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Design of Web GIS Application for Planning of Military River Crossing

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Abstract

Successful ground military operations necessitate thorough comprehension of the operational environment, particularly terrain and water features. This article advocates for the utilization of Geographic Information System (GIS) technology to develop a dynamic web application aimed at analyzing and planning watercourse crossings. By harnessing the capabilities of ArcGIS Pro and ArcGIS Online, the proposed application integrates hydrological and terrain data to provide comprehensive insights into the feasibility of crossing specific water obstacles under varying conditions. Key considerations include terrain characteristics, river channel profiles, and the tactical specifications of military vehicles. While the application is currently in the conceptual phase and awaits verification, its potential in enhancing operational planning for the Czech Armed Forces is underscored. This GIS-based approach promises to enhance decision-making processes by offering real-time, interactive support for evaluating and strategizing water obstacle crossings within military operations.

KEY WORDS: *river crossing, military planning, hydrologic modelling, Web GIS, ArcGIS Pro, ArcGIS Online, HEC RAS.*

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1. Introduction

The ground operations of rescue, security or military units necessitate thorough comprehension of the operational environment. For this purpose, terrain analysis involves a comprehensive assessment of the physical characteristics of the landscape to inform operational forces decision-making and their planning [1]. Terrain analysis involves assessing the natural features of an area to identify potential hazards and mitigate risks for military operations or other activities [1, 2]. There are various approaches to conducting terrain analysis and multiple purposes for which the resulting outputs can be utilized [2]. From a military perspective, terrain analysis focuses on topographic analysis, identification of key terrain, determination of avenues of approach, evaluation of natural and man-made obstacles and cover, assessment of visibility, determination of weather and environmental impacts, and identification of natural hazards [3].

Cross-country movement analysis involves assessing the feasibility and challenges of moving military forces, equipment, and vehicles across varied terrain types [4, 5]. It includes analyzing factors such as topography, soil conditions, vegetation, obstacles, waters and weather conditions to determine the most suitable routes for movement [4, 6]. Techniques used in cross-country movement analysis may include terrain modelling, route planning, and simulation to evaluate different scenarios and identify potential obstacles or hazards that could affect movement efficiency and effectiveness [3, 7, 8, 9]. The goal is to optimize mobility while minimizing risks and resource consumption [10]. A fundamental aspect of terrain passability analysis involves evaluating bodies of water primarily as obstacles to movement [11].

In military operations, the ability to overcome water obstacles swiftly and efficiently is crucial for achieving military objectives [12, 13]. Military forces employ a variety of specialized equipment for crossing water obstacles. This includes amphibious vehicles, pontoon bridges, assault boats, engineer reconnaissance vehicles, and vehicles adapted for fording [14, 15].

These assets are designed to facilitate the rapid movement of troops, vehicles, and supplies across bodies of water, enabling the continuation of operations without delay. In terms of the temporal sequence of situations, for decision-making and planning purposes regarding the overcoming of water obstacles, it is important not only to know the current hydrological situation but also to predict changes depending on the water regime and weather forecasts [1].

Outputs from hydrological modelling can serve as valuable informational resources for military commanders in both combat and non-combat scenarios [16]. For instance, in a combat situation, such outputs can provide insights into the feasibility of river crossings or the vulnerability of certain areas to flooding or erosion. Imagine a scenario where a military unit needs to traverse a river to execute a strategic maneuver. By utilizing hydrological data and predictions, commanders can assess the risk of crossing at different points along the river, considering factors like water depth, flow velocity, and potential changes due to weather conditions. This information enables them to make informed decisions to minimize risks to personnel and equipment.

Similarly, in non-combat situations such as disaster relief operations, hydrological modelling outputs can aid in assessing the impact of natural disasters like floods or landslides on infrastructure and civilian populations [17]. For instance, during a flood emergency, military units involved in relief efforts can use hydrological data to identify areas at high risk of inundation, prioritize evacuation routes, and allocate resources effectively. This proactive approach enhances the efficiency and effectiveness of disaster response operations, ultimately saving lives and minimizing property damage.

In summary, the integration of hydrological modelling outputs into military decision-making processes enhances situational awareness and enables commanders to make well-informed decisions in a variety of operational contexts, ranging from combat missions to humanitarian assistance and disaster relief operations. For this purpose, a GIS-based approach can provide a map-based interactive situational view to enhance decision-making processes.

2. Input assumptions

The topic is important for many different applications in scientific-technical and socio-environmental fields [17]. It is also addressed by components of rescue and safety systems worldwide, which collect precise data for evaluating the physical-geographical conditions of the area of interest. Cross-country movement and river crossing analyses typically involve complex calculations or simulations. The accuracy of these analyses relies heavily on the input assumptions, which shape the behavior of simulated agents or the physics of the environment [3, 5].

The research area of acquiring hydrological data for determining the profile characteristics of watercourses offers an abundance of new possibilities, technologies, and approaches for addressing this issue. One of the methods is multispectral classification of image data. A variation of the multispectral classification model, based on working with Sentinel-2 satellite data, was proposed by Mukhtar et al. (2023) [18], who present this method of data collection about a large watercourse and its surroundings as reliable, fast, and cost-effective. Their model distinguishes the watercourse, sedimentation barriers, vegetation areas, and, thanks to access to Sentinel-2 satellite images, also tracks their development over time. The method is suitable for various scientific applications, especially environmental ones, but does not provide information about the depth at specific locations of the watercourse.

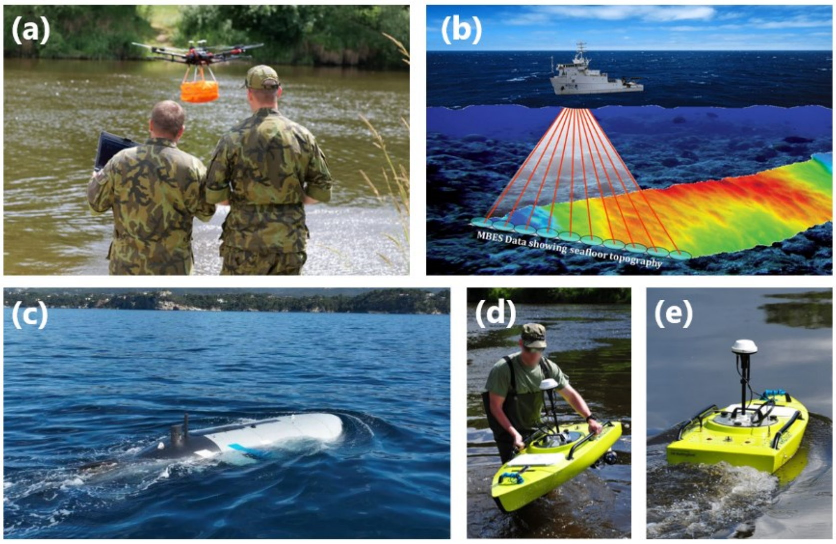

Fig. 1. Possible carriers of various detectors of electromagnetic radiation or sound providing bathymetric data: (a) UAV carrying GPR (Ground Penetrating Radar) [23], (b) ship as surface vehicle carrying SONAR [24], (c) UUV [25], (d) & (e) USV carrying SONAR [23].

To gather data on the relief of the riverbed, an alternative approach can be employed. This method, known as SDB (Spectrally Derived Bathymetry), relies on the absorption of light in the water column, which varies depending on the wavelength. The total radiation captured by the sensor comprises several components: backscatter from the atmosphere, water surface, water column, and riverbed (the primary source of light is the Sun). Assuming uniform surface and subsurface conditions, depth can be inferred from a single channel of a spectral image without requiring external reference data.

However, in practical applications, multiple radiometric bands of multispectral images are typically utilized. This is because the radiation reflected from the water surface is influenced by both water depth and the reflectivity of the riverbed, making these effects interdependent. To address and mitigate this limitation, Stumpf et al. (2003) [19] introduced a calculation method based on the ratio of two specific spectral bands. They observed that within a certain range of wavelengths, the reflectance value of the riverbed remains relatively constant. Consequently, it can be eliminated from the calculations without compromising the accuracy of the resulting depth estimates. The SDB method continues to be refined and enhanced, with advancements such as the integration of machine learning techniques [20].

Global trends in field measurement technology indicate a growing inclination towards gradually phasing out traditional in-situ geodetic methods for spatial data collection due to their time-consuming and costly nature. These conventional methods are now being replaced by modern geodetic measurements employing dGPS transect points [21]. Rather than relying on traditional methods, there is a shift towards contactless hydrological data collection through the transmission and subsequent detection of electromagnetic radiation or sound [22]. Various detectors utilize different carriers, including aircraft, unmanned aerial vehicles (UAVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs) – see figure 1. Additionally, there are throwaway sonars and sonars permanently affixed to bridge structures.

When precise bathymetric data of watercourses are needed and traditional in situ data collection methods are impractical, unmanned aerial vehicles (UAVs) present a suitable alternative. UAVs can navigate challenging terrains and deliver high-resolution data at relatively low costs. In 2023, Keanu Singh [26] authored a comprehensive technical report focusing on direct methods for bathymetric data collection, comparing various UAV approaches, including optical and acoustic measurements.

Green LiDAR (Light Detection and Ranging) represents a precise method for measuring riverbed depth and shape, with its primary advantage lying in its high accuracy. However, measurements can be influenced by factors such as water depth and clarity, bottom type, and flow. In a study conducted by Kastdalen and Heggenes [21], similar to Singh [26], several LiDAR sensors (mounted on different UAVs) were compared, and the results of individual measurements were further contrasted with the accuracy of traditional in situ data collection. While the study demonstrated the high accuracy of reflected green light from LiDAR emitters, it also revealed limitations such as signal loss with increasing depth, turbid water levels, and dark riverbeds.

Some LiDAR systems employ both green and infrared wavelengths to improve the accuracy of bathymetric measurements (Dual-Wavelength LiDAR) [26]. The green wavelength is utilized for water penetration and riverbed mapping, whereas the infrared wavelength is employed for topographic mapping of banks and surroundings. However, errors may still arise in determining the terrain of vegetated areas and due to false reflections caused by sediments in the water column. Mapping regions with river rapids and dam outlets has traditionally presented challenges.

SONAR (Sound Navigation and Ranging) systems are generally categorized into single-beam and multi-beam systems, with single-beam surveys being more cost-effective [26]. However, sonars face challenges when measuring very shallow depths due to surface clutter and multipath effects. Moreover, accuracy diminishes notably in vegetated rivers due to the high level of sound wave reflection from vegetation. Deploying Sonar on boats can be complex in remote regions and is restricted to navigable waters or, particularly for USVs, areas without dense floating aquatic vegetation.

Ground-penetrating radar (GPR) is commonly utilized in terrestrial environments for detecting subsurface features such as buried utilities, bedrock, or archaeological artifacts, but it can also serve bathymetric purposes [26]. It operates by emitting radio waves into the ground or water and measuring the time it takes for the waves to return. For instance, Bandini et al. (2018) [27] conducted field measurements using this method. In their study, the georadar, floating on the surface, was suspended under a UAV equipped with a radar altimeter, enabling the drone to maintain a constant height of 0.5 m above the water level. Georadar measurements were compared with sonar measurements, revealing that georadar significantly outperformed sonar in water bodies with medium or high aquatic vegetation density. Nonetheless, limitations arise in watercourse sections with depths less than 1 m, where georadar struggles to clearly identify underwater bed topography [26].

Digital photogrammetry and automated evaluation methods, such as Structure from Motion (SfM) and photogrammetric depth determination from stereo-images, are also garnering attention. SfM is a technique that identifies corresponding points between images and reconstructs a 3D model based on the geometric relationships between them. The result is a model that enables the determination of how individual 3D coordinates are projected onto camera images. When applied to bathymetry in river and reservoir systems, digital photogrammetry faces challenges due to light reflection and refraction on the water surface. This necessitates refraction correction, which is feasible if the water is clear and well-visible in the images. The approach provides high spatial resolution and performs better if the bottom is sufficiently structured to facilitate feature matching [26]. In summary, the use of photogrammetric methods is limited to water bodies with high water clarity.

The combination of the SfM method and chirp-modulated sonar was introduced by Tripathi and Murphy (2023) [28]. In their study, they utilized the underwater drone Hydronalix EMILY equipped with Humminbird sonar technology, which generates a point cloud of the waterbed surface. Using the Poisson reconstruction algorithm, a 3D model of the underwater relief is then generated, which remains amenable to further refinement (such as removing unnecessary structures caused by false reflections) in the Blender program. Additionally, the USV sonar is accompanied by a Teledyne FLIR camera. This camera produces a 3D model of the nearest relief above the water surface using the SfM method, calibrated to mitigate disruptions from false reflections of water and atmospheric particles. (In this case, the SfM method is modified for shooting in the opposite direction, i.e., from water to atmosphere.) The subsequent merging of the underwater and surface models is facilitated by the fact that both the sonar and the camera generate their models simultaneously from the same location, ensuring that these models are also georeferenced in a consistent manner. This allows for easy integration of the models within the Blender program.

The above-mentioned list of hydrological data collection methods, especially water depth in rivers, sediment deposit on riverbeds, flow velocity, and other parameters, can be utilized for the purpose of crossing watercourses during measurements, or potentially in the near future, assuming no alteration in water conditions due to extreme precipitation in the river basin or human regulation of water levels. Understanding these characteristics can aid in the decision-making process for operational decisions regarding units tasked with river crossing.

Given the planning of river crossing activities, the aforementioned data collection methods can be employed for simulating river flow regimes and numerically modelling the anticipated water state and other river characteristics. Key to this purpose is the knowledge of riverbed terrain morphology obtainable through the aforementioned data collection methods. Advantages lie in the possibilities of remote sensing and non-contact data collection methods rather than traditional terrestrial methods [29]. Currently, data collection methods are evolving through sensors placed on UGVs for object recognition in the vicinity and navigation in open space. It can be assumed that sensors mounted on these vehicles may have multiple applications. Not only do they collect data for spatial orientation and obstacle recognition, but they can also simultaneously gather data for further utilization, such as planning water obstacle crossings. This can play a significant role in operational-tactical preparation within the area of interest [30].

Data transmission and storage methods are not the subject of this article's research; however, it is important to mention this issue, especially concerning the article's topic on designing a web GIS application. GIS software operates with various geographic and hydrological data formats, which can be efficiently stored, for example, in databases. GIS systems represent an effective tool for data processing, analysis, and subsequent visualization. Dynamic and interactive GIS applications enable users to obtain the necessary informational support within the decision-making and planning process.

3. Data and Methodology

Modelling and simulating the overcoming of water obstacles, and respectively planning river crossings, can be extended to a broader global context, considering its potential for general universal utilization. However, due to data availability constraints and the need to simplify the studied phenomenon in order to design a web GIS application, a local modelling study was conducted. The area of interest became the lower course of the Dřevnice River, which flows through the regional city of Zlín in the Czech Republic – see figure 2.

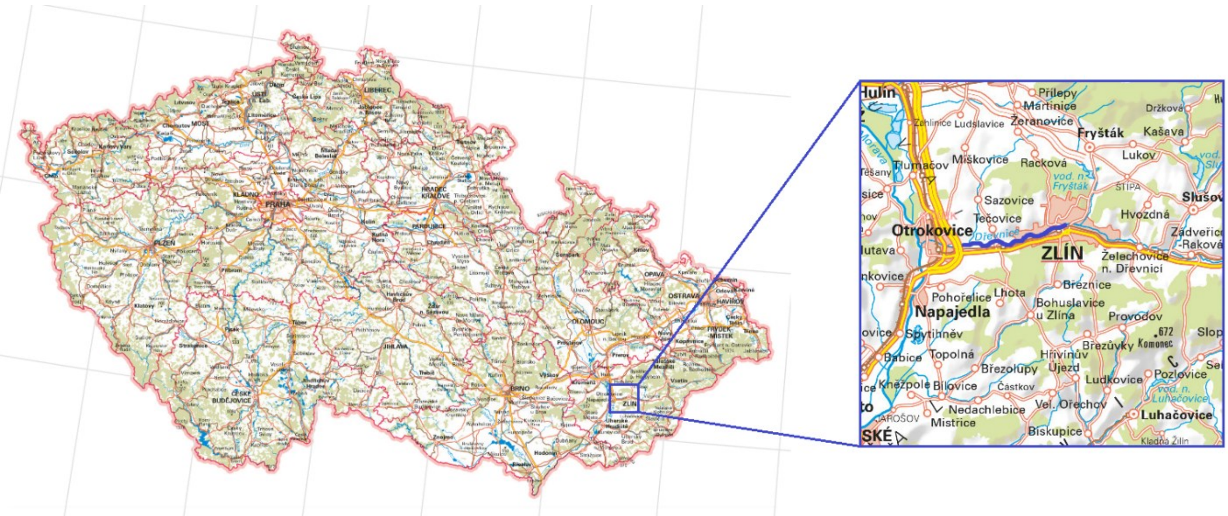

Fig. 2. An overview map and localization of the area of interest with marking of the section of the Dřevnice River [31].

For the development of the Web GIS Application, outputs from a numerical hydrological model were needed, which was carried out using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software. HEC-RAS is a powerful software tool used for hydraulic modelling of riverine environments. The process consists of several steps: data preparation, data schematization and parameterization, and numerical simulation. The individual procedural steps are described in the following paragraphs.

3.1 Terrain morphology of the stream and floodplain

The terrain morphology was inputted into the hydraulic model as a digital terrain model (DTM) in raster TIF format with a pixel size of 0.3 m. The DTM was created based on data from Digital Terrain Model of the Czech Republic of the 5th generation (DMR5G) [31, 32] and the Dřevnice riverbed [33] – see figure 3. The hydraulic model also incorporated structures such as bridges and weirs on the Dřevnice River, as detailed in [33]. The height accuracy of the DMR5G is provided with a total mean height error of 0.18 m in open terrain and 0.3 m in forested terrain.

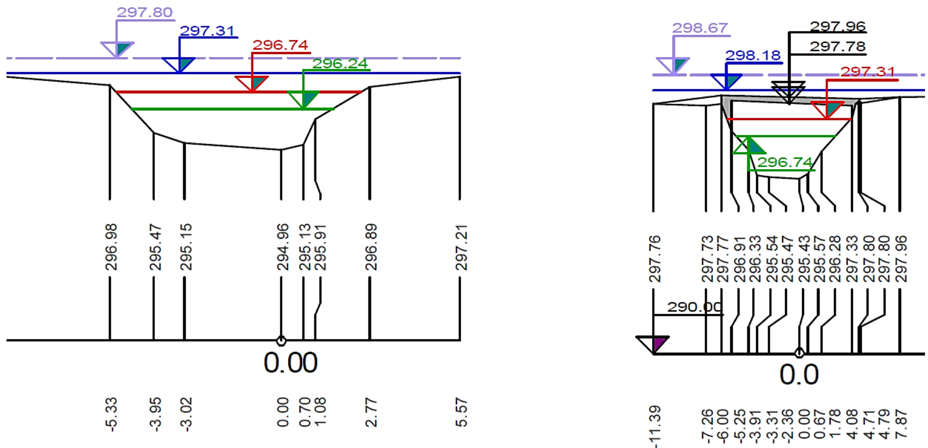

Fig. 3. The terrain morphology of the riverbed is depicted as a river cross-section (primary input dataset) on the left and with an object (bridge) on the right [33]. Colored lines represent heights indicating the modelled *N*-year water surface (output dataset).

3.2 Hydrological data

For hydraulic calculations, the hydrological data listed in table 1 were utilized for the Dřevnice – Zlín river profile, as documented [33]. The provided data were used as initial conditions for numerical hydrological modelling.

Table 1.
Values of *N*-year peak discharges for the Dřevnice River according to [33]

Profile	Qa	Q_1	Q_5	Q_{10}	Q_{20}	Q_{100}	Q_{500}
Dřevnice – Zlín profile on river km 13.200	1.88	48	115	153	196	320	488

*N is annual peak discharges Q_N [m^3/s]; a is long-term average discharge.

3.3 Schematization of the area of interest

The area was schematized in 2D, with cells in the area having irregular shapes with 4 to 8 angles – see figure 4. The upper part of the area was located approximately at river km 12.500 (above the bridge on Gahurova Street), while the lower part was around river km 3.400 under the D55 road bridge. The lateral extent of the area was determined based on the extent of the Q_{500} flood area [33]. The cell size in the inundation varied from 8 to 15 meters, while in the river, it ranged from 2 to 3 meters. Breaklines were incorporated into the mesh at the riverbed axis, bank edges, and axes of dikes and roads. The total number of cells was approximately 130 thousand. Bridges and weirs were schematized using 1D objects, enabling hydraulic calculations using analytical equations.

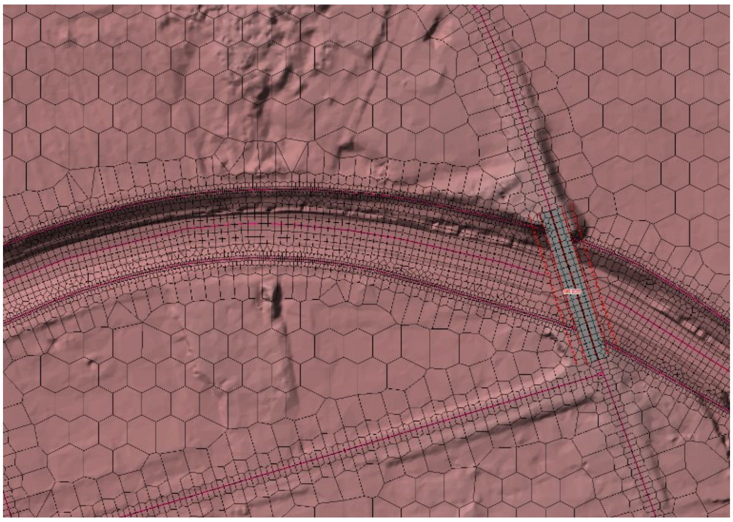
Fig. 4. Detail of the mesh.

3.4 Surface roughness of the river main channel and inundation area

Surface roughness data were incorporated into the model as Manning's roughness coefficients – see table 2. The roughness coefficients for different surface types were derived from The Fundamental Base of Geographic Data (ZABAGED) [34], which provides information on land use – see figure 5.

Table 2.

Values of roughness coefficients according to Manning

Type of surface	Values of roughness coefficient *n* according to Manning
The surface with dense vegetation	0.100–0.300
Other area in settlements	0.045
Buildings (non-flow-through structures)	0.500
Vegetation on the banks of streams	0.060
Forest	0.120
Garden	0.080
Acreage	0.035
Fenced gardens	0.150–0.300
Grassland	0.030
Paved roads	0.020–0.030
Watercourses	0.032–0.045
Fenced land (industrial areas)	0.150

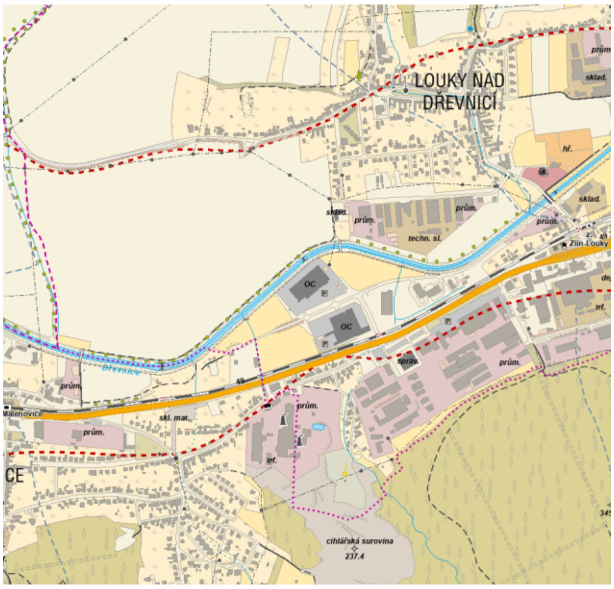

Fig. 5. Screenshot with cartography visualization of ZABAGED [34].

3.5 Boundary condition values

Boundary conditions (BC) for the steady-state calculation were defined at 2 open boundaries – see figure 6. These had the following BC values:

- Upper BC – Dřevnice, approximately river km 12.500 (above the bridge on Gahurova Street) – flow according to hydrological data for the Dřevnice – Zlín profile (see table 1) [33].
- Lower BC – Dřevnice, approximately river km 3.400 (above the road bridge of the D55 road) – energy slope $i = 0.001$ [33].

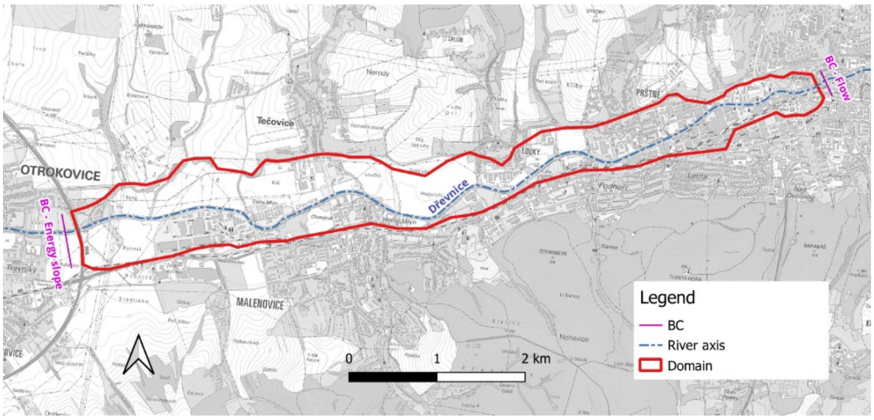

Fig. 6. Picture of the area of interest (Dřevnice River at approximately km 3.400–km 12.500) [32].

3.6 Numerical hydrological modelling and simulation

The HEC-RAS 6.5 numerical model software was utilized, enabling independent modelling of 1D, 2D, and composite 2D and 1D models. The numerical solution within the 2D model is based on solving the Shallow Water Flow equations using the finite volume method.

The simulation was run under steady flow conditions. While the HEC-RAS program can compute unsteady simulations, time-invariant boundary conditions were applied in this model. The simulation duration was 24 hours, with the time step ranging from 0.25 to 1 second based on the Courant number. Convergence criteria for the time step were set to 20 iterations or a level difference of 0.003 m between the last two calculation steps. Results were exported from the program for the final time step, at which water levels and velocities reached a steady flow. Depths and velocities were exported in raster format (TIFF) and represents important inputs for design of Web GIS Application.

4. Design of Web GIS Application

An objective of this contribution is to suggest what an application for planning of military river crossing could look like. In order to develop the design of the application based on real data, ArcGIS Pro Geographical Information System and ArcGIS Experience Builder online tool was used.

4.1. Application development process

As an objective of this contribution, it is set out to design an application for assessing the fordability of watercourses. The application should consider a wide range of variables, including the terrain's relief and micro-relief in the context of the tactical and technical characteristics of the given vehicle, the profile characteristics of the watercourse (especially depth and flow velocity), and other relevant factors. For subsequent analysis and modelling of the decision-making process the ArcGIS Pro software was chosen. The output should be in the form of a traffic light map showing the fordability of the watercourse. Due to the complexity of the problem, a diagram has been made to illustrate the individual criteria for assessing the watercourse's passability – see figure 7.

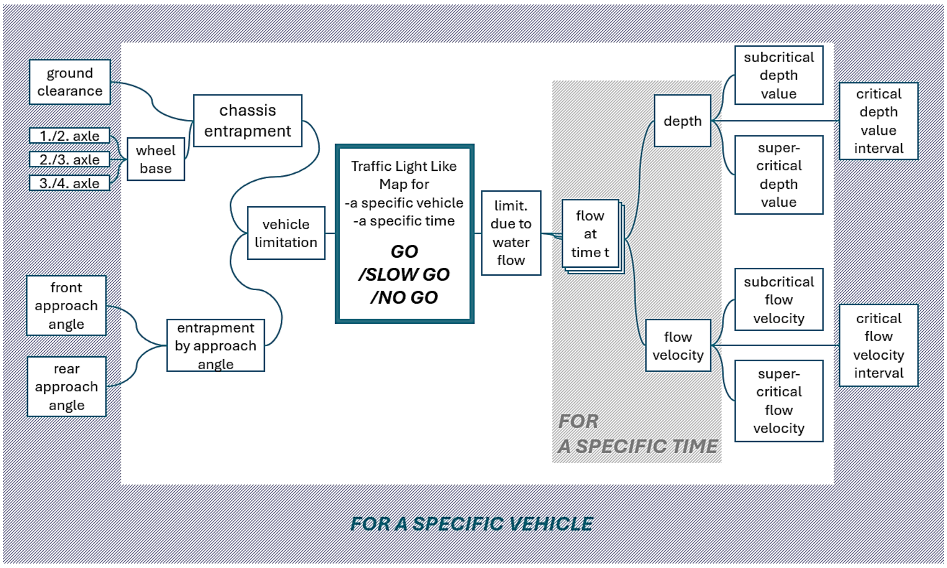

Fig. 7. Diagram of the criteria used to determine a passability of a water obstacle.

Among the most crucial tactical and technical data required to determine a vehicle's ability to traverse a water obstacle are wheelbase, ground clearance, approach and departure angles, wading depth, and limiting current velocity during fording. In a mathematical model, wheelbase and ground clearance determine whether the vehicle's undercarriage might get stuck on some microrelief feature [35]. Similarly, the approach and departure angles determine whether the vehicle will get stuck when entering or exiting the streambed. The limiting values of wading depth and current velocity during fording indicate whether it is even possible for the vehicle to cross a watercourse with these basic characteristics, such as stream depth and current velocity, regardless of relief and microrelief features – see figure 8.

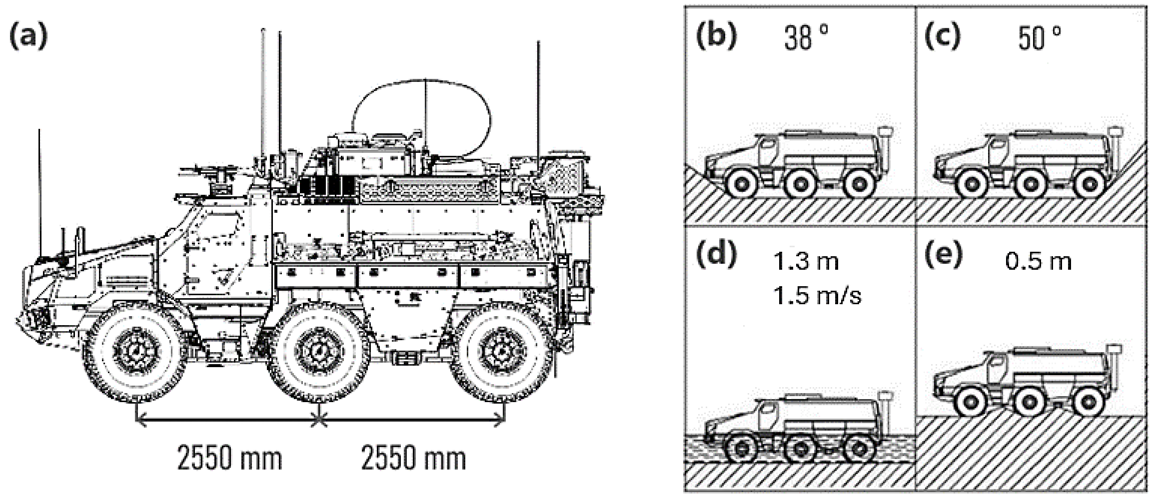

Fig. 8. Parameters of the military equipment necessary to know: (a) wheelbases, (b) front approach angle, (c) rear approach angle, (d) fording depth & limiting current speed during fording, (e) ground clearance [36]

The selection of military vehicles for the application's design is based on the inventory of the Czech Armed Forces. Given the objective of determining the fordability of water obstacles, the focus is narrowed to wheeled vehicles. The primary distinguishing characteristic among the selected vehicles is the number of axles. To ensure variability in the mathematical model's results when incorporating the input tactical and technical data of individual vehicles, vehicles with significant structural differences were chosen – see figure 9.

Fig. 9. Vehicles for which watercourse crossing has been modelled: (a) Toyota Hilux 4x4 [37], (b) Titus 6x6 [36], (c) Pandur II 8x8 [38].

Given the objectives of this research, the streambed, banks, and surrounding area of the watercourse within a 50-meter radius of the channel were selected for the analysis of topographic and micro-topographic features. If the software identified potential vehicle undercarriage entrapment or stalling locations, these areas were designated as red zones and propagated to all subsequent layers as "NO GO" zones – see figure 10. Similarly, the software analyzed the depth and velocity of the watercourse for various temporal scenarios, considering the dynamic nature of stream profile characteristics over time (input from HEC-RAS modelling). The resulting traffic light-style passability map for a specific vehicle varies with different flow rates. As such, the specific time and associated watercourse characteristics become additional input parameters for the application.

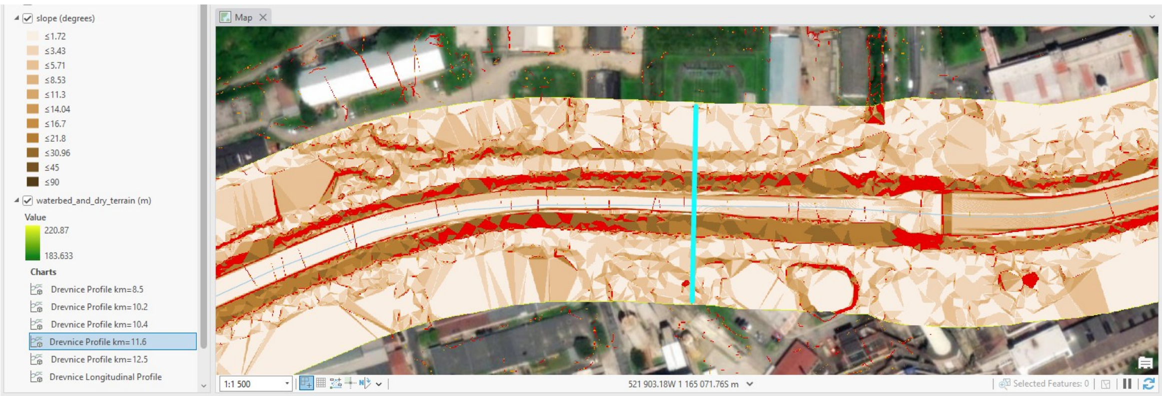

Fig. 10. Slope analysis of the riverbed, banks, and surrounding vicinity of the Dřevnice River.

4.2 Designing Web GIS Application

To create an application that presents the results of GIS modelling in a user-friendly way, ArcGIS Experience Builder is a useful tool. It combines map documents, data, widgets, and other elements into one interface. With that the application is capable of analyzing the possibilities of crossing a watercourse under various conditions by selecting the crossing location, initializing river conditions (forecast data), and choosing a specific military vehicle. The application provides information about the possibility of crossing a watercourse at a specific location; the variables determining the outcome include water level and flow velocity compared to the parameters of the military equipment used for crossing – see figure 11.

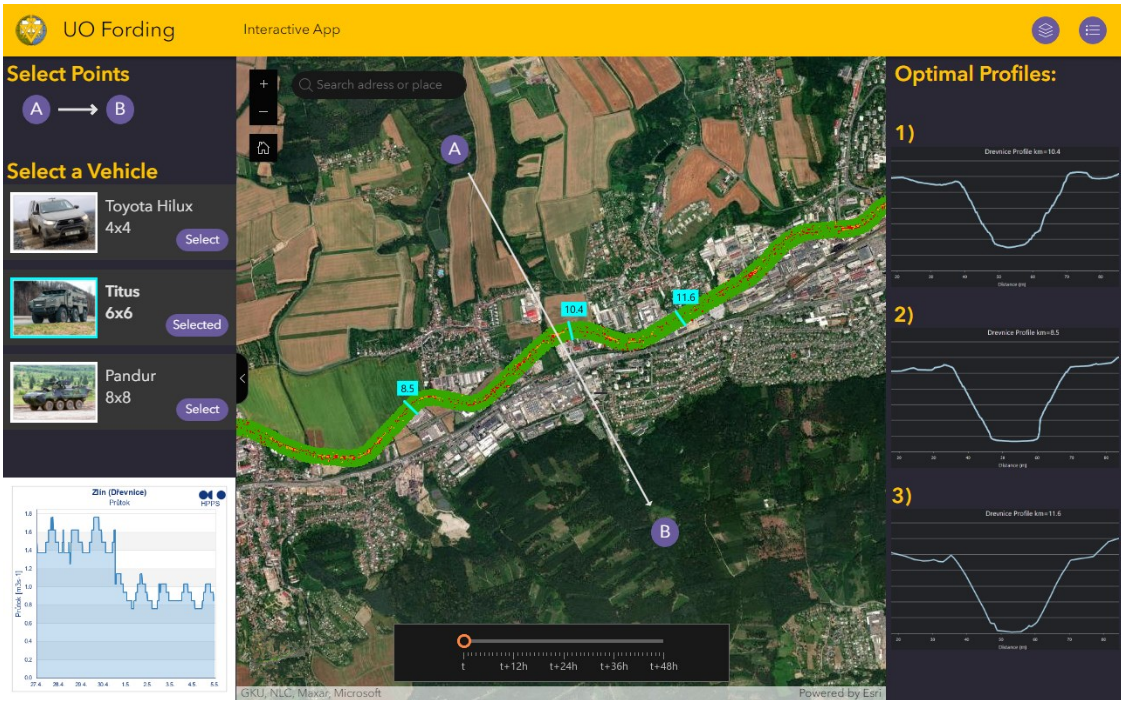

Fig. 11. User interface of the Web GIS application.

This system, designed to support users in combat and crisis situations, integrates various modelling outputs and provide an interactive interface for informed decision-making regarding watercourse access and overcoming strategies. The application is currently in the conceptual phase. Its potential in enhancing operational planning for the Czech Armed Forces is underscored. This GIS-based approach promises to enhance decision-making processes by offering real-time, interactive support for evaluating and strategizing water obstacle crossings within military operations.

5. Conclusion

With the development of new technologies, there are emerging, efficient possibilities for collecting geographical and hydrological data. Simultaneously, there is a growing demand for the quality and accuracy of such data, placing higher requirements on the quality of modelled outputs from numerical and predictive models of observed phenomena. The global trend in data collection is oriented towards non-contact methods utilizing UGVs, UAVs, or UUVs. Unmanned technologies can be effectively utilized in areas with increased security risks, thereby eliminating the danger of harm to human health. The acquired data can be utilized for further analytical purposes, aiding in decision-making and planning processes within the operational deployment of security and rescue forces.

Military engineers utilize HEC-RAS to simulate and analyze the flow of water in rivers and streams, allowing them to assess the feasibility of crossing locations and plan appropriate engineering solutions. HEC-RAS modelling plays a critical role in military operations by providing valuable insights into the hydraulic conditions of water obstacles. HEC-RAS can be used to predict water levels, flow velocities, and channel morphology, helping to identify suitable crossing sites and optimize the design of crossing structures.

Overcoming water obstacles is a complex task in military operations, requiring careful planning, specialized equipment, and advanced modelling techniques. GIS software serves as a valuable tool for obtaining comprehensive spatial information, with advanced analytical GIS tools playing a vital role in decision-making during river crossing planning. A comprehensive web (or desktop) application represents a potent tool for operational commanders, conveying a spatial understanding of the situation in broader contexts and, based on analytical insights, may become a decisive means to achieve operational-tactical objectives.

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