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Structuring of the scientific field of hydropower potential based on keyword analysis and hierarchical clustering

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Abstract. The relevance of this study stems from the need to systematise contemporary scientific approaches to assessing the environmentally safe utilisation of the hydropower potential of rivers. The environmental assessment of the implementation of renewable energy sources on water bodies lies at the intersection of hydrological, ecological, hydropower, technical and economic aspects. The aim of the study was to structure the scientific field of the environmentally safe use of hydropower potential based on keyword analysis, hierarchical clustering and the identification of interrelationships between the main thematic areas of research. Using the STATISTICA software, a statistical analysis of keyword clusters was conducted. For an in-depth analysis, a histogram, a dendrogram constructed using Ward's method, and a heat map of correlation links were applied. The information base consisted of 100 scientific publications from the last 20 years from 22 countries worldwide. During the study, a database of 454 keywords was compiled, followed by their preliminary normalisation, frequency analysis, and clustering. Twelve thematic clusters were identified, among which "hydropower systems and resources", "economics of natural resource use and energy", "hydrological characteristics and data", and "methodology and research tools" were dominant. It was established that the modern scientific field has a multi-level hierarchical structure and is characterised by close interaction between ecological, energy, hydrological, and economic domains. The results obtained confirmed the interdisciplinary nature of the research and demonstrated the appropriateness of applying a comprehensive approach to assessing the hydropower potential of

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rivers, taking into account natural, technical, environmental, and economic factors. The practical significance of the study lies in identifying shortcomings and unresolved aspects in scientific approaches to assessing the environmentally safe use of hydropower potential

Keywords: river systems; small hydropower; environmental safety; water resources; interdisciplinary research

Introduction

In the context of the rapid development of modern science, there has been a significant increase in the number of scientific publications, particularly in the fields of hydropower, ecology, and water resource management. Research is becoming distinctly interdisciplinary, combining hydrological, ecological, technical, economic, and climatic aspects. As a result, a complex and multidimensional scientific field is being formed, in which information is largely fragmented, and the connections between individual research areas are not always obvious. Under such conditions, bibliometric analysis methods, particularly keyword analysis and clustering, are gaining increasing relevance, as they make it possible to reveal the structure of scientific knowledge, identify the main thematic areas, and establish relationships between them.

Contemporary research in the fields of hydropower, water resources and ecology is characterised by an increasingly interdisciplinary approach, combining energy, hydrological, ecosystem, management and analytical aspects. In the latest scientific literature, hydropower is viewed not only as a source of renewable energy, but as a factor in the comprehensive transformation of river systems, influencing the hydrological regime, channel processes, biodiversity and water use. In particular, A. Kuriqi *et al.* (2021) demonstrated that even diversion and run-of-river small hydropower plants can significantly alter natural flow, disrupt ecological water flows and affect the trophic levels of river ecosystems.

Further development of this issue is presented in the work by A. Iho *et al.* (2023), where the sustainability of hydropower is analysed as the result of a balance between energy benefits, environmental constraints, legal norms and public acceptability. The authors demonstrated that the assessment of hydropower project prospects should not be narrowly technical but interdisciplinary, taking into account the conflict between energy production and the conservation of river ecosystems. In the same vein, F. He *et al.* (2024) synthesised global data on the impact of hydropower on river biodiversity and demonstrated that the main consequences are river fragmentation, barrier effects on species migration, and habitat alteration.

The current focus of research has shifted even further towards finding a compromise between energy efficiency and environmental safety. Ukrainian scientists have made a significant contribution to the development of this field. In the works of Ya. Adamenko & V. Maikovych (2025), L. Arkhypova *et al.* (2025) and V. Arkhypova *et al.* (2025), hydropower is considered as a component of the natural and technogenic safety of hydroecosystems. They also justified the need for an environmental assessment of the use of renewable energy sources, taking into account a basin-based approach.

At the same time, contemporary research into water resources is increasingly being integrated with energy and environmental issues. X. Yang *et al.* (2022), analysing water resources as hydropower potential, found that the leading themes are water scarcity, pressure on river basin systems, regional sustainability and multi-criteria assessment methods. They demonstrated that the scientific field is shifting from simple resource accounting to a comprehensive assessment of the limits of sustainable water use. A similar integrative logic was identified by Y. Lv *et al.* (2023), who, within the framework of the water-energy-food nexus concept, demonstrated that water, energy and food form an interdependent cycle, and research in this field is rapidly expanding thanks to cross-sectoral models and scenario analysis.

The methodological foundation for analysing such interdisciplinary fields in contemporary research is bibliometrics. N. Donthu *et al.* (2021) substantiated bibliometric analysis as a tool for identifying the intellectual structure of a scientific domain, its thematic clusters, the evolution of concepts, and scientific linkages. W.M. Lim *et al.* (2024) further clarified that the reliability of bibliometric conclusions largely depends on the integration of multiple databases, data cleaning, and the normalisation of author names, keywords, and sources. This perspective was deepened by M. Nowakowska (2025), who demonstrated that data preprocessing is not merely a technical detail but a critical stage that determines the accuracy of network maps, clustering, and the interpretation of results. The importance of the bibliometric approach for environmental issues was also confirmed in the work of R. Shu *et al.* (2024), which, based on studies of environmental safety network formation, showed that bibliometric analysis enables the identification of stages in the evolution of a scientific field, the core of key themes, emerging trends, and inter-thematic connections.

Thus, contemporary publications indicate that research in hydropower, water resources, and ecology is developing towards the integration of the ecosystem approach, basin management, and modern methods of scientific mapping. For this reason, the use of bibliometric analysis is appropriate for systematising the scientific field, identifying leading thematic clusters, and determining current trends in hydropower research and related environmental domains. Despite the active development of research and the availability of powerful analytical tools, the problem of the lack of a comprehensive structuring of the scientific field remains, particularly for Ukrainian-language publications. This necessitates the application of approaches that combine keyword normalisation with subsequent clustering to obtain a more reliable and generalised picture of the development of scientific research. Thus, the aim of the study was to systematise and structure the contemporary scientific field in the areas of hydropower, water resources, and ecology based on bibliometric analysis, using scientific mapping methods, in particular keyword normalisation and clustering, in order to identify the main thematic areas, relationships, and development trends in research.

Materials and Methods

Bibliometric analysis of scientific publications is one of the most important tools for studying the structure of contemporary scientific knowledge. Its application makes it possible to identify the main trends in the development of scientific research, determine leading thematic areas, and establish relationships between key concepts used in scholarly works. The methodology of the present study was based on a step-by-step bibliometric analysis of keywords from scientific publications, followed by their normalisation, quantitative processing, and clustering in order to structure the scientific field. The study comprised five stages.

The first stage involved the formation of a sample of scientific publications. For this purpose, a search for scientific sources was conducted in international scientometric databases, including Scopus, Web of Science, and Google Scholar. The search was carried out using the following keywords: "hydropower", "small hydropower", "hydropower potential", "water resources", "environmental safety", "environmental impact assessment", "monitoring", "environmental impact assessment", and others. The unit of analysis was a scientific article. For each publication, the following variables were recorded: author(s), year of publication, title, and keywords. The criteria for including articles in the sample were: scientific articles in peer-reviewed journals; relevance to the fields of hydropower, water resources, or environmental assessment;

and the presence of keywords. During the selection process, 58 Ukrainian and 42 scientific publications by authors from 22 countries were analysed, covering the period 2005-2025 and addressing issues of environmental safety in hydropower. As a result, a sample of 100 scientific publications was formed, from which 454 keywords were identified (Adamenko & Maikovych, 2026).

The second stage involved the normalisation of keywords. The aim of this stage was to identify and eliminate duplication of words and their synonymous fragmentation. Normalisation included: merging synonyms (for example: "small hydropower" = "mini hydropower plants"); reducing different grammatical forms to a base form (for example: "river", "rivers", "riverine" = "river"); and unifying variations in wording (for example: "Prut River basin", "Middle Dnipro", "rivers of Ukraine" = "river basins"). The processing was carried out through a combined approach involving manual expert normalisation using an agreed glossary of terms (thesaurus). This stage made it possible to form a unified list of keywords suitable for further statistical analysis. The collected data were systematised in tabular form using Microsoft Excel. In the resulting table, each scientific source corresponds to a set of keywords reflecting the main aspects of the study, including the hydropower potential of rivers, the development of small hydropower, environmental constraints on the use of water resources, as well as the application of geoinformation technologies in water system research.

The third stage – constructing the data matrix. Based on the normalised keywords, a species trait matrix was formed:

$$X = \{x_{i,j}\}, i = 1, \dots, n; j = 1, \dots, m, \quad (1)$$

where n – number of publications; m – number of keywords; $x_{ij} \in \{0.1\}$ – a binary indicator of the presence of keyword j in publication i. The matrix values are binary (0/1). A value of 1 indicates that the keyword is present in the publication; a value of 0 indicates that the keyword is absent. The structure of the binary matrix enabled the formalisation of textual information and subsequent statistical processing of the data, the determination of the frequency of use of key terms, and the performance of a cluster analysis of research themes. This stage allowed for the creation of a structured database, which facilitated the effective subsequent analysis and visualisation of scientific trends.

The fourth stage of the research involved frequency analysis of keywords. The unit of measurement was the keyword, and the indicator was the number of publications in which it appeared, calculated using the formula:

$$f_j = \sum_{i=1}^{n} x_{ij}, \quad (2)$$

where f_j – the number of publications containing the keyword j. No threshold filtering was applied – all keywords were included in the analysis, which allowed the structure of the field under study to be preserved in its entirety. Frequency analysis was used to identify the most frequently used terms, to outline the structure of the research, and to prepare the data for subsequent clustering. It also made it possible to assess the importance of each term, track changes in research interests over time, and identify the most relevant research areas for further analysis.

The fifth stage – cluster analysis – aimed to group keywords into thematic clusters, identify the structure of the research field, and establish interrelationships between research areas. To analyse the structure of the scientific field, hierarchical agglomerative cluster analysis was applied, based on the use of Euclidean distance as a measure of similarity and Ward's method as the criterion for cluster merging. Euclidean distance was calculated using the formula:

$$d(x, y) = \sqrt{\sum_{k=1}^{m} (x_k - y_k)^2}, \quad (3)$$

where x and y – feature vectors (keywords or clusters).

Clustering was performed using Ward's method, which minimises the increase in intra-cluster variance according to the formula:

$$\Delta E = \frac{n_A \times n_B}{n_A + n_B} \times \|\bar{x}_A - \bar{x}_B\|^2, \qquad 4)$$

where n_A, n_B – cluster sizes, $\bar{x}_A$ $\bar{x}_B$ – cluster centres; $|| \times ||$ – Euclidean norm.

Variables were standardised prior to clustering. Ward's method ensured the formation of compact and homogeneous clusters and helped to avoid the "chain clustering" effect. This approach enabled a clear structuring of the scientific field of hydropower and environmental safety, identifying the main thematic groups that interact most closely with one another. To interpret and visualise the research results, a histogram was used to display the frequency distribution of keywords and clusters; a dendrogram to display the hierarchical structure of the clusters; and a heatmap to display the correlation matrix between clusters. The data were visualised using STATISTICA (for constructing the dendrogram) and Python (for constructing the heatmap). The bibliometric analysis methods applied, including keyword normalisation, frequency analysis and clustering, ensured the reliability of the classification, allowing for an accurate interpretation of the main trends and directions in research on hydropower potential and the environmental safety of water resources.

Results and Discussion

The analysis of keyword frequency showed that the most commonly used terms in scientific publications are "hydropower", "capacity", "ecology", "electricity", "small hydropower", and "hydropower potential". This indicates that researchers primarily focus on assessing the energy characteristics of water resources and determining their potential use within renewable energy systems. Based on the conducted frequency analysis of keywords, twelve thematic clusters were identified, reflecting the main directions of scientific research in the field of small hydropower and environmental safety. Each cluster represents specific aspects of the studied topics and includes keywords derived from scientific publications. This makes it possible to assess the structure of the scientific field and determine which research aspects are the most significant.

Cluster 1. Hydrological characteristics and data. This cluster covers research into the quantitative and qualitative parameters of water bodies, including hydrological regime, discharge, water levels and seasonal dynamics. It forms the basis for all research into water systems, as it provides the primary information framework. This cluster includes the following keywords: river discharge, river flow, water level, hydrological regime, water consumption, floods, low water, hydrological data, etc.

Cluster 2. Geographic scope. This cluster reflects the spatial context of the research and includes an analysis of territorial characteristics, regional differences and the geographical conditions shaping natural processes. This cluster includes the following keywords: Carpathian region, Ukraine, Dniester basin, Carpathian Foothills, regional characteristics, etc.

Cluster 3. River basins. This cluster covers research into river basins as integrated natural and territorial systems. It encompasses water resource management, the basin approach and ecosystem interactions. This cluster includes the following keywords: river basin, basin management, catchment, river system, Danube basin, Prut basin, etc.

Cluster 4. Hydropower systems and resources. This cluster covers research into hydropower potential, the operation of hydropower plants and the assessment of hydropower resources. It is of key importance for the development of renewable energy. Characteristic keywords: hydropower potential, hydropower plants, small hydropower plants, energy resources, hydropower, hydropower systems, etc.

Cluster 5. Environmental monitoring and control – includes systems for monitoring the state of the environment, the collection and analysis of environmental data, and the monitoring of pollution levels. This cluster includes the following keywords: environmental monitoring, water quality control, observation, pollution, automated stations, environmental indicators.

Cluster 6. Environmental protection and safety – covers research aimed at reducing negative environmental impacts and ensuring environmental safety. Examples of keywords: environmental safety, nature conservation, environmental protection, anthropogenic impact, environmental risks, etc.

Cluster 7. Engineering and technical aspects of systems. This cluster includes technical solutions, engineering structures and technologies related to water and energy systems. Examples of keywords: engineering systems, hydraulic structures, technical solutions, design, system optimisation, infrastructure, etc.

Cluster 8. Environmental assessment and impact – these are procedures for assessing the impact of activities on the environment, analysing environmental consequences and forecasting changes. This cluster includes the following keywords: environmental impact assessment, environmental assessment, impact on ecosystems, impact analysis, environmental criteria.

Cluster 9. Climatic processes and climate change. This cluster includes research into climate change and its impact on water resources and ecosystems. Examples of keywords: climate change, climatic factors, temperature, precipitation, climate models, global warming, etc.

Cluster 10. Renewable energy – this cluster covers research into alternative energy sources, including hydro, solar and wind energy. This cluster includes the following keywords: renewable energy sources, green energy, solar energy, wind energy, small hydropower.

Cluster 11. Economics of natural resource use and energy. This cluster reflects the economic aspects of natural resource use and energy development. Examples of keywords: economic efficiency, natural resource use, energy market, investment, economic assessment, tariff policy, etc.

Cluster 12. Methodology and research tools – includes methods, models and data analysis tools used in research. This cluster includes the following keywords: mathematical modelling, statistical analysis, GIS technologies, remote sensing, machine learning, research methods, etc.

Individual clusters of keywords reflect thematic areas of research, in particular: hydropower systems and resources, the economics of natural resource use and energy, hydrological characteristics and data, methodology and research tools, engineering and technical aspects of systems, environmental protection and ecological safety, river basins, renewable energy, environmental assessment and impact, environmental monitoring and control, geographical territory, climatic processes and climate change. A histogram was constructed based on the identified clusters, reflecting the quantitative distribution of thematic clusters of keywords within the studied corpus of scientific publications; it serves as an important tool for assessing the structure of contemporary scientific research in the fields of ecology, hydrology and energy (Fig. 1). It allows not only the identification of dominant areas, but also the assessment of the balance between different thematic blocks that form the overall picture of research activity. The analysis of the histogram shows that the most represented cluster is "Hydropower systems and resources", which has the highest value among all clusters. This indicates the high relevance of research in the field of hydropower potential utilisation, optimisation of hydropower plant operation, and assessment of the resource base. The dominance of this cluster may be associated with the active development of renewable energy and the need to transition to more environmentally safe energy sources. The second position is occupied by the cluster "Economics of natural resource use and energy", highlighting the importance of economic aspects in research. This points to the integration of economic analysis into natural science and technical studies, which is a characteristic feature of the modern scientific approach to sustainable development. A significant share is also occupied by the clusters "Hydrological characteristics and data" and "Methodology and research tools".Their high representation indicates considerable attention to data collection, analysis, and interpretation, as well as to the development of new research methods. This forms the foundation for ensuring the reliability and validity of scientific results. The cluster "Engineering and technical aspects of systems" reflects the practical orientation of research, encompassing issues of design, optimisation, and operation of technical systems related to water resources and energy.

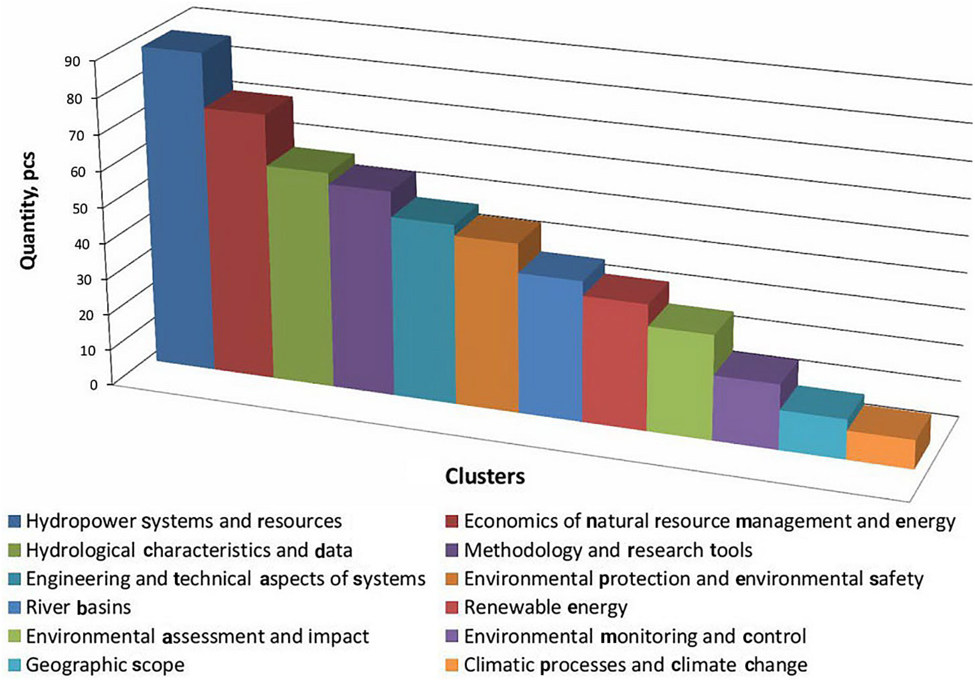

Figure 1. *Histogram of the cluster distribution*

Source: compiled by the authors

The cluster "Environmental protection and ecological safety" demonstrates a moderate level of representation, indicating a steady interest in environmental issues. This area is an integral component of most studies and is often integrated with other clusters. The clusters "River basins" and "Renewable energy" show somewhat lower values but remain important research directions, reflecting both natural science aspects and current energy trends. Less represented are the clusters "Environmental assessment and impact" and "Environmental monitoring and control", which may indicate their integration into other research areas or their relatively narrow specialisation. The lowest frequency is observed for "Geographic scope" and "Climatic processes and climate change". This may be because these areas often serve as supporting or contextual elements in studies rather than primary focuses. Overall, the histogram demonstrates an uneven distribution of clusters, with both dominant and peripheral research areas. This makes it possible to conclude that energy and hydrological studies are prioritised, alongside the importance of integrating economic and environmental aspects. The obtained results confirm the interdisciplinary nature of modern research, combining natural, technical, and socio-economic components. Such a structure is characteristic of comprehensive studies aimed at addressing global environmental and energy challenges.

Analysing the structure of the scientific field using hierarchical agglomerative cluster analysis resulted in a dendrogram (Fig. 2). It reflects the hierarchical structure of similarity between thematic clusters, allowing a visual assessment of how different research areas are interconnected. The dendrogram makes it possible not only to identify groups of terms with the greatest similarity but also to distinguish key thematic blocks at different levels of the hierarchy. Its analysis enabled a detailed characterisation of the structure of the studied domain, contributing to a deeper understanding of the relationships between various aspects of hydropower and environmental safety at different stages of research.

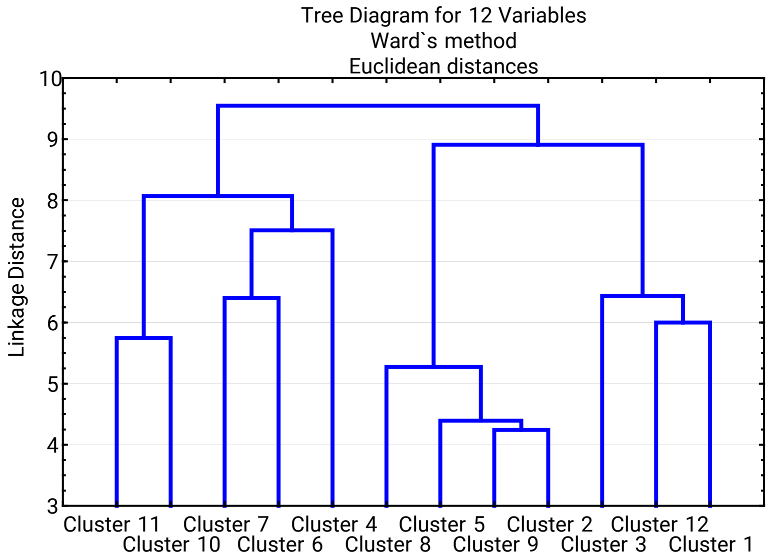

***Figure 2.** Dendrogram of keyword clusters (using Ward's method)*

Note: Cluster 1 – Hydrological characteristics and data; Cluster 2 – Geographic scope; Cluster 3 – River basins; Cluster 4 – Hydropower systems and resources; Cluster 5 – Environmental monitoring and control; Cluster 6 – Environmental protection and ecological safety; Cluster 7 – Engineering and technical aspects of systems; Cluster 8 – Environmental assessment and impact; Cluster 9 – Climatic processes and climate change; Cluster 10 – Renewable energy; Cluster 11 – Economics of natural resource use and energy; Cluster 12 – Methodology and research tools

Source: compiled by the authors

At the lowest level of clustering (distance 3-5), the most homogeneous groups are formed. In particular, a close relationship is observed between "Climatic processes and climate change" and "Geographic scope". This is explained by the fact that climatic phenomena are directly linked to spatial characteristics, and their study is traditionally conducted within a geographical context. Another example is the merging of "Environmental monitoring and control" with "Environmental assessment and impact". Such interaction is logical, as monitoring serves as a tool for data collection, whilst assessment is the result of their analysis. This indicates the methodological unity of these fields.

At the next level (5-7), cluster aggregation occurs. An ecological-climatic block is formed, combining environmental assessment, monitoring, and climatic and geographical aspects. This block reflects the modern approach to studying natural systems as complex and interconnected. In parallel, a hydrological-methodological cluster is formed, including "Hydrological characteristics and data", "River basins", and "Methodology and research tools". This highlights the fundamental role of hydrology as a core science providing the empirical and methodological basis for research. A separate energy-economic block is also distinguished, combining "Renewable energy" and "Economics of natural resource use". This combination reflects contemporary trends in integrating economic mechanisms into the fields of energy and resource management. It emphasises the importance of linking energy and economic aspects to ensure sustainable development, facilitating the efficient use of renewable energy sources and the optimisation of natural resource consumption.

At a higher level of clustering (7-9), a technical-ecological block is formed, including "Hydropower systems and resources", "Engineering and technical aspects of systems", and "Environmental protection and ecological safety". This indicates the applied nature of research aimed at developing technological solutions while considering environmental constraints. At the highest level of the hierarchy (above 9), all clusters are integrated into a single system, confirming the integrity of the studied field and its interdisciplinary nature. It was established that none of the areas exists in isolation; rather, they all form an interconnected scientific system. Thus, the conducted cluster analysis made it possible to identify a clear hierarchical structure of research, determine key thematic blocks, and establish relationships between them. At the lower level of clustering, homogeneous pairs of thematic areas were formed; at the intermediate level, integrated ecological-climatic, hydrological-methodological, and energy-economic blocks emerged; and at the higher level, a generalised technical-ecological block was identified. Overall, all clusters are united into a single interdisciplinary scientific system. The obtained results may be used for further planning of scientific research, the development of interdisciplinary approaches, and the optimisation of the structure of scientific studies.

As a result of constructing the heatmap (Fig. 3), relationships between thematic clusters of scientific research were visualised. The heatmap illustrates correlation relationships between the main directions, where positive values indicate the co-occurrence of clusters within publications, while negative values indicate their mutual independence or opposition. In this case, the variables are the thematic clusters of keywords that characterise scientific directions. The values in the matrix reflect the degree of correlation between clusters: positive values indicate joint representation in studies, whereas negative values indicate independence or contrast between them. As can be seen in the figure, the colour scale ranges from low, including negative values (dark purple and blue shades), indicating inverse or weak relationships, to high positive values (yellow shades), which characterise stronger interactions between clusters. Maximum values (close to 1) are observed along the main diagonal, which is expected, as each cluster is perfectly correlated with itself. The analysis of off-diagonal elements revealed a complex and uneven network of inter-cluster relationships. Among the identified dependencies, moderate positive correlations can be observed between the clusters "Environmental assessment and impact" and "Environmental monitoring and control". This is explained by the fact that environmental impact assessment largely relies on monitoring data, while monitoring results are used to refine and verify impact assessments. It is also important to note the presence of relationships between the clusters "Renewable energy", "Hydropower systems and resources", and "Economics of natural resource use and energy", indicating the integration of technical, resource, and economic aspects in contemporary research, in line with the concept of sustainable development. A noticeable relationship is also observed between the clusters "Climatic processes and climate change" and "Hydrological characteristics and data", although the strength of this connection is moderate or relatively low; however, this does not diminish their conceptual interdependence. At the same time, some clusters demonstrate weak or negative relationships. In particular, "River basins" show a low level of correlation with economic and energy clusters, which may indicate their predominantly descriptive or geographical nature. Similarly, engineering and technical aspects are partially isolated from environmental studies, pointing to a certain degree of disciplinary fragmentation.

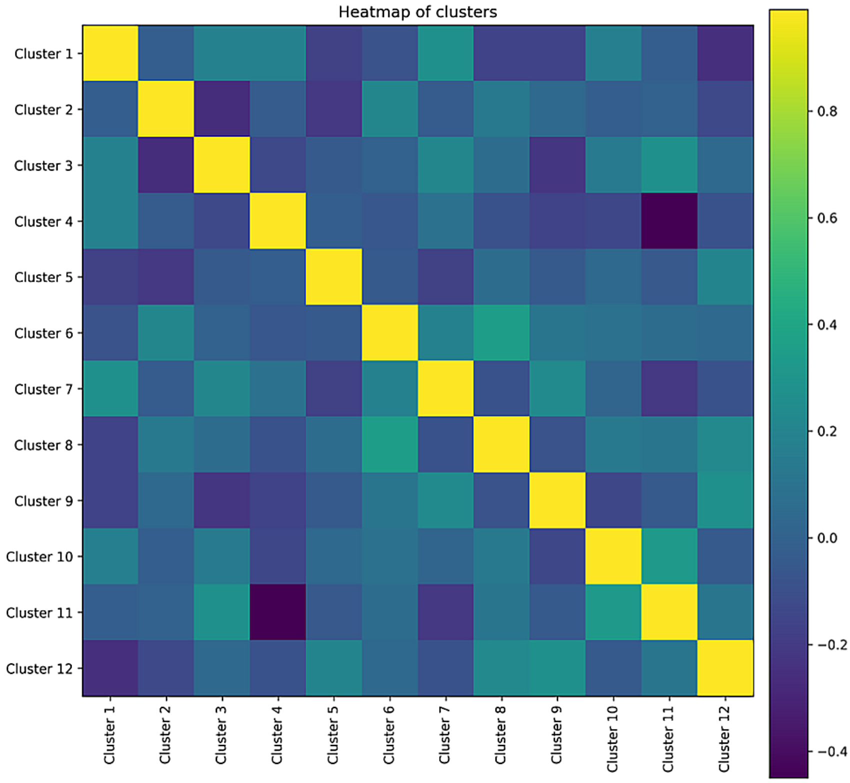

***Figure 3.** Heatmap of keyword clusters*

Note: Cluster 1 – Hydrological characteristics and data; Cluster 2 – Geographic scope; Cluster 3 – River basins; Cluster 4 – Hydropower systems and resources; Cluster 5 – Environmental monitoring and control; Cluster 6 – Environmental protection and ecological safety; Cluster 7 – Engineering and technical aspects of systems; Cluster 8 – Environmental assessment and impact; Cluster 9 – Climatic processes and climate change; Cluster 10 – Renewable energy; Cluster 11 – Economics of natural resource use and energy; Cluster 12 – Methodology and research tools

Source: compiled by the authors

Based on the structure of the heatmap, several functional blocks can be identified:

1) a natural–hydrological block, including "River basins", "Geographic scope", and "Hydrological characteristics";

2) an energy–economic block, combining "Renewable energy", "Hydropower", and "Economics of natural resource use";

3) an environmental block, consisting of "Environmental assessment", "Monitoring", and "Environmental protection";

4) a methodological block, which performs an integrative function and ensures interconnections between different thematic areas. The cluster "Methodology and research tools" plays an important role, as it is linked to a number

of other clusters, confirming the universality of modern research methods applied across various scientific domains.

The resulting heatmap can be used as a tool for the strategic planning of scientific research, as it makes it possible to identify the most integrated areas (in particular, "environmental assessment – monitoring", "energy – economics"), which should be developed as interdisciplinary research; to detect weakly connected or relatively isolated clusters that represent potential research gaps; to justify priority research directions by focusing efforts on key interconnections; and to define the role of the methodological cluster as an integrating foundation for comprehensive studies.

The obtained results of the bibliometric analysis confirm that the modern scientific field in hydropower, water resources, and ecology is formed as a complex interdisciplinary system. Similar conclusions are presented in the work of M. Aria & C. Cuccurullo (2017), which demonstrated that the application of scientific mapping tools makes it possible to identify the structure of research and key thematic clusters. In the present study, a similar approach was applied, but it was extended through keyword normalisation, which improved the accuracy of clustering. A comparison with the study by A. Duran-Sanchez *et al.* (2018) indicates that contemporary research is dominated by themes of sustainable development, resource management, and environmental safety. In the presented cluster model, these areas are reflected in the corresponding thematic blocks ("River basins", "Environmental safety", "Environmental monitoring"), confirming the consistency of the obtained results with international trends.

A significant development of bibliometric methods is presented in the work of N. Donthu *et al.* (2021), which emphasises the importance of combining different approaches, including keyword co-occurrence analysis, citation analysis, and clustering, for a comprehensive study of scientific fields. A similar integrated approach was implemented in the present study. This made it possible not only to identify thematic clusters but also to establish relationships between them, in line with contemporary methodological approaches in bibliometrics. Hierarchical clustering methods are widely applied in modern research on energy and ecology. In particular, N. J. van Eck & L. Waltman (2017) demonstrated that cluster analysis based on relationships between publications (especially citation links) allows for effective structuring of scientific domains and the identification of thematic research groups. In the present study, the use of Ward's method, which minimises within-cluster variance, ensured the formation of clear and logically interpretable clusters, consistent with modern approaches to the analysis of bibliometric data.

Among the key directions of contemporary research are water resource management, assessment of water capacity of territories, environmental monitoring, and the pursuit of sustainable development. This was clearly demonstrated in the bibliometric study by X. Yang *et al.* (2022), which focused on key indicators of water ecosystem development in terms of their capacity to meet human needs. In the present work, these directions are represented by corresponding thematic clusters, confirming the validity and relevance of the obtained structure of the scientific field. An important aspect of contemporary scientific research in the field of hydropower is its interdisciplinary nature. In particular, L. Leydesdorff *et al.* (2019) showed that most research areas emerge at the intersection of ecology, energy, and economics. This conclusion is also confirmed in the present study through the formation of integrated clusters such as "Renewable energy", "Economics of natural resource use", and "Hydropower". The obtained results are also consistent with modern research in the field of renewable energy, particularly the work of P. Kut & K. Pietrucha-Urbanik (2023), which demonstrates that the development of renewable energy is closely linked to environmental constraints, issues of sustainable development, and resource efficiency. In the current cluster structure, this is reflected in the close relationships between thematic blocks related to renewable energy, environmental safety, and the economics of natural resource use, confirming the interdisciplinary nature of the research problem.

Studies by Ukrainian scholars D.V. Stefanyshyn & Y.S. Vlasiuk (2019), as well as Y.S. Vlasiuk & D.V. Stefanyshyn (2019), emphasised the need to improve environmental impact assessment procedures, particularly by accounting for cumulative effects and improving the quality of input data. In the present study, this is reflected in the formation of the clusters "Environmental assessment" and "Environmental monitoring", further confirming the relevance of the obtained results. At the same time, the works of D.A. Szatten *et al.* (2025) focus on the basin approach and hydrological characteristics of river systems. In this study, these approaches are represented in the clusters "Hydrological characteristics" and "River basins".

In summary, the obtained results reflect contemporary trends in the development of scientific research in the field under study and confirm its interdisciplinary nature. The identified relationships between thematic clusters indicate the systemic nature of scientific knowledge and its orientation towards addressing complex environmental and energy challenges. The resulting structure of the scientific field demonstrates coherence between individual research areas and confirms their complementary nature. This indicates the gradual formation of an integrated approach to studying issues related to water resource use and the development of energy systems, taking into account environmental constraints.

Conclusions

As a result of the study, a comprehensive structuring of the scientific field in the areas of hydropower, ecology, and natural resource use was carried out based on bibliometric keyword analysis using normalisation, frequency analysis, hierarchical clustering, and visualisation. The bibliometric analysis confirmed the pronounced interdisciplinary nature of contemporary research, which is formed at the intersection of hydrology, ecology, energy, and economics. The keyword normalisation stage revealed an important pattern: without the unification of terminology, particularly in Ukrainian-language sources, fragmentation of the scientific field occurs. Normalisation made it possible to develop a consistent semantic structure and to increase the reliability of further analysis. Frequency analysis showed the dominance of studies related to hydropower, energy potential, and environmental aspects of water resource use. This indicates the orientation of modern science towards issues of energy efficiency and environmental safety.

Hierarchical cluster analysis revealed a multi-level structure of the scientific field. At the lowest level, homogeneous thematic pairs emerged (monitoring – assessment, climate – geography, hydrology – basins), reflecting the natural interrelationships between research areas. At the intermediate level, these were grouped into functional blocks: ecological-climatic, hydrological-methodological, and energy-economic. At the highest level, an integrated technical-ecological block emerged, indicating a combination of applied and ecological aspects of research. The study also confirmed the role of methodological approaches as an integrating element that influences the degree of proximity between research areas. Correlational patterns were also identified: strong links between environmental assessment and monitoring, the integration of energy and economic research, and the dependence of hydrological processes on climatic factors. At the same time, weakly related research areas were identified, indicating the presence of fragmentation and potential research gaps in the field under study.

The limitations of the study relate to the sample size (100 publications), the possible subjective influence during keyword normalisation, and the use of a binary matrix that does not account for the weight of terms. Furthermore, the absence of a temporal analysis limited the assessment of the dynamics of research areas' development. This may affect the granularity of the results, but does not alter the general patterns identified. Prospects for further research lie in expanding the sample, integrating bibliometrics with network analysis and machine learning methods, applying dynamic analysis and weighting coefficients, and developing automated approaches to terminology normalisation. It is expected that these steps will allow for a more detailed study of the evolution of scientific fields, as well as the identification of new links between hydropower and environmental aspects. Particularly promising are interdisciplinary studies at the intersection of hydropower, ecology, economics and climate change, which may contribute to the development of more effective strategies for the sustainable use of water resources and the reduction of negative environmental impacts.

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Conflict of Interest

None.

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Структуризація наукового поля гідроенергетичного потенціалу на основі аналізу ключових слів та ієрархічної кластеризації

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Анотація. Актуальність дослідження зумовлена необхідністю систематизації сучасних наукових підходів до оцінювання екологічно безпечного використання гідроенергетичного потенціалу річок. Екологічне оцінювання впровадження відновлюваних джерел енергії на водних об'єктах перебуває в полі міждисциплінарного поєднання гідрологічних, екологічних, гідроенергетичних, технічних та економічних аспектів. Метою роботи стала структуризація наукового поля екологічно безпечного використання гідроенергетичного потенціалу на основі аналізу ключових слів, ієрархічної кластеризації та виявленням взаємозв'язків між основними тематичними напрямами досліджень. Використовуючи програмний продукт STATISTICA був проведений статистичний аналіз кластерів ключових слів. Для поглибленого аналізу застосовано гістограму, дендрограму, побудовану методом Варда, та теплову карту кореляційних зв'язків. Інформаційну базу становили 100 наукових публікацій за останні 20 років із 22 країн світу. У процесі дослідження сформовано базу даних із 454 ключових слів, проведено їх попередню нормалізацію, частотний аналіз і кластеризацію. Виокремлено 12 тематичних кластерів, серед яких домінують «гідроенергетичні системи та ресурси», «економіка природокористування та енергетики», «гідрологічні характеристики та дані», «методологія та інструменти досліджень». Встановлено, що сучасне наукове поле має багаторівневу ієрархічну структуру та характеризується тісною взаємодією між екологічними, енергетичними, гідрологічними й економічними напрямами. Отримані результати підтвердили міждисциплінарний характер досліджень і засвідчили доцільність використання комплексного підходу до оцінювання гідроенергетичного потенціалу річок з урахуванням природних, технічних, екологічних та економічних чинників. Практичне значення дослідження полягає у ідентифікації недоліків та невирішених аспектів у наукових підходах до оцінки екологічно безпечного використання гідроенергетичного потенціалу

Ключові слова: річкові системи; мала гідроенергетика; екологічна безпека; водні ресурси; міждисциплінарні дослідження