GIFIS: A Generalized Immersive Flood Information System Specification

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Abstract

This study introduces Generalized Immersive Flood Information Specification (GIFIS), a vendor-agnostic, JSON Schema–based framework for encoding, validating, and exchanging hydrologic and environmental data for reproducible and interoperable virtual and augmented reality applications. By defining standardized semantics for entities such as sensor datasets, hydrological model outputs, warnings and alerts, and infrastructure assets, along with portable document types for spatial anchoring, scene composition, and evidence packaging, GIFIS transforms interoperability into a verifiable property of the data itself. A built-in validator enforces conformance through rule codes and machine-readable diagnostics, ensuring that information published once can be deterministically interpreted across analytical, operational, and immersive environments. Through its schema-centric and engine-neutral design, GIFIS enables any client to load and interpret hydrologic information without reliance on proprietary rendering pipelines or manual data harmonization for immersive platforms and applications. By coupling semantic rigor with open governance and extensibility, GIFIS establishes a sustainable foundation for transparent, FAIR-compliant flood information systems that bridge scientific research, operational decision support, and public communication.

Keywords: Data Interoperability; Decision Support; Digital Twins; Flood Information Systems; Immersive Analytics; Virtual Reality.

Highlights

- Defines a JSON Schema framework for interoperable flood information.
- Makes semantics, units, and coordinates verifiable across systems.
- Validator enforces rule-based, machine-readable data compliance.
- Portable documents support 2D, 3D, and XR visualization platforms.
- Enables FAIR, reproducible, and cross-platform hydrologic data exchange.

Software Availability

Name	Generalized Immersive Flood Information Specification (GIFIS)
Developers	Uditha Herath Mudiyanselage, Yusuf Sermet
Contact information	https://hydrointelligence.github.io/
Software Required	Any IDE
Program language	JSON, Python
Availability & Cost	The GIFIS specification and reference materials are openly available at no cost and can be accessed at: https://github.com/uihilab/GIFIS

1. Introduction

Global hydrological forecasts are now produced operationally on a daily basis. However, the lack of global river discharge observations precludes routine flood forecast evaluation, an essential step in developing more skillful and reliable forecasts (Lavers et al., 2019). Greater and timelier exchange of river discharge data would enhance flood awareness and yield socio-economic benefits, particularly in vulnerable regions (Lavers et al., 2019). Over the past five decades, the representation of spatial information in computerized systems has evolved toward sophisticated visualization and analytical frameworks, yet challenges persist in capturing the inherent complexity of spatial and temporal relationships (Claramunt, 2020). Semantic geospatial ontologies have emerged as promising models for enabling richer, more interoperable representations of geographic information, though their practical implementation remains uneven (Baydaroglu et al., 2023; Sajja et al., 2025a). Meanwhile, despite significant progress in disaster resilience, the socio-economic impacts of extreme weather events continue to escalate (Cikmaz et al., 2025). The lack of interoperability across data, models, communication systems, and governance remains a major barrier to effective risk management and climate adaptation, underscoring the need for transdisciplinary knowledge co-production and federated data infrastructures (Schröter et al., 2024).

While global flood forecasting systems increasingly operate at scale, a critical distinction persists between forecast production and forecast evaluation, which are often conflated in operational settings (Petropoulos et al., 2020; Hewamalage et al., 2022). Forecast production focuses on generating timely predictions through automated pipelines that integrate heterogeneous data, model configurations, and computational constraints, addressing questions of feasibility, scalability, and horizon selection (Mystakidis et al., 2023; Parejo et al., 2025; Athanasopoulos & Kourentzes, 2022). In contrast, forecast evaluation assesses the quality, reliability, and decision relevance of these predictions using statistical accuracy measures, probabilistic calibration diagnostics, and task-specific performance criteria tailored to application contexts such as flood risk management and infrastructure operation (Tabataba et al., 2017; Cerqueira et al., 2025; Cassagnole et al., 2021). Robust evaluation typically requires multi-horizon and rolling-origin validation schemes, as well as comparative assessment across competing methods using complementary metrics rather than a single score, to avoid misleading conclusions under operational variability (Mehdiyev et al., 2016; González & Parada, 2025; Kizilkaya et al., 2025). Although evaluation outcomes are essential for improving model design and informing decision-making, they are frequently constrained by fragmented data provenance, inconsistent metric reporting, and limited interoperability across modeling and governance frameworks, underscoring the need for standardized, machine-verifiable representations that embed evaluation, validation, and decision context directly within hydrologic information systems.

Hydrologic and environmental models increasingly inform high-stakes planning under climate and societal change, yet they are characterized by deep and multi-layered uncertainties arising from data, parameters, model structure, and calibration processes (McMillan et al., 2018; Moges et al., 2020; Herrera et al., 2021). Research has shown that such uncertainties propagate and often amplify through modeling pipelines, complicating interpretation and limiting confidence in forecasts despite technical advances (Moges et al., 2020; Wu et al., 2025). While probabilistic and spatial visualizations can make uncertainty more tangible for analysts and decision-makers, effective use depends on integrating uncertainty into decision frameworks rather than presenting it as ancillary information (Zarzar et al., 2018; Zaniolo et al., 2025). Beyond statistical performance, trust in environmental modeling systems hinges on transparent uncertainty communication, alignment with decision contexts, and governance processes that support credibility, legitimacy, and sustained user engagement (McMillan et al., 2018; Shafiee-Jood et al., 2021; Naugle et al., 2025).

Recent advances illustrate the potential of connected digital ecosystems to bridge these gaps (Hofmeister et al., 2024; Sajja et al., 2025b; Kadiyala et al., 2025). Dynamic knowledge graphs and digital twins have been proposed to integrate cross-domain data, from hydrology and meteorology to infrastructure and real estate, offering holistic situational awareness during floods (Hofmeister et al., 2024; Kaynak et al., 2025). Digital twin frameworks in urban flood risk management demonstrate how real-time data integration and predictive modeling can improve responsiveness by up to 40%, though scalability and interoperability remain persistent challenges (Hlal et al., 2025). These developments align with broader efforts to modernize hydrologic information systems, including web-based cyberinfrastructure platforms such as RIMORPHIS, which enhance data accessibility, analytics, and interoperability for river morphology and hydrological applications (Sermet et al., 2025).

Provenance-aware workflows further emphasize the need for traceable, reproducible analytics: coupling OGC Web Processing Services (WPS) with W3C PROV standards enables detailed provenance tracking for geoprocessing workflows, reinforcing trust and reusability across distributed systems (Zhang et al., 2020). These innovations align with ongoing efforts in hydrology to formalize reproducibility through model-agnostic configuration workflows, such as the Community Workflows to Advance Reproducibility in Hydrologic Modeling (CWARHM), which decouple model-specific and preprocessing steps to improve transparency and reuse (Knoben et al., 2022). Similarly, metadata schema initiatives and repositories like HydroShare provide extensible frameworks for storing and publishing hydrologic datasets and models as social, annotated research objects (Maghami et al., 2024; Horsburgh et al., 2016; Tarboton et al., 2024). Complementary approaches such as RO-Crate extend this philosophy, using JSON-LD packaging to make research outputs FAIR and machine-actionable across disciplines (Soiland-Reyes et al., 2022).

Beyond hydrology, standardization efforts in semantic urban modeling offer valuable analogs (Bachert et al., 2024). CityGML 3.0 and its Energy ADE extension enable interoperable, lossless mapping of energy and urban building models, though they reveal the persistent difficulty of aligning evolving data standards (Bachert et al., 2024). The Urban Digital Twin paradigm also exposes structural challenges in integrating multi-source data throughout a city's lifecycle, demanding conceptual frameworks for consistent creation, usage, and modification of urban datasets (Jeddoub et al., 2025). In parallel, the water sector's adoption of digital twins underscores their promise for real-time monitoring and predictive control of infrastructure systems, yet highlights governance and interoperability as enduring bottlenecks (Ghorbani Bam et al., 2025).

The broader challenge is semantic alignment across domains, sensors, observations, and actuation, addressed by ontologies such as SOSA/SSN, which provide lightweight but rigorous vocabularies for describing observation and measurement data on the web (Janowicz et al., 2019). Provenance-oriented approaches further demonstrate that documenting inputs, processes, and outputs at fine granularity enhances scientific credibility, transparency, and traceability (Spiekermann et al., 2019). Hydrologic monitoring frameworks like the WMO Hydrological Observing System integrate these principles, emphasizing linked data exchange and quality-controlled observation workflows to strengthen climate resilience and hazard forecasting (Pecora and Lins, 2020; Jones & Horsburgh, 2025).

Fragmentation in flood information ecosystems, the proliferation of heterogeneous data formats, semantics, coordinate systems, and provenance, poses comparable challenges to those observed in ecological and hydrological fragmentation (Mitchell et al., 2015; Demir & Szczepanek, 2017). When connectivity between system components such as river channels and floodplains is disrupted, ecosystem productivity and service provision decline (Thoms et al., 2005). Analogously, in information systems, fragmented flood data hinder integration, modeling, and prediction efforts, ultimately constraining effective risk mitigation (Yesilkoy et al., 2024). Research on hydrological and landscape fragmentation underscores the need for spatially explicit, standardized approaches to data management (Thomas et al., 2020; Fuller et al., 2015). The absence of unified data standards mirrors ecological fragmentation, producing inefficiencies, data silos, and loss of systemic coherence. Addressing this requires harmonization of data formats, semantics, coordinate systems, and transparent provenance tracking to ensure interoperability and integrated flood management.

Barriers to interoperability among agencies such as USGS, NOAA, NWS, NCEI, and state RWIS programs exacerbate this fragmentation (Abdeen et al., 2021). These barriers include technical incompatibility, organizational silos, and cultural differences that undermine trust and collaboration. The lack of standardized platforms and shared protocols hinders development of a unified operational picture during flood events (Abdeen et al., 2021; Haltas et al., 2021). Semantic and structural inconsistencies in data formats and terminologies further obstruct integration across diverse GIS and hydrologic systems (Oukes et al., 2024; Demir et al., 2015). Beyond technology, social and organizational dynamics, such as misaligned priorities, institutional inertia, and weak interagency communication, limit effective coordination and timely information exchange (Davidson et al., 2025). Overcoming these challenges requires both technical interventions, through open data standards and interoperable frameworks, and socio-organizational initiatives that build shared identity, leadership, and sustained collaboration among agencies (Davidson et al., 2025; Oukes et al., 2024).

As environmental sensing, cyberinfrastructure, and visualization technologies continue to evolve, bridging these divides becomes imperative. The convergence of interoperable data standards, digital twin paradigms, provenance frameworks, and immersive visualization technologies presents an opportunity to transform how flood information is represented, validated, and shared. Immersive platforms for environmental science, training, and decision support, including VR-based environmental monitoring tools (Rahmani et al., 2025), immersive hydrologic visualization systems (Mudiyanselage et al., 2025; Sermet & Demir, 2019), and XR-based environmental education and disaster training applications (Sermet & Demir, 2020), further demonstrate the transformative potential of spatially contextualized virtual environments in hazard preparedness and environmental data communication.

In this context, the Generalized Immersive Flood Information System (GIFIS) is introduced as a vendor-neutral specification and reference framework designed to unify hydrologic data semantics, ensure machine-verifiable interoperability, and support multi-modal visualization, from web-based GIS to immersive extended reality (XR). By coupling standardized JSON-Schema contracts with an open validation framework, GIFIS aims to make interoperability, reproducibility, and trust inherent properties of the data itself rather than optional outcomes of software integration.

2. Methodology

2.1. Scope and Purpose

We envision a world in which flood information moves seamlessly across platforms, services and devices because it is expressed in a common, vendor-agnostic language. The GIFIS specification defines that language. Its scope centers on the data itself, encompassing entities such as sensors, forecasts, alerts, and assets and their relationships in space and time, formalized through portable documents for spatial anchoring, scene composition, scenario description, annotations, and audit evidence.

GIFIS explicitly improves the semantics that routinely fracture interoperability, including units, coordinate and vertical reference systems, temporal conventions, provenance, identifiers, and cross-references, encoding them as machine-readable JSON-Schema contracts with clear conformance profiles. The specification deliberately refrains from prescribing storage technologies, rendering engines, network protocols, or deployment architectures. Instead, it ensures that any compliant producer can publish once and any compliant consumer, whether 2D, 3D, or XR, can interpret the same dataset deterministically.

The overarching purpose of GIFIS is to make reliability, reproducibility, and composability intrinsic properties of the data itself. By pairing schemas with a public validator and machine-readable diagnostics, GIFIS shifts quality assurance to the boundary of exchange: data artifacts either conform or fail with actionable feedback. This approach enables agencies to adopt conformance as a data-sharing requirement, allows researchers to reproduce analyses from evidence bundles, supports developers in integrating without bespoke adapters, and empowers educators to assemble portable, immersive learning scenes. In essence, GIFIS aims to reduce integration costs, enhance trust, and accelerate innovation by standardizing both the meaning and verifiable correctness of flood information, while leaving implementation flexibility to the communities that adopt it.

2.2. Design Principles and Objectives

The design of GIFIS emerged through feature elicitation from three main sources: (i) operational hydrologic platforms, (ii) established community standards, and (iii) practitioner workflows. Data models and API payloads from representative flood-information systems, such as the Iowa Flood Information System (IFIS), USGS Water Services, NOAA/NWS forecast and alert endpoints, NCEI precipitation archives, and state RWIS programs, were analyzed to catalogue the entities, identifiers, units, coordinate references, and provenance attributes used in practice.

In parallel, mature specifications and ontologies were reviewed to avoid reinventing existing semantics. This included JSON Schema (draft 2020-12) for structural validation, OpenAPI 3.x for transport descriptions, OGC and EPSG resources for coordinate and vertical datums, OASIS CAP for alert messaging, GeoJSON for geometric representation, and hydrologic data vocabularies for time-series practices. Interviews and collaborative workshops with domain practitioners informed how real-world data types, events, and interoperability requirements should be categorized to reflect operational realities rather than idealized models.

From this foundation, GIFIS established explicit design objectives: a) Interoperability was treated primarily as a semantic rather than a transport problem; thus, the specification prioritizes unambiguous meaning for units, coordinates, timestamps, identities, and cross-references; b) Extensibility is achieved through a disciplined profile system, Core, Extended, and Experimental, allowing innovation to proceed without destabilizing stable contracts; c) Verifiability is ensured by pairing each schema with validator rules and machine-readable diagnostics, making conformance testable and reproducible across platforms; d) Portability is preserved through strict engine and vendor neutrality: while GIFIS defines portable data structures for entities and scenes, it imposes no requirements on storage or rendering technologies; e) Backward compatibility is governed by semantic versioning, with clearly documented change types and migration guidance, enabling producers and consumers to evolve independently without breaking integrations.

The JSON-Schema design follows consistent, implementation-agnostic conventions to operationalize these principles. All payloads declare a *schema* and globally unique *id,* carry a *specVersion* aligned with semantic versioning, and include stable identifiers with validated formats. Temporal fields conform to ISO-8601 UTC with explicit *observedAt* timestamps and optional *asOf* attributes for data freshness. Spatial fields employ EPSG codes for both horizontal and vertical references, and uncertainty can be represented through optional credible intervals and quality flags. Enumerations govern categorical values and units, nullable fields are explicitly typed, and document references rely on stable IDs with integrity checks rather than positional assumptions.

Derived document types (i.e., Scene, Scenario, Annotation, and Evidence) inherit the same conventions: they reference validated entities, embed sufficient provenance for audit, and remain composable across clients without semantic loss. Where mature standards already exist (e.g., OASIS CAP for alerts or RFC 7946 GeoJSON for geometries), GIFIS aligns with them rather than redefining, providing explicit mapping guidance from common source payloads to GIFIS-compliant structures.

Governance and community participation are foundational design features. The specification is maintained openly on GitHub, with tagged releases corresponding to schema and validator versions. All changes pass through public Requests for Comments (RFCs) that document their motivation, impact, and migration strategy. Proposal branches host draft schemas, examples, and test vectors, which are automatically validated using the GIFIS validator. Issues serve to capture real-world interoperability pain points, while Discussions facilitate design deliberations and implementation feedback. Each release publishes machine-readable artifacts, including schema files, rule catalogs, test vectors, and “golden” example documents, allowing producers to self-certify and consumers to verify compatibility. This community-driven structure ensures that GIFIS remains a living, evolving standard rather than a static specification.

2.3. Data Model and Specification Architecture

The GIFIS data model defines the structural foundation for representing hydrologic and flood-related information in a consistent, machine-readable manner. The specification is organized as a hierarchical suite of JSON Schemas, with each layer introducing increasing specificity while maintaining backward compatibility through semantic versioning. The model is composed of three primary tiers: the Core Schema, a set of Domain Profiles, and a collection of Portable Document Types.

<u>*Core Schema*</u>**:** The Core Schema provides the essential structural elements common to all GIFIS-compliant documents. It defines universal properties such as unique identifiers (id), schema version (specVersion), timestamps (observedAt, updatedAt), spatial geometries (geometry, crs), and metadata (provider, provenance, license, contact). These base fields ensure that all entities, regardless of domain, can be validated and interpreted deterministically across systems.

Domain Profiles: On top of the Core Schema, Domain Profiles constrain and extend the model for specific applications such as *Flood Events*, *Water-Quality Hazards*, *Infrastructure Assets*, or *Sensor Observations*. Each profile inherits the structure of the core schema and introduces domain-specific fields, enumerations, and validation rules. For example, the Flood Event Profile defines attributes such as floodExtentKm2, waterLevelMeters, and severity, while the Water-Quality Profile includes hazardCategory, status, and pollutants. Profiles follow a modular structure so that new domains can be introduced without affecting existing ones, ensuring scalability and interoperability across evolving use cases.

Portable Document Types: Complementing the core and profile schemas, Portable Document Types define how GIFIS data entities are organized, contextualized, and exchanged across systems. These document types establish logical and spatial scaffolding that allows diverse datasets to coexist and interact coherently within immersive or analytical environments. Specifically, (a) the Spatial Anchor defines the geographic reference and coordinate context for all entities, ensuring spatial consistency across producers and consumers; (b) the Scene specifies the compositional layout of multiple entities within a 3D or immersive environment, establishing how layers, geometries, and assets are visually and logically arranged; (c) the Scenario encapsulates temporal or conditional relationships among scenes, enabling representations of evolving states such as "pre-flood," "peak," and "recovery"; (d) the Annotation document links human or algorithmic insights, such as observations, warnings, or interpretive tags, to specific spatial or temporal entities; and (e) the Evidence Bundle aggregates source data, schemas, and provenance metadata to support reproducibility and auditability across workflows. Together, these components create a modular architecture that allows data producers, analytics engines, and visualization clients to interoperate seamlessly. For example, a flood-extent polygon can be published as a GeoJSON-compliant entity with embedded GIFIS metadata, validated independently, and later referenced within a Scene document that defines how it should appear in an immersive viewer such as Unreal Engine or a browser-based 3D application.

Cross-Schema Relationships and Inheritance: Each schema component includes internal references ($ref) that maintain cross-document integrity and reusability. Shared definitions for temporal ranges, bounding boxes, and metadata are centralized in $defs modules to minimize redundancy. All cross-references are resolved through globally unique, stable identifiers, and integrity is enforced through the validator at both the schema and instance levels. This approach guarantees consistency between datasets while supporting partial updates, federated publishing, and distributed version control.

Alignment with External Standards: GIFIS intentionally aligns with existing open standards wherever feasible. Geometric primitives conform to GeoJSON (RFC 7946); coordinate references use EPSG codes; alert messages align with OASIS CAP; and sensor data semantics are compatible with OGC SOSA/SSN. By harmonizing with established frameworks rather than replacing them, GIFIS ensures compatibility with major GIS, hydrologic, and web-data ecosystems, facilitating integration into workflows that span USGS, NOAA/NWS, NCEI, and state-level systems.

This architecture enables GIFIS to function as both a data-exchange specification and a semantic contract, defining not only the format of hydrologic information but also its meaning, provenance, and interoperability guarantees. Each component, from entities to scenes, is self-describing, auditable, and versioned, ensuring that flood information remains portable and verifiable across analytical, operational, and immersive platforms.

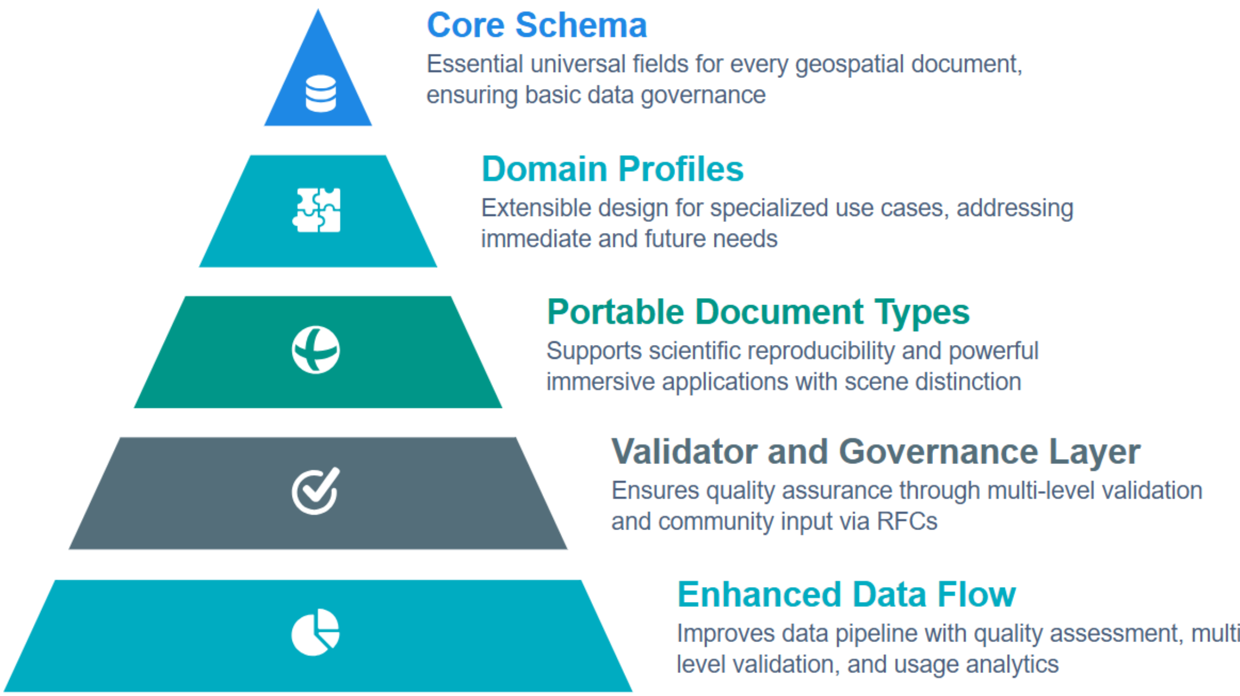

Figure 1. Hierarchical architecture of the Generalized Immersive Flood Information System

The overall hierarchy of these components is illustrated in Figure 1, which depicts how the specification layers, Core Schema, Domain Profiles, Portable Document Types, Validator and Governance, and Enhanced Data Flow, build upon one another to enable standardized, reproducible, and cross-platform flood information exchange.

2.4. Validator Framework

The GIFIS Validator is an enforcement mechanism that operationalizes conformance and reproducibility across implementations. It ensures the structural and semantic integrity of both data instances and schema definitions aligned with the GIFIS standard. Its primary function is to verify that externally created JSON schemas and instances comply with JSON Schema Draft 2020-12 and adhere to GIFIS-specific rules concerning identifier syntax, versioning consistency, temporal coherence, and metadata completeness.

By providing an automated and transparent validation pipeline, the tool enables data publishers, developers, and researchers to detect deviations early in the workflow, transforming interoperability and quality assurance into verifiable, testable properties. This automation promotes reproducibility, reduces integration errors, and builds confidence in data exchange between independent systems and visualization environments. From a software-engineering perspective, the validator is implemented as a modular Python application, leveraging the Json schema library for baseline schema and instance validation, augmented with a custom rule engine for domain-specific compliance checks. The architecture consists of three main modules:

- **Schema Validator** – Ensures correctness of schema definitions against the official meta-schema.
- **Data Validator** – Evaluates JSON instances against GIFIS schemas to confirm compliance.
- **Rule Module** – Enforces GIFIS-specific logical and syntactic constraints, such as required metadata fields, coordinate reference integrity, and version syntax.

This layered design allows the validator to operate both as a Command-Line Interface (CLI) for interactive use and as a programmable module integrated within continuous integration/continuous deployment (CI/CD) workflows. Open-source architecture invites community contributions: users can define new rule sets, test them against conformance suites, and submit pull requests through a transparent, reproducible process. In doing so, the validator not only enforces the current specification but also embodies its evolution, serving as a shared foundation for trust, accountability, and long-term sustainability in flood information interoperability.

3. Results

The GIFIS Core Schema defines the fundamental contract shared across all compliant documents. It specifies how every entity, regardless of domain or visualization platform, must declare identifiers, temporal and spatial attributes, provenance metadata, and versioning information. These fields provide the minimal but sufficient structure for any hydrologic or environmental feature to be validated, exchanged, and visualized deterministically across systems. Each GIFIS-compliant object represents a GeoJSON-style Feature enriched with schema versioning, provenance, and cross-reference metadata. The key parameters of the top-level object are summarized in Table 1, which outlines the expected JSON paths, data types, constraints, and validation rules that guarantee cross-system compatibility and auditability.

Table 1. Top-level object (root) parameters

JSON Path	Type / Enum	Required	Constraints	Description
type	"Feature"	No	Constant value	GeoJSON-style feature discriminator.
id	string	Yes	Globally unique (recommend UUID/ULID with type prefix, e.g., loc-, sns-, fmap-)	Stable identifier for the feature across systems.
specVersion	string	Yes	Regex ^gifis-[a-z]+@\d+\.\d+$ (e.g., gifis-core@1.0)	Declares the GIFIS profile namespace and version the object conforms to.

schemaRef	string (uri)	No	Valid URI	Canonical URL of the JSON Schema used to validate this object.
updatedAt	string (date-time)	Yes	ISO-8601 UTC	Last modification timestamp.
name	string	No	None	Human-readable name.
description	string	No	None	Human-readable description.
time	object	No	One of: TimeInstant or TimeRange (see Table 2)	Temporal tagging of the feature.
geometry	object	No	One of GeoJSON geometries (see Table 3)	Spatial footprint per RFC 7946 (optional altitude).
crs	string	No	Recommended EPSG:4326	Declared spatial reference system.
bbox	array	No	2D or 3D (see Table 2)	Spatial bounding box for quick queries/tiling.
metadata	object	Yes	See Table 2 (Metadata)	Provider, license, provenance, etc.
links	Array <object>	No	Items are Link (see Table 2)	Related resources (APIs, datasets, docs).
keywords	Array <string>	No	uniqueItems: true	Free-form tags for discovery.
properties	object	No	Domain-specific	Application/domain attributes attached to the feature.

In addition to the root parameters summarized above, several reusable sub-objects are defined under the $defs section of the schema. These structures standardize temporal, spatial, and metadata representations, ensuring consistent tagging, provenance capture, and linkage across all GIFIS-compliant entities. Their definitions are summarized in Table 2.

Table 2. Supporting definitions: temporal, spatial, metadata, and link objects referenced by the Core Schema.

Definition	**Shape**	**Required Fields**	**Constraints / Notes**	**Purpose**
TimeInstant	object	timestamp	timestamp: string (date-time)	A single instant in time.
TimeRange	object	start, end	start/end: string (date-time)	Inclusive start/end temporal window.
BBox (2D)	Array <number>	–	Length 4: [minLon, minLat, maxLon, maxLat]	2D extent.
BBox (3D)	Array <number>	–	Length 6: [minLon, minLat, minAlt,	3D extent incl. altitude.

			maxLon, maxLat, maxAlt]	
Metadata	object	license	additionalProperties : false	Minimal, interoperable metadata for reuse/governance.
Metadata.provider	string	–	–	Data publisher/owner.
Metadata.contact	object	–	Fields: name, email (format), url (uri)	Point of contact for the feature.
Metadata.provenance	string	–	–	Lineage or processing history.
Metadata.license	string	Yes	–	Usage license (e.g., CC-BY-4.0, ODbL).
Metadata.termsOfUse	string	–	–	Additional terms beyond license.
Metadata.createdAt	string (date-time)	–	–	Creation timestamp.
Metadata.title	string	–	–	Short title for display.
Metadata.description	string	–	–	Richer metadata description.
Link	object	rel, href	href: string (uri); optional type, title	HATEOAS-style relations to external/internal resources.

Spatial representations in GIFIS follow the GeoJSON standard (RFC 7946) with optional altitude dimensions for 3D compatibility. Each geometry type includes validation rules to ensure interoperability with GIS, 3D, and XR environments. The supported geometry objects and their constraints are summarized in Table 3.

Table 3. Geometry object definitions compliant with GeoJSON (RFC 7946) and GIFIS extensions.

Geometry	**Required Fields**	**Coordinate Schema**	**Notes**
Point	type="Point", coordinates	Position	Single position.
MultiPoint	type="MultiPoint", coordinates	array<Position>	Multiple points.
LineString	type="LineString", coordinates	LineStringCoords: array<Position> (minItems 2)	Path with ≥2 positions.
MultiLineString	type="MultiLineString", coordinates	Array <LineStringCoords>	Multiple paths.
Polygon	type="Polygon", coordinates	PolygonCoords: array<LinearRing>	First ring = shell; subsequent rings = holes.
MultiPolygon	type="MultiPolygon", coordinates	array<PolygonCoords>	Multiple polygons.

Geometry Collection	type="GeometryCollection", geometries	array<Geometry>	Collection of any above geometries (no nesting of collections).
Position	–	[lon, lat, (alt?)]	Altitude is optional (meters, recommended).
LinearRing	–	array<Position> (minItems 4)	Closed ring (first==last expected by GeoJSON practice).
PolygonCoords	–	array<LinearRing> (minItems 1)	One shell + optional holes.

Building upon the Core Schema and supporting definitions, GIFIS defines a series of domain-specific profiles that extend the foundational structure for particular hydrologic applications. The Flood Event Profile is the principal domain implementation in this release. It inherits all structural components from the Core Schema while constraining selected fields and introducing flood-specific semantics within the properties object. The profile ensures that observations, simulations, or forecasts of flood phenomena share a uniform representation across web-based GIS, analytical pipelines, and immersive visualization clients. The root-level parameters of the Flood Event Profile are summarized in Table 4, showing inherited fields, required elements, and validation constraints that govern data exchange and rendering consistency across systems.

Table 4. Top-level (root) parameters for the Flood Event Profile.

JSON Path	**Type / Enum**	**Required**	**Constraints**	**Description**
allOf[0]	$ref	–	https://spec.gifis.org/gifis-core/1.0/core.schema.json	Inherits all Core fields (id, specVersion, updatedAt, time, geometry, metadata, etc.).
type	"Feature"	–	From Core	GeoJSON discriminator (via Core).
id	string	Yes	From Core	Stable, globally unique ID.
specVersion	string	Yes	From Core (e.g., gifis-event@1.0)	Profile/version contract.
updatedAt	string (date-time)	Yes	From Core	Last modification time (UTC).
metadata	object	Yes	From Core (license required)	Provider, license, provenance, contact, etc.
time	TimeInstant | TimeRange	–	From Core	Event time instant or start–end window.
geometry	GeoJSON object	–	From Core	Spatial footprint of the event (RFC 7946).

bbox	array <number>	–	From Core	2D/3D bounding box.
crs	string	–	From Core (recommend EPSG:4326)	Declared spatial reference.
links	array <object>	–	From Core (Link)	Related APIs, runs, docs.
keywords	array <string>	–	From Core (uniqueItems: true)	Discovery tags.
properties	object	Yes*	This profile constrains domain fields below	Flood-specific attributes (Table 2).

Within the Flood Event Profile, the properties object defines the domain-specific attributes that characterize flood phenomena in a standardized, machine-interpretable form. These attributes capture both the physical metrics of the event, such as inundation extent and water-level elevation and the contextual descriptors required for operational or analytical use. By constraining the attribute set to a closed schema (additionalProperties: false), GIFIS ensures consistency across data producers and consumers, facilitating deterministic parsing, visualization, and comparison of flood scenarios. The full set of field definitions is summarized in Table 5.

Table 5. Domain-specific properties for the Flood Event Profile.

JSON Path	Type / Enum	Required	Constraints	Description
properties	object	Yes	additionalProperties: false	Container for flood-specific fields (closed set).
properties.eventType	string	–	Enum: flood, riverFlood, flashFlood, coastalFlood	Primary hazard sub-type classification.
properties.floodExtentKm2	number	–	minimum: 0	Estimated inundation area (km^2).
properties.waterLevelMeters	number	Yes	–	Observed/modeled stage relative to datum (e.g., NAVD88).
properties.riverGaugeId	string	–	Provider-specific ID	Linked gauge/station identifier (e.g., USGS site).
properties.severity	string	Yes	Enum: minor, moderate, major, extreme	Event severity class.
properties.source	string	–	–	Data/model source (e.g., “USGS gauge”, “HEC-RAS run ID”).

In addition to flood-related applications, GIFIS supports cross-domain extensibility through specialized profiles that address other hydrologic phenomena. The Water-Quality Event Profile exemplifies this capability by adapting the Core Schema to represent episodic or continuous water-quality observations, hazards, and alerts. Like the Flood Event Profile, it inherits the universal data structure while introducing domain-specific semantics within the properties object, such as pollutant type, concentration, and status indicators. The root-level parameters governing Water-Quality Event objects are summarized in Table 6, which outlines their inheritance from the Core Schema, required fields, and validation constraints that ensure deterministic interpretation across monitoring platforms, analytical pipelines, and immersive visualization systems.

Table 6. Top-level (root) parameters for the Water-Quality Event Profile.

JSON Path	Type / Enum	Required	Constraints	Description
allOf[0]	$ref	–	https://spec.gifis.org/gifis-core/1.0/core.schema.json	Inherits all Core fields (id, specVersion, updatedAt, time, geometry, metadata, etc.).
type	"Feature"	–	From Core	GeoJSON discriminator (via Core).
id	string	Yes	From Core	Stable, globally unique ID.
specVersion	string	Yes	From Core (e.g., gifis-event@1.0)	Profile/version contract.
updatedAt	string (date-time)	Yes	From Core	Last modification time (UTC).
metadata	object	Yes	From Core (license required)	Provider, license, provenance, contact, etc.
time	TimeInstant | TimeRange	–	From Core	Event instant or start–end window.
geometry	GeoJSON object	–	From Core	Spatial footprint of the event (RFC 7946).
bbox	array<number>	–	From Core	2D/3D bounding box.
crs	string	–	From Core (recommend EPSG:4326)	Declared spatial reference.
links	array<object>	–	From Core (Link)	Related APIs, datasets, docs.
keywords	array<string>	–	From Core (uniqueItems: true)	Discovery tags.
properties	object	Yes*	This profile constrains domain fields below	Water-quality–specific attributes (Table 2).

The properties object within the Water-Quality Event Profile encapsulates the specialized fields required to represent environmental hazard conditions in a standardized and interoperable form. These attributes describe both the nature of the hazard, such as algal blooms, chemical or pathogen contamination, and the operational status of advisories or warnings. By enforcing a closed set of permissible fields (additionalProperties: false) and enumerated values for key attributes, GIFIS ensures consistency across monitoring networks and decision-support platforms. The complete set of water-quality-specific attributes is summarized in Table 7.

Table 7. Domain-specific properties for the Water-Quality Hazard Event.

JSON Path	Type / Enum	Required	Constraints	Description
properties	object	Yes	additionalProperties: false; required: hazardType, hazardCategory, status	Container for water-quality fields (closed set).
properties.hazardType	string	Yes	const: "water_quality"	Declares this feature as a water-quality hazard event.
properties.hazardCategory	string	Yes	Enum: algal_bloom, chemical_contamination, pathogen_contamination, sediment_turbidity, low_dissolved_oxygen, other	Category of the hazard.
properties.status	string	Yes	Enum: advisory, warning, emergency, resolved	Current advisory state.
properties.severity	string	–	Enum: low, moderate, high, extreme	Hazard severity (optional but recommended).
properties. affectedWaterBody	string	–	–	Name/ID of affected river/lake/reservoir.
properties. affectedArea	$ref	–	https://spec.gifis.org/gifis-core/1.0/location/location.schema.json	Area of impact linked to a GIFIS Location.
properties. pollutants	array <string>	–	–	Detected/suspected contaminants (e.g., nitrates, heavy metals, cyanotoxins).
properties. healthAdvisories	array <string>	–	–	Issued guidance (e.g., boil-water notice, no-swim advisory).
properties.source	string	–	–	Reporting agency/system (e.g., EPA, local water authority).

The preceding tables establish the complete structural and semantic framework of the GIFIS. Together, they formalize how hydrologic and environmental data from core entities to domain-specific profiles can be encoded, validated, and exchanged in a consistent, machine-interpretable form. These schemas collectively provide the foundation for interoperable analytics and visualization across 2D, 3D, and XR environments, ensuring that flood and water-quality information can be represented with semantic precision and verifiable provenance.

4. Discussions

4.1. Scientific and Technical Impacts

The principal contribution of GIFIS lies in transforming interoperability from an aspiration into a testable and enforceable property. Through its combination of vendor-agnostic schemas and an enforcement-grade validator, GIFIS establishes a reproducible foundation for cross-platform data exchange in hydrology and environmental sciences. By standardizing units, coordinate and vertical references, temporal semantics, identifiers, and cross-references, the specification enables data producers to publish once and ensures that any compliant consumer, whether 2D, 3D, or XR, can interpret the data deterministically.

The portable document suite comprising Entities, Spatial Anchors, Scenes, Scenarios, Annotations, and Evidence Bundles supports reproducible analysis, traceability, and audit without prescribing a specific runtime. The integrated validator operationalizes these guarantees by providing stable rule codes, profile gating (Core, Extended, Experimental), and machine-readable diagnostics that integrate directly into continuous integration workflows. Together, these components lower integration costs, prevent silent data failures, and improve transparency and provenance, producing a resilient foundation for next-generation hydrologic information systems and immersive visualization frameworks.

4.2. Limitations

While GIFIS establishes a strong interoperability framework, it does not address all challenges inherent to hydrologic data ecosystems. A specification cannot compensate for sparse sensing, incomplete metadata, or inconsistent upstream modeling practices, it can only expose these deficiencies and prevent ambiguous data from being treated as valid. The current version focuses primarily on hydrologic entities and anchoring semantics, without yet incorporating full uncertainty vocabularies, detailed quality metrics, or jurisdiction-specific ontologies.

Moreover, performance, storage, and deployment strategies remain intentionally out of scope, allowing implementers flexibility while still requiring adherence to schema contracts. Successful adoption therefore depends not only on the technical design but also on community governance and sustained curation, maintaining profiles, test vectors, migration guides, and validator reports to prevent re-fragmentation. Addressing these limitations through uncertainty extensions, richer quality descriptors, and open governance processes represents an essential direction for future research and standardization.

4.3. Broader implications

Beyond its immediate technical scope, GIFIS contributes to the broader scientific and institutional movement toward open, FAIR, and reproducible environmental data. Its schema-driven architecture enables transparent, machine-verifiable exchange of flood and hazard information across agencies such as USGS, NOAA/NWS, NCEI, and state-level RWIS programs, fostering collaboration and reducing duplication of effort. The modular structure further promotes education, innovation, and policy integration, allowing researchers, developers, and educators to build interoperable tools and learning environments grounded in verified data semantics.

Future work will expand these impacts through community engagement and tooling. Planned activities include open workshops, modular curricula, and pre-registered evaluations measuring the effects of GIFIS adoption on development efficiency, defect rates, and cross-tool compatibility. Complementary technical initiatives, such as automated translators, typed model generators, and multi-language validators (Python, TypeScript, C#), will streamline adoption and facilitate compliance. In the long term, stewardship by an open consortium and the development of optional extensions for uncertainty representation, GIS interoperability, and distributed processing will ensure that GIFIS remains a living, adaptive standard responsive to the evolving landscape of hydrologic and environmental data systems.

5. Conclusions

GIFIS introduces a comprehensive, standards-based framework for encoding, validating, and exchanging hydrologic and environmental data in a reproducible and interoperable manner for virtual and augmented reality frameworks, platforms and services. By combining vendor-agnostic JSON Schemas with well-defined semantic rules and an enforcement-grade validator, GIFIS redefines interoperability as a verifiable property of the data itself rather than an emergent property of software integrations. Its layered architecture, comprising Core Schemas, Domain Profiles, and Portable Document Types, ensures that every observation, model output, or visualization artifact carries explicit meaning, traceable provenance, and testable conformance across institutional and technological boundaries.

The specification's modular design enables seamless fusion of real-time sensor feeds, model results, and geospatial assets into a single, deterministic data stream that can power both analytical systems and immersive environments. This paradigm demonstrates that flood and water-quality information can be authored once and rendered anywhere, from 2D GIS dashboards to fully immersive 3D or XR clients. By codifying how spatial, temporal, and semantic dimensions interrelate, GIFIS provides a stable bridge between hydrologic science, information technology, and visual communication.

While current limitations involve uncertainty vocabularies, quality-assessment metrics, and sustained community governance, the specification lays a foundation for continuous, open evolution. Planned extensions, including translators, conformance registries, and an open consortium for semantic stewardship, will expand its scope and resilience. In doing so, GIFIS advances the broader scientific mandate for FAIR, transparent, and reproducible environmental data, positioning itself as a cornerstone infrastructure for next-generation hydrological modeling, decision support, and public engagement.

Data Availability

All data produced and analyzed in this manuscript are included within the paper. The GIFIS schemas, documentation, and reference materials are openly available at: https://github.com/uihilab/GIFIS

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