Spatial Concepts for Hydrography Ontology Alignment

Dalia E. Varanka and Michelle Cheatham

ABSTRACT: The publication of multiple hydrography ontologies has demonstrated that such applied designs will inevitably result in differences based on varying project perspectives and objectives. The alignment of different models offers the opportunity to link databases for multiple purposes, though the way to do that has not been previously demonstrated. This paper describes an approach to geospatial ontology alignment based on relative spatial relations. Three hydrography ontologies were selected for the manual alignment with the objective to identify a general approach leading to harmonizing differences and expanding capabilities. Some aspects of ontologies were aligned with established approaches of matching annotation properties such as labels or synonyms. In other cases, subclass relations were aligned through the application of standard Resource Development Framework (RDF) vocabularies that support inference. The remaining challenges required deeper semantic analysis. The consistent concept that supported the semantic alignments of designs was spatial relations that are evident through the specification of triple subgraphs. Included are hydrographic features as landform slope enabling the collection and containment of surface water; the extension of a basic feature pattern to form a network enabled by inference on triple properties; and applied hydrography such as engineered features through an upper ontology pattern. The Cartesian product of an instance matrix is proposed as the approach for testing these spatial relations on ontology class sets.

KEYWORDS: Ontology alignment, Hydrography, Spatial relations

Introduction

Geographical space is recognized as a critical element of physical and social environmental studies. Ontology recognizes that all phenomena exist in spatial and temporal dimensions, yet spatial and temporal relations are often omitted as core concepts in applied ontologies. When spatial and temporal relations are included, they may be a peripheral attribute associated with the entity, but not a core concept defining the topical domain. The application of spatial analysis in the sciences and humanities has come to be called the 'spatial turn' and offers an ontological approach that is relevant to geospatial semantics. The spatial turn generally emerged with the work of Michel Foucault, who argued that geography acts as the "condition of possibility for the passage between a series of factors" to be related (Gordon, 1980, p. 77). Though geographical space is an ontological constant, the struggle to represent spatial aspects of ontology relies on models that are socially slanted, even if their technical application seems objective to physical science. For example, cartographers don't always make up hydrography based on what was found on the ground; conventional mapping schemas and practices already existed in the discipline. The manipulation of spatial features and spatial representation that is inherent to geographic information sciences in turn affects the worldview of users and their relation to the environment.

This study focuses on spatial organization as an approach to resolve geospatial ontology alignments that would enable the harmonization of hydrographic aspects of ontologies to expand the semantic aspects of any single design without unnecessary duplication. The hypothesis is that spatial semantics are the defining characteristics is made evident by a manual comparison of three hydrography ontologies. Though ontology design is a result of a perspective, it is also embedded in its technical applications. Geospatial ontology draws from new technologies that could support expanded spatial semantics for the long-range goal to develop a vocabulary that would advance geospatial ontology alignment in general.

The sections of the paper first review ontology alignment in general and geospatial ontology specifically. Established alignment approaches are shown to easily equate some triples with the support of standard Resource Description Framework (RDF) vocabularies (Cyganiak et.al, 2014). The remaining resources to be harmonized are less evident. A discussion of the remaining challenges and the relative spatial relations inherent to them is followed by a proposed method to test for alignment between ontologies using spatial relation rules.

Ontology Alignment

In general, alignment seeks to relate equivalent entities of one ontology to those of another. One approach is to construct a single inclusive ontology where users of one design can see ways to relate terms to different designs within the same model (Manual Ontology Alignment, 2016). This approach, however, is computationally intensive. An alternative method is to create a framework to relate ontology specifics. To do so, a list of the properties that are needed to relate the classes of two ontologies is developed in a way to allow semantic expansion to include other candidate models. This approach was used in this study, described in greater detail below, with the goal of using results as feedback to improve the alignment principles and processes in general.

Ontology alignment approaches consist of three general and interrelated contexts: linguistic, semantic, and structural (Partyka et al., 2008). Alignment along linguistic similarity involves natural language comparisons such as matching labels, comments, or other annotation. String matching can pair exact matches, such as the term 'Waterbody' appearing in more than one ontology and are thus considered equivalent; or set similarity, for example the relation of Feature and HydrographicFeature, where the string Feature is found to closely relate both classes, but not in an exactly explicit way. Semantically understandable content matching consists of mentally comparing natural language concepts to understand how they may relate in ways that do not appear in the ontology annotation or structure. For example, synonyms, such as the terms 'Feature' and 'Object' may be equivalent as they are defined in annotations; or subtle differences between two similar terms, such as 'Spring' and 'River' can be distinguished and formally clarified. Similarity of formalized graph structures is an approach where a small subgraph of triples composing the criteria of a class is compared to others. An example method is described by Parundekar et al. (2010). Structural differences between classes are often variations of semantic specification resolutions.

The alignment approaches mentioned here also refer to coded analysis (Ehrig, 2007). The difference between manual and automated alignment is that though many of the same semantic principles are recognized, the approaches have different strengths. The dataset sizes for which solutions can be considered is significantly smaller for manual alignment, but a better match may be possible that way and the findings can be transferred to automated systems. A reliance on string matching in automated alignment, though effective for automated approaches, is not a high priority for manual alignment. Rather manual techniques are more suited for analyzing user semantics and identifying and designing complex data structure solutions such as triple reification.

Geospatial Ontology Alignment

Large graphs of geospatial linked data are often based on a small vocabulary of geospatial terms. Predominant among these is a single coordinate pair; Geonames.org has properties for latitude/longitude point, feature, and feature type or code (GeoNames, 2015). Instances, usually placenames, are linked by using rdf:sameAs and have no additional alignment. More advanced alignments of geospatial concepts have been demonstrated by modeling ontology classes and properties using class restrictions, such as Web Ontology Language (owl) constraints on cardinal values (Parundekar et al., 2011). Restrictions on classes define the semantics of the term to help identify equivalent and relevant sets. Upper ontologies model knowledge in a generally agreed way to align with applied perspectives. An upper ontology of geospatial water features is available using relations of containment, support and dependence, and variable or rigid wholes (Broderic, Hahmann, and Gruninger, 2015). Upper ontology has been applied in support of data interoperability in a related use case of hydrology (Brodaric and Hahmann, 2014). All three of these approaches – equivalence properties, complex subgraphs, and upper ontology – are relevant to this study.

Hydrography Ontologies

Several applied ontologies address hydrographic concepts for varying objectives (Raskin, 2005; Dornblut and Atkinson, 2014; Buttigieg, et.al, 2013). The ontologies of this study were developed specifically for hydrography: Surface Water Ontology; Semantically Enhanced HydroGazetteer; and Surface Water Network Ontology. The ontologies and their resources will be identified by their International Resource Identifier (IRI) prefix in the rest of the paper.

An ontology called Surface Water Ontology (SWO) was derived from a semantic analysis of a large geographic information system (GIS). The National Hydrography Dataset (NHD) of the U.S. Geological Survey has been the repository of hydrographic data collected over the course of the late-nineteenth through twenty-first centuries (Varanka and Usery, 2015). As such, hydrographic concepts are structured as several relational tables representing the complex NHD data model. The IRI prefix swo: was assigned to this ontology.

A semantically enhanced hydro-gazetteer was designed for the purpose of expanding geospatial feature and spatial reference semantic specifications and to use inference for information retrieval (Vijayasankaran, 2015). The modules include a hydrologic feature ontology that was used in this study and a gazetteer ontology for instantiating the knowledgebase with names, coordinates, and other information. The IRI prefix semgaz: was assigned to this ontology.

The Surface Water Network Ontology was developed by a group of geospatial ontologists at a GeoVoCamp meeting 2013 (Sinha et al., 2014; Berg-Cross, 2013). The resulting ontology design pattern (ODP) is an abstract representation of two modules, the surface water, called the Wet Model, contained within terrain, called the Dry Model. The objective was to identify and represent basic concepts of surface water ontology that are consistent between, yet customizable for use by multiple applications. Though no prefix was used for the Surface Water Network

Ontology modules at the time of their design, the acronym gvc appears in the IRI and was selected for use in this paper as the ontology identifier.

Method

Geospatial ontology suffers from a major drawback that potential users are unfamiliar with the technology. The spread of geospatial semantics depends on building intuitive and easily used tools. A user-centered design (UCD) perspective is taken for the analysis and application of ontology alignment in this study. UCD is a series of processes in which the end users are the focus of the product. For example, logical consistency is a crucial property for geospatial ontology, though most users have limited or no experience with such formal logic. Because a reasonable assumption is that users would select an easily available tool, such as free and open source software, to begin to develop their work, checking the effectiveness of the alignment involved the application of reasoning software in commonly used products such as Protégé (Stanford Center for Biomedical Informatics Research, 2016). Ontology design software typically offers the support of reasoned software that is designed to check the consistency of a logic model, among other things. The user can assume that if the reasoner concludes that a user's ontology is consistent, then the ontology passes the consistency check implemented in the reasoner.

All ontology files of the study were aligned on a one-to-one basis to each other. The formula for the total number of required alignments is:

$$\frac{n\,(n-1)}{2}$$

where n is the number of sets. So, O(ntology)$_1$ must be compared to O_2 and O_3, and O_2 must be compared to O_3 for a total of 3 alignments. The alignments consisted primarily of RDF properties and OWL axioms, and the possibility of developing specific properties needed for the alignment was expected. Triple resources were cognitively compared with the support of a variety of software, including text files, spreadsheets, and concept maps. The analysis of term definitions in glossaries assisted this analysis (Varanka et al., 2011; Caro and Varanka, 2011; Varanka and Caro, 2013). These steps were followed by importing terms to ontology design software to design the alignment framework. Some classes and properties are clearly equivalent or synonymous, based on identical labels or annotated definitions. Examples follow.

Matching annotations

semgaz:Coastline owl:equivalentClass swo:Coastline .
semgaz:Rapids owl:equivalentClass swo:Rapids .
semgaz:Levee owl:equivalentClass swo:Levee .
semgaz:Reservoir owl:equivalentClass swo:Reservoir .
semgaz:Falls owl:equivalentClass swo:Waterfall .

Synonymous annotations

gvc:Exfluence owl:equivalentClass swo:Withdrawing .
gvc:Influence owl:equivalentClass swo:Contributing .
gvc:Fluence owl:equivalentClass swo:Watercourse .
gvc:Terrain owl:equivalentClass swo:Feature .

These alignments required no further specification and were simply serialized and listed.

Classes with subsumption relations are aligned with some adjustment by first applying standard RDF vocabulary and running reasoning software to infer new triples. For example, if one ontology has a class semgaz:HydrologicalFeature and the other ontology has a more specific subclass, such as swo:SwampOrMarsh, then these would have an equivalent parent class through the application of the transitive property (Figure 1). In this way an applied hydrography such as swo can link to or share membership with the core gvc ODP Stream class. This process could apply to any transitive properties in the ontology, followed by manually examining the results.

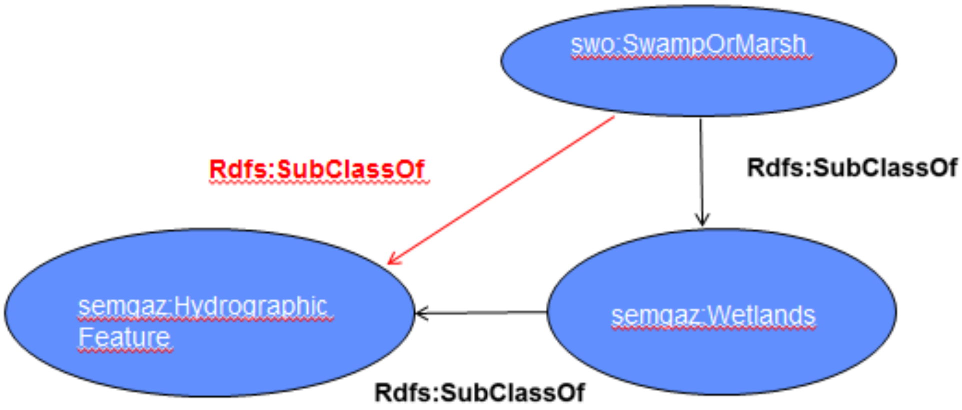


Figure 1: Subclass alignment through Inference

A number of equivalent triples that are evident between two models demonstrate that large, open source databases may influence ontology design in the user community. The semgaz ontology is populated with NHD data and so is similar to the swo ontology, which was a conversion of the NHD GIS data model refined for hydrographical principles. Because the objective of the semgaz ontology was to function as a gazetteer, it included only a subset of NHD classes that typically bear toponyms.

Hydrographers have become accustomed to the unarticulated assumption of treating landform slope and surface water semantics together. One of the first challenges to resolve was the alignment of the key root class semgaz:HydrographicFeature in contrast to swo:Feature, used to indicate a landform, and swo:Flow for surface water elements captured within swo:Feature. The semgaz and gvc ontologies differed in the HydrographicFeature class in contrast to the Wet/Dry models (table 1). The swo and gvc ontologies aligned well along similar specifications for the slope and surface water distinctions and their extension into networks. Water collection for the gvc ODP is indicated by a containment property and the spatial shape of these entities is differentiated into generally channel vs basin types. Swo acknowledges containment as a Boolean relation and makes no such feature shape distinction. None of the ontologies has a property that would infer a third dimension for slope.

Table 1. Classes indicating surface water feature containment and collection

Ontology Objective	Shape/Contains	Collected Water
gvc (general pattern)	Channel	StreamSegment
	Basin	Waterbody
swo (GIS)	Feature	Flow
semgaz (gazetteer)	Hydrographic	

Relatedly, the class semgaz:HydrographicBoundary is the parent class to semgaz:Coastline and semgaz:Watershed and implies the containment of hydrographic networks on land. Boundaries, however, are a part of any nested hydrologic unit, such as a watershed, and of singular landform/surface water features, such as those specified in gvc and swo, e.g., swo:Lake or gvc:Channel.

The hydrographic network representation of all three ontologies is different. Swo has a single class swo:SurfaceWaterNetwork that includes the total number of multiple stream reaches in an dataset within an area of interest as defined by a user. The gvc pattern of a single feature includes gvc:Node for topologically connecting multiple stream segments into a network. The water flow terms are mostly synonymous, but include inverse relations between confluence and divergence, reflecting the natural hydrology in contrast to the engineered applications of water use (Table 2). In contrast to gvc and swo classes, semgaz was designed to build inferred topological networks from a base feature through the application of an extensive property vocabulary (table 3). All three ontologies have asserted properties to model from/to flow direction.

Table 2: Classes indicating network specifications between the GVC and SWO ontologies.

GVC	SWO	Relation
gvc:Fluence	swo:Flow	Synonym
gvc:Confluence	swo:Divergence	Antonym
gvc:Exfluence	swo:Withdrawing	Synonym
gvc:Influence	swo:Contributing	Synonym
gvc:Node	swo:SurfaceWaterNetwork	Meronym

Another difference between ontologies is that the classes for engineered structure types such as dam, gaging station, and levee. The semgaz ontology has triple properties that are linguistically related to those classes, such as the asserted properties :hasDam and its inverse, :isDamOf, and similar ones for :GagingStation and :Levee. In contrast, swo uses a more general property class called :Event to refer to activities pertaining to the stream (Table 3). The swo ontology has a large number of application-specific sub-properties, such as :relationshipToSurface, used with pipelines or other engineered waterways; :stage, for water monitoring; or :status, for operational devices. A primary difference between the gvc and these concepts shared by the swo and semgaz models is that gvc excludes engineered and functional aspects of surface water systems.

When all ontology properties were compiled in a spreadsheet based on their general semantic equivalence, the properties grouped along three general levels. Table 3 shows the organization of object properties as landform/water representations of a feature (colored in beige); network topology (colored in blue); and engineered structures and their function (colored in grey). The set of properties of the gvc ontology relate waterbodies to landform formation, such as :containedBy, :end, or :rim. Properties addressing mereotopologic connections enable inference largely through subsumption and domain and range properties.

Table 3: Ontology properties indicating spatial patterns of alignment

GVC		SEMGAZ			SWO	
containedBy		isPartOf	isHydrologicPartOf	isFreshWaterBayOf		
end	lowerEnd			isMainStemOf		
	upperEnd			isRapidsOf		
endOf	lowerEndOf			isSaltWaterBayOf		
	upperEndOf			isSubWatershedOf		
sink		hasPart	hasHydrologicPart	hasFreshWaterBay		
source				hasMainStem		
hasJunction				hasRapids		
rim				hasSaltWaterBay		
shoreline				hasSubWatershed	temporality	
		hasHydrographicRelation	flowsfrom		flow	
			flowsinto			
			flowsthrough			
			has inflow			
			has outflow			
			is downstream to			
			is upstream of			
		isHydrologicallyConnectedTo	hasMouth		spatialExtent	
			hasSource			
			hasTributary			
			isMouthOf			
			isSourceOf			
			isTributaryOf			
		hasHydrographicStructure			event	
			hasDam		status	inundationControlStatus
			hasGagingStation		stage	operationalStatus
			isDamOf		constructionMaterial	
			isGagingStationOf			
					relationshipToSurface	
					product	

Not all ontology terms of this study could be aligned. Some terms, particularly measurement units such as swo:Acre, swo:Mile, swo:Area, or swo:Length, would be appropriate to link to other commonly used standard ontologies such as the Open Geospatial Consortium Observations and Measurements Ontology that would further connect ontologies over the Semantic Web (Cox, 2012).

Spatial Relations

The previous section presented alignment challenges. This section describes the alignment of the three hydrography ontologies by developing subgraph structures that succeed for almost the entire set of the ontology elements. These structures that combine spatial concepts of feature, network, and applications, with established alignment approaches. The alignment approaches are the ODP; the extension of the ODP to a network based on reasoning; and an upper ontology pattern called Realizable Entity for applications.

Ontology properties support an expanded system of sets beyond the taxonomic tree-like structure that are called asserted or named classes. Such sets, created by selecting a number of criteria in the form of attributes, are sometimes called anonymous, defined, or unnamed classes, meaning they consist of a graph of an entity formed by its relations that describe it (Allemang and Hendler 2011). Such sets are often defined by the application of owl:equivalentTo property used for their formation. This approach is used for analyzing the spatial relations for semantic specification. It has the advantage of allowing covered sets, whereby entities can be included in multiple concepts.

The critical spatial abstraction at the geospatial feature level is primarily the addition of a third dimensional variable in the form of landform slope to the semantic vocabulary to account for water collection and containment. The ontology of surface water delineates the difference between a contained space, formed by the static terrain, and water that fills, but also flows through it as an event or process, not an object (Hayes, 1985). Further, the boundary concept refers to earth elevations, particularly slope. The gvc ontology accounts for this variable with an asserted property gvc:contains, a natural language preposition. Semantics are required to complete the necessary specifics for these surface water feature creation criteria, for example the ontology of contour lines (Hahmann and Usery 2015).

Spatial property string matching failed as a method for alignment the gvc and semgaz with regards to structuring a network from a base feature (Cheatham, 2014). A smaller number of gvc properties were generalizations of more specific semgaz properties that were labeled with natural language terms. For example, the properties gvc:sink and gvc:source include a variety of types of points at which water flow begins or ends a stream segment; these include the semgaz properties :flowsFrom, :flowsTo, :hasInflow, :hasOutflow, :hasMouth, and :hasSource. This difference can be resolved through the application of inference through property/subproperty relations. In expanding the topological characteristics of surface water networks, the class semgaz:Boundary, meaning the edge of networks at the interface with wider terrain boundaries, such as Coast or Watershed, was added to the surface water/landform distinction of the gvc feature ODP.

As shown in Table 3, surface water network relations may be explicitly inferred through topological relations using domain and range classes. More specific hydrographic network concepts such as routes and paths can be determined using mereotopological approach as well. The relation :partOf is transitive, and augments the topological approach (Rector and Welty 2005). Spatial properties would again be essential to such specifications. Examples of spatial qualities can be found implicit to the semantics of asserted object classes and properties. For example, spatial relations are implied in subclasses of gvc:Fluence despite that the gvc ontology intentionally excludes spatial and temporal details of instance data.

An alignment problem was the distinction between classes normally thought of as natural vs. designed, similar to land cover classes like :Lake in contrast to land use classes like :RecreationArea. The class semgaz:hasHydrographicStructure relates engineered objects to the surface water feature. Engineered features normally serve a purposeful role or function reflected in their related classes and properties. Sometimes these relations are implied but left ambiguous by similar string matches in the entity labels, as in semgaz:GagingStation and swo:StreamGauge. Such correspondences can be classified as Realizable Entities as described in the Basic Formal Ontology, prefix bfo: (Arp et al., 2015).

Bfo:RealizableEntity involves the bearer of a disposition that assumes a function or role through a process of realization. Examples shown in Figure 2 indicate different levels of generalization. With time, realizable entities may lose their function or role, or it may change – a quarry may eventually fill with water and become a local swimming spot – but the physical bearer continues to exist. Thus, time is a defining element of a realizable entity, for its process of realization and for its period of existence.

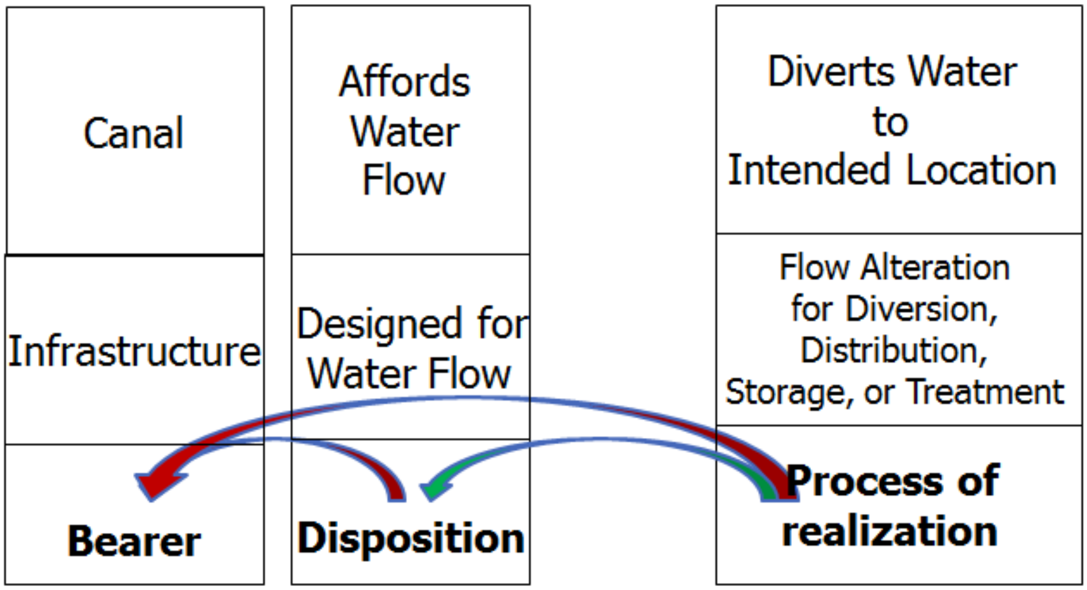


Figure 2 : Engineered hydrographic features as realizable entities using water infrastructure and canal as examples. Figure is based on one published in Arp et.al., 2015.

Spatial realizable entities are entities that are realized though a spatially based process. The distinction made by the semgaz ontology between freshwater and saltwater features demonstrates this idea. The primary distinction between freshwater and saltwater is the salinity of the water. Without resorting to a hydrology ontology that specifies water quality, freshwater can be considered as the realizeable entity of saltwater after it undergoes a spatial realization process consisting of evaporation from the oceans, movement over the continents, and collecting on the earth's surface as the result of precipitation. Freshwater is spatially contained within the continental borders, except in areas of brackish water that have an outlet. Figure 3 illustrates how a number of hydrographic categories are spatially controlled and for which spatial semantics may organize a number of attributes.

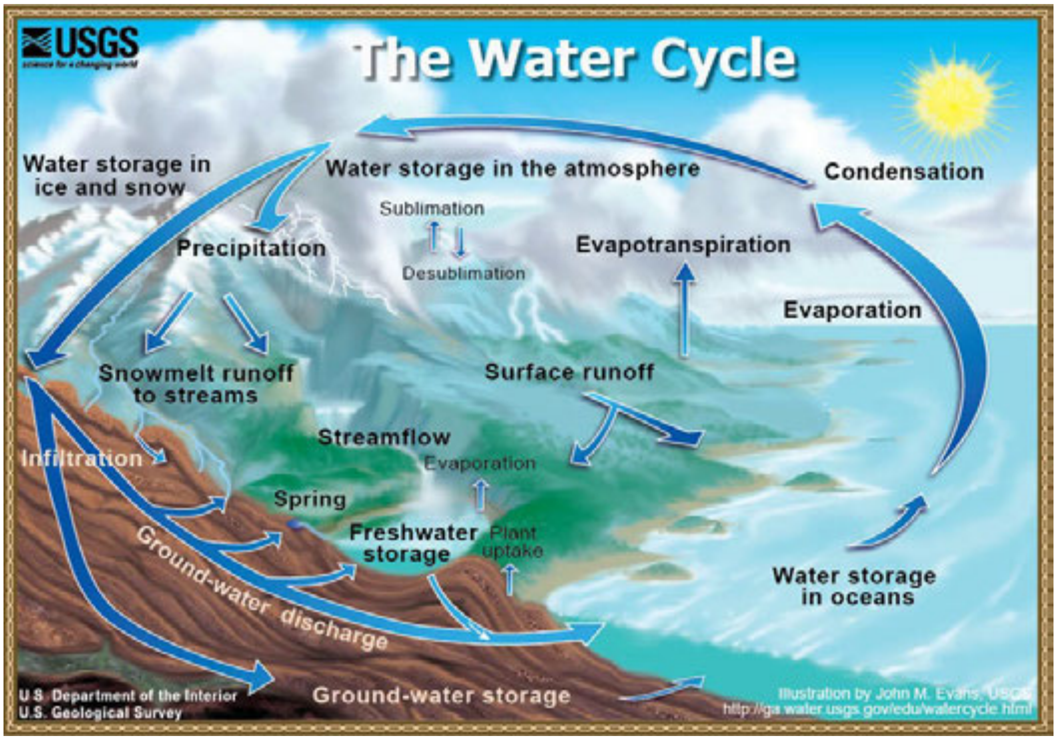


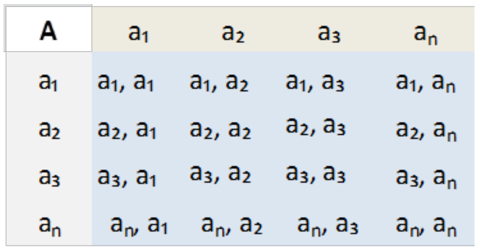
Figure 3: The hydrologic cycle as spatially depicted.

Spatial Alignment

The proposed alignment approach uses the classes and properties of the ontologies to compile an instance matrix of the Cartesian product of the sets. Relative space is a property defined on a set of objects and that orders members of sets as a system of interconnected relations. Such spatial separations can be described in many ways, not just in metric or geometric terms. Some possible approaches to analyzing relations on sets include drawing a map, diagramming a graph depicting objects as vertices and their relations as lines, or populating an incidence matrix for binary or weighted relations. The relations are the object of an inquiry itself (Gatrell, 1983).

The application of an instance matrix determines relations between all classes of two ontologies for alignment. Cartesian product is the set of all ordered pairs obtained by taking an element of the set of ontology classes as a member of the pair. The concept is visualized as shown in Table 4.

Table 4. Basic framework of an instance matrix



A	a_1	a_2	a_3	a_n
a_1	a_1, a_1	a_1, a_2	a_1, a_3	a_1, a_n
a_2	a_2, a_1	a_2, a_2	a_2, a_3	a_2, a_n
a_3	a_3, a_1	a_3, a_2	a_3, a_3	a_3, a_n
a_n	a_n, a_1	a_n, a_2	a_n, a_3	a_n, a_n

A relation on a set may be defined as a subset of the Cartesian product set. Relations are defined either by listing all ordered pairs that are related, or by postulating a defining property or rule that associates some or all of the elements of A with each other. The later approach is used because it allows the introduction of new ontologies. Relations determined to be reflexive, symmetric, and transitive are equivalent.

In the same way that a property such as bfo:function serves as a parent class of properties specific to engineered object classes, such as swo:impound, we create parent classes of properties that can serve as rules. Taking all classes (sets) from the sample ontologies and all properties (relations), we abstract higher typologies for possible rule tests: mereotopology of lowness and slope, and containment and flow of surface water. The first type will be called mereotopological relations and the second type will be called prepositional relations, as reflected by their respective ontology properties. The gvc ODP has three types of classes shared by both the Wet and Dry models: areas of terrain lowness, both elongated and round-like, and nodes of converged or terminal lowness. The properties between them are almost all mereological except for gvc:containdBy that connects the Wet and Dry models. The ODP in general organizes sets as part of a single feature and the relations between multiple features as a part of a complex. The mereotopological and prepositional relations are expressions of the postulated rules for comparing the two ontologies for upper level relations.

Specific steps are to compile the set of all object classes, discounting string matches, also synonyms if possible; then classify triple properties associated with the classes as subtypes of mereotopology or prepositional parent classes. Actual properties will be considered as one of the two types where they occur between sets. Their binary presence may indicate alignment between classes if variations between subproperties are just linguistic or some other informal types.

Conclusions

Efforts toward hydrography ontology matching had mixed results when based on methods proposed in alignment literature, particularly when based on matching annotations, semantic comparisons, and subsumption relations. Closer examinations of the different ontology terms revealed key concepts and relationships of consensus definitions suggesting that different models matched well along spatial relations. These spatial relations were often embedded or assumed in asserted triple resources. Specifying spatial relations, together with established methods of ontology pattern applications, inference, and upper ontology aligned almost all of the hydrography model vocabularies, including engineered realizable entities. A hydrography ontology that enables the capabilities of anyone model could be assembled from multiple patterns for specific objectives, rather than devoting an entire ontology to a single function.

References

Arp, R., Smith, B., Spear, A.D. 2015. Building Ontologies with Basic Formal Ontology. Cambridge, Massachusetts. The MIT Press.

Berg-Cross, G. 2013. GeoVoCampDC2013. http://vocamp.org/wiki/GeoVoCampDC2013.

Brodaric, B. and Hahmann, T. 2014. Toward A Foundational Hydro Ontology For Water Data Interoperability. International Conference on Hydroinformatics. CUNY Academic Works. http://academicworks.cuny.edu/cc_conf_hic/424.

Broderic, B., Hahmann, T., and Gruninger, M. 2015. An Ontology Representation for Water Bodies. American Geophysical Union (AGU) Fall Meeting, San Francisco, CA. December 16, 2015.

Buttigieg PL, Morrison N, Smith B, Mungall CJ, Lewis SE, and the ENVO Consortium (2013) The environment ontology: contextualising biological and biomedical entities. J Biomed Semant. 4:43

Caro, H.K. and Varanka, D.E., 2011, Analysis of spatial relation predicates in U.S. Geological Survey feature definitions. U.S. Geological Survey Open-File Report 2011-1235, 37 p. http://pubs.usgs.gov/of/2011/1235/.

Cheatham, M. 2014. The Properties of Property Alignment on the Semantic Web. Ph.D. Dissertation, Computer Science and Engineering Ph.D. Program, Wright State University.

Cox, S.J.D. 2012. An explicit OWL representation of ISO/OGC Observations and Measurements. Proceedings of the 6th International Workshop on Semantic Sensor Networks co-located with the 12th International Semantic Web Conference (ISWC 2013).

Cyganiak, R., Wood, D., and Lanthaler, M. 2014. RDF 1.1 Concepts and Abstract Syntax. W3C, accessed July 15, 2016 at: http://www.w3.org/TR/rdf11-concepts/.

Dornblut, I. and Atkinson, R. 2014. OGC HY_Features: a Common Hydrologic Feature Model. OGC 11-039r3. Open Geospatial Consortium.

Ehrig, M. 2007. Ontology Alignment, Bridging the Semantic Gap. Springer.

Gatrell, A.C. 1983. Distance and Space: A Geographical Perspective. New York, Oxford University Press.

Gordon, C., Ed. (1980) Power/Knowledge: Selected Interviews and Other Writings, 1972–1977. New York: Pantheon.

Hahmann, T. and Usery, E.L. 2015. What is in a Contour Map? A Region-based Logical Formalization of Contour Semantics. Proc. of the Int. Conference on Spatial Information Theory (COSIT-2015), LNCS, Springer.

Hayes, P. (1985) Naive Physics I: Ontology of Liquids. in: J. Hobbs and R. Moore (Eds.), Formal Theories of the Commonsense World. Norwood, NJ: Ablex, pp. 71-108.

Manual Ontology Alignment. University of Texas at Dallas Semantic Web Repository. Accessed June 9, 2016 http://www.cs.utdallas.edu/semanticweb/Ont-Alignment/Manual/Manual_Alignment_Writeup.pdf

Partyka, J., Alipanah, N., Khan, L., Thuraisingham, B., and Shekhar, S. 2008. Ontology Alignment Using Multiple Contexts. Proc. Of International Semantic Web Conference (Posters & Demos), Karlsruhe, Germany, October, 2008.

Parundekar, R., Knoblock, C.A., and Ambite, J.L. 2010. Aligning Ontologies of Geospatial Linked Data. In Proceedings of the Workshop on Linked Spatiotemporal Data in Conjunction with the 6th International Conference on Geographic Information Science (GIScience 2010).

Parundekar, R., Ambite, J.L., and Knoblock, C.A. 2011. Aligning Unions of Concepts In Ontologies of Geospatial Linked Data. In Proceedings of the Terra Cognita 2011 Workshop in Conjunction with the 10th International Semantic Web Conference, Bonn, Germany, 2011.

Raskin R, Pan M: Knowledge representation in the semantic web for Earth and environmental terminology (SWEET). Comput Geosci 2005, 31:1119–1125.

Rector, A. and Welty, C. 2005. Simple part-whole relations in OWL Ontologies. W3C Editor's Draft 24 Mar 2005. W3C. Accessed March 14, 2016 http://www.w3.org/2001/sw/BestPractices/OEP/SimplePartWhole/simple-part-whole-relations-v1.3.html

Sinha, G., Mark, D., Kolas, D., Varanka, D., Romero, B.E., Feng, C., Usery, E.L., Liebermann, J., and Sorokine, A. 2014. An Ontology Design Pattern for Surface Water Features. Proceedings of Geographic Information Science, 8th International Conference, GIScience, Vienna, Austria, September 24-26, 2014.

Stanford Center for Biomedical Informatics Research. 2016. Protégé. Stanford University School of Medicine. Accessed June 7, 2016 http://protege.stanford.edu/

Varanka, D.E., Carter, J.J., Shoberg, T., and Usery, E.L., 2011, Topographic Mapping Data Semantics Through Data Conversion and Enhancement, *in* Sheth, Amit and Ashish, Naveen, Eds., Geospatial Semantics and the Semantic Web, Foundations, Algorithms, and Applications. Semantic Web and Beyond, Vol. 12: Computing for Human Experience, Springer. P. 145–162.

Varanka, D. and Caro, H., 2013, Spatial Relation Predicates for Topographic Data Triples. In Martin Raubal, Andrew Frank, and David Mark, Eds., Cognitive and Linguistic Aspects of Geographical Space, New Perspectives on Geographic Information Research. Lecture Notes in Geoinformation and Cartography Springer. p. 175-193. http://cegis.usgs.gov/pdf/Varanka-Caro_2013predicates.pdf.

Varanka, D.E. and Usery, E.L. 2015. An Applied Ontology for Semantics Associated with Surface Water Features. In Karl Ahlqvist, Dalia E. Varanka, Steffen Fritz, and Krzysztof Janowicz, Eds., Land Use and Land Cover Semantics: Principles, Best Practices, and Prospects. Boca Raton, Florida, CRC Press.

Vijayasankaran, N. 2015. Enhanced Place Name Search Using Semantic Gazetteers. Masters thesis, University of Maine.

Dalia E. Varanka, U.S. Geological Survey, U.S. Department of the Interior, 1400
Independence, Rolla, MO 65401

Michelle Cheatham, Department of Computer Science and Engineering, Wright State
University, Dayton, OH 45435