

Spatio-temporal data visualization for monitoring of control measures in the prevention of the spread of COVID-19 in Bosnia and Herzegovina

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ABSTRACT

Aim The damage caused by the COVID-19 pandemic has made the prevention of its further spread at the top of the list of priorities of many governments and state institutions responsible for health and civil protection around the world. This prevention implies an effective system of epidemiological surveillance and the application of timely and effective control measures. This research focuses on the application of techniques for modelling and geovisualization of epidemic data with the aim of simple and fast communication of analytical results via geoportal.

Methods The paper describes the approach applied through the project of establishing the epidemiological location-intelligence system for monitoring the effectiveness of control measures in preventing the spread of COVID-19 in Bosnia and Herzegovina.

Results Epidemic data were processed and the results related to spatio-temporal analysis of the infection spread were presented by compartmental epidemic model, reproduction number R, epi-curve diagrams as well as choropleth maps for different levels of administrative units. Geovisualization of epidemic data enabled the release of numerous information from described models and indicators, providing easier visual communication of the spread of the disease and better recognition of its trend.

Conclusion The approach involves the simultaneous application of epidemic models and epidemic data geovisualization, which allows a simple and rapid evaluation of the epidemic situation and the effects of control measures. This contributes to more informative decision-making related to control measures by suggesting their selective application at the local level.

Key words: COVID 19 pandemic, decision making, epidemiological techniques, geocoding, health information systems, reproduction number

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Original submission:

11 June 2020;

Revised submission:

14 June 2020;

Accepted:

20 June 2020

doi: 10.17392/1215-20

Med Glas (Zenica) 2020; 17(2): 265-274

INTRODUCTION

Following reports on the first patients with viral pneumonia caused by COVID-19 in December 2019, in the city of Wuhan in China, the disease spread rapidly throughout the world (1). Due to the major global problems caused by this new coronavirus, prevention of its spread has become the top priority for most governments, medical, economic, and political communities around the world (2).

In order to respond quickly to the rapid development of the epidemic situation related to the spread of COVID-19 in Bosnia and Herzegovina (B&H), the Committee for Microbiology and Related Disciplines of the Department of Medical Sciences at the Academy of Sciences and Arts of Bosnia and Herzegovina (ANUB&H) launched the Project of Epidemic Location and Intelligence System (ELIS) for monitoring the spread of COVID-19. The system was tasked with providing research and collecting epidemic data on COVID-19, communicating with epidemiological teams, exchanging information on infection control, analysing the situation and control measures efficiency, reporting to public health institutions on the evaluation of epidemic surveillance system, informing government institutions and the general public about the epidemic situation.

The ELIS functionality includes: data structure analysis and modelling (3), geocoding and mapping of tested, confirmed and active cases (4) using different address models (5), visualization of infection spread over time, mapping of areas with vulnerable age groups, mapping of health capacities with available medical resources to respond effectively to the current epidemic situation (6), epidemic modelling and prediction, and communication and cooperation tools for the epidemic surveillance professionals.

Due to its importance for the whole country and its role in the academic community, this system has been accepted as a common platform for further research and a source of information for monitoring the effectiveness of control measures in preventing the disease spread.

Of particular importance for the monitoring and evaluation of control measures are the functions of the system related to modelling and communication, because they enable presentation of key indicators and critical information on the dynam-

ics of the disease spread and spatio-temporal visualization of data with a clear presentation of the geographical area and time interval related to these indicators, which allows easier comparison of the effects of control measures.

These functions are built into the ELIS geoportal, which is a presentation tool for spatio-temporal data visualization.

The aim of this research was to improve the application of epidemiological techniques with visualization of spatio-temporal epidemic data and the functionality of the geoportal in terms of simpler and faster epidemic analysis and communication of the results to make more informative decisions related to the application of control measures. The paper describes the approach used in Bosnia and Herzegovina through the Project of the Epidemic Location Intelligence System, which will serve for the implementation of epidemic analysis functionality important for emergency response to the epidemic threat.

MATERIALS AND METHODS

Study setting and design

The public health system in B&H is organized in accordance with its administrative and political structure as a country consisting of Brčko District (BD) and two entities: Republic of Srpska (RS) and the Federation of Bosnia and Herzegovina (FB&H) with 10 cantons.

For the needs of the Epidemic Location and Intelligence System (ELIS) implementation, due to the heterogeneity of health information systems and protocols for the use of epidemiological data in B&H, a special network for data exchange was established allowing direct access to epidemic records and databases of public health institutes (as the main data sources at the local level), and providing continuous downloading of data published via the official websites of B&H institutions. Epidemic data collected from these sources were processed applying the adopted analytical methodology, and the results were presented by tables, diagrams, interactive maps and animations, arranged in the geoportal (Figure 1).

Methods

To analyse the data and to identify the trend of infection spread, several different methods were

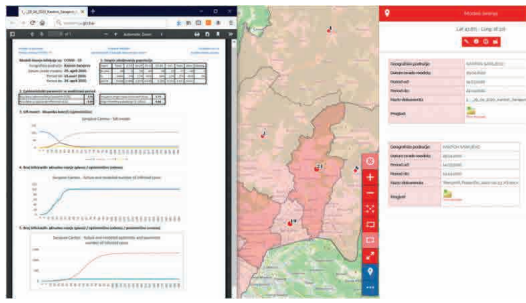


Figure 1. Epidemic Location and Intelligence System (ELIS) geoportal: presentation of interactive map of the infection spread by municipalities with a related report and epidemic models

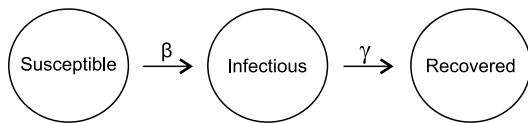


Figure 2. Susceptible – Infectious – Recovered (Resistant) model with parameters β (probability of contact between infected and susceptible persons) and γ (probability of recovery of the infected person)

applied including compartmental epidemic model, reproduction number R , epi-curve diagrams, descriptive statistics (with different types of graphs), as well as choropleth maps for different levels of administrative units. Each of the methods is useful for indicating spatial and temporal changes related to the spread of the disease, but for the correct interpretation of the results their simultaneous use is often required.

Modelling of epidemiological data for monitoring and predicting the spread of COVID-19.

Basic data sets including officially daily reported values on cumulative number of laboratory confirmed cases of COVID-19 for B&H entities, Brčko District and the whole country, and epidemiologi-

cal data for cantons and municipalities, were taken from databases and available records of public health institutions (10). These data sets were supplemented by other available clinical and laboratory information necessary to develop the model for prediction of the spatio-temporal spread of infection.

Analytical models for monitoring the spread of COVID-19 were selected in accordance with the availability of epidemiological data sets. The dynamics of infectious growth was modelled using the SIR (Susceptible; Infectious; Recovered) model (Figures 2, 3) applied for the two possible scenarios (Figure 4), i.e. for the pessimistic and optimistic scenario of the infection spread. Also, epi-curves (Figure 5) and reproduction number R (Figures 6, 7, 8) were used to monitor the effectiveness of control measures. Based on these models, reports with epidemiological parameters related to the dynamics and prediction of the disease spread were generated and published via the ELIS geoportal.

For modelling of the growth dynamics of diseased cases, the SIR model (Figures 2, 3) was applied, which was fitted by calculating the parameters β (probability of contact between infected and susceptible persons), γ (probability of recovery of the infected person, which is inverse to the average recovery time) (11), and the total number of susceptible persons, N_{opt} for the optimistic scenario and N_{pes} for the pessimistic scenario (1). The genetic algorithm was used as a mechanism to calculate the optimal values of the parameters β and N_{opt} .

He optimistic scenario (Figure 4b) refers to the assumption that due to the action of the control

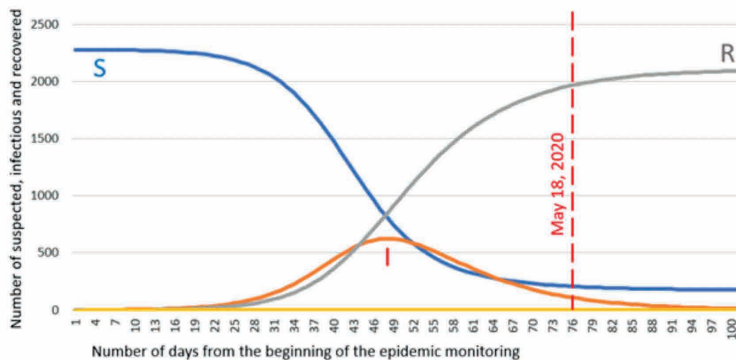


Figure 3. The Susceptible – Infectious – Resistant (SIR) model for Bosnia and Herzegovina based on an optimistic scenario and data collected from March 4 to May 18, 2020. The model is updated by continuous data entry on new confirmed cases

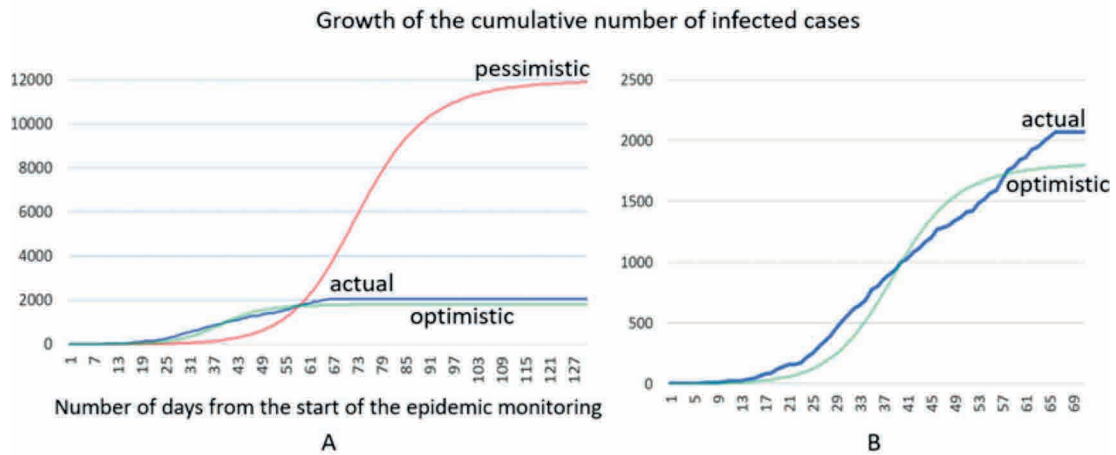


Figure 4. Growth of the number of infected cases from March 4 to May 8, 2020 (66 days from the beginning of the epidemic monitoring) in Bosnia and Herzegovina: A) current and modelled optimistic and pessimistic growth of infection and B) current and modelled optimistic growth of infection (detailed view)

measures taken, the spread of COVID-19 will rapidly slow down and stop. The pessimistic scenario (Figure 4a) refers to the assumption that the proportion of the total infected cases will be similar to those countries that took similar control measures, but had a significantly higher rate of the disease. These two scenario models are based on continuously updated data enabling continuous prediction of the disease dynamics in time close to the current moment. This approach was used to report on current dynamics and prediction of the growth of the infection at all levels of spatial units in B&H, i.e. for settlements, municipalities, cantons, entities, district and the country as a whole.

Reproduction number R. The reproduction number (R) represents the average num-

ber of secondary cases of the disease caused by a single infected individual over his/her infectious period. The R_0 (basic reproduction number) represents a starting value (at the beginning of the epidemic), assuming that the whole population is susceptible to the infection and no restrictive societal measures have been undertaken so far. Although R_0 is useful for judging of general severity of the epidemic at its own start, it is of limited use for assessing a subsequent change caused by population behaviour changes. Calculating instantaneous reproduction number R_t allows an evaluation of restrictive policies imposed that it results in higher alertness of the population, which should lead to a decrease of R_t .

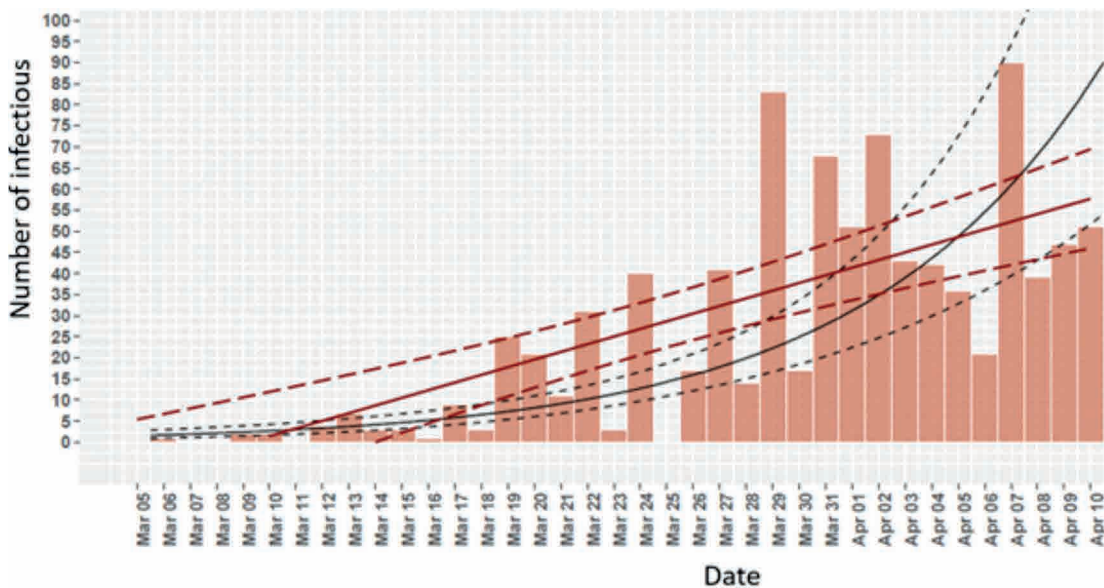


Figure 5. Epi-curve diagram based on daily confirmed cases in Bosnia and Herzegovina from March 5 to April 10 2020

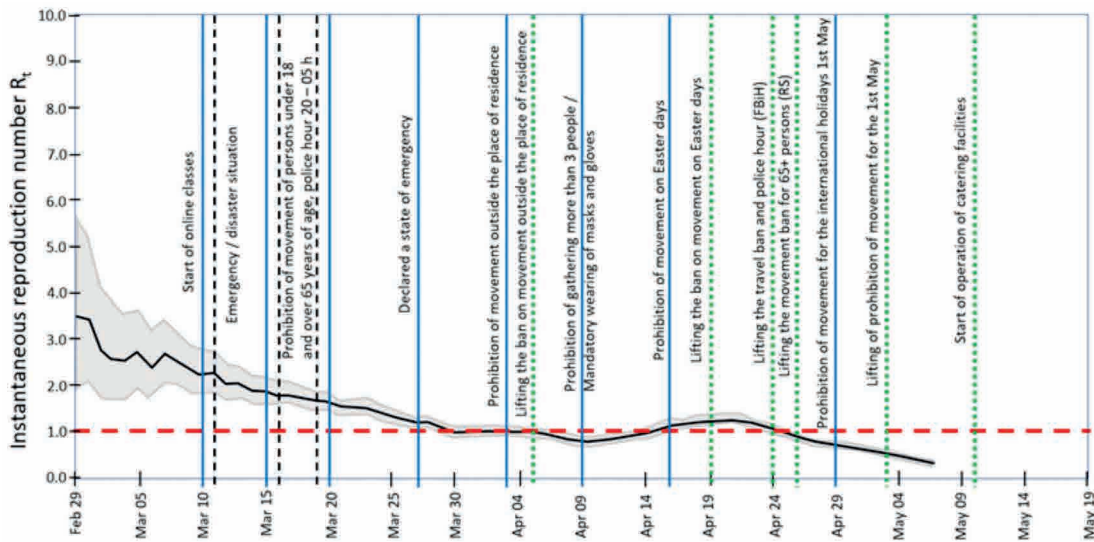


Figure 6. Instantaneous reproduction number R_t for Bosnia and Herzegovina (B&H) with control measures introduced in Republic of Srpska (RS) (full vertical lines) and the Federation of B&H (dashed lines), and relaxing of the introduced measures (dotted lines)

Mapping of epidemic data. In general, epidemiological data, such as, for example, quantitative data on the representation of tested or infected persons, qualitative data on the manufacturer and type of test, or territorial jurisdiction of dispensaries and hospitals, relating to specific spatial units (settlements, municipalities, cantons) can be classified according to the appropriate ranks and shown with the applied classification scheme of colours on the map (8). As a special method for spatial-temporal visualization of epidemic data, the technique with series of maps was used (Figure 9). Also, to show the growth of the

cumulative number of infected cases and their geographical distribution, a time lining animation technique was applied (Figure 10).

RESULTS AND DISCUSSION

Key indicators on the dynamics of the disease spread for certain geographical areas were obtained from the SIR epidemic model, for the whole country (Figure 3), entities, cantons or cities. Also, epi-curves were used to show the growth rate of diseased cases (Figure 5), and diagrams showing the R reproduction number (7) were used as a special mechanism for monitoring the effectiveness

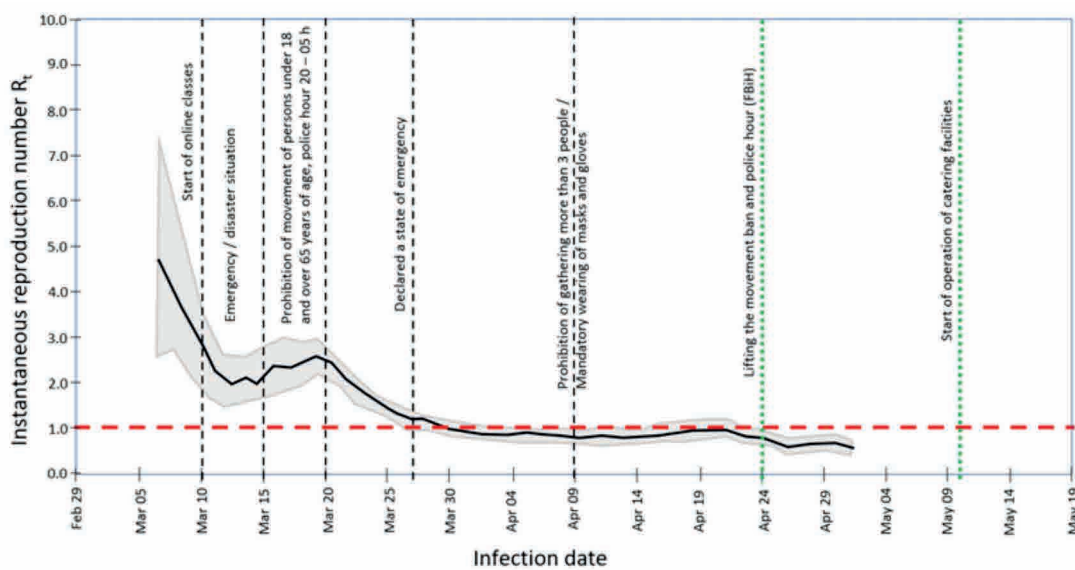


Figure 7. Instantaneous reproduction number R_t for Federation of B&H: inception of the restrictive measures (dashed vertical lines) and relaxing of the measures (dotted lines)

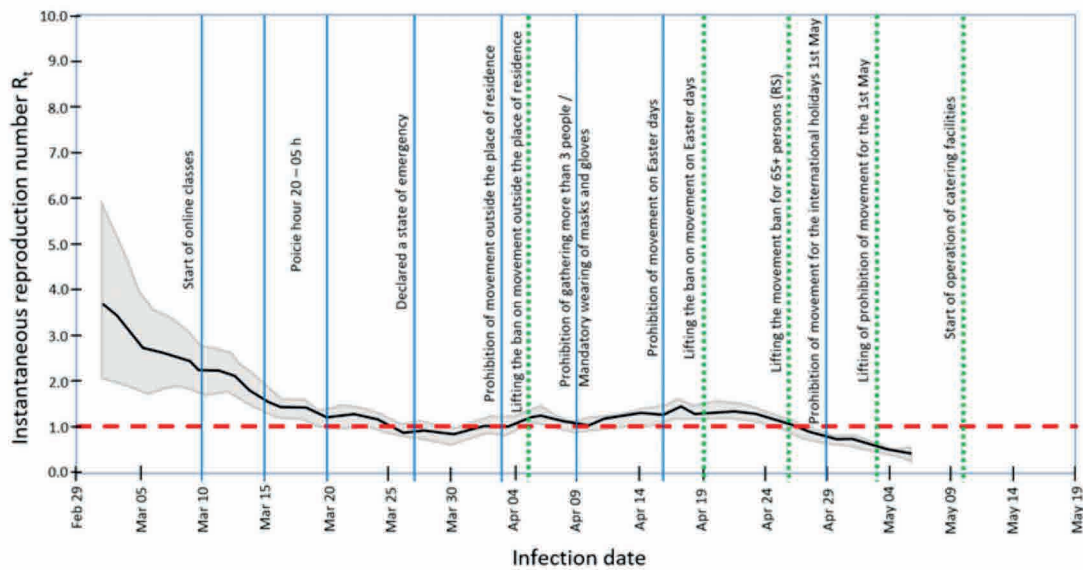


Figure 8. Instantaneous reproduction number R_t for Republic of Srpska: inception of the restrictive measures (full vertical lines) and relaxing of the measures (dotted lines)

of control measures and making decisions on their intensification or relaxation. These techniques are very useful for temporal presentation (12); however, they are not suitable or sufficient *per se* for comparing different indicators and epidemic information by geographical regions. For example, a diagram with the R reproduction number represents the relative change in the growth rate of infected persons in a given time interval for the observed region, which can be useful for recognizing the effect of current control measures. It cannot be used for quantitative comparison of the effects of the same control measures between different regions. Furthermore, tabular and graphical representations of epidemic parameters and information for a limited number of spatial units are descriptive and understandable, but not suitable for comparison between a large number of units at different administrative levels, such as settlements or municipalities. However, geovisualization of epidemic data in conjunction with diagrams and tabular data can achieve spatio-temporal visual communication and thinking (14) about the distribution of a disease magnitude (9).

It is necessary to emphasize the importance of geovisualization and its synthesis with epidemic modelling techniques in recognizing the trend of the disease spread, correct inference and more informative decision-making related to control measures. This synthesis proved to be a particularly useful approach with the reproduction

number application for monitoring of the control measures in the prevention of the spread of COVID-19 in B&H.

Being able to calculate the instantaneous reproductive number R_t allows an evaluation of effectiveness of the introduced societal measures and to recognize good time for them to be intensified or relaxed. The R_t and the rate of spread (exponential model) of the epidemic are functionally related, and the relationship depends on the assumed epidemiological model (12). The R_t value that exceeds 1 implies that the infection is spreading at an exponential rate. In practice, using the real data from the field, the R_t is calculated using time delayed data: since R_t captures the potential of the infectious spread, reporting data need to be adjusted for the length of symptomatic period before reporting day, as well as, the length of the incubation period. A difference between reporting date of the first known COVID 19 case and imputed date of an infection (Figures 6, 7, 8) illustrates this time difference.

Figure 6 shows the change of the R_t for B&H, illustrating the changes in the disease trend that were affected by all control measures applied in FB&H and RS.

Figures 7 and 8 show the change of the R_t for FB&H and RS, respectively, with the inception of control measures and dates of their relaxation. From the diagram of the reproduction number R

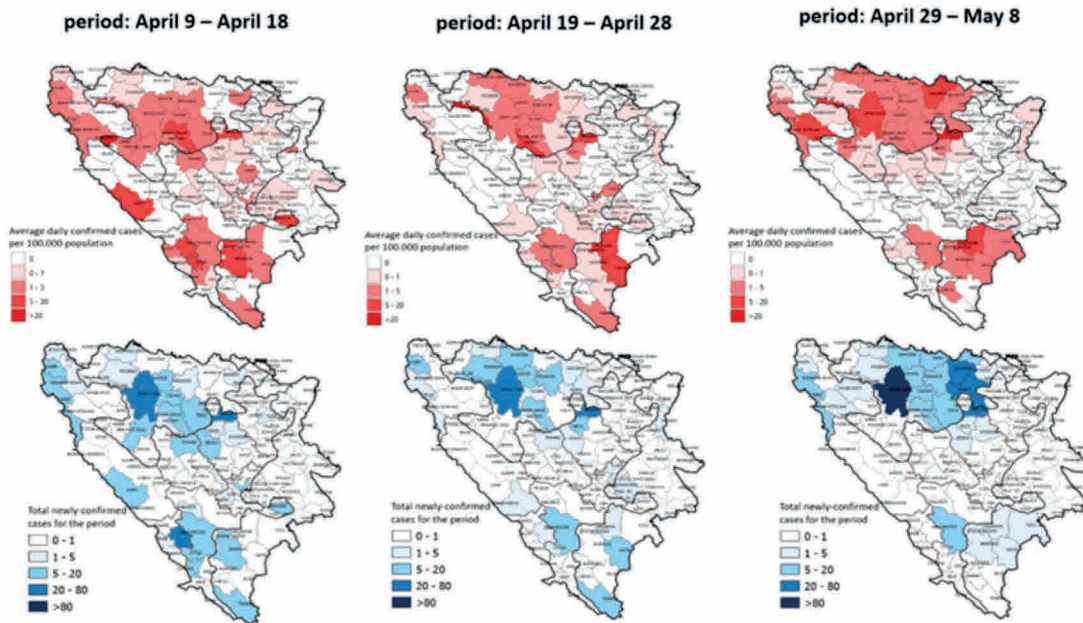


Figure 9. Daily average of confirmed cases per 100,000 inhabitants (top row) and total number of cases per ten-day interval (bottom row) in municipalities over three ten-day periods from April 09 to May 08 2020

for the entity of RS (Figure 8), where the last reading was below 0.5, it could be concluded that the current situation is generally better and that control measures work better than in the entity of the FB&H (Figure 7), where the last reading was 0.5. However, this is not the case, because these diagrams represent the relative change in the rate of infection spread and cannot be compared with each other in absolute terms. In order to be able to make a quantitative comparison of the effects of control measures between entities, i.e. geographical regions in general, it is necessary to have a broader understanding of changes in the rate of the

infection throughout the area of interest. In addition to the application of reproduction number R , this implies geovisualization of relevant epidemic data and their proper simultaneous interpretation.

Visualization of spatio-temporal epidemic data

Epidemic data can be aggregated at different administrative levels and presented through various chart types. This presentation is clear and understandable, and the values related to individual spatial units can be easily compared with each other. Figure 11 shows a bar chart with the number of confirmed cases per 10,000 inhabitants for the various administrative levels, i.e. for the three most affected cities, for B&H, RS, FB&H, BD and 10 cantons. In this way, the number of confirmed cases can be compared among spatial units at administrative levels (for example for municipalities), cantons and entities in B&H. However, if it is necessary to expand the comparison by certain time periods, this type of presentation is not sufficiently readable and clear, and it is necessary to introduce other techniques of presentation, e.g. visualization of data.

One of the visualization possibilities is the application of time lining tool for geovisualization, e.g. animation in the ELIS geoportal, which enables temporal analysis of the epidemic data by giving a broader overview of the spatial distribution and rate of spread of the infection (Figure 10).

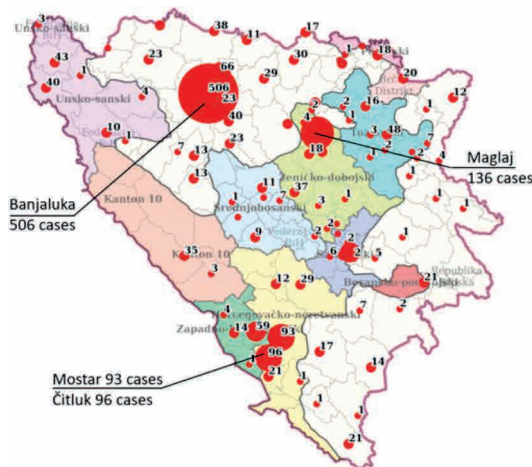


Figure 10. Spatial distribution of laboratory-confirmed cases of COVID-19 in Bosnia and Herzegovina for May 18, 2020. The figure shows the cities and municipalities with higher intensity of infectious spread

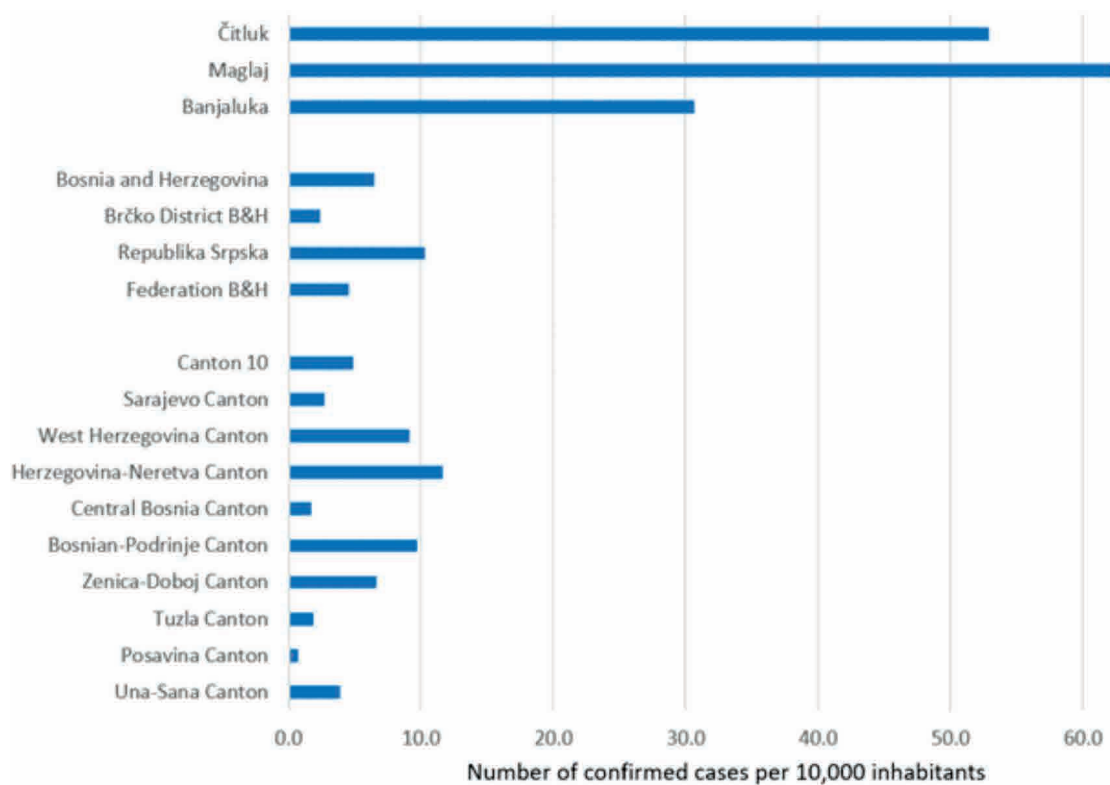


Figure 11. Number of confirmed cases per 10,000 inhabitants for the three the most affected cities in Bosnia and Herzegovina (B&H) with two entities, the district, and for ten cantons in the Federation of B&H

This tool can be used simultaneously to sequentially view changes for an epidemic phenomenon on a map (number of infected and resistant), and to temporally animate these changes in a space (13). Combined with interactive symbols, annotations and thematic maps, it represents a very useful and powerful mechanism for monitoring the development and identification of spatio-temporal patterns of behaviour of an epidemiological phenomenon, such as the rate of spread of the disease and its spatial distribution (14). This mechanism can also be applied to the thematic presentation of data with a choropleth map (14). As an example, Figure 9 shows the daily average of confirmed cases per 100,000 inhabitants and the total number for the period in B&H municipalities for three ten-day periods from April 9 to May 8, 2020. Such maps, in combination with other thematic representations, such as socio-demographic data (risk age groups, sensitive social categories), meteorological data, contamination, and with background contextual layers (orthorectified images, street maps) represent a very useful set of information for epidemiological analysis. Their role in the context of assessing epidemic situation and monitoring control measures is to

provide a dynamic comparison and broader understanding of changes in the intensity of the infection between spatial units at a given administrative level.

Epidemic analysis and communication of the findings

Interactive maps and control panels were used to communicate the findings via the ELIS geoportal (Figure 1) so that the epidemic surveillance professionals can quickly communicate the current situation and be informed about its expected development. Interactive dashboards are a particularly useful tool because they display key indicators and provide summary critical information (3). Geoportal users, scientists, health and other professionals responsible for epidemic surveillance, have access to cartographic layers, diagrams, tables, animations, series of maps, reports, various records and other documents related to specific spatial units used to analyse the epidemic situation (Figure 1). This analysis should offer answers to questions related to the assessment of the current situation, the effectiveness of control measures, the growth trend of infected and resistant cases, spatial spread of the infection throughout and in parts of the

country etc. It is especially important to continuously monitor the situation in the regions that have recorded an intensive spread of the infection and rapid observation of spatial patterns to indicate new outbreaks (13).

The following epidemic indicators are used for monitoring the situation: cumulative growth of confirmed cases, number of daily confirmed, recovered, tested cases and deaths, expected number of new cases and their ratios by age and gender groups, reproduction number R and other relevant information. They are mainly presented in the form of individual values, tables and diagrams. However, only when they are applied simultaneously with mapped data that give them a geographical context, this information can provide a complete overview of the epidemic situation in the space (13).

Based on epidemic models (SIR) and diagrams (epi-curves and R), spatial-temporal animation and series of maps of the infection spread, the spread of COVID-19 virus can be monitored and predicted, and the effects of control measures in individual regions can be evaluated. Based on the SIR model it can be concluded that on May 18 2020, the trend in the number of confirmed cases in B&H (Figure 4) was declining. Reproduction number R (Figure 6) was below 1, indicating that the situation was generally good and that the control measures taken were effective and on time. However, the situation differed at lower administrative levels. In the RS entity, the number of infected persons was significantly higher (Figure 11), but declined faster than in the Federation of B&H (Figures 7, 8). The trend of infection spreading in the entity of the Federation of B&H has been somewhat more favourable in the period of last twenty days (Figure 9) compared to the whole previous period, what is also confirmed by the declination in the reproductive number R (Figure 7). Furthermore, the situation is different at the lower level in some entities. In the city of Banja Luka (RS), the situation has deteriorated over the last twenty days (Figure 9), while in most cantons the spread of the infection has stopped. Potential outbreaks may be associated with the cities of Mostar (Herzegovina-Neretva Canton) and Maglaj (Zenica-Doboj Canton), as they had a slower declining trend compared to other citi-

es and municipalities (Figures 9, 10). In terms of the number of infected persons, Banja Luka was the most severely affected city in B&H (Figures 9, 10) and had a risk for the infection to spread to other areas. This suggests the application of selective control measures at the local level (by individual cantons, municipalities or settlements) that would be balanced between economic and social justification in terms of sustainability of economic activities and minimal impact on the vulnerable population (15).

Such an epidemic analysis and description of the situation throughout the country would not be simple without the simultaneous application of epidemic models, geovisualization of the epidemic data and the communication functionality of the geoportals that arrange all this.

In conclusion, epidemiological techniques for monitoring of the spread of infection and the effectiveness of control measures are very useful for temporal presentation, but are often not sufficient to compare different indicators and epidemic information by geographical regions. Geovisualization of epidemic data enables the release of numerous information from described models and indicators, providing an easier visual communication of the spread of the disease. Its synthesis with epidemiological modelling techniques provides better recognition of the trend of the infection spread and a more transparent assessment of the epidemic situation.

ACKNOWLEDGEMENT

Would like to thank to President of the Presidency of Bosnia and Herzegovina for supporting the Project of the Epidemic Location Intelligence System, to the Academy of Sciences and Arts of Bosnia and Herzegovina (ANUB&H) for the material provided for the preparation of this paper, and to the Cantonal Institutes for Public Health for epidemic data provided.

FUNDING

No specific funding was received for this study.

TRANSPARENCY DECLARATION

Conflicts of interest: None to declare.

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