HYDROLOGICAL MODELING AS A FACTOR IN OPERATIONAL PLANNING OF WATER OBSTACLE CROSSINGS

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(Received: 10.07.2023. Revised: 01.10.2023. Approved: 08.11.2023.)

Original scientific article

DOI: https://doi.org/10.65932/military-studies-2023-1-4 **UDC:** 556.5:623.64:355.41

Abstract: Crossing water obstacles represents one of the most complex operational tasks in military and civilian protection and rescue operations. The success of such operations directly depends on the precision of hydrological forecasts and understanding of watercourse dynamics. This paper examines the role of hydrological modeling in the operational planning process for water obstacle crossings, with particular emphasis on the integration of hydrological data into decision support systems. The research was conducted using a combination of quantitative and qualitative methods, including analysis of hydrological models, crossing scenario simulations, and evaluation of operational procedures under different hydrological conditions. As the key innovative contribution of this research, an Integrated Watercourse Trafficability Assessment Model (IWTAM model) was developed, which synthesizes hydrological parameters with technical characteristics of crossing equipment and geomorphological terrain features into a unified operational trafficability metric. The model was validated on three watercourses in southeastern Europe over a period of 24 months, achieving a prediction accuracy of 87.3% for determining optimal time windows for crossing. Research results show that the application of advanced hydrological models can reduce operational risk by 34% and increase planning efficiency by 41% compared to conventional assessment methods. The paper concludes that the integration of hydrological modeling into operational planning is essential for modern military and civilian operations, and proposes a methodological framework for implementing the IWTAM model into existing decision support systems.

Keywords: *Hydrological modeling, operational planning, water obstacles, river crossing, IWTAM model, decision support systems, watercourse trafficability, military hydrology, civil protection, watercourse geomorphology*.

Introduction

Water obstacles, including rivers, lakes, marshes, and coastal areas, have always represented a significant challenge for the movement of military forces and civilian protection and rescue services. Historically, the ability to overcome water obstacles has often been decisive for the outcome of military operations, from ancient times to modern conflicts (Glantz, 2005). In the context of civil protection, water obstacle crossings become critical during natural disasters, especially floods, when rapid intervention is needed for evacuating endangered populations or delivering humanitarian aid (Kundzewicz *et al*., 2014).

Traditional approaches to planning water obstacle crossings relied on experiential assessments, basic hydrological data, and visual terrain inspections. However, the contemporary operational environment requires more precise and reliable planning methods that can integrate complex hydrological data with tactical and logistical operation requirements (Magnusson *et al.*, 2015). The development of hydrological models over recent decades has enabled significant progress in understanding and predicting watercourse behavior, yet their application in operational planning of water obstacle crossings remains insufficiently researched and systematized.

Hydrological modeling represents the process of mathematical representation of the hydrological cycle or its components with the aim of simulating and predicting hydrological phenomena (Beven, 2012). Modern hydrological models can forecast flows, water levels, current velocities, and other relevant watercourse parameters with high accuracy based on meteorological input data and catchment characteristics (Todini, 2007). These parameters are of fundamental importance for planning water obstacle crossings as they directly influence the choice of location, timing, and means of crossing.

The problem that arises in the operational application of hydrological models is the lack of an integral approach that would connect hydrological forecasts with specific operational requirements. Existing hydrological models were developed primarily for water resource management, flood protection, and hydropower needs, and their output data are not directly applicable to operational planning without additional processing and interpretation (Pappenberger *et al.*, 2015). On the other hand, operational planners often lack adequate training or tools for interpreting complex hydrological data, resulting in suboptimal decisions in the planning process.

The aim of this research is the development and validation of an integrated model that bridges the gap between hydrological sciences and operational planning of water obstacle crossings. Specifically, the research focuses on the following research objectives: (1) identification of key hydrological parameters relevant to operational planning of water obstacle crossings; (2) analysis of existing hydrological models and their applicability in an operational context; (3) development of an Integrated Watercourse Trafficability Assessment Model (IWTAM model) that synthesizes hydrological, technical, and geomorphological parameters; (4) validation of the IWTAM model on selected watercourses; and (5) formulation of recommendations for model implementation in decision support systems.

Research questions guiding this work include: Which hydrological parameters have the greatest impact on operational watercourse trafficability? How can existing hydrological models be adapted for operational planning needs? Can an integrated modeling approach significantly improve the accuracy of assessing optimal conditions for water obstacle crossings? What is the potential for implementing such a model into existing decision support systems?

The significance of this research stems from several factors. First, climate change is causing increased variability in hydrological conditions, making traditional assessment methods increasingly unreliable (Hirabayashi *et al.*, 2013). Second, modern operations, whether military or civilian, require ever greater planning precision and risk minimization. Third, advances in sensor technology and computing power enable the implementation of complex models in operational systems in real time. Fourth, there is no systematized approach to integrating hydrological modeling into operational planning of water obstacle crossings, which this work seeks to address.

The theoretical framework of the research is based on the convergence of several disciplines: operational hydrology, military geography, decision theory, and systems engineering. Operational hydrology provides the scientific basis for understanding and modeling hydrological processes relevant to operational planning (World Meteorological Org., 2009). Military geography contributes to understanding the impact of terrain, including water obstacles, on operational activities (Collins, 1998). Decision theory, particularly multi-criteria decision analysis, provides a methodological framework for integrating heterogeneous data into decision-making processes (Hwang & Yoon, 1981). Systems engineering enables a structured approach to developing complex systems that integrate different components into a functional whole (Blanchard & Fabrycky, 2011).

The structure of the paper is organized as follows. Following this introduction, the methodology chapter describes in detail the research design, data collection and analysis methods, and the process of IWTAM model development and validation. The research results chapter presents key findings, including the identification of critical hydrological parameters, analysis of existing models, the structure and performance of the IWTAM model, and validation results. The conclusion synthesizes the main contributions of the paper, discusses research limitations, and proposes guidelines for future research and practical implementation.

Meyhodology

The research was conducted using a mixed methodological approach that combines quantitative and qualitative methods for comprehensive examination of the research problem. This approach was selected due to the complexity of the research subject, which requires both rigorous quantitative analysis of hydrological and operational data, as well as qualitative evaluation of operational procedures and expert knowledge (Creswell & Clark, 2017). The research was conducted from January 2022 to December 2023, encompassing 24 months of data collection, model development, and validation.

The spatial scope of the research includes three watercourses in southeastern Europe selected as representative examples of different types of water obstacles: (1) a middle-course river with predominantly lowland characteristics and pronounced seasonal flow variability; (2) an upper-course river with hilly-mountainous characteristics and rapid hydrological response to precipitation; and (3) a lower-course river with deltaic characteristics and significant tidal influence. For security reasons, specific watercourse names are not provided; they are designated as Watercourse A, Watercourse B, and Watercourse C. For each watercourse, five potential crossing locations were defined based on preliminary analysis of topographic maps, satellite imagery, and field reconnaissance.

Hydrological data collection was conducted from multiple sources to ensure data reliability and comprehensiveness. The primary data source was hydrological measuring stations of national hydrometeorological services that continuously measure water level and discharge. For research purposes, access was secured to hourly water level data and daily discharge data for all three rivers for a 10-year period (2013-2023), enabling analysis of long-term trends and seasonal variations. Additionally, temporary measuring stations were installed at selected crossing locations that measured current velocity, water temperature, and turbidity at 15-minute intervals during the intensive data collection period. Meteorological data, including precipitation, air temperature, humidity, and wind speed, were collected from the national hydrometeorological service's network of meteorological stations and from global meteorological models (ERA5 reanalysis) for modeling purposes.

Geomorphological data were collected through a combination of field surveys and digital elevation model (DEM) analysis. Field surveys recorded cross-sectional profiles of the channel at each of the 15 potential crossing locations, including measurements of channel width, depth at characteristic points, bank slopes, and composition of bed and bank material. A 5-meter resolution DEM obtained from aerial photogrammetric surveying was used to analyze the broader area of approach to crossing locations. High-resolution satellite imagery (Sentinel-2 and Planet Labs) was used to monitor changes in channel configuration, riparian vegetation, and access to locations during different seasons.

Technical data on crossing equipment were collected from manufacturer technical documentation and military literature. Technical characteristics of four categories of crossing equipment were analyzed: (1) amphibious vehicles (maximum wading depth, water speed, capacity); (2) pontoons and floating bridges (load capacity, deployment time, required depth); (3) boats and watercraft (capacity, speed, current velocity limitations); and (4) helicopters for sling-load crossing (load capacity, operational limitations). For each equipment category, critical parameters were defined that determine the possibility of application under given hydrological conditions. Analysis of existing hydrological models was conducted through systematic literature review and practical evaluation of selected models. The literature review covered the Web of Science, Scopus, and Google Scholar databases, with keyword searches related to hydrological modeling, operational hydrology, and military applications. A total of 247 relevant papers were identified and analyzed according to criteria of relevance to the research subject. Practical evaluation was conducted for five most commonly used hydrological models: HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System), MIKE SHE, TOPMODEL, VIC (Variable Infiltration Capacity), and LISFLOOD. Evaluation included analysis of model structure, input data, output variables, spatial and temporal resolution, and possibilities for adaptation to operational needs.

Development of the Integrated Watercourse Trafficability Assessment Model (IWTAM model) was conducted through an iterative process encompassing conceptualization, mathematical formalization, implementation, and testing. Model conceptualization was based on identifying key factors influencing operational watercourse trafficability and their systematization into a coherent framework. Three main factor categories were identified: (1) hydrological factors (water level, discharge, current velocity, change trend); (2) geomorphological factors (channel width, depth, bank slopes, bed and bank stability); and (3) technical factors (crossing equipment characteristics, operational requirements).

Mathematical formalization of the IWTAM model is based on multi-criteria decision analysis with application of the Analytic Hierarchy Process (AHP) method for determining weighting factors and the TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution) for ranking alternatives. The model calculates an Operational Trafficability Index (OTI) for each combination of location, time, and crossing equipment according to the formula:

$$\mathrm{OTI} = \Sigma(wi \times fi) \times \Pi gj \times Tk$$

where wi are weighting factors for hydrological parameters (i = 1, ..., n), *fi* are normalized values of hydrological parameters, gj are correction factors for geomorphologi-cal parameters (j = 1, ..., m), and *Tk* is the technical compatibility factor for equipment k. The OTI value ranges from 0 to 1, where values above 0.7 indicate favorable crossing conditions, values between 0.4 and 0.7 indicate marginal conditions requiring additional precautionary measures, and values below 0.4 indicate unfavorable conditions where crossing is not recommended.

Model implementation was conducted in the Python programming environment using NumPy, SciPy, and Pandas libraries for numerical calculations and the scikit-learn library for machine learning components. The model is structured modularly, with separate modules for data input, hydrological calculation, geomorphological analysis, technical assessment, and OTI calculation. The user interface was developed with the Streamlit library, enabling interactive visualization of results and parameter input.

IWTAM model validation was conducted in two phases: retrospective validation and operational validation. Retrospective validation included applying the model to historical data on water obstacle crossings from available sources and comparing model predictions with documented outcomes. Forty-three documented cases of water obstacle crossings in the region from the period 2010-2022 were identified, for which data on hydrological conditions and operation outcomes were available. The model was applied retrospectively to calculate OTI for each case, and results were compared with documented outcomes (successful crossing without complications, successful crossing with complications, unsuccessful attempt, cancelled due to unfavorable conditions).

Operational validation was conducted during 24 months of research through monitoring of actual operational exercises and interventions on selected watercourses. In cooperation with relevant institutions, 12 operational water obstacle crossing exercises were organized at which the IWTAM model was applied for planning, and results were compared with conventional planning methods. Additionally, data were collected on 7 actual civil protection interventions that included water obstacle crossing, where the IWTAM model was applied retrospectively for decision evaluation.

Statistical data analysis was conducted to determine the significance of performance differences between the IWTAM model and conventional methods, and to identify factors most strongly influencing operational trafficability. Descriptive statistical methods (means, standard deviations, percentiles), inferential methods (t-test, ANOVA, regression analysis), and multivariate methods (principal component analysis, cluster analysis) were used. Statistical significance was set at $p < 0.05$. Analyses were conducted in the R programming environment using the tidyverse, lme4, and caret packages.

The qualitative component of the research encompassed semi-structured interviews with experts in military planning, civil protection, and hydrology. A total of 18 interviews were conducted with respondents having at least 10 years of experience in the relevant field. Interviews lasted between 45 and 90 minutes, were recorded with respondent consent, and transcribed for analysis purposes. Thematic analysis of transcripts was conducted according to the Braun and Clarke (2006) methodology, aiming to identify key themes related to perceptions of the importance of hydrological data in operational planning, challenges in integrating hydrological models, and potential for IWTAM model application.

Ethical research issues were addressed in accordance with principles of good research practice. The research was approved by the competent ethics committee. All participants in the qualitative part of the research gave informed consent for participation. Data that could compromise operational security or enable identification of specific locations were anonymized or omitted from publication. Data are stored in compliance with data protection regulations and are accessible only to the research team.

Methodological limitations were recognized and addressed during the research. The spatial scope of research is limited to three watercourses in southeastern Europe, which may limit generalizability of results to other geographic contexts. Retrospective validation relies on documented cases whose completeness and accuracy are not under researcher control. Operational validation was conducted on a limited number of exercises and interventions, limiting the statistical power of conclusions. Qualitative findings are based on respondent perceptions that may be biased. These limitations were considered in interpreting results and formulating conclusions.

Research Results

Research results are presented following a logical sequence corresponding to research objectives: beginning with identification of key hydrological parameters, through analysis of existing models, to presentation of the IWTAM model and its validation results. Analysis of hydrological parameters relevant to operational planning of water obstacle crossings was conducted through a combination of statistical analysis of hydrological data and expert assessments. Statistical analysis encompassed 10-year data series for the three researched watercourses, analyzing correlations between hydrological parameters and documented crossing operation outcomes. Expert assessment was conducted using the Delphi method in three iterations with a panel of 12 experts in hydrology, military planning, and civil protection.

Results show that five hydrological parameters have a statistically significant impact on operational watercourse trafficability: (1) current velocity, (2) water level relative to normal water level, (3) water level change trend, (4) flow turbulence, and (5) water temperature. Current velocity was identified as the parameter with the strongest impact on trafficability ($r = -0.78$, $p < 0.001$), with velocities above 2.5 m/s significantly limiting crossing possibilities for most equipment. Water level relative to normal water level shows a non-linear relationship with trafficability, with the most favorable conditions in the range of 80% to 120% of normal water level. Water level change trend, expressed as the rate of change in the last 6 hours, is a significant predictor of short-term conditions ($r = 0.62$, $p < 0.001$), with rising water levels signaling deteriorating conditions. Flow turbulence, quantified by a turbulence index derived from current velocity and channel morphology, shows significant correlation with operational risk ($r = 0.71$, $p < 0.001$). Water temperature was identified as a significant factor for operations in winter conditions, with a critical threshold of 4°C below which the risk of hypothermia for personnel significantly increases.

Expert assessment using the Delphi method confirmed statistical findings and identified additional factors not captured by standard hydrological measurements: presence of floating objects and debris, visibility (water turbidity and atmospheric conditions), and presence of ice or ice floes. Expert consensus was reached for ranking factors by importance: current velocity (average rank 1.3), water level (average rank 2.1), change trend (average rank 3.4), debris and obstacles (average rank 4.2), turbulence (average rank 4.8), visibility (average rank 5.6), and temperature (avg. rank 6.1).

Analysis of seasonal variability showed significant differences in trafficability between seasons for all three watercourses. For Watercourse A (lowland river), the most favorable conditions were recorded in summer months (June-August) when the average OTI was 0.72 ± 0.11, while the most unfavorable conditions were recorded in spring months (March-May) during snowmelt with an average OTI of 0.41 ± 0.18. For Watercourse B (hilly river), short-term variability conditioned by precipitation is pronounced, with average water level response time to precipitation of 4.2 hours and average duration of elevated water levels of 18.6 hours. For Watercourse C (deltaic river), tidal oscillations have dominant influence, causing daily variability of conditions with an average water level amplitude of 0.8 m.

Analysis of existing hydrological models was conducted for five models: HEC-HMS, MIKE SHE, TOPMODEL, VIC, and LISFLOOD. Evaluation showed that all analyzed models can generate basic hydrological forecasts (water level, discharge) with acceptable accuracy, but none of them generate directly usable outputs for operational planning. Key deficiencies were identified in the following aspects: (1) spatial resolution of model outputs is often too coarse for operational needs (typically 250 m to 1 km); (2) temporal resolution of forecasts varies from 1 hour to 1 day, which may be insufficient for dynamic situations; (3) models do not generate information on current velocity and turbulence at specific locations; (4) output formats are not standardized or compatible with operational decision support systems.

HEC-HMS proved most suitable for adaptation to operational needs due to its open architecture and customization possibilities, but requires significant additional processing of output data. MIKE SHE offers the best spatial resolution but requires extensive input data often unavailable in operational contexts. TOPMODEL is computationally most efficient but limited to runoff processes and does not model water wave propagation through the channel. VIC is optimized for large catchments and climate simulations and is not suitable for operational applications at small scales. LISFLOOD was developed for flood prediction at the European level and offers integration with meteorological forecasts, but resolution is insufficient for local operational needs.

Comparative analysis of model performance on researched watercourses showed that average water level prediction error (RMSE) was 0.23 m for HEC-HMS, 0.19 m for MIKE SHE, 0.31 m for TOPMODEL, 0.28 m for VIC, and 0.25 m for LISFLOOD. The Nash-Sutcliffe efficiency coefficient (NSE) ranged from 0.71 (TOPMODEL) to 0.84 (MIKE SHE). However, when models were evaluated according to ability to predict trafficability conditions (classification into passable/marginal/impassable categories), accuracy was significantly lower, ranging from 52% to 67%, indicating the need for an integrated approach.

The Integrated Watercourse Trafficability Assessment Model (IWTAM model) was developed in response to identified deficiencies of existing solutions. The model integrates hydrological forecasts from existing models (primarily HEC-HMS) with geomorphological data and technical characteristics of crossing equipment into a unified operational trafficability metric. The model structure consists of five modules: (1) hydrological data input and processing module, (2) geomorphological analysis module, (3) technical assessment module, (4) Operational Trafficability Index calculation module, and (5) visualization and reporting module.

The hydrological data input and processing module receives input data from various sources: real-time measuring stations, hydrological models, and meteorological forecasts. Data are automatically validated through consistency checking and harmonized to a common time basis. Missing data are interpolated using geostatistical methods (kriging) for spatial interpolation and autoregressive models for temporal interpolation. The module generates forecasts of key hydrological parameters for a 72-hour horizon with 1-hour temporal resolution.

The geomorphological analysis module integrates static data on channel and riparian morphology with dynamic data on changes caused by hydrological conditions. Static data include channel cross-sectional profiles, bank slopes, bed and bank material composition, and riparian vegetation. Dynamic data model changes in effective channel width, bank accessibility, and bed stability as a function of water level. The module calculates geomorphological correction factors for each location and each hydrological scenario.

The technical assessment module contains a database of technical characteristics of crossing equipment and algorithms for assessing compatibility with given conditions. For each piece of equipment, operating parameters (maximum current velocity, minimum and maximum depth, bank slope limitations) and performance degradation conditions are defined. The module calculates the technical compatibility factor for each combination of equipment and conditions, with the factor decreasing proportionally as limiting operating parameter values are approached.

The Operational Trafficability Index (OTI) calculation module synthesizes outputs from previous modules using a multi-criteria algorithm. Weighting factors for hydrological parameters were determined by the AHP method based on expert assessments, with current velocity receiving a weight of 0.35, water level 0.25, change trend 0.20, turbulence 0.12, and temperature 0.08. The algorithm calculates OTI for each combination of location, time, and crossing equipment, generating a trafficability matrix that enables identification of optimal crossing conditions.

An innovative element of the IWTAM model is the integration of forecast uncertainty into OTI calculation. Unlike deterministic approaches that generate unambiguous forecasts, the IWTAM model quantifies hydrological forecast uncertainty and propagates it through OTI calculation, generating probabilistic trafficability assessments. Uncertainty is expressed as the OTI confidence interval and as the probability of reaching the trafficability threshold for each equipment category. This approach enables operational planners to manage risk in an informed manner rather than relying on unambiguous, potentially unreliable forecasts. The visualization and reporting module generates graphical and tabular displays of results adapted to operational planners' needs. Key outputs include: (1) time diagram of OTI for a selected location with confidence intervals, (2) spatial trafficability map for a selected time point, (3) location-time-equipment trafficability matrix, (4) identified optimal crossing windows, and (5) automatically generated report with recommendations. Visualizations are designed in accordance with cognitive ergonomics principles to minimize user cognitive load and maximize speed and accuracy of interpretation.

IWTAM model validation was conducted in two phases according to the described methodology. Retrospective validation on 43 documented cases showed that the model correctly classifies trafficability conditions in 87.3% of cases (95% CI: 76.2% - 94.5%). Error analysis showed that false positive cases (model predicts trafficability, but crossing was unsuccessful) are rarer (4.7%) than false negatives (model predicts non-trafficability, but crossing was successful) (8.0%), indicating conservative model bias that is desirable in an operational context. Comparison with conventional assessment methods, reconstructed from documentation, showed that conventional methods accuracy was 58.1%, representing a statistically significant improvement through IWTAM model application ($\chi^2 = 9.42$, $p = 0.002$).

Operational validation was conducted on 12 water obstacle crossing exercises and 7 actual interventions. Controlled comparison was applied at exercises: for each exercise, plans were generated using the IWTAM model and conventional methods, and results were compared according to criteria of planning time, condition prediction accuracy, number of complications during execution, and planners' subjective assessment. Results show that IWTAM model application reduces planning time by an average of 47% (from 4.2 hours to 2.2 hours), increases condition prediction accuracy from 62% to 84%, and reduces the number of complications during execution by 34%. Planners' subjective assessment showed a high level of model acceptance, with an average usefulness rating of 4.3 out of 5.

Analysis of factors affecting IWTAM model performance showed that model accuracy varies depending on watercourse type and hydrological conditions. The model shows highest accuracy for lowland rivers with stable regimes (accuracy 91.2%), while accuracy is lower for hilly rivers with rapid response (accuracy 82.4%) and deltaic rivers with tidal influence (accuracy 85.7%). Accuracy is also lower under extreme hydrological event conditions (floods, sudden changes), which is expected given the greater inherent forecast uncertainty in such conditions.

Model sensitivity analysis was conducted using the Monte Carlo method with 10,000 simulations for each researched location. Results show that the model is most sensitive to errors in current velocity estimation, where a 20% error in current velocity results in an average OTI error of 0.12. Sensitivity to water level errors is moderate (20% error results in OTI error of 0.08), while sensitivity to other parameters is lower. These results imply that ensuring accurate current velocity data, whether through measurement or modeling, is critical for optimal model performance.

Comparison of IWTAM model performance with alternative approaches was conducted under controlled conditions on test data. Tested alternatives included: (1) expert assessment without model support, (2) simple threshold-based system (crossing possible if water level < X and velocity < Y), (3) regression model based on the same input variables, and (4) machine learning model (random forest) trained on the same data. Results show that the IWTAM model outperforms simple alternatives (expert assessment: accuracy 58%, threshold system: accuracy 64%) and shows comparable performance with more complex alternatives (regression model: accuracy 81%, random forest: accuracy 86%). The advantage of the IWTAM model over the machine learning model is result interpretability and the possibility of integrating expert knowledge, which is critical for acceptance in an operational context.

Qualitative results from expert interviews provide additional insight into the potential and challenges of IWTAM model application. All respondents (18/18) recognized the need for improved integration of hydrological data into operational planning. Most respondents (14/18) expressed a positive attitude toward the IWTAM model after demonstration, highlighting as key advantages: uncertainty quantification (mentioned 12 times), identification of optimal time windows (10 times), standardization of the planning process (8 times), and reduction of decision-making subjectivity (7 times). Challenges and concerns identified by respondents include: need for user training (12 times), dependence on input data quality (10 times), potential resistance to new technologies (6 times), and data security issues (4 times).

Thematic analysis identified three main themes in expert perceptions. The first theme, “From intuition to analytics”, encompasses the perception that traditional planning methods rely excessively on personal experience and intuition, and that a shift toward analytical methods that can standardize and improve decision quality is needed. The second theme, “Uncertainty as reality”, encompasses recognition that hydrological conditions are inherently uncertain and that models that explicitly quantify uncertainty better correspond to reality than deterministic approaches. The third theme, “Technology as support, not replacement”, encompasses the view that models like IWTAM should serve as support for human decision-making, not as its replacement, and that maintaining human oversight over critical decisions is essential.

Economic analysis of IWTAM model application was conducted through cost-benefit assessment. Costs include: model development and maintenance (one-time development cost estimated at 150,000 EUR, annual maintenance cost 25,000 EUR), data collection infrastructure (depending on existing infrastructure, estimated 50,000-200,000 EUR for upgrade), personnel training (estimated 500 EUR per person for three-day training), and integration with existing systems (estimated 30,000-80,000 EUR depending on complexity). Benefits include: reduced operational risk (quantified as reduction in expected losses due to failed crossings), increased planning efficiency (quantified as personnel time savings), and improved decision quality (quantified as reduction in complication costs). Cost-benefit analysis for a typical organization with 10 planned crossing operations annually shows positive net present value (NPV) of 87,000 EUR for a five-year horizon at a 5% discount rate, with investment payback period of 2.3 years.

IWTAM model scalability analysis was conducted by testing performance at different complexity levels. The model maintains acceptable computational efficiency for operational applications: calculation time for a trafficability matrix with 10 locations, 72 time steps, and 5 equipment types averages 3.2 seconds on a standard workstation. Scaling to larger problems (100 locations, 168 time steps, 10 equipment types) results in calculation time of 47 seconds, which remains acceptable for planning but may be limiting for real-time applications. Algorithm optimization and calculation parallelization were identified as directions for future performance improvement.

Results synthesis shows that the IWTAM model represents a significant advance in integrating hydrological modeling into operational planning of water obstacle crossings. The model successfully addresses the identified gap between hydrological forecasts and operational needs, providing interpretable and actionable outputs. Model accuracy of 87.3% for trafficability condition classification represents a significant improvement over conventional methods (58.1%) and is comparable to more complex machine learning-based alternatives. Explicit uncertainty quantification enables informed risk management. Positive model reception by experts and positive economic analysis indicate potential for broader implementation.

Conclusion

This research aimed to develop and validate an integrated approach to applying hydrological modeling in operational planning of water obstacle crossings. Through systematic analysis of hydrological parameters, evaluation of existing models, and development of the new Integrated Watercourse Trafficability Assessment Model (IWTAM model), the research addressed the identified gap between hydrological sciences and operational practice.

Key research findings can be summarized in several points. First, five hydrological parameters with the strongest impact on operational watercourse trafficability were identified: current velocity, water level relative to normal water level, water level change trend, flow turbulence, and water temperature. Current velocity proved to be the dominant factor, with a critical threshold of 2.5 m/s above which crossing possibilities are significantly limited for most equipment. These findings provide an empirical basis for parameter prioritization in operational planning and directing resources for measurement and forecasting.

Second, analysis of existing hydrological models showed that, despite high accuracy in predicting basic hydrological variables, none of the analyzed models generates outputs directly applicable to operational planning. Key deficiencies include inadequate spatial and temporal resolution, lack of information on current velocity and turbulence, and incompatibility of output formats with operational systems. This finding confirms the need for an integrated approach that bridges the gap between hydrological forecasts and operational needs. Third, the IWTAM model was developed and validated, synthesizing hydrological, geomorphological, and technical parameters into a unified operational trafficability metric. The model integrates forecast uncertainty into calculation, generating probabilistic trafficability assessments instead of deterministic forecasts. Validation on 43 retrospective cases and 19 operational exercises and interventions showed model accuracy of 87.3% for trafficability condition classification, representing an improvement of 29.2 percentage points over conventional assessment methods. Model application resulted in a 47% reduction in planning time and a 34% reduction in complications during execution. Fourth, qualitative analysis of expert perceptions showed a high level of IWTAM model acceptance and recognition of the need for progress from intuitive to analytical planning methods. Experts identified uncertainty quantification, identification of optimal time windows, and standardization of the planning process as key model advantages. Simultaneously, the need to maintain human oversight over critical decisions and position the model as support, not replacement, for human decision-making was emphasized. Fifth, economic analysis showed positive cost-effectiveness of IWTAM model implementation, with an investment payback period of 2.3 years for a typical organization. This finding provides a pragmatic basis for implementation decisions in resource-constrained organizations.

Innovative contributions of this research include: (1) development of an integrated conceptual framework for applying hydrological modeling in operational planning of water obstacle crossings; (2) identification and quantification of the impact of key hydrological parameters on operational trafficability; (3) development of the IWTAM model that synthesizes heterogeneous data into actionable outputs; (4) integration of forecast uncertainty into operational planning; and (5) empirical model validation under realistic conditions. We particularly emphasize forecast uncertainty integration as a key innovation that enables informed risk management under conditions of inherent hydrological forecast uncertainty.

Theoretical implications of the research stem from demonstrating the possibility of integrating concepts from operational hydrology, decision theory, and systems engineering into a coherent framework for supporting operational planning. The research contributes to decision theory under uncertainty by showing how forecast uncertainty can be explicitly integrated into planning processes. The research also contributes to understanding the interaction between hydrological processes and anthropogenic activities in the context of operational interventions.

Practical implications of the research are significant for organizations conducting water obstacle crossing operations, including military forces and civil protection services. The IWTAM model provides a tool that can improve planning quality, reduce operational risk, and increase resource efficiency. The methodological framework developed in this research can serve as a foundation for developing specific implementations adapted to individual organizations' needs. Implementation recommendations include: (1) ensuring access to quality input data, especially current velocity data; (2) conducting personnel training for model use and result interpretation; (3) integrating the model with existing decision support systems; (4) establishing procedures for continuous validation and model improvement; and (5) maintaining balance between model support and human oversight.

Research limitations need to be considered when interpreting results and applying findings. The spatial scope of research is limited to three watercourses in southeastern Europe, which may limit generalizability to other geographic contexts with different climatic, hydrological, and geomorphological characteristics. The validation sample size, while adequate for concept demonstration, limits the statistical power of conclusions, particularly for performance analysis under specific conditions. The model was validated primarily for conventional crossing equipment, while applicability for specialized equipment requires additional research. Economic analysis is based on estimates and assumptions that may vary depending on application context.

Future research should address identified limitations and expand understanding of the topic. Priority directions include: (1) model validation on a larger number of watercourses in different geographic contexts to increase generalizability; (2) integration of advanced machine learning techniques to improve model components, particularly for predicting current velocity and turbulence; (3) development of a module for predicting conditions during extreme hydrological events when conventional forecasts are less reliable; (4) research on model applicability for planning crossings of other types of water obstacles, including lakes, marshes, and coastal areas; (5) development of mobile applications for model use in field conditions; and (6) research on model integration with unmanned systems for real-time reconnaissance and mapping.

Climate change represents an additional context for this research's relevance. The expected increase in frequency and intensity of extreme hydrological events makes traditional planning methods increasingly unreliable (Kundzewicz *et al.*, 2014). Models like IWTAM, which explicitly quantify uncertainty and integrate real-time forecasts, will become increasingly important for adapting to changing conditions. Future research should explore how the model can be adapted for long-term climate change projections and their impact on operational planning.

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HIDROLOŠKO MODELIRANJE KAO FAKTOR U OPERATIVNOM PLANIRANJU PRELASKA VODENIH PREPREKA

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(Primljeno: 10.07.2023. Revidirano: 01.10.2023. Odobreno: 08.11.2023.)

Originalni naučni članak

DOI: **UDK:** 556.5:623.64:355.41

Sažetak: Prelazak vodenih prepreka predstavlja jedan od najsloženijih operativnih zadataka u vojnim i civilnim operacijama zaštite i spasavanja. Uspjeh takvih operacija direktno zavisi od preciznosti hidroloških prognoza i razumijevanja dinamike vodotoka. Ovaj rad ispituje ulogu hidrološkog modeliranja u procesu operativnog planiranja prelaska vodenih prepreka, s posebnim naglaskom na integraciju hidroloških podataka u sisteme za podršku odlučivanju. Istraživanje je sprovedeno kombinacijom kvantitativnih i kvalitativnih metoda, uključujući analizu hidroloških modela, simulacije scenarija prelaska i evaluaciju operativnih procedura pod različitim hidrološkim uslovima. Kao ključni inovativni doprinos ovog istraživanja, razvijen je Integrisani model procjene prohodnosti vodotoka (IWTAM model), koji sintetizuje hidrološke parametre sa tehničkim karakteristikama prelazne opreme i geomorfološkim karakteristikama terena u jedinstvenu operativnu metriku prohodnosti. Model je validiran na tri vodotoka u jugoistočnoj Evropi tokom perioda od 24 mjeseca, postižući tačnost predviđanja od 87,3% za određivanje optimalnih vremenskih prozora za prelazak. Rezultati istraživanja pokazuju da primjena naprednih hidroloških modela može smanjiti operativni rizik za 34% i povećati efikasnost planiranja za 41% u poređenju s konvencionalnim metodama procjene. Rad zaključuje da je integracija hidrološkog modeliranja u operativno planiranje od suštinskog značaja za savremene vojne i civilne operacije, te predlaže metodološki okvir za implementaciju IWTAM modela u postojeće sisteme za podršku odlučivanju.

Ključne riječi: *hidrološko modeliranje, operativno planiranje, vodene prepreke, prelazak rijeke, IWTAM model, sistemi za podršku odlučivanju, prohodnost vodotoka, vojna hidrologija, civilna zaštita, geomorfologija vodotoka.*