

Integrating geodetic technology with legal governance for global monitoring of water and soil dynamics: Kalman filter and inverse modeling approaches

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Abstract

The need for accurate, reliable geodetic data has never been greater, particularly as water and soil systems face growing threats from global challenges such as agricultural development, land deformation, and flood vulnerability. This study examines the integration of advanced geodetic systems with international legal frameworks to support collaborative and cross-border environmental monitoring, with specific implications for water and soil management. An innovative five-component methodology was developed, comprising data acquisition, standardization, sharing, analytical processing, and model integration, aimed at enhancing data accuracy and interoperability for hydrological and soil-related applications. Techniques such as Kalman filtering, inverse modeling, covariance analysis, and PSD-based spectral decomposition were employed to reduce uncertainty and isolate critical environmental signals. Kalman filtering–augmented time series analysis reduced uncertainty in sea-level estimates by 38%, achieving millimeter-level precision. Tectonic frequencies down to 0.05 Hz were detected, enhancing the monitoring of land deformation processes. Inverse modeling produced a 42% reduction in uncertainty for glacial and groundwater mass loss estimates, directly informing water resource assessments. GNSS displacement vectors improved land deformation risk models by 53%, while altimetry-based sea-level trends enhanced forecasting accuracy by 50%, benefiting coastal water management. Standardization mitigated data variability, and international legal mechanisms, including agreements and licensing protocols, enabled broader data access and institutional collaboration. Elevation data strengthened flood vulnerability assessments by 52%, and cryosphere modeling experienced a 53% error reduction in mass balance estimates. The Combined Earth System Model, integrating global geodetic inputs, achieved a maximum accuracy gain of 54%. This study highlights that embedding legal infrastructures within scientific geodetic modeling enhances the governance, reliability, and equity of water and soil monitoring systems across national boundaries.

Keywords: Geodetic data, Environmental monitoring, Water and soil modeling, International legal frameworks, Uncertainty reduction

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1. Introduction

The need for accurate, reliable, geodetic data has never been greater, as the field of environmental monitoring evolves at a breakneck speed. Geodetic data, including high-precision measures of the figure of the earth, the orientation of the axis of the figure of the earth in space, and the gravitational field, hold the key to unlocking information on sea-level variations, tectonic activity, and climate-induced land deformation (Gharibreza et al. 2018; Othman et al. 2025). With environmental challenges on the rise, and as the effects of climate change cause changes in sea levels and more frequent extreme weather events, the need for clear international management of geodetic data has arisen (Ciski & Rzaşa, 2021). However, the inherently global nature of environmental monitoring, particularly water and soil monitoring, to which we're becoming accustomed, raises a fundamental question: How can this data be coordinated, shared, and standardized across national boundaries to the degree that it can be most effectively used? This question stands above all others we hope to address in this research on what role international law can play in regulating access to geodetic data for the practice of monitoring the global environment (Lisboa et al., 2024).

Geodetic science is based on accurate observations and measurements, which are performed with the help of a large network of ground stations, satellites, and advanced sensors. These are not referenced only to national borders; rather, they provide a complete account of dynamic systems on Earth changes that may start in one place with effects felt everywhere (Amini & Hesami, 2017). For one thing, sea-level rise precipitated by glacial melting in one hemisphere affects coastal populations on the other side of the planet, and tectonic shifts give rise to seismic activity that can spread across continents. Such interconnectivity highlights the importance of a unified approach to data governance and the necessity of international cooperation. The lack of a coherent legal framework could render global and even regional initiatives in regard to the monitoring and mitigation of environmental alterations

challenging due to the underlying differences in standards of data collection, disparities in methodological approaches, and the limitations surrounding data sharing (Demir & Yomralioglu, 2024). International law provides the framework to resolve such disputes (Kaganovska et al., 2022). International law can facilitate the collection, sharing, and use of geodetic data by allowing countries to establish treaties, conventions, and agreements. Such frameworks not only ensure that data are collected according to consistent standards and methodologies, but also provide a space for adjudicating disputes and fostering trust between nations. Legal agreements, for instance, can be utilized to specify roles in maintaining critical infrastructure, establish protocols for the handling of sensitive information, and institute methods for guaranteeing data integrity. In this way, international law contributes to the establishment of a stable environment for the efficient utilization of geodetic data for environmental monitoring without the uncertainties associated with uncoordinated national efforts (Koupatsiaris & Drinia, 2024).

Furthermore, the function of international law goes beyond technical standardization. Legal principles are also similar to ensure transparency, accountability, and equitable access to geodetic data (Krisch, 2005). Even in cases where they have the capacity, smaller or less technologically sophisticated countries may not have the resources to operate independent geodetic networks or sophisticated monitoring systems. These include international agreements that can generate knowledge transfer, be a source of financial funding, or promote capacity-building actions to guarantee that the countries have the data available (Madani & Natcher, 2024). These frameworks not only improve the overall quality and reliability of geodetic data but also promote a more equitable global response to environmental challenges. The internalization of all countries in data-sharing programs leads to comprehensive and representative data that enhances environmental monitoring and policy decision-making (Madani & Natcher, 2024).

Besides legal and governance powers, international law facilitates the integration of

geodetic data into more general environmental monitoring schemes. Today's environmental issues are multi-dimensional and crosscutting from climate science, to natural disaster response, to urban planning, to resource conservation (Amini et al., 2009). International law serves as an intermediary between geodetic science and applied environmental policy by facilitating transdisciplinary and transnational intersections of information. International legal frameworks empower governments, researchers, and organizations to use data for evidence-based decision-making and their potential to develop long-term strategies to optimize sustainable development by providing a greater degree of guidelines on the sharing and use of data (Mai, 2024).

Despite advances in geodetic technology and its systematic importance as an indicator of the solid Earth's processes and water and soil monitoring, ensuring adequate use of this data remains a challenge worldwide. Rybina et al. (2022) analyzed the development of approaches and practical strategies to improve land management in the EU. They compared landscape planning systems across European countries, noting that differences in history, politics, culture, and legal systems make unified standards impractical. The study highlights that environmental planning will be a key focus in the future, and countries should actively participate. While society is increasingly reliant on digital technologies, the pace of innovation often exceeds the speed at which laws can adapt or emerge. As a result, our ability to utilize geodetic data for monitoring large-scale processes and changes of interest worldwide is limited by the aforementioned factors at the local and regional levels, as well as by the international context in which these data are obtained. It is here that international law's inbuilt flexibility and its possibility of continuing negotiation and rewriting come into their own (Costantino et al., 2024).

Geodetic data management is a critical yet complex foundation of global environmental monitoring, essential for tracking phenomena such as sea-level rise, land subsidence, water and soil monitoring, and climate change. However, challenges persist due to fragmented datasets,

inconsistent standards, limited accessibility, and the absence of a cohesive international legal framework to govern data acquisition, sharing, and interoperability. This research examines how international law can address these governance gaps by establishing enforceable standards and promoting cross-border cooperation to ensure the reliability, accuracy, and equity of geodetic information systems. The novelty of this research lies in its innovative objective to integrate legal infrastructures with scientific data frameworks, thereby enhancing the institutional accountability and operational effectiveness of global monitoring systems. By analyzing key treaties, protocols, and cooperative mechanisms, the paper demonstrates that a legally supported, standardized geodetic regime is essential for advancing sustainable environmental governance worldwide.

2. Materials and Methods

This analytical framework combines sophisticated geodetic concepts with international legal governance tools, which contribute to the effective global monitoring of environmental processes. The strategy is divided into five intermediary sectors: geodetic data gathering, standardization, dilated protocols for data sharing among diverse research teams, analysis, and incorporation into the models of environmental changes. Each component relies on both legal and geoscientific disciplines, with complex mathematical models to support the accuracy, interoperability, and operational value of the geodetic dataset.

2.1. Geodetic Dataset Selection and Categorization

The geodetic datasets used in this study were selected to support accurate monitoring of environmental processes, including sea-level rise, land subsidence, and groundwater changes. These datasets are categorized into three primary types: (i) satellite altimetry data for sea surface height measurements, (ii) gravimetric data for detecting mass redistribution and gravity anomalies, and (iii) GNSS positional data for modeling vertical and horizontal land motion.

The selection of these datasets was based on their high spatial and temporal resolution, global coverage, and demonstrated reliability in previous environmental studies. To achieve meaningful results, strict requirements were applied for data collection and estimation, including centimeter-level precision, temporal consistency, and minimization of instrumental and atmospheric biases. Data were acquired through multi-sensor arrays, comprising satellite altimeters, gravimeters, and GNSS constellations, with continuous monitoring and onboard calibration to reduce observational errors. The collection process relied on advanced processing algorithms, including bias corrections, covariance estimation, and Kalman filtering, to ensure data accuracy and interoperability. Additionally, standardized reference frames (ITRF2020 and EGM2008) and encoding formats (NetCDF-4) were employed, allowing integration across diverse datasets and compatibility with international legal frameworks for shared geospatial data. The geodetic data provide essential information on spatial and temporal variations in Earth's surface, including sea-level changes, land deformation, and mass redistribution.

2.2. Advanced Data Acquisition Techniques

To achieve centimeter-level accuracy and reduce systemic observational bias, geodetic data was acquired via multi-sensor arrays, including satellite altimetry, gravimetric sensors, and GNSS constellations. Observational consistency was maintained through continuous measurements and onboard correction protocols (Sarkar et al., 2023; Rozhi et al., 2024). Corrected sea surface height (h) is calculated from the raw satellite altimetry signal using Eq. 1, by removing various atmospheric and instrumental biases:

$$h = h_{sat} - (h_{dry} + h_{wet} + h_{iono} + h_{inst}) \quad (1)$$

where h_{sat} is raw altimeter range measurement; h_{dry} , h_{wet} are dry and wet tropospheric delay corrections; h_{iono} is ionospheric path delay; h_{inst} is the instrument calibration offset. Vertical land motion was modeled using a weighted least squares adjustment for positional shifts observed in GNSS networks (Eq. 2):

$$\hat{x} = (A^T W A)^{-1} A^T W y \quad (2)$$

where $\hat{x}$ estimated vertical displacement; A is the design matrix; W weight matrix (inverse of observational variances); y observation vector. This formulation enables rigorous adjustment of 3D ground deformation vectors, especially in tectonically active zones (Serpelloni et al., 2022).

2.3. Standardization Protocols and Reference Frames

To ensure harmonization across international systems, all datasets were referenced to the ITRF2020 and EGM2008 standards. NetCDF-4 was employed as the standard data encoding format, complying with metadata requirements outlined in ISO 19115 (Piech et al., 2023; Lee et al., 2024). Geospatial transformations between local and global coordinate frames were executed using rotational matrices, Eq. 3:

$$|Y| = R(\theta, \phi, \lambda) \cdot |y| \quad (3)$$

where $R(\theta, \phi, \lambda)$ is a composite rotation matrix depending on latitude, longitude, and orientation angles. This equation facilitates alignment of geodetic points across datums and national grids, improving cross-border spatial interoperability (Koupatsiaris & Drinia, 2024).

2.4. Cross-Border Data Sharing Frameworks

Decentralized repositories were used to operationalize the sharing of geodetic data, and these were licensed across countries via international licensing schemes such as Creative Commons (CC BY 4.0). There was a hybrid legal-institutional setup regulating the authentication and dissemination of datasets (Hojati, 2023; Wang et al., 2024). Legal backing for the repositories of shared content made it possible to use spatial data trusts to govern access control (Radosevic et al., 2023; Rozhi et al., 2024), through which data access rights necessarily reflected both ethical and legal tenets (Goi et al., 2024). To characterize positional uncertainty on pooled datasets, we used Eq. 4 to compute a covariance matrix:

$$\Sigma = E[(x - \mu)(x - \mu)^T] \quad (4)$$

where Σ is the covariance matrix, x is the observation vector, and μ expected (mean) position. This matrix is essential for risk-sensitive

applications such as flood modeling and infrastructure placement near fault zones.

2.5. Analytical Techniques for Signal Interpretation

Advanced denoising and predictive modeling techniques were employed to enhance the interpretability of geodetic time series. A Kalman filter was used to dynamically update measurements with real-time correction:

$$x_k = x_{k-1} + K_k(z_k + Hx_{k-1}) \quad (5)$$

where x_k updated state estimate; z_k new observation; H is the observation model; K_k is the Kalman gain. This recursive filter was particularly effective for GNSS data streams with periodic observation gaps or sensor drift (Costantino et al., 2024). Noise in the sea level and gravity series was mitigated using spectral analysis. Power spectral density (PSD) was estimated for long time series via Fourier transforms using Eq. 6:

$$S_{xx}(f) = \lim_{T \rightarrow \infty} \frac{1}{T} |X_T(f)|^2 \quad (6)$$

where $S_{xx}(f)$ is the power spectrum and $X_T(f)$ Fourier transform of the signal over a time window T . This filtering enhanced trend clarity in areas of high seasonal and tectonic variability (Lisboa et al., 2024; Mashala et al., 2023).

2.6. Integration into Environmental Models

Inverse modeling, through Eq. 7, was used to integrate geodetic mass change signals, for example, from gravity field changes into environmental impact models:

$$\Delta M = \rho \cdot \Delta g \cdot V / G \quad (7)$$

where ΔM is estimated mass change (glacial melt); ρ material density; Δg gravity anomaly; V volume of displaced material, and G

gravitational constant. This equation is particularly applicable for cryosphere and groundwater depletion studies (Lumban-Gaol et al., 2024; Madani & Natcher, 2024). The methodologies presented above are designed to align with legal mandates outlined under international treaties such as UNCLOS and the Paris Agreement, which mandate shared environmental data protocols. These legal instruments support geospatial data harmonization, promote capacity-building in developing states, and reduce geopolitical friction in transboundary monitoring initiatives (Mai, 2024; Phelan and Sirleaf, 2023; Usman et al., 2022).

1. 3. Results

3.1. Precision and Coverage of Geodetic Data Acquisition Techniques

High-grade geodetic data acquisition is the foundation for reliable environmental modeling. By relying on satellite altimetry, GNSS-based land motion monitoring devices, gravimetric satellites, and tide gauges, this study acquired spatiotemporally dense measurements. Moreover, advanced data fusion was performed through Kalman filtering and weighted least squares adjustment to resolve inconsistencies between systems. This dual approach, having reliable estimates at both the observational and coverage levels, allowed for a careful definition of baseline environmental parameters to be integrated into larger models. We summarize the technical specifications and performance metrics across five primary data acquisition approaches in Table 1.

Table 1. Accuracy and Operational Characteristics of Geodetic Data Acquisition Techniques

Measurement Type	Instrument	Accuracy (cm)	Coverage (%)	Repeatability (days)
Satellite Altimetry	Altimeter A	±2.5	98	10
GPS Measurements	GNSS Network B	±1.2	92	Continuous
Gravimetric Observations	Satellite C	±0.5	99	30
Tide Gauges	Coastal Tide Stations	±3.0	85	Continuous
Fused Multi-Sensor Data	Kalman + WLS Fusion	±1.0	96	Dynamic

Gravimetric satellite data have provided the greatest precision (±0.5 cm) and almost global

perspective, which is opening up an opportunity to track longer-term mass redistribution such as

artificial groundwater, and fluctuations of ice sheets. GNSS networks exhibited a considerable continuity and regional precision (± 1.2 cm) that qualified them as proper for the monitoring of tectonic processes and the collapse of land. Tide gauges continued local measurements but with lower precision and were often sparsely sited along the coast. These results, which were enabled by the use of Kalman filtering and weighted least squares within the fused multi-sensor dataset, resulted in high accuracy (± 1.0 cm) and dynamic repeatability at various spatial scales. These combined approaches allowed both data sparsity (i.e., observational gaps) to be filled and for precision with respect to cross-referencing to be improved, providing a breakthrough over conventional single-instrument techniques.

3.2. Standardization Efficacy in Reducing Measurement Variance

Standardization is crucial for deriving comparability between geodetic datasets collected by heterogeneous systems and platforms. The study consists of ITRF2020, EGM2008, ISO 19115 metadata protocols, and Kalman-based data pipelines. These standards established uniform reference frames, standardized data structures, as well as uniform pre-processing methods. Equally, the use of NetCDF and GeoJSON helped to enhance interoperability across geographic information systems and modeling environments. The effectiveness of each standardization element in decreasing measurement deviation and promoting consistency across the globe is quantified in Table 2.

Table 2. Reduction in Measurement Variability through Standardization Protocols

Standard Applied	Pre-Standard Deviation (cm)	Post-Standard Deviation (cm)	Improvement (%)	Global Coverage (%)
ITRF2020	5.0	2.0	60	100
EGM2008	3.0	1.5	50	100
ISO 19115	Inconsistent	Consistent	—	100
Kalman Filter Pipeline	4.5	2.0	56	100
GeoJSON/NetCDF Interoperability	3.2	1.4	56	100

Standard deviation of positional data decreased from 5.0 cm to 2.0 cm (i.e., improved by 60%) after the application of the ITRF2020 geodetic reference frame. Likewise, using the EGM2008 gravity model reduced the vertical positioning error to half its original range. Consistency in terms of documentation and retrieval has been achieved through metadata harmonization based on ISO 19115, and improvement is qualitative. The Kalman filtering pipeline and file format interoperability tools like GeoJSON and NetCDF showed nearly the same improvements, respectively, cutting error margins by 56% each. Principally, these standards have provided consistency in spatial referencing, reduced inter-model obstructions, and allowed for the transfer of data between national/institutional platforms.

3.3. Participation and Accessibility in Geodetic Data Sharing Frameworks

Where datasets cross geopolitical boundaries, mechanisms for effective data sharing are critical for international environmental cooperation. This study explored cross-border data access through the use of centralized repositories regulated through multilateral legal agreements and open licensing frameworks. The performance had been assessed for three years, ranging from 2022 to 2024, for example, and measured using metrics like Data Availability Index (DAI), the number of agencies involved, and download statistics. In the context of this three-year time period, Table 3 quantitatively summarizes the evolution in accessibility, platform efficiency, and institutional engagement.

Table 3. Evolution of Cross-Border Data Availability and Legal Accessibility

Year	Data Availability Index (%)	Participating Agencies	Downloads per Year	Avg Access Time (s)	Geo-Legal Framework
2022	75	12	2,500	10	Bilateral Agreements
2023	90	18	4,000	5	Multilateral MOUs
2024	95	25	6,500	3	Global Legal Data Portals

The Data Availability Index increased from 75% to 95% between the years 2022 and 2024, representing an expansion of access to geodetic datasets around the globe. Over 25 agencies participated in the flag day, which was an increase from the previous 12 agencies, the average access time was optimized from 10 seconds to 3 seconds due to optimized web and authentication services. Download volumes then soared from 2,500 to 6,500 annual transactions. Such an approach indicates a departure from the restrictive nature of bilateral agreements towards global legal portals, which can enable multilevel governance, data democratization, and scientific transparency.

Geodetic data reliability is tightly linked with the robustness of analytical techniques for extracting signal trends, filtering noise, and quantifying uncertainties. This work facilitated advanced data processing techniques such as Kalman filtering, power spectral density (PSD) analysis, inverse modeling, covariance estimation, and graph-based denoising methods for incoming complex datasets. The tools to accomplish this were evaluated both for their potential in improving analytical clarity (like reducing measurement uncertainties). The performance of each method is centered on uncertainty reduction, spatial-temporal resolution, and application domain, which are illustrated in Table 4.

3.4. Analytical Performance of Advanced Geodetic Processing Techniques

Table 4. Analytical Capabilities and Accuracy Gains from Advanced Processing Techniques

Technique	Application	Uncertainty Reduction (%)	Resolution	Coverage (%)
Time Series + Kalman Filter	Sea-Level Trend	38	1 mm/year	100
Spectral Analysis (PSD)	Tectonic Signals	30	0.05 Hz	100
Inverse Modeling	Mass Balance Estimates	42	2 Gt/year	100
Covariance Analysis	Error Estimation	36	Covariance Matrix	100
Spatiotemporal Denoising (GNN)	Slip Event Extraction	40	Event Probability	100

Kalman filtering-augmented time series analysis lowered uncertainty in sea-level estimates by 38%, to millimeter-level resolution needed for coastal infrastructure plans. The signal identification was greatly improved with PSD analysis, isolating out tectonic frequencies down to 0.05 Hz through spectral decomposition. The largest uncertainty reduction (42%) was obtained

when estimating glacial and groundwater mass loss using inverse modeling. Covariance analysis also offered multi-variable estimation of the error, a key requirement for legal reporting. Lastly, graph neural network-based denoising made transient slip events more again and had a 40% increased event resolution probability. Together, these tools both intensified analytical

rigor and enhanced the evidentiary strength of geodetic observations.

3.5. Predictive Accuracy Gains through Environmental Model Integration

Including geodetic data in environmental models greatly increases the reliability of projections regarding sea-level rise, land deformation, and

the risk of flooding. In this study, dynamic coupling, inverse modeling, and other geodetic data were used to constrain five different modeling domains. Table 5 summarizes the improvements in accuracy and forecast error observed from geodetic integration.

Table 5. Forecast Accuracy and Error Reduction from Geodetic Model Coupling

Model	Model NO.	Pre-Integration Error (%)	Post-Integration Error (%)	Accuracy Gain, Rate (%)	Geodetic Input Type
Sea-Level Forecast	1	20	10	50	Sea-Level Trends
Land Deformation Risk	2	15	7	53	GNSS Displacement
Flood Vulnerability Map	3	25	12	52	Elevation Models
Ice Sheet Loss Model	4	30	14	53	Mass Change (ΔM)
Combined Earth System Model	5	28	13	54	Full Geodetic Data Stack

Figure 1 presents a comparative evaluation of the models through three complementary performance indicators: Pre-Integration Error

(%), Post-Integration Error (%), and Accuracy Gain (%).



Figure 1. Comparative evaluation of the models using three complementary performance indicators: Pre-Integration Error (%), Post-Integration Error (%), and Accuracy Gain (%).

The previous model for forecasting the sea level was 50% better accurate after incorporating sea-level trends from altimetry. This led to a 53% improvement in the accuracy of land deformation risk models thanks to GNSS displacement vectors. Elevation models enhanced flood

vulnerability assessments by 52%, and cryosphere models benefited from mass balance estimates with a 53% reduction in error. The Combined Earth System Model, employing integrated geodetic data throughout the entire planet, gained the highest accuracy improvement (54%). Such results highlight the vital

contribution that geodetic observations make to produce actionable, high-fidelity environmental forecasting. These results from Fig. 1 underscore that while pre-integration errors can be substantial, the integration process reduces error across all models and yields measurable gains in accuracy. Models 4 and 5 achieve the highest accuracy improvements, reflecting the potential for substantial performance gains when integration is effectively applied to geodetic-informed forecasting pipelines.

4. Discussion

The study confirms the need to have international legal instruments for the governance of the management, standardization, and cross-border sharing of geodetic data for a stable global environment. This article showcases how precision geospatial measurements can become more reliable, accessible, and actionable for environmental forecasting through the combined utilization of sophisticated analytical methodologies and unified bodies of law. The results reported not only corroborate hypotheses posited regarding the operational influence of international coordination but also build on and complement prior literature in the area.

A major innovation of this effort is the coupling of enhanced geodetic data-acquisition techniques with legally supported data-sharing protocols. This research is unique in that its methodology is multidimensional, connecting both domains, scientific and legal, while previous research has been limited in scope, examining only one or the other. For example, Lumban-Gaol et al. (2024) introduced the progressive consideration of harmonized sea-level rise and land subsidence data in flood risk assessments in Medan City; their approach nevertheless remains limited to the regional scale, and they did not include legal governance mechanisms to ensure interoperability of data across geographical and jurisdictional contexts. In contrast, the present study anchors such technical processes within a globally harmonized legal framework, which will be of a more widespread utility for transboundary environmental risk assessments and policy planning.

Moreover, the unprecedented integration of Kalman filtering, covariance matrix, and inverse modeling techniques in this research led to a remarkable reduction in uncertainties as well as signal enhancement, facilitating the analysis of both mass balance and land development. These results corroborate and expand on the research of Serpelloni et al. (2022) with a massive GPS dataset to analyze surface strain rates in the Euro-Mediterranean region. However, although their findings dealt mainly with raw geophysical interpretation, the present study demonstrates how such high-resolution geodetic results can flow into legally bounded environmental models, improving their predictive validity and thus making them relevant for policymakers and international institutions.

Also significant is the study's examination of legal and ethical aspects of geodetic data governance. The eleven-fold increase in data—from the equivalent of the often quoted 30,000 10-second videos per year to the figures of 27 billion 3-second videos per second mentioned between 2009 and 2013—is illustrated with infrastructure measures described thematically per country including data and exclusive forms of security for common goods, obstacles to data availability where 75% of intermediaries not using the data in developing nations falls to 5% with access latency dropping from 10s to 3s per transaction. These findings extend the observations made by Wadowska et al. (Wadowska, Pęska-Siwik, & Maciuk, 2022), who have noted systemic challenges in the collection, processing, and distribution of geospatial data due to fragmented institutional practices. This article directly responds to those challenges by highlighting how standardized legal protocols, including but not limited to ISO 19115 and Creative Commons licensing, can decrease these inefficiencies and democratize access to vital environmental data (McMullen et al., 2022).

However, some limitations of this study should be noted. While the analysis achieved complete geographic coverage in selected datasets, some areas of the Global South might not have the technological capacity to generate or process high-resolution geodetic data. This concern is consistent with findings by Ebinne et al. (2022),

who highlighted the limitations of digital elevation models in data-sparse regions and sought better data equity mechanisms. This study suggests a global harmonized system, but implementation is uneven and relies on local technical facilities and institutional capacity. This study addresses governance mechanisms for geospatial data interoperability, while recognizing ongoing debates about privacy and data sovereignty. Although open geospatial data raises privacy concerns, Solymosi et al. (2023) highlight ethical dilemmas at the intersection of open data, population identifiers, and state surveillance. We argue for data transparency and public access, but emphasize international legal safeguards to prevent misuse while preserving robust analyses.

Policy and institutional discussions have become more alive in recent years through talks on international cooperation. Goi et al (2024) highlighted the importance of legal harmonization and international cooperation for the sharing of cadaster and geospatial data. The present paper resonates with this thought, indicating that the utility of geodetic data for climate monitoring, resource management, and risk mitigation is much stronger when it is framed within a coherent international legal infrastructure. Moreover, the article resonates with the larger issues that Usman et al. (Usman, 2022) argued for the creation of international legal regimes to regulate emerging Geoengineering technologies and climate reaction strategies. Here, we witness just how essential law is in governing technological applications in the fields of environmental science: not just for the sake of scientific rigor, but for equity on the geopolitical scale. Simultaneously, the inherent complexity and variability among legal systems still present a challenge to the realization of comprehensive harmonization of geodetic data. Divisions in national legislation, different readings of data sovereignty, and institutional resistance to relinquishing control of key geospatial datasets are longstanding problems. The study proposes that socioenvironmental protection standards require regulatory, as well as cultural and institutional, changes within a collaborative

governance model (Wolfgang & Silva, 2020). This aligns with the current study's emphasis on multilateral agreements and long-term institutional commitments for shared data governance.

Several avenues for future work arise from this work. There is a need for further investigation of machine learning and artificial intelligence algorithms to further improve geodetic data analysis and in situ real-time environmental applications. Second, further work is needed to articulate legal solutions that can both keep pace with technology and respond to divergent regional capacities and legal traditions. Third, the role of decolonization perspectives when examining geospatial law and the access to and use of geospatial data should be further debated in the context of data sharing between the developed and developing world, as described by Phelan and Sirleaf (2023). Lastly, the X comparative case studies of parts of this law and geodetic framework being put into operation in different geopolitical contexts will yield still more insights into the challenges and the factors associated with success in integrating the legal and geodetic realms. The study confirms that the synergy between advanced geodetic science and international legal frameworks can contribute to the enhancement of the precision, reliability, and usability of earth monitoring systems on a global scale.

5. Conclusions

The study shows the powerful combination that results from the integration of international legal frameworks with sophisticated geodetic methodologies for the management of geodetic data and the monitoring of global environmental changes. By providing a thorough assessment of data acquisition methods, allocation techniques, cross-border exchange protocols, analytic tools, and model integration frameworks, the research has responded to the main goal of identifying a governance-based underpinning for the effective utilization of geodetic data in cross-national environmental applications.

1- The results demonstrate how formal data frameworks are crucial to converting disparate

national data activities into integrated global systems that can sustain high-resolution, accurate, and interoperable data sets. The study confirmed the hypothesis that legal frameworks are not ancillary but foundational to the operational success of global environmental observation through the embeddedness of legal accountability and institutional cooperation into the technical fabric of geodetic data collection and distribution. Law is more than a regulatory overseer; it has the potential to shape data access, establish ethical lines of code, and promote equity among states with different technological capacities.

2- One of the most important things is that the research has provided a multi-level answer to the question of how international law can assist environmental monitoring. But that also allows us to have standardized and precise measurement practices at the technical level. On an operational level, it enables the flow to cross borders in a timely and secure. Institutionally, it promotes the long-term sustainability of monitoring activities via open governance and collaborative policy-making. This multi-level integration is a major contribution to geoscience practice and to legal-institutional theory, emphasizing the importance of interdisciplinary frameworks for tackling planetary-scale environmental challenges.

3- The studies confirmed that substantial advancements have been achieved in terms of data standards harmonization and model accuracy improvement, while also indicating points that still need work. The ongoing evolution of the technological landscape, continued asymmetries in data access, and the challenges of ensuring data privacy and sovereignty necessitate the adaptation of legal frameworks and institutional arrangements. These challenges highlight the dynamic nature of geodetic science and international law, where static solutions cannot keep up, and adaptive governance is essential.

4- Based on the findings, future work should focus on designing scalable legal models to support emerging technologies, explicitly fundamental data architectures used in AI-based geospatial analysis and real-time remote sensing platforms. It is also important to consider the influence of regional legal traditions and

geopolitical factors in the operationalization of international standards, particularly in regions with low technical capacity or rising resource-based conflicts. Inclusive environmental stewardship will require frameworks that are not only standardized but also contextualize data governance in local realities.

5- The final takeaway of the article is that international law is crucial in the effective governance of geodetic data and their use in global environmental monitoring. Aligning legal, technical, and ethical considerations serves as a comprehensive framework for future efforts to protect the health of our planet through informed, collaborative, and legally established geospatial intelligence. Its evolution in light of new environmental, technological, and societal challenges will depend on continued interdisciplinary collaboration.

Author Contributions:

Wasan Maki Mohammed: Conceptualization, methodology, formal analysis and investigation, visualization, writing-original draft.

Ata Amini: Conceptualization, supervision, formal analysis, and investigation.

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Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Data availability statement:

The data supporting the findings of this study are available from the original sources mentioned in the methodology section.

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