khmelnytsky", *Podillya News*. Available: https://podillyanews.com/2020/12/17/u-shkolah-hmelnytskogo-provely-eksperyment-z-testuvannyam-na-covid-19/

Received 11.05.2022

INFORMATION ON THE ARTICLE

Igor G. Nesteruk, ORCID: 0000-0001-7250-2729, Institute of Hydromechanics, National Academy of Sciences of Ukraine, Ukraine, e-mail: inesteruk@yahoo.com

МОДЕЛЮВАННЯ НОВИХ ХВИЛЬ ПАНДЕМІЇ COVID-19 В УКРАЇНІ ТА СВІТІ ЗА УЗАГАЛЬНЕНОЮ МОДЕЛЛЮ SIR / І.Г. Нестерук

Анотація. Нові хвилі пандемії COVID-19 в Україні, що розпочалися влітку 2021 року та після свят у середині жовтня 2021 року, характеризувались майже експоненціальним зростанням згладженої щоденної кількості нових випадків. Це викликає велике занепокоєння та необхідність негайного прогнозування динаміки епідемії, щоб оцінити можливі максимальні значення нових випадків, ризику зараження та кількості смертей. Узагальнену SIR-модель та процедуру ідентифікації відповідних параметрів використано для моделювання і прогнозування динаміки двох нових епідемічних хвиль в Україні та однієї у світі. Результати розрахунків показують, що нові випадки в Україні не перестануть з'являтися до листопада 2022 року. Якщо глобальна ситуація з вакцинацією, тестуванням та лікуванням не зміниться, пандемія може тривати ще десять років.

Ключові слова: пандемія COVID-19, епідемічні хвилі, епідемічна динаміка в Україні, глобальна динаміка пандемії, математичне моделювання інфекційних захворювань, модель SIR, ідентифікація параметрів, статистичні методи.