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Implementation of the 1992 Helsinki Convention in Transboundary Groundwater Management: A Comparative Analysis with the Case of the Shu Basin

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Abstract. In the context of increasing freshwater scarcity and climate change, effective transboundary water management, including groundwater resources, is particularly important. The 1992 Helsinki Convention provides an international legal basis for states to cooperate to protect and rationally use transboundary watercourses and aquifers. This article is aimed at a comparative analysis of the practice of implementing the provisions of the Convention in different regions of the world - Europe, Central Asia and Africa - with an emphasis on hydrogeological aspects. Particular attention is paid to the Shuya transboundary basin, located on the territory of Kazakhstan and Kyrgyzstan, as a case of partial implementation of international standards. Based on a systemic analysis of groundwater management, monitoring, and protection practices, recommendations are proposed to integrate the Convention's provisions into regional water policies and institutional mechanisms. The study aims to conduct a comparative analysis of the practice of applying the 1992 Helsinki Convention in various regions of the world, with an emphasis on transboundary groundwater, highlighting the problems and prospects of its implementation using the example of the Shuya basin. The study confirmed that the application of the 1992 Helsinki Convention varies significantly across geographical and political-institutional contexts.

Keywords: *transboundary groundwater, water security, legal regulation, Central Asia.*

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1. Introduction

Rational use and protection of transboundary water resources are key tasks in sustainable water management, especially amid increasing global environmental challenges and climate change. Today, against the backdrop of increasing anthropogenic impact, urbanization, agricultural pressure and changing hydroclimatic conditions, the vulnerability of both surface and groundwater systems is increasing. In particular, there are stable trends towards decreases in groundwater levels, increases in mineralization, degradation of aquifers, and disruption of natural water exchange regimes [1-4].

At the same time, the transboundary interdependence of states sharing common water resources is increasing. This is particularly relevant in arid and semi-arid regions where transboundary rivers and aquifers are the only source of fresh water for millions of people. Conflicts of interest between countries over the distribution and use of water are increasingly becoming the subject of not only technical but also political and legal discussions [5-8].

In these conditions, the development and implementation of effective international legal regulatory mechanisms capable of ensuring fair and sustainable management of water resources, protection of aquatic ecosystems and prevention of transboundary water conflicts becomes particularly relevant [9, 10]. The 1992 Helsinki Convention plays a key role in this process, the first universal international treaty aimed at promoting cooperation in the protection and use of transboundary waters [11, 12].

However, practice shows that the degree of implementation of the Convention varies significantly from region to region. In some cases, it has served as the basis for the creation of sustainable institutions and comprehensive management programs, while in others, its provisions remain formal declarations, unsupported by institutional or technical implementation. This is especially true for components such as groundwater, which often remain outside the scope of transboundary regulation despite their critical importance for sustainable water use.

Thus, in the context of increasing water and environmental pressures and transboundary challenges, the development of effective models of international water cooperation grounded in the principles of the Convention is not only desirable but also a necessary condition for ensuring water security in the 21st century [13-15].

One of the key international documents in this area, as mentioned above, is the UNECE Convention on the Protection and Use of Transboundary Watercourses and Interna-

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tional Lakes (Helsinki, 1992) [12], which has now moved from a regional to a global status, becoming a universal instrument of international water law. The Convention establishes principles of cooperation among states for preventing transboundary impacts, exchanging information, monitoring, and protecting groundwater [16, 17].

Of particular interest in the comparative analysis is the Central Asian region, where transboundary rivers and groundwater aquifers play a key role in ensuring water and food security. An example is the Shu transboundary basin, located on the territories of Kyrgyzstan and Kazakhstan, including the Zhambyl region, where essential groundwater resources are formed and used for drinking and agricultural water supply. Despite the existence of an interstate agreement on joint management (2000) [18], issues of integrating the provisions of the Helsinki Convention, particularly regarding groundwater protection and monitoring, remain insufficiently developed [19, 20].

The purpose of this study is to conduct a comparative analysis of the application of the 1992 Helsinki Convention across various geographical and institutional contexts (Europe, Central Asia, Africa), with an emphasis on hydrogeological aspects and an assessment of the degree of implementation of the key provisions in transboundary basins. Particular attention is paid to the Central Asian region as a zone of complex water resource challenges and potential application of international legal norms.

2. Materials and methods

The methodological framework of this study combines complementary analytical approaches to assess the implementation of the 1992 Helsinki Convention across diverse geographical and institutional contexts, with particular emphasis on transboundary groundwater [11, 12].

First, a comparative analytical approach was employed to identify similarities and differences in the application of the Convention in Europe, Central Asia, and Africa. The comparison was structured according to predefined criteria, including: the legal status of the Convention, the level of institutionalization of transboundary cooperation, the inclusion of groundwater in basin management frameworks, monitoring mechanisms, and procedures for data exchange [21].

Second, geoecological and hydrogeological analyses were conducted to evaluate aquifer conditions, groundwater mineralization levels, seasonal variability of groundwater levels, and vulnerability to anthropogenic pressures. Particular attention was given to the Shu transboundary basin, encompassing the Zhambyl region of Kazakhstan and the adjacent territories of Kyrgyzstan.

Third, a content analysis of legal and institutional documents was performed, including bilateral and multilateral water agreements, official UNECE materials, and strategic documents of national and regional water authorities [22, 23]. This approach enabled an assessment of both formal compliance and the practical implementation of Convention principles within regional governance systems.

Fourth, a case study methodology was applied to the Shu transboundary basin. This approach facilitated an in-depth examination of institutional arrangements, hydrogeological characteristics, existing coordination mechanisms, and the potential for adapting international standards to the regional level [24-26]. In addition, geographic information system (GIS) data, cartographic materials, and available groundwater monitoring reports from the Zhambyl region were analyzed. Where data permitted, spatial visualization of aquifer distribution and groundwater availability dynamics was conducted to support the comparative assessment [27-30].

The integrated application of these methods ensured both regulatory-institutional and hydrogeological depth of analysis, providing a foundation for evidence-based recommendations for transboundary groundwater governance within the framework of international legal instruments.

3. Results and discussion

3.1. Institutional and legal frameworks in transboundary water management

3.1.1. European experience in the Danube Basin

In the European region, the 1992 Helsinki Convention has not only been widely ratified but also integrated into transboundary water management practices through sustainable institutional arrangements. One of the most illustrative examples is the International Commission for the Protection of the Danube River, which unites 14 countries in the basin [31, 32].

Based on the Convention and the EU Water Framework Directive (2000/60/EC) [33], Danube River Basin Management Plans have been developed and implemented, in which groundwater is considered alongside surface water within a single hydrological unit. Systems for monitoring groundwater quality and levels have been implemented, and regular data exchange is carried out between countries.

Particularly noteworthy is the inclusion of transboundary aquifers in strategic management, such as the karst and alluvial systems along the Upper and Middle Danube. Methods for assessing aquifers, mapping vulnerability zones and establishing sampling standards have been developed. A critical component is the participation of all basin countries in unified reporting and planning cycles (every 6 years), which fosters high transparency and mutual responsibility.

In Europe, the Danube basin is one of the most successful examples of implementing the principles of the 1992 Helsinki Convention. It implements integrated transboundary management, including both surface and groundwater. This was made possible by a combination of international legal mechanisms (including the Helsinki Convention and the EU Water Framework Directive) [11, 12, 34], a high level of institutional coordination and technical sophistication of monitoring.

Particular attention in the Danube Region is paid to transboundary groundwater bodies, which play an essential role in water supply, agriculture, and the maintenance of ecosystems. Within the framework of the activities of the International Commission for the Protection of the Danube River, several hydrogeological studies were carried out and a register of TGWBs was created, covering 11 major aquifers, including: Karst aquifers in Austria, Slovakia, Hungary and Slovenia; Pannonian Basin aquifers, covering Hungary, Serbia, Romania; alluvial and fluvioglacial systems in the lower and middle reaches of the Danube [35-37].

Each ICPDR Member State is required to provide information on groundwater status, water abstraction volumes, pollution sources, and the risk of depletion. This information is synthesised within the framework of the joint Danube Basin Management Plan, where groundwater is considered as an integral part of «water bodies» in accordance with the EU Framework Directive [38, 39].

A coordinated monitoring system has been technically implemented, including general parameters (pH, mineralization, nitrates, heavy metal concentrations), as well as an assessment of the chemical and quantitative state of groundwater. The integration of GIS systems and joint data platforms ensures rapid exchange of information between countries.

The legal framework for cooperation includes not only the provisions of the Helsinki Convention, but also special regional agreements, such as: the Danube River Protection Agreement [11, 12, 34], which clearly sets out obligations for groundwater management; joint technical guidelines for assessing the risk of groundwater pollution; participation of countries in the EU Climate Change Adaptation Strategy, which recognizes groundwater as a strategic resource.

Thus, the European experience shows that it is possible to implement the principles of integrated water management, in which groundwater is not separated from surface water and is considered within a single ecosystem and legal framework. This creates sustainable forms of cross-border interaction based on trust, scientific evidence and legal responsibility. The European experience shows that multilateral agreements and directives complementing the Convention's provisions provide not only a legal framework but also effective institutional implementation.

3.1.2. Transboundary cooperation in the Nile Basin

The Nile River basin, spanning 11 countries, is one of the largest and most politically sensitive transboundary water bodies in the world. Although the 1992 Helsinki Convention has been ratified by only a fraction of the countries in the region, its principles, including equitable and reasonable use, prevention of significant harm, and the exchange of information, have been partially implemented through regional initiatives and agreements [40-42].

The key mechanism for cooperation in the Nile Basin is the Nile Basin Initiative [42], founded in 1999. It unites all riparian states and seeks a sustainable, equitable distribution of water resources. Unlike European models, there is no single legally binding agreement covering the entire basin, reflecting the complex political environment and the differences in interests between upstream and downstream countries [43].

As for groundwater, its role in basin management has long remained secondary. However, in recent years, there has been growing interest in transboundary aquifers, particularly in the arid border areas between Sudan, South Sudan, Ethiopia and Uganda. Key underground systems include the deep Nubian Sandstone Aquifer System, partly connected to the eastern Nile Basin, and the aquifers of the East African Rift System, which are heavily used to supply rural populations and are under pressure due to climate fluctuations [44-47].

The NBI is implementing projects to improve monitoring and create groundwater databases, but there is still no agreed institutional system for managing them. Most research is funded by international donors (GEF, World Bank) [48], and implementation at the national level is often not synchronized across countries.

Specific challenges for groundwater include: limited data on water supplies and quality; lack of standards for transboundary information exchange; inconsistent licensing of water abstraction in border areas; climate vulnerability and weak institutional integration.

Thus, the experience of the Nile River basin demonstrates a partial implementation of the principles of the Helsinki Convention, with a primary focus on surface waters and an initial phase of accounting for groundwater resources. However, the potential of groundwater as a sustainable resource in a changing climate requires increased regional cooperation, scientific research and the establishment of a legally binding framework.

3.1.3. The Shu transboundary basin in Central Asia

The Shu transboundary basin, located on the territories of Kazakhstan and Kyrgyzstan, is a vital water management system in Central Asia's arid climate. The main watercourse, the Shu River, crosses the state border, providing water for irrigation, municipal services and partly industry in both countries. The basin is characterized not only by a well-developed surface water system but also by significant groundwater reserves, which, however, are not sufficiently accounted for in transboundary water management [49].

Kazakhstan ratified the 1992 Helsinki Convention in 2001, while Kyrgyzstan remains only a participant in several UNECE programs. At the same time, bilateral agreements are in force in the region, including the Agreement between the governments of Kazakhstan and Kyrgyzstan on the joint use of water management facilities on the Shu and Talas rivers (2000) [50]. This document creates coordination mechanisms for joint management, but the focus is almost exclusively on surface water, infrastructure and flow distribution during the growing season.

Groundwater of the Shu basin is represented by several alluvial and intermountain aquifers, such as the Shu alluvial aquifer (Zhambyl region, Kazakhstan), actively used for water supply; Merke and Kordai depressions, containing fresh and slightly mineralized waters; and Groundwater deposits in the Chui Valley (Kyrgyzstan), including those used in the agricultural sector [51-52].

Hydrogeological information on the basin is fragmentary and, in general, based on Soviet and post-Soviet research. There is currently no regular state or transboundary monitoring of groundwater. The level of mineralization of water in the basin fluctuates between 0.3 and 1.5 g/L, with seasonal variations influenced by melioration and climatic conditions. In some areas, increased nitrate concentrations have been recorded due to agricultural activities.

A significant obstacle to implementing the provisions of the Helsinki Convention is the lack of institutionalized mechanisms for accounting for and coordinating groundwater management. Unified assessment methods have not been developed; there are no maps of transboundary aquifers; and there is no coordination regarding zoning sanitary protection zones. There is also no publicly available digital database, although individual hydrogeological reports are available from specialized institutes.

In addition, the Shu basin is highly vulnerable to climate change, especially in the mountainous areas where runoff originates. Decreasing snow cover and increasing interannual runoff variability increase the pressure on groundwater as a reserve source, further increasing the need for its regulation in a transboundary context.

Thus, the experience of the Shu basin demonstrates a significant gap between the principles of the Helsinki Convention and the actual practice of groundwater management in Central Asia. The potential for integrating these resources into bilateral and regional cooperation mechanisms is obvious, but requires:

– data systematization;
– strengthening the scientific base;
– legal consolidation of the status of transboundary aquifers;
– as well as the involvement of international organizations in the development of monitoring and dialogue.

Without the formal delineation of transboundary aquifers, the establishment of a joint monitoring system, and the integration of groundwater into the mandate of the bilateral commission, the practical implementation of the Helsinki Convention in the Shu Basin will remain largely declarative thereby limiting the sustainability of transboundary water governance in the basin.

3.2. Comparative analysis of transboundary water governance in Europe, Central Asia, and Africa

The results of the analysis show significant differentiation in the degree and form of application of the provisions of the 1992 Helsinki Convention in different regions [11, 12]. In the European context, using the example of the Danube basin [31-32], the Convention serves as a basis for establishing sustainable management institutions, in which groundwater is considered an integral part of the basin approach. Regular monitoring, coordinated aquifer protection programmes and joint scientific research ensure a high level of transparency and transboundary trust (Table 1).

Table 1. Comparative assessment of transboundary groundwater governance under the 1992 Helsinki Convention

Criteria	Europe (Danube Basin)	Africa (Nile Basin)	Central Asia (Shu Basin)
Ratification status	Ratified by most basin states; fully operational within EU legal framework	Partially ratified; limited legal harmonization	Kazakhstan ratified; Kyrgyzstan not a Party; limited implementation
Level of institutionalization	High: ICPDR, binding basin management plans, structured reporting cycles	Medium: Nile Basin Initiative; limited binding authority	Low: Bilateral agreement (2000); weak coordination mechanisms
Integration of groundwater into basin management	Fully integrated into River Basin Management Plans; groundwater treated as water bodies	Limited integration; primary focus on surface water	Very limited integration; groundwater not systematically incorporated
Delineation of transboundary aquifers	Clearly identified and mapped transboundary groundwater bodies (TGWBs)	Partially identified; limited formal delineation	No formal delineation of transboundary aquifers
Groundwater monitoring	Regular monitoring with unified methodology and reporting standards	Episodic and project-based monitoring	Fragmented or local monitoring; no coordinated transboundary system
Use of GIS and hydrogeological data	Actively integrated into basin planning and decision-making	Basic and project-dependent use	Isolated initiatives; no system-wide integration
Coordination of water use standards	Regulated through multilateral agreements and EU directives	Ongoing negotiations; heterogeneous national standards	No coordinated standards for groundwater abstraction
Formal basin agreements	Danube Convention and EU directives provide binding framework	Basin cooperation agreements; limited groundwater coverage	Bilateral agreements exist; groundwater largely excluded
Key challenges and gaps	Balancing national interests; pollution control	Political instability; funding constraints	Limited monitoring capacity; absence of coordinated groundwater governance

In Africa (the Nile River basin) [40-42], despite attempts to harmonize legal regulation, the level of institutional implementation remains low. Groundwater is practically not considered an object of transboundary regulation, which creates preconditions for environmental risks (Table 1).

Central Asia, despite formal agreements, shows limited implementation of the Convention's hydrogeological components. In particular, in the Shu River basin (Zhambyl region, Kazakhstan), groundwater monitoring is not systematic, and legal regulation is declaratory [49-52]. The Interstate Commission on the Use of Waters of the Shu and Talas Rivers functions irregularly, and the protection of underground aquifers is practically not included in its mandate (Table 1).

Table 1 provides a comparative analysis of the application of the Helsinki Convention in different regions of the world, reflecting the extent to which countries have formalized and institutionalized cooperation in transboundary water governance. In particular:

– Europe demonstrates the most advanced level of implementation of the Convention with regard to groundwater, supported by strong institutional structures and technological capacity.

– Africa is progressing toward groundwater integration but continues to face resource, legal, and coordination constraints.

– Central Asia, despite the existence of formal cooperation frameworks, has not yet systematically incorporated groundwater, including in the Shu Basin, into a sustainable transboundary governance system.

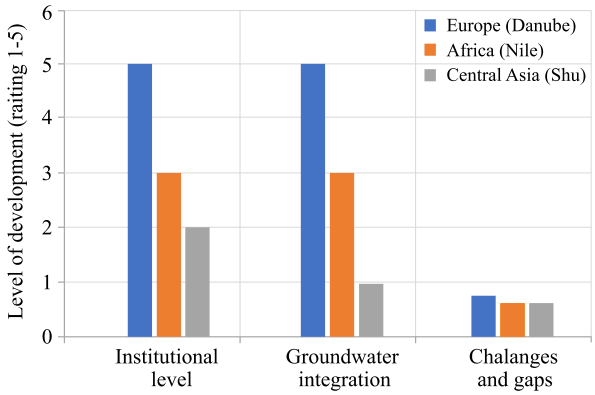

Figure 1. Comparative assessment of transboundary groundwater governance in Europe, Africa, and Central Asia

Figure 1 illustrates the comparative scoring of three regions across key dimensions of transboundary groundwater governance. Europe (Danube Basin) demonstrates consistently high performance across all assessed criteria. Africa (Nile Basin) shows a moderate level of institutionalization and partial integration of groundwater, though significant governance challenges remain. Central Asia (Shu Basin) exhibits the lowest scores, particularly with respect to groundwater monitoring and institutional integration.

Overall, the effectiveness of the Convention's implementation depends on political commitment, the strength of institutional arrangements, and the technical capacity to monitor and manage hydrogeological systems.

3.3. Perspectives for further research

Further research should focus on the development of a formalized assessment framework for evaluating the implementation of the Helsinki Convention with respect to transboundary groundwater. In particular, there is a need to operationalize measurable indicators covering aquifer delineation, monitoring density, data exchange frequency, abstraction control mechanisms, and institutional mandates. The construction of a composite governance index would allow moving from qualitative comparison to quantitative benchmarking across regions.

For the Shu transboundary basin, priority should be given to hydrogeological delineation of potential transboundary aquifers using updated geological, geophysical, and GIS-based spatial analysis. Joint field investigations aimed at identifying hydraulic connectivity across the Kazakhstan-Kyrgyzstan border would provide an empirical basis for formal recognition of shared groundwater bodies. Establishing a harmonized monitoring network with agreed observation wells and standardized chemical parameters would allow assessment of long-term trends and climate-driven variability.

A separate line of research should address the legal dimension by conducting a structured gap analysis between specific provisions of the Helsinki Convention (Articles on monitoring, information exchange, and prevention of transboundary impact) and the current mandate of the bilateral Shu-Talas Commission. Such analysis could support proposals for expanding the Commission's competence to explicitly include groundwater.

Finally, climate impact modelling for the Shu basin should be integrated with groundwater recharge assessments to evaluate the role of aquifers as buffer systems under decreasing snow cover and increasing interannual runoff variability. Coupling hydrological and hydrogeological models would enable scenario-based evaluation of future water security risks.

4. Conclusions

The study confirmed that the application of the 1992 Helsinki Convention varies significantly across geographical and political-institutional contexts. The European region demonstrates the highest level of integration of the Convention's provisions, including groundwater protection, through developed institutions and sustainable funding. In Central Asia, implementation is limited, particularly regarding groundwater, despite the existence of transboundary agreements. A weak institutional framework and the absence of a systematic approach to hydrogeological components characterize the African context.

Sustainable transboundary water management is impossible without integrating groundwater into the international regulatory system. The Helsinki Convention provides the necessary legal framework, but its practical implementation requires political will, institutional maturity and technical capacity. In Central Asia, and in particular the Shu River basin, there is an urgent need to develop joint groundwater monitoring programs, to incorporate hydrogeological data into decisions of interstate commissions, and to adapt best international practices at the local level. The article confirms that the transition from formal to functional cooperation is possible only with sustainable funding, access to data and institutional openness.

Author contributions

Conceptualization: DKA; Data curation: YZM, DKA; Formal analysis: EVS, JS, SRT; Funding acquisition: YZM; Investigation: AMB; Methodology: SRT, DKA; Project administration: EVS; Resources: EVS, JS, SRT; Software: ABM, SRT; Supervision: YZM; Validation: DKA, EVS; Visualization: EVS, JS; Writing – original draft: DKA; Writing – review & editing: YZM. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Трансшекаралық жерасты суларын басқару бойынша 1992 жылғы Хельсинки конвенциясының жүзеге асырылуы: Шу бассейнінің жағдайы мен салыстырмалы талдауы

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Аңдатпа. Тұщы су тапшылығының артуы және климаттың өзгеруі жағдайында жерасты суларының ресурстарын қоса алғанда, трансшекаралық суды тиімді басқару ерекше маңызға ие. 1992 жылғы Хельсинки конвенциясы трансшекаралық су ағындары мен сулы горизонттарды қорғау және ұтымды пайдалану саласындағы мемлекеттердің ынтымақтастығына халықаралық құқықтық негіз береді. Бұл мақала гидрогеологиялық аспектілерге баса назар аудара отырып, әлемнің әртүрлі аймақтарында – Еуропада, Орталық Азияда және Африкада Конвенция ережелерін іске асыру тәжірибесін салыстырмалы талдауға бағытталған. Халықаралық стандарттарды ішінара енгізу жағдайы ретінде Қазақстан мен Қырғызстан аумағында орналасқан Шу трансшекаралық бассейніне ерекше назар аударылады. Жерасты суларын басқару, мониторинг және қорғау тәжірибесін жүйелі талдау негізінде Конвенцияның ережелерін өңірлік су саясаты мен институционалдық тетіктерге интеграциялау бойынша ұсыныстар ұсынылады. Зерттеудің мақсаты – 1992 жылғы Хельсинки конвенциясының трансшекаралық жерасты суларына баса назар аудара отырып, әлемнің әртүрлі аймақтарында қолдану тәжірибесіне салыстырмалы талдау жасау, Шу бассейнінің мысалында оны жүзеге асырудың проблемалары мен перспективаларын көрсету. Зерттеу 1992 жылғы Хельсинки конвенциясын қолдану географиялық және саяси-институционалдық контекстке байланысты айтарлықтай өзгеретінін растады.

Негізгі сөздер: *трансшекаралық жерасты сулары; су қауіпсіздігі; құқықтық реттеу; Орталық Азия.*

Имплементация Хельсинкской конвенции 1992 года в управлении трансграничными подземными водами: сравнительный анализ и пример Шуйского бассейна

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Аннотация. В условиях нарастающего дефицита пресной воды и изменения климата особое значение приобретает эффективное трансграничное водное управление, включая подземные водные ресурсы. Хельсинкская конвенция 1992 года обеспечивает международно-правовую основу для сотрудничества государств в сфере охраны и рационального использования трансграничных водотоков и водоносных горизонтов. Настоящая статья направлена на сравнительный анализ практики реализации положений Конвенции в различных регионах мира – Европе, Центральной Азии и Африке – с акцентом на гидрогеологические аспекты. Особое внимание уделено Шуйскому трансграничному бассейну, расположенному на территории Казахстана и Кыргызстана, как кейсу частичной имплементации международных

норм. На основе системного анализа практик управления, мониторинга и защиты подземных вод предложены рекомендации по интеграции положений Конвенции в региональные водные политики и институциональные механизмы. Целью исследования является в проведении сравнительного анализа практики применения Хельсинкской конвенции 1992 года в различных регионах мира с акцентом на трансграничные подземные воды, выделяя проблемы и перспективы её имплементации на примере Шуйского бассейна. Проведённое исследование подтвердило, что применение Хельсинкской конвенции 1992 года существенно варьируется в зависимости от географического и политико-институционального контекста.

Ключевые слова: *трансграничные подземные воды; водная безопасность; правовое регулирование; Центральная Азия.*

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