A Comprehensive Review of Ontologies in the Hydrology Towards Guiding Next Generation Artificial Intelligence Applications

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Abstract

Big data generated by remote sensing, ground-based measurements, models and simulations, social media and crowdsourcing, and a wide range of structured and unstructured sources necessitates significant data and knowledge management efforts. Innovations and developments in information technology over the last couple of decades have made data and knowledge management possible for an insurmountable amount of data collected and generated over the last decades. This enabled open knowledge networks to be built that led to new ideas in scientific research and the business world. To design and develop open knowledge networks, ontologies are essential since they form the backbone of conceptualization of a given knowledge domain. A systematic literature review was conducted to examine research involving ontologies related to hydrological processes and water resource management. Ontologies in the hydrology domain support the comprehension, monitoring, and representation of the hydrologic cycle's complex structure, as well as the predictions of its processes. They contribute to the development of ontology-based information and decision support systems; understanding of environmental and atmospheric phenomena; development of climate and water resiliency concepts; creation of educational tools with artificial intelligence; and strengthening of related cyberinfrastructures. This review provides an explanation of key issues and challenges in ontology development based on hydrologic processes to guide the development of next generation artificial intelligence applications. The study also discusses future research prospects in combination with artificial intelligence and hydroscience.

Keywords: Ontology, Hydrology, Water Resources Management, Knowledge Generation, Knowledge Representation, Knowledge Networks, Knowledge Graph

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1. Introduction

A massive and expanding amount of data is collected and generated in a wide range of disciplines, from sensors to web, and crowdsourcing in this digital age (Jones et al., 2018). By 2025, the world's digital data will have grown to 175 zettabytes (Reinsel et al., 2018). Furthermore, according to a report by the World Economic Forum, roughly 70% of the data generated is never utilized. The lack of interoperability and connectivity of data in separate silos is the primary cause of this limitation in usage. In addition, software and tools must be able to read data automatically to access, process, and integrate this information. The data is heterogeneous, and problems stemming from heterogeneity are very common in the domain of Earth science (Demir et al., 2015). Because of the different terminologies that are used to identify these observations and the unstructured, incomplete, and diversified nature of the data, making this data accessible and reconcilable is a major challenge (Masmoudi et al., 2021). Effective tools are required for the management, analysis, and communication of these massive data streams.

To overcome these challenges, knowledge graphs and ontology-based data management (Sermet and Demir, 2019) introduced as a new paradigm. From the computer science point of view, ontology deals with the classification and explanation of entities for information integration and retrieval on the Internet and knowledge management (Mukhopadhyay and Shikalgar, 2013). Knowledge graphs use ontologies and semantics to provide context and relationships to data for integration, analytics and sharing. Ontologies are critical to efficiently inferring knowledge from data in the environmental domain (Haltas et al., 2021), where full utilization of ever-growing sensor data depends on easy accessibility and optimized data standards and structures (Demir and Szczepanek, 2017).

With the common and well-known definition, an ontology is an explicit specification of a shared conceptualization in the Artificial Intelligence (AI) literature (Gruber, 1993, Studer et al., 1998). The terms "conceptualization and explicit" refer to an abstract model of some phenomenon in the world by having identified the relevant concepts of that phenomenon and, the type of concepts used, and the constraints on their use are explicitly defined, respectively. Ontologies are primarily motivated by the ability to share and reuse knowledge bodies in computational form (Studer et al., 1998). Ontologies support knowledge-based AI applications (Bergman et al., 2018) and provide data and information via information systems (Demir et al., 2009) and knowledge with Decision Support Systems (DSSs) (Sun and Jung, 2016; Teague et al., 2021). A knowledge-based system is a form of AI that aims to capture the knowledge of human experts to support decision-making and problem solving (Ewing and Demir, 2021).

In hydrology, as in other environmental domains, there is a massive amount of heterogeneous data that lacks interoperability and connection. Effective data and information management are necessary for understanding and processing these complex data structures, making future estimates, and planning based on these estimations. This need requires the development of ontologies in hydrology to improve and automate data management and processing, and serve as the foundation for the next generation of intelligent information and decision support systems

(Sermet and Demir, 2018). Ontologies can also play a critical role in the development of AI-powered educational products and the strengthening of related cyber infrastructures.

Liao (2005) reviewed ontology-based expert system applications in different fields including flood (Shu and Burn, 2004) and water supply forecast (Mahabir et al., 2004) in the hydrology domain. Liu et al. (2013a) investigated different ontologies in crisis management. They examined the UK Ordnance Survey Hydrology Ontology, which represented the topological features of water bodies. Zenner (2019) focused on reviewing the importance of fresh water in different sectors from a socio-economic point of view. Mughal et al. (2021a) completed a review of streamflow and flood data management issues. With the developments in AI and the revelation of big data-oriented use cases, a comprehensive review of ontologies in the hydrology domain is needed.

To fulfill the described knowledge gap, we have investigated state of the art ontology-related studies in the hydrology domain as part of a comprehensive review. The overarching purpose of this paper is to guide the hydrological stakeholders (e.g., knowledge engineers, domain experts, and researchers) on how to leverage ontologies for the next-generation hydrological data sensing, knowledge generation, communication, and DSSs.

This manuscript is structured as follows. Section 2 explores the origin and basic terminology on ontology, knowledge graphs, management and networks on representation and sharing. The main components, types, construction tools, and used languages for ontology development are explained. Also, we illustrate review methodology to search publications and selection criteria. In Section 3, related studies in the hydrology, water resources, and geosciences domain are presented, respectively. Summary and findings section presents detailed analysis of literature with summaries and tables. In Section 4, key findings and challenges are described. It also consists of the recommendations and conclusions.

2. Methodology

This section provides a summary of ontologies as well as their purpose and foundation, structured specifically to address the associates of the water domain and to rationalize the utility of ontologies in the hydrological domain.

2.1. Terminology and Foundation

Data and information management, analysis, visualization, modeling, and sharing have all benefited from recent advancements in information and communication technologies (Demir and Beck, 2009). Information systems play an important role in many disciplines, including hydrology (Raj and Lakshmikantha, 2012; Contreras et al., 2014; Pacheco et al., 2021). Traditional data and information sharing systems are limited in their ability to integrate remote sources, visualize, analyze, and communicate modeling results (Hu and Demir, 2021). Because they are usually computation-oriented rather than communication-oriented, these systems deliver either static reports or maps and allow little interaction between data and users. Information systems, on the other hand, include web-based management (Xu et al., 2019), visualization, and sharing capabilities (Yildirim and Demir, 2021) for environmental time-series data utilizing web services.

Knowledge Management is a set of strategies and practices organizations use to become more systematic about managing intellectual capital - the intangible assets and resources that are not captured by conventional accounting reports, but still contribute to its value and help it achieve competitive advantage (Wallace, 2018). The representation, organization, acquisition, development, usage, sharing, and evolution of knowledge in its various forms are all addressed by knowledge management (Jurisica et al., 2004).

Open Knowledge Network *(OKN)* is an "open" and shared infrastructure to link data related entities (NITRD, 2018). Figure 1 illustrates the basic schema of OKN. A ***Knowledge Graph*** *(KG)* is a multi-relational graph made up of nodes (entities) and edges (relations). A ***Semantic Web*** is an extension of the current web in which information is given a well-defined meaning, making it easier for machines and people to collaborate (Berners-Lee et al., 2001). Semantic webs are developed based on ontologies. Ontology is an effective tool for representing and sharing knowledge (Chungoora et al., 2013; Yoo and No, 2014; Jelokhani-Niaraki, 2018; Gayathri and Uma, 2018; Qi et al., 2020).

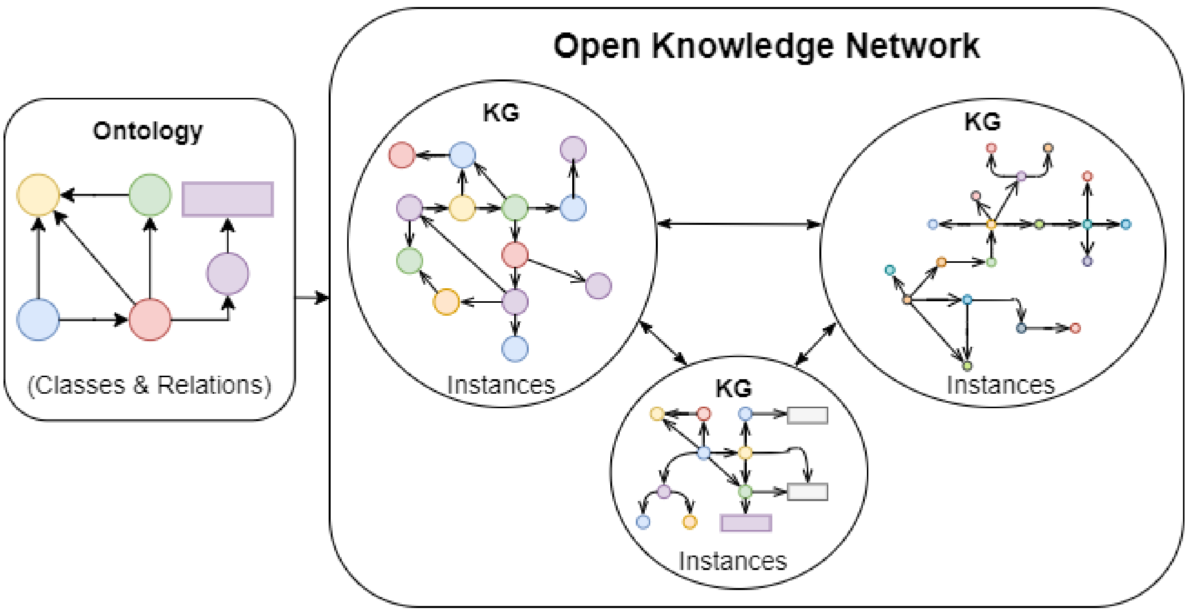

Figure 1. A graphical representation of an Open Knowledge Network

2.2. Ontology

An ontology is defined as an explicit semantic model of the concepts and structures that are used to represent and manage those concepts and structures. One of the most common purposes in constructing ontologies is to achieve a shared understanding of the structure of information among people or software agents. (Musen 1992; Gruber 1993; Noy and McGuinness, 2001). Table 1 summarizes some of the key historical understanding and definitions of ontology in information sciences.

Table 1. Major definitions of ontology in information science

Authors	Year	Definition
Musen	1992	Standardized lexicon that also includes information about how items are categorized and related to one another
Gruber	1993	Explicit specification of a conceptualization
Borst	1997	Formal specification of a shared conceptualization
Studer et al.	1998	Formal, explicit specification of a shared conceptualization
Welty and Guarino	2001	A working application that is based on a conceptual model
Noy and McGuinness	2001	Formal explicit description of concepts in a discourse domain (classes, also called concepts), properties of each concept (slots, occasionally called roles or properties), and limits on slots (facets, sometimes called role restrictions).
Smith	2003	A set of concepts written in a standard syntax with widely agreed definitions to produce a lexical or taxonomic framework for knowledge representation that can be shared across various information technology communities.
Brank et al.	2005	The fundamental data structure for comprehending knowledge
Raskin and Pan	2005	A formal representation of technical concepts and their interrelationships in a way that supports domain knowledge
Guarino et al.	2009	A special kind of information object or computational artifact
García and Gil	2010	A clear alternative for formally representing content value chains and allowing copyright management solutions to be implemented on top of that formalization
Arp et al.	2015	A representational artifact that includes a taxonomy and whose representations are intended to denote a set of universals, defined classes, and relationships between them
Nasution	2018	Foundation of semantic
Khider et al.	2019	Formal means of representing objects and their properties, and it represents consensus knowledge that allows a community to explain major concepts in a domain using common language.
Khadir et al.	2021	The product of a shared body of information that has been organized in such a way that it can be read by machines and captures a specific conceptualization of the universe

2.2.1. Ontology Development Languages and Tools

In the development process of an ontology, a number of languages can be used to represent knowledge. Ontology languages should meet the requirements (well-defined syntax and semantics, efficient reasoning support, sufficient expressive power, convenience of expression) to be advantageous for knowledge modeling (Antoniou and Harmelen, 2004). Besides, ontology should be machine readable and understandable (Middleton et al., 2004). Particularly, Web Ontology Language (OWL) and Resource Description Framework (RDF) are prevalent for building ontology. The W3C-endorsed OWL (Lite, DL, and Full) is the semantic web standard ontology language. It is interoperable with previously created ontology languages such as SHOE and

DAML+OIL. The W3C (World Wide Web Consortium) established the RDF, which is expressed in eXtensible Markup Language (XML), for the purpose of defining web resources (Slimani, 2015).

There is various ontology visualization, manipulation, and editing tools available on the web. They are actively used by a number of knowledge engineers or domain scientists. Some of them have gained prominence in recent years, including Protégé (Stanford University, 2019), OntoSoft (Gil et al., 2015), Hozo (http://www.hozo.jp), OntoGraf (Falconer, 2010), and Neo4j (https://neo4j.com). There are important considerations for ontology developers when selecting these tools: Reusing existing ontologies and documentation, as well as exporting and importing data in various formats, views, and libraries (Dudáš et al., 2018). In particular, Musen (2015) emphasized that Protégé can easily be said to be the dominant program that meets all these features.

2.2.2. Ontology Design Methodologies

There is no "correct" methodology for building an ontology that represents domain-specific consensus knowledge. The semantic links between concepts and classes must be defined in an ontology. An ontology building process brings together domain experts and knowledge engineers. Developing an ontology emphasizes not only its scope and aim, but also its features, such as domain-oriented, information-centric, and user-centered. Some of the major methods of building an ontology are listed as follows.

Grüninger and Fox (1994; 1995) firstly define the process of building an ontology, which is structured as follows: motivation, specifying the competency questions, specifying the terminology, defining the definitions and constraints, and evaluation of the ontology. Uschold and King (1995) suggest an approach, which is updated by Uschold and Grüninger (1996). This method follows these stages: describing the aim of the ontology; building the ontology; coding; integration of existing ontologies; evaluation; and documentation. However, this method does not clearly define ontology evaluation and integration of existing ontologies. In 1996, the Kactus methodology is proposed by Bernaras, which includes: specification of application; the list of terms and tasks; preliminary design based on the related top-level ontologies as input; expanding domain concepts and relations between them; and finalizing the design of the ontology.

Gómez-Pérez et al. (1996) present the "methontology" framework, which is later detailed by Fernández-López et al. (1997), López et al. (1999), and Gómez-Pérez (1999). This framework defines the following processes: specification; conceptualization; formalization; implementation; and maintenance. The most crucial part of the "methontology" is to conceptualize the ontology, which includes the building of a glossary of terms, concept taxonomies, binary relation diagrams, and concept dictionaries. Schreiber et al. (2000) propose an approach (CommonKADS), which has been gradually developed and is known by a wide range of companies worldwide.

Noy and McGuinness (2001) proposed an ontology building approach that is based on specifying the domain and scope of the ontology; reusing existing ontologies; listing the important terms; determining class, class hierarchy, and properties; and creating instances. Kamel et al. (2007) proposed a methodology to build the OWL ontology. This method has seven steps:

determining the scope and application of the ontology; creating a list of relevant concepts in the domain; creating the class hierarchy; defining properties; describing classes using property restrictions and complex definitions; classifying the ontology with a reasoning tool; creating instances and filling property values. The NeOn methodology (Suárez-Figueroa et al., 2012) is based on the reuse of public ontology repositories and the integration of their required ontologies.

In addition to all the ontology building methods mentioned above, some components (Elag and Goodall, 2013; Howell et al., 2017) or hybrid applications (Hahmann et al., 2016; Wang et al., 2021) of these methods are quite common, depending on the scope and purpose of the study. Existing collaborative ontology development systems involve a clear staged separation between ontology creation, ontology publication, and ontology use. However, an ontology would need to be part of a framework that supports constant change while being used (Gil et al., 2017). Crowdsourcing has evolved as a new approach for leveraging human knowledge and intelligence to complete activities that are difficult for computers to complete efficiently (Alabduljabbar and Al-Dossari, 2019). Therefore, for the past few years, crowdsourcing has been used in the creation and development of ontologies (Gil et al., 2017; Khider et al., 2019; Waagmeester et al., 2020).

Computers can now navigate through metadata and discover data that would otherwise be hidden from them using ontology (Khider et al., 2019). Artificial Intelligence (AI) enables the community to construct community infrastructure for effective data integration and analysis thanks to a consensual ontology that has been embraced. The use of AI to synthesize new scientific knowledge that did not exist previously is a groundbreaking achievement that must be emphasized (Gil, 2022). Moreover, ontologies are used with great success in education and smart assistant applications (Sermet and Demir, 2021) as they allow to formulate the representation of a learning domain by specifying all concepts involved, relations between concepts, and properties and conditions that exist (Stancin et al., 2020; Grivokostopoulou et al., 2019). With AI integration, ontologies can be used in intelligent educational systems as a common vocabulary for multi-agent systems, as a chain between heterogeneous educational systems, and e-learning or e-tutoring tools (Salem and Cakula, 2012).

2.3. Review Methodology

This review is conducted using a systematic literature search in water resources management and hydrology domains. Key information regarding the review process (e.g., databases, keywords, fields) is described in Table 2. In the first stage, articles published between the years of 2009 and 2021 are gathered based on their compliance with the keyword search criteria, which comprise titles, abstracts, and keywords linked to subject areas. A total of 878 studies are found under these search conditions. All these papers are examined meticulously, and the papers which are developed or used existing ontology in hydrologic processes and water resources management fields are included in this review. 69 papers remained after the filtering and used in the review.

All selected articles have been analyzed to extract features and aspects that will be instrumental in the literature analysis with respect to providing guidance on the described research questions. These parameters are utilized in later sections to provide both qualitative and quantitative analysis of the status-quo as well as to establish trendlines for future work. They include domain, application areas, utilized languages, ontology sources and tools, methods, development/usage categories, target users, and accessibility, all of which are summarized below.

Table 2. Methodology details of the literature review.

Databases	Scopus, Web of Science, Science Direct, IEEE Xplore, Springer Link, Wiley Online Library, The Int. Water Ass. Publishing Online, Google Scholar
Search Keywords	"Ontology and water", "Ontology and hydro", "Knowledge generation", "Knowledge management", "Knowledge graph", "Knowledge representation", "Knowledge network", "Semantic and water", "Semantic and hydro", "Open knowledge network"
Subject Area	Environmental Sciences, Water Resources, Atmospheric Sciences and Meteorology, Earth and Planetary Sciences
Search Within	Abstract, Title, Keywords
No. of Publications	878 (full set)
	69 (after filtering)

Domain: The fields of hydrology, which covers the water cycle and its components, as well as water resources management, are investigated in this study. Flood and water quality related ontologies are evaluated in the natural disasters or disaster management domain and environmental pollution domain, respectively. Hence, they are excluded in the review process.

Application area: Application areas are categorized under 6 different titles, namely, data search, integration, process, sharing, retrieval; ontology-aided simulation, modeling, and assessment; developing a tool for intelligent systems; developing a markup language; developing ontologies; sharing, enhancing knowledge (Figure 4).

Language: OWL, ASP.NET, Java, XML, DL (Description Logic), CL (Common Logic), UML, RDF, DAML, XOL, and MOWL (Multimedia OWL) are the languages used to create and/or develop ontologies (Figure 7).

Ontology Source: Data, existing ontologies, knowledge, and methodologies are employed as ontology resources in the publications.

Tool: Spotter, HydroTagger, sensorML, OntoSim, ThManager, Protégé, tModel, OntoKEM, Facet Mapping, XML schema, Open Provenance Model, IHMC CmapTools, Container schema, Hozo Ontology Editor, OWL API, ProBMoT, FluidEarth, Environment, Inspire Ontology Construction Tool, NeonToolKit, OntoGraf, Weka 3.8.0, GraphViz, Neo4j are the tools used to build and/or improve ontologies (Figure 8).

Method: In ontology development, either an existing method is used, hybrid methods are created by combining existing methods, or new methods are developed. The methods used in these papers can be listed as follows: Noy and McGuinness (2001), Semantic Mapping, Methontology, Formal Concept Analysis (FCA), Process-centric ontological approach, Information retrieval system, Tree-like, Ontology Engineering, Multiple Layer Feed-Forward Neural Network (MLFFN), Provenance model, Adopted from Uschold and Grüninger (1996), IKnow Model, Top-down approach, Semi-automated construction method, NeOn, Seven-step, semantic method, Top-level Basic Formal Ontology (BFO), Distributed- ontology technology, UPON (Figure 9).

Development/Usage: This parameter is defined as whether the article is an attempt to create a new ontology, improve or use an existing one.

Target user: The target users of the ontologies used or developed in these papers are educators, students, hydrologists, researchers, scientists, developers, decision and policy makers, stakeholders, data managers, domain experts, practitioners in water-related disciplines, and institutions like agencies, universities, and data centers.

Accessibility: This parameter is defined as whether the ontology is publicly accessible.

We have considered adding the size of the ontology as a critical parameter of this review, however, decided to leave it out since (1) the number of entities that exist in an ontology does not reflect its usefulness and accuracy in fulfilling its purpose, and (2) many open-source ontologies are subject to revision throughout its lifespan.

3. Results

The information retrieved from each reviewed publication is included in the literature review. The subsections provide a brief overview of articles in water resources management and hydrology domains. The publications that are examined are either ontology development or ontology use. Table 3 shows major water and hydrology-related ontologies. Bermudez and Piasecki (2003) developed an OWL-based Hydrological Ontology for the Web (HOW). The Semantic Web for Earth and Environment Technology (SWEET) is a middle-level ontology (Raskin and Pan, 2005; Tripathi and Babaie, 2008) for environmental terminology, which produces a domain-specific hydrology ontology. Beran and Piasecki (2009) outlined an ontology-aided search engine (Hydroseek).

Table 3. Water resources and hydrology related ontologies.

Ontologies	**Context**	**Definition**
HY_Features	Hydro domain ontology	Emphasizes on surface water features.
SWOP	Surface water ontology design pattern	Models abstract flow paths rather than processes with spatio-temporal properties
SWEET	Hydro domain ontology	Contains surface and sub-surface domain concepts with mostly taxonomic relations.
INSPIRE	Hydro domain ontology	Allows users to search geospatial data.
hydrOntology	Domain ontology of hydrographic features	Integrates hydrological data sources.
Surface Water Ontology	Hydro domain ontology	Based on the NHD in the National Map Specifies taxonomic type of hydro features.
HOW	OWL-based hydrological ontology for the Web	Presents the main concepts of hydrologic data.
HyFo	Hydro foundational ontology	Focuses on a few core classes of surface, subsurface, and atmospheric water.

There are some organizational efforts, such as CUAHSI-HIS, USGS (Varanka and Usery, 2018), World Meteorological Organization Hydrological Observing System (WHOS; Pecora and Lins, 2020), and European Union Commission (INSPIRE), to create ontology-aided search engines, which include hydrOntology (Vilches-Blázquez et al., 2009), Surface Water Ontology Pattern (SWOP; Sinha et al., 2014), Surface Water Ontology (Varanka and Cheatham, 2016), and Hydro Foundational Ontology (HyFo; Hahmann et al., 2016), to access, share, and integrate water and hydrological data sources.

3.1. Water Resources Management Domain Summary

For information and decision support systems (Alabbad et al., 2022), many ontologies function as universal interfaces. The studies that develop and improve ontologies integrated into these systems in the water resources management domain are as follows. Alabri et al. (2009) build The Ecosystem Health Monitoring Program (EHMP) ontology, the underlying water information management system, and a web portal. They create annual ecosystem report cards and generate WaterWiki. Garrido and Requena (2011) design an ontology for Environmental Impact Assessment (EIA) to be used directly as a reference for EIA methodology developers, as well as for managing knowledge in an expert system for EIA. Salah (2014) proposes an approach for facilitating decision-making in web-based DSSs for water management. Katsiri and Makropoulos (2016) develop DiHydro, a novel ontology that can be used to regulate the gray water reuse process, detect, and react to any failures or unexpected events, evaluate and enhance the efficiency of water reuse, and anticipate the best time for maintenance in a decentralized water management enabled sustainable smart home.

Goel et al. (2017) develop a context-aware ontology-driven method for water resources management in smart cities that can dynamically obtain a range of water-specific information in an IoT (Internet of Things) environment for delivering appropriate water supply to inhabitants. By unifying water systems with clean and waste networks and empowering smart water solutions at an urban scale, Howell et al. (2017) create a semantic knowledge management service and domain ontology to combine Geographic Information System (GIS) and topological network descriptions, telemetry data, Building Information Modeling (BIM), smart metering, and devices. Oliva-Felipe et al. (2017) present an ontology (WasteWater Ontology+, WaWO+) to support reasoning to make decisions related to environmental water management in a river basin. Howell et al. (2018) propose a knowledge management platform with the goal of making utility decision support software and develop a domain ontology that incorporates existing standards and a representative GIS schema with additional smart water concepts, as well as the Semantic Sensor Network (SSN) ontology, which is a critical step for the smart water concepts. Oprea (2018) provides a knowledge modeling framework for intelligent environmental DSSs. The framework includes an ontological approach as well as two data analysis approaches that can be applied to the water, air and soil domains.

There have also been some efforts to develop ontology in the Water-Energy-Food (WEF) nexus studies. Endo et al. (2015; 2018) build and use an ontology as a case study tool for qualitative methods, and create the WEF nexus domain ontology database, combine qualitative ontology and quantitative network analysis methods to determine major themes in the WEF nexus domain ontology that serve as linking hubs, and depict human-nature connections. Through tests involving two groups, Kumazawa et al. (2017) investigate the effectiveness of the ontology engineering approach as a strategy for providing common terms, concepts, and semantics in this nexus. Babaie et al. (2019) create FEWsOnt, a WEF systems ontology that specifies the many physical, biological, and social-behavioral processes to represent the semantics of the structure and dynamics of the interactions among the WEF systems' parts.

Within the scope of data search, integration, analysis, sharing and retrieval, Huang et al. (2016) propose an approach to build a water environment ontology and develop an ontology-based water environmental data retrieval system. Shu et al. (2016) study whether semantic web technologies can capture the types of limitations and support in data consistency checks when data is encoded in the Water Data Transfer Format (WDTF). Huang et al. (2017) develop OntoWE, an ontology-based water environmental data retrieval and visualization system including a semi-automated technique to construct a broad-coverage water environment domain-specific ontology from various potential corpuses. Acharya et al. (2020) provide an ontological framework that encapsulates the combinatorial complexity of river water sharing. Lopez-Pellicer et al. (2019) develop an ontology, OntoInnova, that gives understanding of the various elements associated with water management research, development, and innovation exchange and collect spatial water management data. For semantic knowledge formalization, Mughal et al. (2021b) develop an ontology for River Flow and Flood Mitigation (ORFFM). They provide a novel strategy for connecting the hierarchies of water-producing sources, water distribution systems, as well as contributing to interoperable data sharing for effective water management and flood disaster response.

3.2. Hydrology Domain Summary

Many advanced intelligent systems require ontologies for data organization and knowledge generation. The ontology studies that contribute intelligent systems in the domain of hydrology are as follows. Piasecki and Beran (2009) develop 4-layer data ontology with OWL for hydrological applications. Beran and Piasecki (2009) create an ontology-aided search engine for hydrological data. This search engine provides users with hydrological data from over 1.8 million stations across the US. Latre et al. (2009) propose an information retrieval system for the integration of hydrological data that is based on the usage of a multilingual ontology to assist mapping across different sources' local data models. Devaraju et al. (2010) develop both sensor network and hydrology ontologies using a process-centric ontological approach and the concept of evapotranspiration as a running example. Yi et al. (2011) presented an ontology and domain modeling-based design method for an integrated modeling and assessment DSSs in hydroinformatics. Liu et al. (2013b) present a generic knowledge model and knowledge management framework that captures hydrological data from different sources. They integrate four different ontologies into a single model.

Various ontologies have been developed for watershed management and its components. Yaguinuma et al. (2011) build a data integration system based on fuzzy ontology and executed a real experiment in the domain of watershed analysis. Shu et al. (2012) develop a streamflow forecasting ontology and test their ontology-based model. Yi and Sun (2013) release an ontology framework for digital watersheds and design the ontologies for integrated watershed flood risk assessment. Kaewboonma et al. (2014) offer a drought ontology model that includes river basin, statistics, and task ontology and develop a drought management IS. Kwon et al. (2014) use an ontology-based simulation framework and automatic calibration algorithm to analyze groundwater table fluctuations and drainage practices on four farm basins. Škerjanec et al. (2014) create a component library (ontology) for semi-distributed watershed modeling that consists of organized and structured modeling knowledge. Basic modeling knowledge is incorporated into the library, allowing for accurate modeling of various water fluxes and nutrient loadings on a watershed scale.

The surface water ontology design pattern is developed by Sinha et al. (2014) for domain knowledge distillation and as a conceptual building block for more complicated or specialized surface water ontologies. Varanka and Usery (2018) create an applied surface water ontology in order to establish a framework for the collection of various types of hydrological data. Brodaric et al. (2016) use a spatial data infrastructure architecture to overcome the data heterogeneity problem for groundwater data. This study results in the creation of two separate national groundwater data networks for the US and Canada. Hahmann et al. (2016) use the Hydro Foundational Ontology (HyFO) to investigate the usage of a reference ontology (Noy, 2004) as a tool for boosting semantic precision and coherence in geoscience data models to prepare for automated integration of geoscience knowledge. They stratify GWML2 (Groundwater Markup Language) classes, increase reusability and compatibility with other hydro ontologies. Varanka and Cheatham (2016) construct an empirically-based surface water ontology (SWO) for fundamental inference utilizing asserted, domain, range, and specified classes.

To improve river water management, enable efficient use of natural resources, and save the additional water released into the sea and non-irrigated areas, Mughal and Shaikh (2017) design an ontology (WaterOnto) for context-aware information representation of the riverine water management system. Brodaric et al. (2018) establish and develop GroundWater Markup Language 2 (GWML2) to address the lack of an international groundwater data representation. Cheatham et al. (2020) analyze the relationships between a set of surface water ontologies and the utility of two major automatic alignment methods to integrate four pairs of ontologies. Their findings suggest that existing alignment systems perform poorly in this domain compared to typical ontology alignment benchmarks. Li and Jiao (2013) provide a multi-level business process-based construction technique for data resources in the Yellow River domain ontology, as well as a distributed ontology integration framework based on multi-mapping. Yi and Zuo (2021) examine data sharing methodologies, propose intelligent data sharing technologies, and create a digital watershed ontology. This study focuses on watershed scale hydrology modeling and surface and groundwater hydrology.

Ontologies have also been developed for data management purposes. For instance, Li et al. (2011) build a hydrology ontology for arctic areas to improve effectiveness of data search. They build a spatial data infrastructure to support scientific modeling and data sharing. Huang et al. (2011) develop an online service-oriented water data discovery and retrieval system. They use water ontology to enhance the ability of search engines. Kinceler et al. (2011) develop an ontology for hydrologists to easily access weather, climate, and water databases. Ames et al. (2012) build a web-based, open source, freely available software, called HydroDesktop, to search, download, visualize, and analyze the data in a single environment. It has an ontology-powered search engine. Li et al. (2014) design an information resource sharing system with the technology of semantic ontology metadata and the technology of web service for the Yellow River Basin and build a basin ontology database. Li et al. (2015) create a semantic search tool for intelligent polar dataset discovery. Ontology-assisted semantic search and smart search based on knowledge mining techniques are part of this tool's search strategy.

Yu and Liu (2015) investigate how to establish a linked sensor web using the linked data approach of integrated water resource decision support (IWRDS). By creating and implementing a system to achieve greater data interoperability and integration by republishing real-world data into linked geo-sensor data. Harpham (2015) proposes a general framework with the MAP-Metadata, Adaptors, and Portability paradigm. The Model MAP is applied to a hydro-meteorological research infrastructure, after being compared to the component-based water resource model ontology. Lingua and Noardo (2015) structure a GIS-based on parts of two different self-integrated ontologies from the viewpoint that the system plays a major role in interoperability and data sharing through a web-GIS platform for the extraction, management, and sharing of earth and water information. Essawy et al. (2017) perform the Variable Infiltration Capacity (VIC) hydrologic model to evaluate the OntoSoft (Gil et al., 2015) ontology for describing metadata for scientific software.

Hahmann and Stephen (2018) investigate whether the Hydro Foundational Ontology (HyFO) can be used as a reference ontology for the water domain and The GWML2 is used to test this. Yan et al. (2018) present a technique for building a KG whose conceptual model and logical foundation is ontology, by merging water-related structured and unstructured data to suit users' expectations for water data integration. By importing the time and space ontologies, instantiating the hydrological classes, and constructing reasoning rules, Wang et al. (2018) propose a hydrological sensor web ontology based on the SSN ontology to characterize heterogeneous hydrological sensor web resources. The World Meteorological Organization (WMO) has developed a hydrological ontology for WMO Hydrological Observing System (WHOS). The WMO Hydrological Ontology incorporates OWL reasoning to give semantic access to connected data. The approach of enriching the searchable information that is related with hydrological data and information supports the proposed methodology (Pecora and Lins, 2020).

There are also ontology studies conducted to determine semantic similarity. Li et al. (2012) develop a feature-based framework to automatically quantify semantic similarity between spatial objects by integrating an ontology and a multi-layer neural network to model the human similarity

perception process. Bharambe and Durbha (2018) propose a Pareto-based approach to combine multiple similarity measures and develop an adaptive hybrid geo-ontology matching system. Gao et al. (2020) create a similarity algorithm that combines the instance-based and define-based methods to provide a superior similarity calculation approach that can better realize mapping between different water ontologies. Wang et al. (2021) propose a semantic similarity measuring method including features and relations. This method captures geo-semantic similarity by evaluating contributions for ontological attributes, quantifying the effect of relative position in the ontology hierarchy structure, and computing geometric feature similarity for geospatial entities.
Other ontologies in the hydrology domain can be listed as follows:

Vilches-Blázquez et al. (2009) provide a method for evaluating three hydrographical ontologies in order to determine which ontologies cover the domain better. Kwon et al. (2010) use an ontology-based simulation (OntoSim) to model hydrologic processes. A Water Resources Component (WRC) ontology is established by Elag and Goodall (2013) to foster collaboration with bigger communities and multidisciplinary research. Brodaric and Hahmann (2014) employ an ontological analysis to discover the hydro container schema as a conceptual foundation for hydro ontology development. The OntoAgroHidro is an ontology proposed by Bonacin et al. (2016) to capture knowledge regarding the effects of climatic change and agricultural activities on water supplies and support the research network system for facilitating information sharing and integration. Stephen and Hahmann (2017) examine hydrogeological entities and analyze basic flow processes in the hydrology domain. They develop a taxonomy of distinct flow patterns by identifying the source and goal entities, as well as the transported water.

Wang et al. (2017) develop a prototype hydrological ontology model for hydrological monitoring. An ontology for representing concepts, contents, and relationships among sensors, observations, and events in the hydrological monitoring domain has been defined with this ontology. Brodaric et al. (2019) develop a new ontological characterization and representation of water features. The ontology is technically expressed as an extension of the DOLCE foundational ontology, and it is also at the heart of the HyFO ontology, which is being developed as a hydro domain reference ontology. Li et al. (2021) propose a web-based geo-simulation method that incorporates KGs and model services. The preparation of the knowledge source, the creation of an ontology library, the acquisition of hydrological simulation information, and the creation of an urban hydrological simulation KG are all steps in the development of the simulation KG.

3.3. Summary and Findings

Our findings demonstrate that there are no clear boundaries between ontologies pertaining to various fields. This intricate structure of ontologies underscores the necessity of multidisciplinary research. Besides, ontologies in hydrology domain are utilized for diverse purposes as seen in Table 4. Publications reviewed may address more than one of the aforementioned objectives. This was taken into account while calculating percentages. Table 4 shows that 66.4% of the research was concerned with ontology development and data discovery. 31.3% of the research is devoted to modeling, the creation of intelligent systems, and the dissemination of knowledge. Ontology was only utilized in one study (2.3%) to develop the markup language. These purposes were summarized as follows:

Table 4. Ontology-aided applications in the hydrology domain.

Objective of the Studies	**Percent (%)**
Ontology Development	36.7
Data Search / Integration / Process / Sharing / Retrieval	29.7
Develop a tool for Intelligent System	13.3
Ontology-Aided Simulation / Modeling / Assessment	10.2
Share / Enhance Knowledge	7.8
Markup Language Development	2.3

Developing Ontologies: Proposing new ontologies, merging, and developing existing ontologies account for 36.7% of the publications reviewed. These studies cover 72% and 28% of hydrology and water resources management, respectively. 72.7% of ontology development studies used OWL to create an ontology. Protégé, OntoGraf, and Hozo are just a few of the many tools available for creating ontologies. Protégé (30%) is the most commonly used tool for ontology development in research (28%). Twenty-four other tools besides Protégé were employed in 42% of the research projects. When it comes to creating ontologies, there is no one-size-fits-all approach. Methods of the ontology development was not mentioned in 35.2% of the studies. Methontology and ontology engineering approaches were each used in 8.5% of the studies. Hybrid approaches and methods adopted from existing studies for ontology construction were calculated as 9.9% and 4.2%, respectively. 17 different development methods were utilized in 33.8% of the studies.

Ontologies for Data Discovery: Researchers spend considerable effort (Beran and Piasecki, 2009) on collecting different types of data, and metadata information from heterogeneous sources (Huang et al., 2016) while doing their work. An important part of ontology studies is aimed to provide, share, exchange, or process data for researchers via an infrastructure (Li et al., 2015). Ontology-assisted data integration and sharing solutions also help in the long-term management of data. This improves collaborations between scientists in different domains. In this way, it accelerates studies on climate resilience, and disaster risk management (Pecora and Lins, 2020). 29.7% of the papers analyzed in this study are utilized in the development of data search engines, data retrieval, integration, analysis, and sharing frameworks.

Ontology-Based Intelligence System: Water resource management requires an intelligent system that optimizes data utilization, knowledge acquisition, and simulation procedures. Numerous studies of ontology-based intelligence system have been conducted on hydrological monitoring (Wang et al., 2017), including flow (Stephen and Hahmann, 2017), drought (Kaewboonma et al., 2014), flood (Wang et al., 2018) and mitigation (Mughal et al., 2021b), water (Howell et al., 2018) and water resources management at river (Oliva-Felipe et al., 2017; Mughal and Shaikh, 2017) and watershed scale (Salah, 2014; Oprea, 2018; Mughal et al., 2021b; Yi and

Zuo, 2021) applications. In 13.5% of selected publications, systems are created with the help of machine-readable and understandable ontologies.

Ontology-Aided Simulation/Modeling/Assessment: Ontology allows simulation (Gil et al., 2016), assessment, and modeling if the mathematical formulations of important processes in any domain are known based on the representation of structured knowledge. There are some examples in this focus area for water modeling in agriculture (Kwon et al., 2010; 2014), environment (Garrido and Requena, 2011), hydrology (Shu et al., 2012), and natural disaster (Li et al., 2021) research fields. 10.3% of reviewed publications performed ontology-based simulation, modeling activities, and assessment.

Ontologies for Sharing and Enhancing Knowledge: Establishing a framework with an ontology can support not only diverse applications but also provide collaboration (Kumazawa et al., 2017; Bharambe and Durbha, 2018) in any domain. Ontology's building process in interdisciplinary research areas requires various perspectives and brings together domain experts, knowledge engineers, stakeholders, and policy-makers. Especially hydrological and water related ontologies concern the whole community (Babaie et al., 2019). It is feasible to share research findings using ontology-assisted frameworks (Endo et al., 2015; Bonacin et al., 2016). 7.9% of review papers are devoted to disseminating and enhancing information or outcomes.

Developing Markup Language: Ontologies allow the development of markup languages that consist of keywords, names, or tags to help format the overall representation of a page or data. In this way, researchers (Brodaric et al., 2018) can contribute collaboratively to the revision and implementation (Hahmann and Stephen, 2018) of these markup languages (GWML and GWML2). In the hydrology domain, markup languages are used in the analysis of groundwater, and these studies cover 2.4%.

3.4. Limitations and Challenges

There are some limitations to this study that should be acknowledged. Firstly, after the filtering stage of the review, 69 publications remained from an initial list of 878. There could be more ontologies published or archived on different indexes that are not included in our review sample. Secondly, publications in the fields of hydrology and water resources management, which are in the hydrology domain, are examined in this study. However, some ontology papers that have common points in different but close domains, like water-related disasters, water treatment, or water quality, may have been missed. Thirdly, some of the publications use and/or develop ontologies for more than one purpose. For example, in some papers, both ontology development and ontology integration with intelligent systems have been provided. Such intersections are effective on the percentage values in the figures given in the study. Finally, another limitation is that approximately 84% of the ontologies in the reviewed publications cannot be accessible today.

3.5. Key Issues and Recommendations

Several key issues have been identified that may hinder the process of unlocking the full potential of ontologies in the future studies for ontology development and usage.

Issue #1: Ontologies are still in their infancy for the domain of hydrology considering their practical application for pertaining tasks. A major setback in front of their adoption and integration is the lack of established standards for development and assessment. As the literature yielded, there is a variety of methodologies exhibited in ontology development, that is if a formal one is taken on. Also, systematic evaluations are mostly nonexistent, while for the ones that follow a methodological assessment and quality assurance approach, methods are nonuniform.

Recommendation: A validation and evaluation technique must be used to create trust in the suggested ontologies and carefully analyze whether use cases are appropriate for an application. As stated by Brank et al., there are numerous systematic methodologies and strategies to use when analyzing an ontology (2005). These strategies are classified into four categories: comparing to a 'golden standard', assessment by humans, comparison to a collection of documents (i.e., data-driven), and application-based evaluation. Ontology designers should ideally embrace at least one of these approaches, if not a combination of them, to continuously validate the scope and content of the ontology and confirm the competency questions are satisfied.

Issue #2: Ontologies' power comes from its comprehensive representation of the area of interest, which can only be ensured by the involvement of diverse parties and their agreement to produce a comprehensive and consensual ontology. While several organizations, that have the potential of serving as an authority to coordinate such an effort, have initiatives for hydrology-related ontologies (Bonacin et al., 2016). Such ontologies usually address a specific need of the organization and focus on a mere vocabulary rather than the ontologies' application to real-world problems. More importantly, a collaborative effort to coordinate the collaboration among stakeholders is limited.

Recommendation: Consortiums and working groups needs to be organized to involve interdisciplinary, interorganizational, and international stakeholders with interest to area- and purpose-specific ontologies not just for the sake of ontology, but with the motivation of bringing the background and requirements of their respected use cases, data formats, definitions, conflicts and priorities, and end goals. This may lead to community-driven open source ontologies that can readily support next-generation hydrological applications with capacity to serve interoperable and intelligent use cases among different organizations and countries.

Issue #3: While there are tremendous efforts in the hydrological community to employ state-of-the-art technologies, there is still an observable discrepancy and disconnection between the available technical resources for cutting edge techniques and the adaptability of water-related tasks. While there is a clear path for already computational tasks to be upgraded to increased efficiency and quality with modern approaches (e.g., deep learning-based forecasting as opposed to statistical forecasting), innovative and groundbreaking approaches that would challenge the status quo is not transparent.

Recommendation: Better communication is needed among the associates of AI and hydrology domains to overcome the prevalent problem of AI researchers not having the expertise to identify the aspects to provide value to hydrology, and likewise, hydrology researchers not having the expertise to identify the novel technologies that can provide tangible value to their daily work and persisting problems. Interdisciplinary conferences can provide the perfect venue to organize workshops inviting stakeholders from industry, educational initiatives and communities, and organizations in order to provide a forum for consensual and collaborative development of the ontologies as well as to provide the means to sharing the vision and expectations, and assessing the needs of stakeholders with respect to decision-making, training, education, and research, hence, building lasting partnerships and transforming the classroom for interdisciplinary education.

Issue #4: A major setback of ontology adoption in environmental fields is their abstract nature, with some existing examples in the literature not posing tangible and clear use cases. Furthermore, even for cases when a potential value is identified, it is difficult to convey the need and visible outcome which especially demotivates funding acquisition efforts and research. Rapid prototyping options based on custom ontologies are also limited given the lack of automated tools for integration and analysis (Amith et al., 2018).

Recommendation: The water resources domain is not unaccompanied with the challenge of addressing this issue, as it is a consequence of ontologies, especially with respect to their domain-specific application to intelligent and web-oriented solutions, still being an emergent technology. While a direct path to overcoming this issue solely from a hydrology perspective may not be provided, there are multiple recommendations that can be made, including the organization of student and professional hackathons to ignite the conception of creative use cases and technical components to support ontology analysis and intuitive visualization products as well as the publication of popular science articles and environmental blog posts (e.g. EOS by AGU, CUAHSI Blog) to increase awareness in the domain.

Issue #5: Some of the ontologies created for hydrology and water resources management are developed only for data discovery, while others address a very small part of the relevant domain. Ontologies in the domains of hydrology and water resources management need to be developed and completed due to factors such as the connections between classes and entities not being defined well enough, interdisciplinary studies not being carried out, and FAIR (Findable, Accessible, Interoperable, and Reusable) data principles (Wilkinson et al., 2016) not being followed while developing the ontology.

Recommendation: The existence of an open-source hydrology ontology that can be collaboratively enhanced by experts will enable knowledge graphs to be produced for regions sensitive to natural disasters and climate change. Hence, it may significantly contribute to the creation of OKNs that will increase the environmental resilience and social awareness of climate sensitive regions. In addition, FAIR is a set of guiding principles to facilitate knowledge discovery by assisting humans and machines in their discovery of, access to, integration, and analysis of task-appropriate scientific data and their associated algorithms and workflows. The development of ontologies in accordance with FAIR principles will allow the reuse (Gómez-Pérez, 2019) of ontologies and the addition of new methodologies. These rules should be followed to avoid duplication of effort and ensure the development and broad usage of ontologies.

4. Conclusions and Future Work

Ontologies are keystones in the creation of Open Knowledge Networks. From an environmental perspective, hydrology and water resources management ontologies feature in all environmental, climate, agriculture, and water sciences since knowledge representation, sharing, data management, and integration of knowledge into intelligent systems are provided by these ontologies. This paper provides a comprehensive review of ontologies in the hydrology domain. According to systematic review methodology, ontology development is performed in 37% of the total of 69 articles. The rest of the 63% is about data discovery, intelligence systems, knowledge management, markup language development, ontology-based simulations, modeling, and assessments. OWL is used as the main language in approximately 73% of ontology development studies. Moreover, Protégé has been shown to be the most preferred tool for creating ontologies. In ontology development, it would be incorrect to assert that a certain approach is frequently employed. Ontology developers employ a variety of methods, some of which were developed by themselves.

The review and analysis of the literature yields an abundant number of potential application and research areas pertaining the utilization of ontologies to amplify the future of hydroinformatics. The following incomplete list describes such areas to provide recommendations to the associates of the water domain and propel future work.

Markup Language: As described as a key challenge that may potentially hinder the advancement in big data-oriented hydrological solutions, the high variance of data formats and expressions are in need of addressing. A prominent solution in overcoming the compatibility issues among organizations, establishments, and countries in terms of expressions, formats, definitions, and parameters is the development of markup languages. Such languages can be powered by consensual ontologies that are active (i.e., continuously revised and validated by stakeholders).

Data Curation: In the age of big data and scattered nature of information resources, access to representative and accurate knowledge is becoming substantially more challenging and time-consuming (Muste et al., 2017). Digitalization of conventional resources and accessibility of web-based platforms brings forward the motivation and the means to automatic parsing of resources to extract knowledge. The ontology vision described in this article can inform the scraping, annotation, and structuring of vast digital resources (e.g., web documents, books, videos) for the purpose of generating hydrological knowledge bases.

Intelligent Assistants: Next step to the establishment of hydrological knowledge bases is to make it accessible and analyzable on demand with convenience, hence, offering the required information instantly to decision-makers, researchers, and officials. Voice-enabled and ontology-powered conversational AIs can fulfill the gap of knowledge inaccessibility and allow the stakeholders to extract critical pieces of time-sensitive and spatiotemporal knowledge with human-like interaction by using natural language questions.

Virtual Tutors: Another important application area for intelligent assistants is supporting the education of the next-generation of hydrological and environmental professionals. Virtual teaching assistants can help K-12 and college-level students with their hydrological questions and encourage experiential learning. Such tutors can be powered by ontologies for general domain understanding and fed with course-specific resources (e.g., syllabus, schedule, lecture slides, announcements, homework, quizzes and exams, e-books, forum discussions, class recordings) for dedicated service.

Educational Systems: A major use case for ontologies is to convey the domain dynamics in the educational setting. Ontologies can be integrated into interactive web platforms for visual exploration by students to build conceptual understanding in hydrology and sustainability. Such initiatives are shown to aid in establishing a learning environment to blend theory and practice in a holistic manner by investigating the knowledge maps and comprehending the interconnection among environmental processes (Lalingkar et al., 2014).

Immersive Systems: With the increasing popularity of digital twins and availability of heads up displays with strong graphics processing capabilities, augmented and virtual reality systems (Sermet and Demir, 2020) have become a petri dish for effective communication of in-situ event dynamics, which poses a substantial potential to hydrology in the contexts of a command center, education, and public outreach. While open-source and commercial solutions are available to facilitate immersive application development, domain knowledge has to be integrated for realistic simulations in an efficient and reproducible manner. Ontologies can power immersive applications to embed environmental behavior and interactions (e.g., water flow, structural integrity, sensor data, populational information, weather conditions) into the simulations which in turn enables analytics in addition to observation in extreme conditions, including context-aware hydrological disaster simulations, mitigation strategy assessment, environmental phenomena development.

Machine Learning: The use cases and benefits of deep neural networks in hydrology are well-established ranging from data augmentation (Demiray et al., 2021) and realistic image generation (Gautam et al., 2020). Though often black box approaches are taken to let the data determine the priorities and infer the relevant correlations, physics-informed networks have recently gained traction for both during data preparation as well as network design (Baker et al., 2019). Ontologies provide a remarkable opportunity to drive such experiments by defining constraints, boundaries, and equations in the model training process. Such solutions can especially be fruitful in studies with the goal of increasing the performance (i.e., runtime) of hydrologically relevant operations.

Reinforcement Learning: Going along with machine learning studies, another aspect that can particularly benefit from the domain representation in ontologies is optimization problems. In water resources management, virtual environment representations informed by ontologies can be used to solve complex problems (e.g., forecasting, watershed analysis, reservoir control) via intelligent agents with reinforcement learning. Furthermore, immersive systems can act as a playground for experimentation on a plethora of hydrological optimization problems.

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