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Use of the Computer Modelling for the Analysis of Dangerous Areas during Flooding of Territories

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ABSTRACT

The main goal of the article is to develop a toolkit algorithm for the application of computer modelling in the analysis of hazardous areas during flooding using ArcGIS software for representatives of administrative-territorial authorities. The created toolkit algorithm can be utilized at the regional and local self-government levels for analysing potential negative consequences of flooding, followed by decision-making regarding the implementation of appropriate protective measures. The authors have developed a toolkit algorithm for the application of computer modelling to analyse hazardous areas during the flooding of territories using ArcGIS software, specifically designed for representatives of administrative-territorial authorities. This algorithm involves modelling the watershed basins of the area and identifying hazardous areas that may pose additional dangers or lead to a "domino effect" during the flooding of the studied territory. The authors have identified a list of hazardous areas that pose additional risks to the population's livelihood in the territory that may be affected by flooding. Additionally, the practical application of the proposed computer modelling algorithm has been examined using the example of the Drohobych district in the Lviv region, where frequent flooding has been observed in the past. The Drohobych district includes the territorial communities of Medenychi, Drohobych, Truskavets, Skhidnytsia, and Boryslav. In the region, there are two solid household waste landfills near the villages of Bronytsia and the city of Boryslav, which can be considered hazardous areas in the event of flooding. The greatest danger of consecutive contaminations due to flooding occurs in the area of the cities of Borislav and Truskavets. Water covers four cemeteries and comes dangerously close to the landfill as a result of flooded territories. The city of Drohobych is in a relatively safe zone; however, the water sources supplying the city are within the boundaries of the city of Truskavets, which also causes an additional danger to these and adjacent settlements. Subsequently, the developed toolkit algorithm can be utilized at the regional and community levels for analysing potential negative consequences of flooding, followed by decision-making regarding the implementation of appropriate engineering protection measures in specific areas.

Keywords: civil protection, sustainable development, data visualization, catchment basins, ArcGIS software.

INTRODUCTION

In the analytical report by the United States National Intelligence Council, "Global Trends 2030: Alternative Worlds" (2023), potential dangers that could cause maximum devastating impact have been identified. One of the primary threats to international security is climate change. The rise in ocean temperatures and the reduction in the amount of snow and ice have resulted in an increase in sea levels. Between 1901 and 2010, due to the growing volume of water in the oceans, the global sea level rose by 19 cm, attributed to overall warming and glacier melting. Each decade since 1979, the area of Arctic sea ice has decreased by 1.07 million square kilometres, and the water level in all water arteries is consistently increasing (National Intelligence Council, 2023). This leads to the occurrence of flooding in territories, which becomes more extensive each year, resulting in substantial damages.

Climate change disrupts the economic development of countries and has distinctly measurable financial and ecological consequences that only escalate each year. On the other hand, it is evident that there is a growing awareness today that solutions and ways out of the situation exist not only at the level of a country or region but also at the local level, specifically at the levels of districts and united territorial communities (UTCs).

In Ukraine, a sustainable development strategy for the period until 2030 has been approved (Verkhovna Rada of Ukraine, 2023), outlining its main goals, including ensuring the safety, resilience, and environmental sustainability of cities and other populated areas. It is clear that achieving sustainable development of territories depends not only on nationwide policies but also directly on measures taken at each administrative-territorial level. However, the decentralization process in Ukraine has just recently begun, so newly established districts and communities require organizational, methodological, and practical assistance to effectively and timely respond to dangers and prevent their consequences, including those related to flooding. The main goal of the article is to develop a toolkit algorithm for the application of computer modelling in the analysis of hazardous areas during flooding, used ArcGIS software, specifically designed for representatives of administrative-territorial authorities. The created toolkit algorithm can be utilized at the district and UTC levels for analysing potential negative consequences of flooding, followed by decision-making regarding the implementation of appropriate protective measures.

Extended tasks of the toolkit algorithm may also include:

- compiling a list of types of flooding that occur and considering their differences,
- identifying and monitoring hazards associated with flooding,
- compiling a list of meteorological, human, and topographic factors contributing to flooding,
- describing cases of illness and mortality related to flooding,
- explaining the difference between flood damage and diseases at different stages of flooding,
- describing demographic groups at the highest risk of being affected by flooding, with an explanation of the reasons,
- compiling a list of specific actions that can be taken to reduce the risk of flooding,
- explaining why immediate actions can reduce the risk during flooding.

METHODS AND MATERIALS

During the research process, modelling methods, system analysis, and structural analysis were employed to study the subject area of the emergency situations prevention system and conduct a comparative analysis of existing models as well as the development of new ones. Simulation modelling software tools were utilized to visually represent the consequences of emergency situations and simulate the watershed basins of the territory.

In the works (Fedorchak 2018 a,b; Ivanova 2020) an analysis and assessment of the peculiarities of the functioning of the organizational mechanism of state risk management for emergencies in Ukraine were considered. The authors focused on defining and constructing a state model of risk management, without taking into account lower administrative levels. In articles (Kuleshov, Yashchenko 2022; Zahidna, Zakorko 2022) consider the relevance and peculiarities of UTC functioning under martial law, including responding into emergency situations.

In the work of Rohulia (2018), modern aspects of implementing state policy in the field of vital activity safety for territorial communities are explored, and the role of management is outlined, where the state, during the decentralization of local self-government bodies, delegates its powers to ensure the safety of population life to the local level. Based on the research, the author proposes ways to address problems arising during the implementation of state policy in civil protection. As stated in the article, further and deeper research in this direction is necessary, as it is only beginning to function. In the article (Rohulia 2021), the author conducts a detailed analysis of the effectiveness of the activities of local self-government bodies in organizing the safety of life for territorial communities based on econometric modelling. However, this analysis does not consider the effectiveness of ensuring safety through the implementation of projects to protect territories from natural and man-made factors by economic entities or volunteer organizations and does not provide any methodological guidance or tools.

The authors of the scientific paper (Dankevich et al., 2020) have demonstrated the expediency of implementing the European participative model of management for united territorial communities as a means of shaping their local security, activating, and accumulating internal development opportunities. The conclusions of the article mainly pertain to the economic component of security rather than the security from the perspective of civil protection for the population.

In the works (Baratian, Kashani 2022; Sharif et al., 2023) consider the models of response to emergency situations and the restoration of life after them using the examples of communities. The proposed modelling framework can examine the effectiveness of various coordination schemes in disaster response and recovery, which can be used to develop plans to better respond to probable future disasters. However, the proposed methodology is focused on responding to earthquakes, not complex emergency situations.

Examples of the application of computer modelling methods in specific territories can be found in the articles (Kinaneva et al., 2019; Havrys et al., 2023), where the broad possibilities of using models, including with the use of ArcGIS software, are demonstrated for preventing large-scale forest fires. The research (Dudek et al., 2020; Dudek, Tajduś 2021) describes approaches to modelling dangers arising from the flooding of underground mines, providing the ability to predict the occurrence of emergencies on the surface. The proposed methodology by the authors is based on the finite element method, allowing, after calibrating the 3D numerical model using surface subsidence measurements and geological-mining data, to simulate the flooding process by changing the density of the environment according to the classical principles of soil mechanics and rock mechanics, and then obtain forecasted values of changes in the land surface. However, this methodology works only in confined spaces (mines) and does not include conditions of soil saturation with floodwaters.

The articles (Lei et. al., 2021; Qi et. al., 2021) describe various known methods for modelling flooding in urban areas, but these descriptions are generally abstract. Other examples include works (Bonafilia et. al., 2020; Kharazi, Behzadan 2021; Chen et. al., 2022), where diverse approaches to detection and prediction of flooding based on artificial intelligence are presented. The proposed ideas are innovative, and it will take some time for their practical implementation in Ukraine.

In the articles (Starodub, Havrys 2018; Starodub et. al., 2018; Starodub et. al., 2022), models and mechanisms for implementing projects to protect territories from flooding are described. However, the authors do not specify whether these methods have been applied in practice at the district or united territorial community level. Additionally, there is no mention of the toolkit for implementing these models.

RESULTS AND DISCUSSION

After the initiation of the decentralization process in 2020, as per the document (On the Formation and Liquidation of Districts, 2020), Ukraine formed 136 districts, replacing the previous 490 that existed. The reorganization of districts began in December 2020, following the enactment of the law on the distribution of powers and resources between districts and communities. Each district was subdivided into communities, and as of today, 1469 UTCs have been established. According to (On Local Self-Government in Ukraine, 2023), specific areas of competence and authority have been outlined for each district and community. It is noted that among the tasks of districts and UTCs in the field of civil protection are:

- Preparation, approval, organization of implementation, and execution of local programs in the field of civil protection.
- Establishment and use, in accordance with the legislation, of material reserves to prevent and eliminate the consequences of emergencies on the territory of the territorial community.
- Creation on the territory of the territorial community of local commissions on emergency situations to coordinate activities related to ensuring the protection of the population and territories from the consequences of emergencies, preventing emergencies, and responding to them.
- Ensuring notification and informing of the population residing in the respective territory about the threat and occurrence of emergencies, including in formats accessible to individuals with visual and hearing impairments.
- Development of measures aimed at ensuring the sustainable operation of objects of economic entities within their management scope in emergency situations and special periods, and monitoring the implementation of these measures by economic entities.
- Development, provision, and implementation of plans in the field of civil protection, mandatory for implementation on the territory of the territorial community.
- Organization on the territory of the territorial community of works to eliminate the consequences of emergencies and carry out recovery

efforts, involving, in accordance with the law, economic entities, voluntary formations of civil protection, volunteers, and the population in these works.

This list is not exhaustive, but it is clear that to fulfill their tasks in the field of civil protection, newly formed local administrations require organizational, methodological, and practical support. Additionally, it is important to remember that emergency situations can lead to a "domino effect," which, in most cases, results in even greater consequences. Flooding is an example of such emergencies. Dangerous areas during flooding that pose additional risks include:

- Landfills – flooding of landfills can lead to the release of toxic substances, contaminating water and soil. There is also a risk of the release of hazardous chemical compounds.
- Cemeteries – flooding of cemeteries can result in the release of various substances from graves and vaults, potentially affecting water quality.
- Animal burial sites and livestock burial grounds – flooding can lead to the release of waste and toxins from animal carcasses, posing a risk to the environment and public health.
- Agricultural enterprises using mineral fertilizers, pesticides, and having large livestock populations – enterprises using mineral fertilizers and pesticides may contaminate water when these substances enter water bodies during flooding. Large livestock populations can also create problems with the release of livestock waste.
- Sources of freshwater – flooding can affect water quality and contaminate agriculture, leading to challenges in ensuring clean water and safe food.
- Infrastructure objects – flooding can lead to the destruction of roads, bridges, power grids, and other infrastructure elements, resulting in restricted access, traffic jams, and significant challenges in restoring normal functionality. This point is particularly crucial during catastrophic flooding events in the area.

Considering these risks, it is crucial to develop and implement emergency plans and preventive measures, as well as improve infrastructure to reduce the impact of natural disasters on people and the environment. The use of the toolkit algorithm proposed by the authors is expected to facilitate the execution of some of the aforementioned tasks in the field of civil protection, particularly those related to forecasting, prevention, and alerting the population about emergency situations.

In general, computer modelling of watersheds is divided into the study of two situations: hydrological and hydrodynamic. Hydrological modelling focuses on studying precipitation and evaporation, allowing the determination of the amount of water (water flow rates over a specific period) on the Earth's surface. In other words, it answers the question of how much water and where the water flow is directed. Hydrodynamic modelling examines the movement of water in rivers, streams, or other bodies of water. This enables the consideration of how water moves in space, how floods form, and which areas may be at risk.

Together, these two groups of models provide a detailed overview of the hydrological cycle and potential flood consequences. Hydrodynamic modelling utilizes data on the amount of water on the Earth's surface, the direction of flow, and determines with what speed, height (depth) the water spreads, and which area will be covered by the flood. These two models are based on the digital elevation model (DEM) of the Earth's surface.

The initial data for the digital elevation model are obtained from the EarthExplorer website (2023), where elevation data is available in various formats suitable for specific processes. There are two types of elevation data that can be used in watershed modelling:

- DEM (digital elevation model) – represents the bare earth surface.
- DSM (digital surface model) – includes features such as buildings and trees along with the bare earth surface.

These data are provided in the form of GRID files or TIN files with a dataset of the terrain. GRID files, with image extensions, are used to create a digital elevation model, particularly for large-scale drainage analysis. Triangulated Irregular Networks (TIN files) are used to record linear objects in hydrological analysis and design.

Both formats have their advantages and disadvantages, and their selection depends on the specific requirements of the project during emergency situation modelling. GRID files are suitable for extensive drainage analysis, while TIN files are useful for recording linear features in hydrological analysis and design. The choice between them is made considering the specific needs and challenges of the project.

Triangulated irregular network (TIN) extension has several advantages, including adaptively distributed sample points according to the surface, precise values for linear characteristics, structural lines for smoothness and continuity determination, sample points for rank drainage are in specific locations, absence of unnecessary data, and the ability to enhance surface accuracy (density), create precise projections, and define specific watershed boundaries. However, TIN files have significant drawbacks such as the need for substantial memory storage for point information, considerable CPU workload for watershed basin calculations, lack of functional transformations in the mesh structure, and the potential complexity of the TIN generation process.

On the other hand, GRID image extension files have more advantages compared to TIN extensions, making them more widely used. Their benefits include a simple and effective data structure, the presence of an algebraic rank drainage map, open configuration, and diverse data sources that can be used for modelling. However, they also have drawbacks, such as the absence of detailed map features (point objects), memory space reservation, and projection issues (grid data cannot be overwritten by other data).

Therefore, comparing all the advantages and disadvantages of different types of image extensions, it is better to use digital elevation model (DEM) files (so-called GRID files) as input data in the process of watershed basin modelling.

The process of computer modelling of watershed basins using the ArcGIS program (ArcGIS Resources, 2023) includes the following steps:

1. Save your geographic information data:
   - load the digital elevation model (DEM) in georaster format;
   - ensure that your DEM data has correct spatial referencing.
2. Open the ArcGIS program and create a new project.
3. Add DEM to your project:
   - select “add data” and choose your DEM file and other necessary layers, including layers of hazardous areas.
4. Use the “fill” tool to fill sinks:
   - select “spatial analyst” under the “extensions” menu.
   - find the “fill” tool and specify your DEM as the input layer. This tool removes sinks so that they do not affect basin modelling.
5. Use the “flow direction” tool to determine the flow direction:
   - now that you have filled sinks, use the “flow direction” tool to determine the flow direction from each point on the DEM to the neighbouring point.
6. Use the “flow accumulation” tool to calculate flow accumulation:
   - this tool helps determine how many streams gather at each point on the DEM, helping you identify the size of the watershed basin.
7. Use the “stream link” tool to identify the main stream:
   - this tool helps you identify the main stream in the basin.
8. Use the “watershed” tool to determine the basin boundary:
   - specify your main stream to determine the boundary of the watershed basin.
9. Mark the basin boundary on your map and examine the modelling results.

All these steps are part of the toolkit algorithm for identifying hazardous areas during the flooding of administrative-territorial regions, as depicted in Figure 1. This is a general algorithm for identifying hazardous areas on the basis of watershed modelling in the ArcGIS program. Please note that specific steps and parameters may vary depending on the version of the ArcGIS program (ArcGIS Resources, 2023) and your input DEM.

Let’s consider the application of the toolkit algorithm for computer modelling using the example of the Drohobych district in the Lviv region, where, according to historical-statistical data, flooding occurs most frequently, leading to extensive consequences. The Drohobych district includes the territorial communities of Medenychi, Drohobych, Truskavets, Skhidnytsia, and Boryslav. In the region, there are two solid household waste landfills near the villages of Bronytsia and the city of Boryslav, as shown in Figure 2, which can be considered hazardous areas in the event of flooding.

In addition, there are five large livestock farms in the villages of Dobrohostiv, Yasenytsia-Silna, Derezhychi, Verkhniy Dorozhiv, and Vynnyky on the territory of the district. There are also smaller livestock complexes within the communities that should be considered in a detailed examination of community areas. However, in the scale of the district, the authors present the largest of them.

The largest number of hazardous areas in the selected territory is occupied by cemeteries.

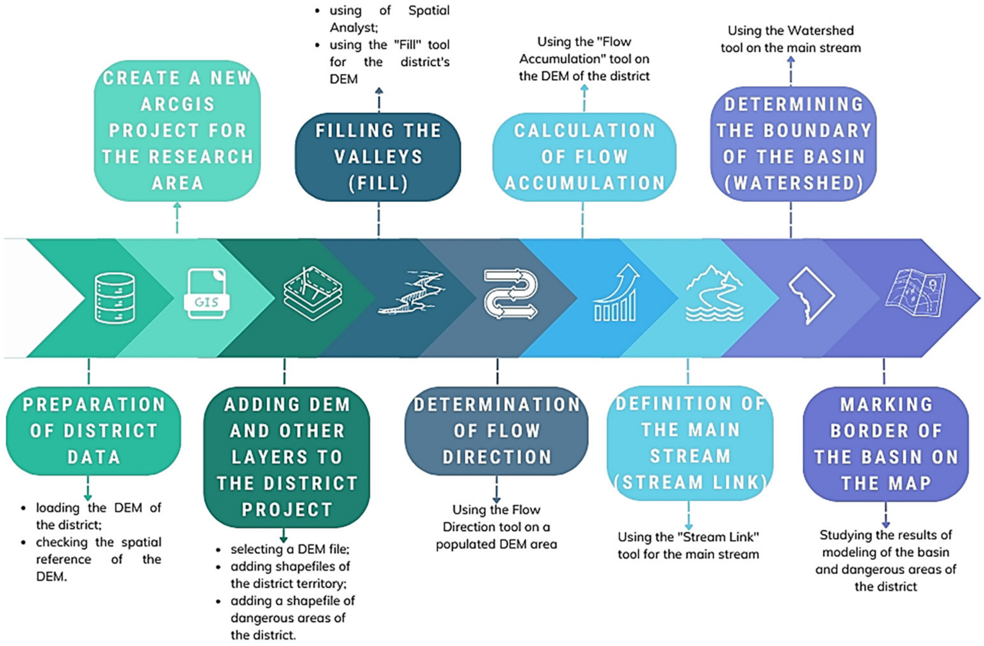

Figure 1. Toolkit algorithm for identifying hazardous areas during flooding of territories

The article's authors took into account both old, no longer used cemetery plots and new ones that have been in operation for a relatively short time. In the majority of cases, cemeteries are located on the outskirts or not far from large cities such as Borislav, Drohobych, and Truskavets. For the investigation, the authors selected water collection points (Figure 2), where, according to the data from the State Emergency Service of Ukraine (State Emergency Service of Ukraine, 2023), the most frequent water level rises are observed, posing a threat to nearby settlements.

As seen from the modelling results in Figure 2, the greatest danger of consecutive

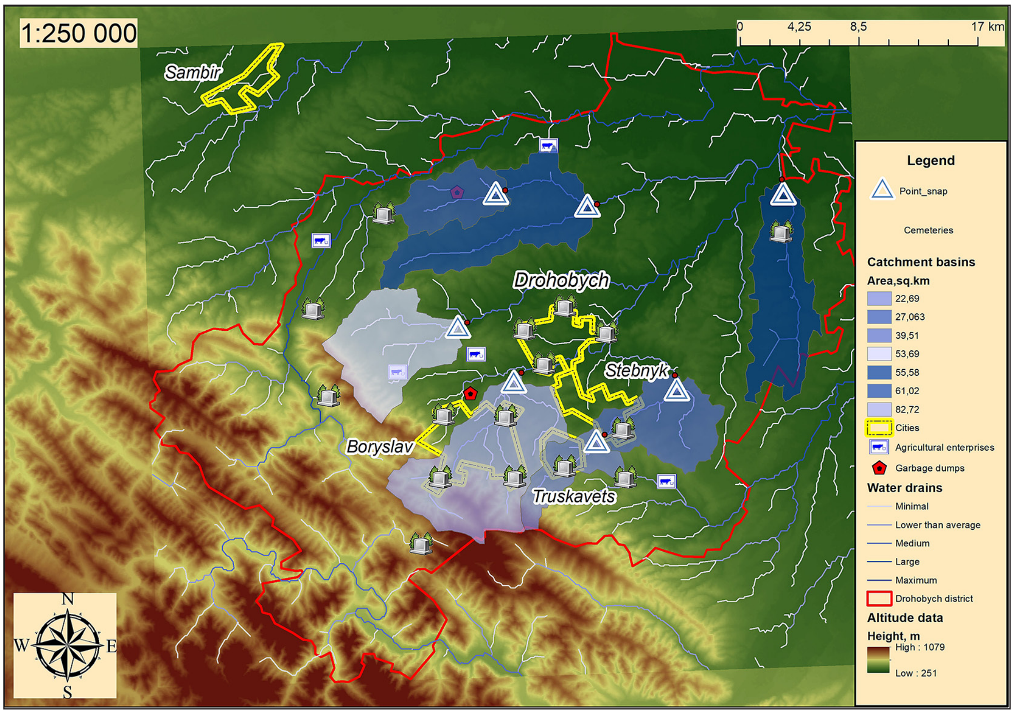

Figure 2. Application of the toolkit algorithm for computer modelling in the Drogobych district of the Lviv region using the ArcGIS program

contaminations due to flooding is in the area of the cities of Borislav and Truskavets. As a result of flooding this territory, water covers four cemeteries and comes dangerously close to the landfill. The city of Drohobych is in a relatively safe zone; however, the water sources supplying the city are within the boundaries of the city of Truskavets, which also poses an additional danger to these and adjacent settlements.

There is a risk of flooding and the infiltration of hazardous substances into underground layers from the landfill of solid household waste near the village of Bronytsia. Additionally, in this community, there is a livestock enterprise with 13,000 cows that may also be inundated, posing an additional danger to the community's population. In the area of the city of Stebnyk, the threat of groundwater pollution exists due to the flooding of the local cemetery and water supply sources located near the city of Truskavets.

The example provided in Figure 2 of the application of the toolkit algorithm for computer modelling in the Drogobych district of the Lviv region schematically illustrates the possibilities of using this algorithm at the administrative-territorial levels of the district and community for protection, flood forecasting, and prevention of their harmful impact due to additional factors present in the researched territory.

CONCLUSIONS

The authors have developed a toolkit algorithm for the application of computer modelling to analyse hazardous areas during flooding using ArcGIS software for representatives of administrative-territorial authorities. This algorithm involves modelling the watershed of the area and identifying hazardous areas that may pose additional dangers or lead to a "domino effect" during flooding of the investigated territory. The authors have identified a list of hazardous areas that pose additional risks to the population's livelihood in the area that may be flooded.

Extended tasks of the toolkit algorithm may also include: compiling a list of types of flooding that occur and considering their differences; identifying and monitoring hazards associated with flooding; compiling a list of meteorological, human, and topographic factors contributing to flooding; describing cases of illness and mortality related to flooding; explaining the difference between flood damage and diseases at different stages of flooding; describing demographic groups at the highest risk of being affected by flooding, with an explanation of the reasons; compiling a list of specific actions that can be taken to reduce the risk of flooding; explaining why immediate actions can reduce the risk during flooding.

Additionally, the practical application of the proposed computer modelling algorithm has been examined using the example of the Drohobych district in the Lviv region, an area that has experienced frequent flooding in the past. As a result of the modelling, the most hazardous areas for the occurrence of subsequent contaminations due to flooding have been identified in the areas of the cities of Borislav and Truskavets.

Subsequently, the developed toolkit algorithm can be utilized at the regional and community levels for analysing potential negative consequences of flooding, followed by decision-making regarding the implementation of appropriate engineering protection measures in specific areas. This will enable more effective planning of flood protection measures and reduce financial expenditures for their implementation, contributing to the sustainable development of the territories.

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