# 7

# An Applied Ontology for Semantics Associated with Surface Water Features

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CONTENTS





**ABSTRACT** Surface water land cover plays a major role in a range of geographic studies, including climate cycles, landform generation, and human settlement and natural resource use. Extensive surface water data resources exist from geographic information systems (GIS), remote sensing, and real-time hydrologic monitoring technologies. An applied ontology for surface water was designed to create an information framework to relate data in disparate formats. The objective for this project was to test whether concepts derived from a GIS hydrographic data model based on cartographic relational table attribute data can be formalized for semantic technology and to examine the differences evident using the ontology for database semantic specification. The surface water ontology was initially derived from the National Hydrography Dataset (NHD) GIS data model. The hypothesis is that ontology semantics can be consistent with a long-term empirically collected database. An automated conversion of classes and properties was then manually refined with the support of an upper ontology. The results were tested for reliable class associations, inferred information, and queries using SPARQL Protocol and RDF Query Language (SPARQL). The ontology reflects studies of the physical environment, the objectives of the supporting institution, the reuse of GIS, and the adaptation of semantic technology. The results contribute to the development of an ontology model that leverages large data volumes with information user access. 

**KEY WORDS:** *geospatial ontology, hydrography, semantic technology.*

## 7.1 Introduction

Surface water accumulates in depressions on the earth's surface at geographic scales, persists for periods of time, and flows or recedes over the surface as a function of elevation. Surface water is a primary category of human environmental interest; its study and representation as land cover has a long history. The charting of surface water crosses cultures, technologies, and symbolic languages. The recognition of surface water features results in part from the direct experience of the environment, such as from overland travel, but because features at the geographical scale can become too broad to easily see, then ideas of landscape often result from the study of geographical texts and maps. Varying criteria are possible for categorizing and labeling surface water entities in texts. For example, water bodies may persist over a period, or appear periodically or intermittently due to movement through seepage, replenishment by precipitation, or loss through evaporation. In many cases, the specific meanings of categories become ambiguous when separated from their context or defined by different groups of users.

Ontology is the study of what exists, and findings from this branch of philosophy can be applied to guide the design of data models. A central objective of applied ontology is to specify semantic information about data that usually remain within a broader context of knowledge and experience of users, or are represented in texts such as writing or graphic sources. Such knowledge is not encoded as part of the data but provided cognitively by the user during database interaction. Such contextual semantics are difficult to include as coherently reasoned media because they are technically incompatible with geographic information system (GIS) databases, the conceptual developments of which are based on expanding the capabilities of mapping by manipulating related data attribute tables.

The National Hydrography Dataset (NHD), the surface water component of *The National Map* of the U.S. Geological Survey (USGS), is one such GIS database (USGS 2014a, 2014b). The NHD is the digital version of the surface water theme appearing on topographic maps of the United States since the late nineteenth century. The data were collected according to surveying instructions, both from field and aerial photography sources, and converted from maps to digital vector data in the late twentieth century. The NHD is centrally maintained with information edits from state partners, resulting in a complex technical design that has been developed over 25 years by an extensive user community. An ontology design for surface water data and its integration with empirical data as a semantic technology system are expected to improve the clarity of surface water data such as the NHD. In turn, empirical data are needed to validate ontological surface water concepts.



The objective of this study is to present the development of a surface water ontology for semantic technology that reflects information about real-world entities and leverages legacy databases aligned with a different technical data model. The vision for the ontology is that its future application by users will aid accessibility to the data. The approach is to build semantic concepts with ontology modeling practices on a foundation of NHD data as they were developed through extensive hydrographic modeling practice, and to test whether this specific surface water ontology, which will be called SWO NHD, can be used to clarify the NHD semantics that are not supported or are often confusing in GIS. Typical of GIS, the NHD data model consists of numerous tables defining feature classes in various forms: as points, lines, and areas; as feature domains (types); events; the Watershed Boundary Dataset (WBD); attribute tables; metadata; and processing domains. The hypothesis is that a semantic approach will clarify these tables, making them more categorically aligned with the expectations of users. This will be achieved by reorganizing the geometrically constrained data categories, clarifying codes, and relating similar concepts to reduce redundancy while still supporting semantic detail.



The sections of this study are organized as follows. Section 7.2 is a review of significant literature on applied surface water ontology, and the approach is briefly summarized in Section 7.3. Section 7.4 details the development of the SWO NHD. The steps include the automated conversion of NHD data from GIS to Resource Description Framework (RDF) triples that result in an ontology called GIS NHD and the manual refinement of the GIS NHD as the SWO NHD (Cyganiak et al. 2014). The SWO NHD follows top-level knowledge models, including upper ontology and surface water science. The SWO NHD has an instance database component organized as gazetteer. Section 7.5 describes testing the SWO NHD by applying reasoning to the ontology for inferred triple statements, and Section 7.6 describes information retrieval using use case queries with competency questions and SPARQL graph patterns. The ontology application is followed by discussion and conclusion. The digital ontology file is available on the Internet (Varanka 2014).

## 7.2 Literature

An ontology design is abstracted from the context of a subject at varying levels, including the physical world; cultural abstractions represented through language; quantitative, scientific, and logic models; upper ontology concepts; and technical implementations. Research contributions have been made toward these aspects of surface water ontology, though toward different objectives and with varying parameters. The results of some key studies are summarized in this section.

The study of semantics normally begins with natural language. In a major systematic linguistic analysis, the lexical term "body of water" was parsed into English-language synsets by the WordNet project (Princeton University 2014). Body of water was assigned to domain categories of river, lake, and ocean, and related with two predominant properties, type and part, to broader or narrower classes. This synset provides a basic level of surface water semantics, but excludes important spatial and temporal relations, and provides no other context for each term other than a natural language definition (gloss). Synsets are designed for computational linguistics and natural language processing, related to semantic technology, but different in their focus on informal terms rather than formal variables and relations; terms in semantic technology are arbitrarily assigned labels.

Although language is an important source for ontological analysis and resolution, linguistically derived ontology will lead to several inconsistencies because terms vary for reasons such as cultural and geographic difference, geographic scale, or technological approach. Research in multilingual categorization indicates the complexity of drawing equivalent or related classes for data integration or interoperability of multilanguage spatial data infrastructures (Duce and Janowicz 2010; Feng and Sorokine 2014). Although these studies confirm the variability in the concepts used to distinguish water features between languages and cultures, some qualities, such as shape and size differentiation, may be widely recognized across cultures.

A hydrology ontology published by the British Ordnance Survey (OS) is rooted in national topographic data sources similar to SWO NHD. The files list extensive geospatial feature types as primitive classes with spatial relation properties, Web Ontology Language (OWL) axioms, and annotations to help clarify the semantics (OS 2008; Hart and Dolbear 2012; W3C OWL Working Group 2012). The ontologies are supported by reasoning software. Most terms, however, rely on information derived from natural language with few defined classes that specify class criteria based on ontological analysis. Because a large number of information queries are satisfied by identifying the taxonomic type of a geospatial feature, hierarchy and subsumption play a central role in ontology development and function. Taxonomic specification is limited, however, with a single property between primitive, meaning basic, terms. Primitive terms alone are insufficient in specifying the relations forming a complex proposition formed by multiple related properties. Without a formally defined framework involving properties such as parts or specifically identified properties for the application, an ontology composed of predominantly natural language terms lacks sufficient specificity and equivalence for the operation of inference.

Ontologies aim to resolve semantic variability by creating restrictions on category criteria that reflect complex relations. Among these may be aspects of physical reality based on direct observation or experience of the world, such as size, shape, and material. Property restrictions to include spatial semantics may be functions such as navigation, force dynamics such as water flow, or metric values such as hydrographic shape or size. For example, an ontology of Cree hydrography specified geospatial feature pairs, such as big brother/little brother lakes (Wellen and Sieber 2013). Quantitative methods have been applied for surface water ontology design, including artificial neural net processing (Li et al. 2012). Santos and Bennett (2005) used formal concept analysis to create a concept lattice of object attribute ranges for the water domain: shape, size, flow, depth, and origin. Supervaluation semantics are applied to model threshold-value variability (Bennett 2001). This approach differs from the development of ontology from cognitive or experiential-derived observation, where specifics can be applied at the instance level. The automatic classification of quantitative data helps build ontology by identifying salient qualities from reoccurring instances of a preselected object.

Hydrographic ontology requires further logical restrictions based on systematically organized science principles concerning surface water features. For example, the objective of EnvO is the formalization of environmental ontology (EnvO 2013). In the EnvO ontology, surface water is a subclass of water and environmental material. EnvO has a class called Hydrographic Feature, defined as "a geographical feature associated with water" with 22 subclasses. Unfortunately, variability, even among scientists, persists. Synonyms for Hydrographic Feature include Fluvial Feature, Marine Feature, Tidal Rip, Upwelling, Eddy, and Overfalls; these classes are not synonyms with one another. Some of these terms could arguably be called superclasses of feature events; others could be events rather than features of an enduring type. Some sibling classes include mixed surface water/terrain features types, such as island, inlet, coast, and harbor, but also include biological elements to surface water, such as algal bloom, or causes, such as beaver dam; and engineered features such as wells, which are subsurface water.

The extension of spatial representation to other science ontologies is an important function of a surface water ontology. The realm HydroBody module of the Semantic Web for Earth and Environmental Terminology (SWEET) ontologies has mostly hydrologic classes and properties, such as MethaneIce, with some included hydrographic features, such as Floodbank (SWEET 2013). The class Coastal, sharing the EquivalentTo property with CoastalRegion, for example, has sibling classes consisting of mechanical and chemical hydrology, imported from other separate modules. Unlike SWEET, the SWO NHD aims to clearly define spatial elements while supporting hydrologic modeling.

Hahmann and Brodaric (2012) clarified aspects of hydro-ontology by formalizing spatial voids, primarily holes and gaps that help define the integration of surface and subsurface parts of hydrogeology. Voids define areas within the earth's surface or other physical materials that host surface water. A top-level ontology was used to establish rules for earth/water spatial properties within voids. The demonstrated research of the study specifically focuses on groundwater formalizations, but that can also apply to the creation and persistence of surface water areas or features within their terrain hosts for surface water. Upper ontology also guided a surface hydrologic ontology developed with the Basic Formal Ontology (BFO) for the design of a hydro-ontology (Feng et al. 2004).

A surface water ontology pattern published by Sinha et al. (2014) is composed of two essential modules, one representing earth surface terrain that supports the accumulation and flow of water, called a dry model, and the second representing surface water and its properties, called a wet model. The central focus of the ontology is that the dry model influences the shape of the water bodies and water courses in the wet model, but water flow and pooling, and flow direction, is modeled in the wet model. The nature of a pattern is that as a small ontology, reasoning may be complete within the pattern, but is incomplete when expanded to specific applied situations (Gangemi and Presutti 2010). For example, though channels need incline to be on a path of greatest descent, elevation and slope are neither implied in the Dry Model, nor are obstructions and natural or artificial diversions such as dams or rapids. These exclusions are partially because other inputs for determining flow and pooling are possible, such as groundwater rise and rainfall. Instances of Fluence, an object class defined in the ontology pattern roughly representing surface water flow, would normally include "micro" features, such as water turbulence, mixing of water qualities such as temperature, and so forth, or the extension of a feature into a topologically joined feature, such as the movement of a river beyond the ocean coastline. Such microfeatures are neither accounted for by the pattern, nor are events such as flood conditions. Also, there are no prescriptive directions for feature geometry, for example, whether a channel should be represented as a line or linear feature with width. However, the presence of features may be scale independent, so the basic ontology model is not affected greatly this way.

Surface water ontologies have contributed linguistic propositions, quantitatively measured morphology, earth science dynamics, and formal logic designs to surface water studies. The SWO NHD allows for these ontological sources, and adds the benefit of technical integration with GIS and a large empirical database. An approach to creating a stable ontology that systematically organizes extensive data must allow repeated application with changing empirical detail and is sufficiently abstract so that inference relations produce intuitively true statements. These goals, used in the approach to develop the SWO NHD, are detailed later.

## 7.3 Approach

Classes and properties for the SWO NHD were initially converted directly from the GIS data model of NHD to enable the capture of all concepts considered to be relevant to the database users and to capture all legacy data. This initial version of the SWO NHD is called GIS NHD. In addition to classes and properties, many domain and range sets were identified based on the GIS attribute table. GIS NHD was manually aligned with top-level concepts, particularly upper ontologies, geographic theory, and RDF data model design. The SWO NHD is characteristic of descriptive logic, involving classes, instances, and properties, and first-order logic, such as domain and range classes (Pease 2011). Restrictions were applied to surface water domain–level classes and properties, such as hydrographic feature types, surface water flow processes, and spatial and temporal constraints.

The resulting version of the ontology was validated by producing inferred triples using SPARQL Inference Notation (SPIN) and examining the results to see if they seem reasonable. Three use cases and corresponding competency questions and SPARQL queries were developed to demonstrate capabilities for retrieving data that could be particularly challenging using GIS. These include "What types of waterbodies are subject to inundation?" and "What is the temporality of surface water flow associated with particular terrain feature types?" Lastly, the project is discussed and conclusions drawn.

## 7.4 Surface Water Ontology

### 7.4.1 Geographic Information Systems National Hydrography Dataset

The initial trial triple data were converted directly from GIS relational tables to the RDF triple data model by a custom designed program creating subjects from unique identifiers of rows, properties from column headings, and objects from cell values (Mattli 2013). Output triples of data from *The National Map* use Resource Description Framework Schema (RDFS) and OWL vocabulary terms in addition to RDF (Brickley and Guha 2014). Universal Resource Identifiers (URIs) are assigned to each resource and can be found in the header of the RDF document. The relational data model of NHD stores segments of the spatial geometry of features as unique rows in a database table, but the conversion program creates geometry objects in Well Known Text (WKT) format for GeoSPARQL standard compatability. The sample data set includes almost all NHD classes and properties, but is not an exact replica of NHD data at any specific time or version. The NHD data model changes and inconsistencies may occur between the data model and data set documentation.

After the sample data set was converted, it served as a starting point for further ontology development (Viers 2012). No URIs were created for table row groupings of geometry feature classes—point, line, and polygon—because the instance triples in the ontology, which is not constrained by geometry, were reorganized into topographic feature classes. In addition to feature instances created by the conversion program, however, tables specifying the column formats were manually converted to domain and range classes for NHD properties as part of the ontology. This allowed all instances, that is, rows with unique identifiers that share the same generated attribute values, to be part of the domain class that restricts the instances the property can draw upon to serve as the subject. For example, the NHD table called NHD VerticalRelationship describes three column headings available to any instance that participates in a vertical relationship, where one feature crosses over another feature. The relationship itself has an ID (Permanent_Identifier), the feature above has an ID (Above_Permanent_Identifier) and the feature below has an ID (Below_Permanent_Identifier). Those three attributes were converted to properties to connect subjects to the possible or allowed object values, for example belowPermanentIdentifier. By establishing NHDVerticalRelationship as the domain class for belowPermanentIdentifier, only members of NHDVertical_Relationship are useable subjects for that property.

Because the conversion resulted in the creation of a very large number of properties, a subset of data triples was selected to focus on the specific question of surface water feature types. Though the design and recognition of feature types and classes are highly cognitive, implementations to support geospatial data analysis involve technical specification as well. Classes and properties without geospatial qualities, such as source data identification, were not considered. Much of the information that was unspecified in SWO NHD was moved to other modules where they could be linked to other major ontologies used within the semantic technology community, such as one of several well-established provenance, metadata, or business systems ontologies (Figure 7.1). Important linkages exist for dimension and measurement units, such as the OGC Observations & Measurements ontology to provenance ontologies such as PROV-O and others (Cox 2011; Lebo et al. 2013). No software is known for ontology-driven mapping, but data can be exported to the Geography Markup Language (GML) to be digitally mapped.

New classes and properties were created only when essential and missing from the many column headings that were converted to properties from the GIS NHD model. The need for new triple resources occurred because of unspecified assumptions in the database or the lack of properties due to the tabular design of GIS rather than graphs.

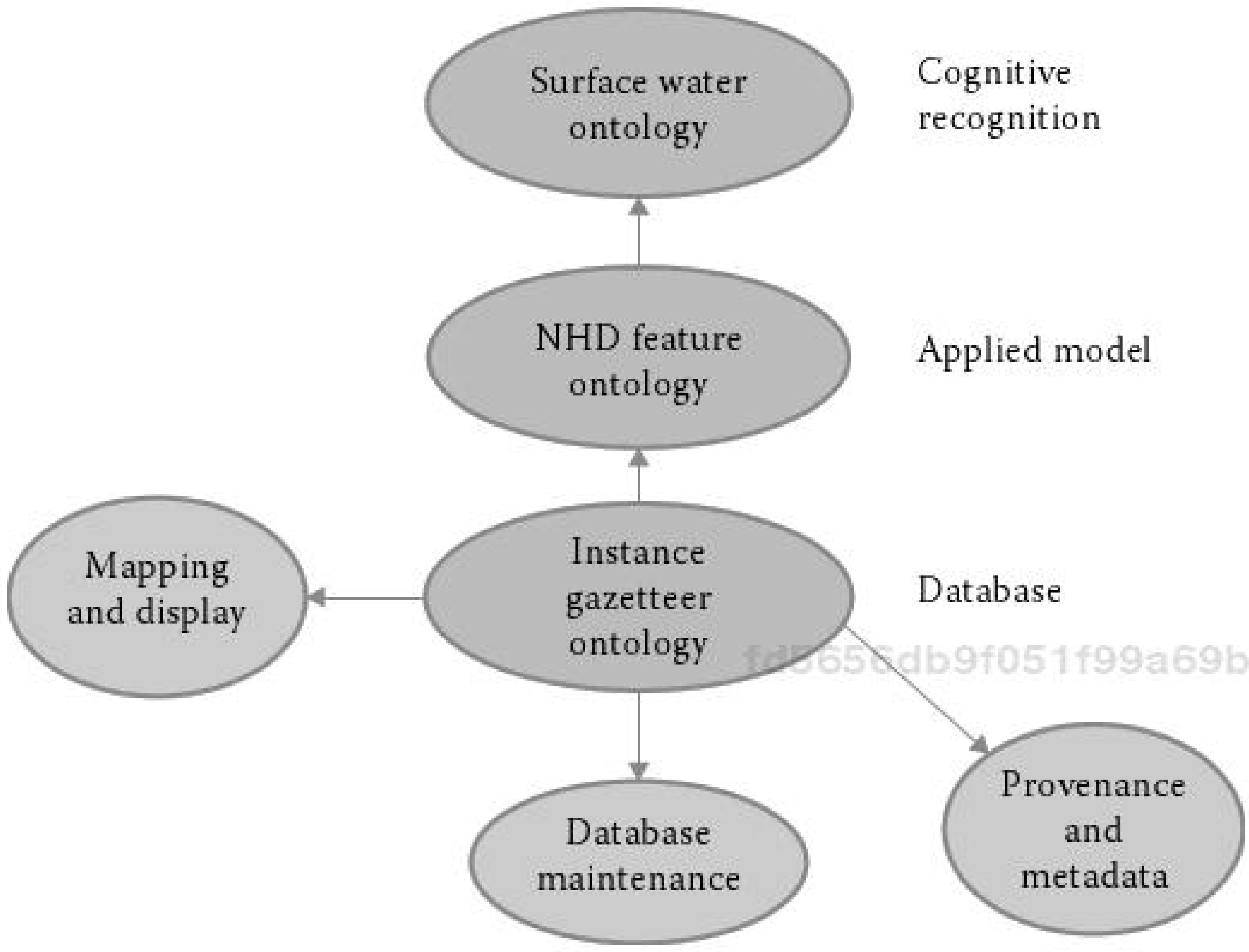


**FIGURE 7.1**
Surface water ontology layers and ancillary modules.

### 7.4.2 Top-Level Concepts

Though top-level principles are relatively independent of more specific subject domains, guidelines from upper ontology, geographic theory, and general database design principles provided insight to more specific SWO NHD classes and properties. Upper ontologies were used to provide guidance for forming the taxonomic order. Geographic concepts, such as elevation measurement, provided insight to interrelations between entities. Database design aligned the ontology to the instance gazetteer.

Upper ontology formalizations specify the relations between material objects and nonmaterial concepts and their attributes, such as qualities, roles, and the processes within which they engage. These general rules then apply to subject-specific subclasses and subproperties through inference, the inheritance of relations through the transitive property. Two documented upper ontologies were used: the BFO and the Suggested Upper Merged Ontology (SUMO) (Pease 2011; Smith 2014). For more intuitive understanding of the ontology described in this study, some upper ontology concepts were renamed to more specifically indicate spatial surface water land cover concepts. The *natural language* term is rather arbitrary because the ontology resource is defined by the formal logic.

Every triple resource (subject, property, or object) representing an entity takes the conventional form of a qualified name, meaning a prefix to indicate the URI separated from the class, property, or instance name by a colon. For example, BFO uses bfo as the prefix for its qualified names, so an example of a class name from that ontology is bfo:Entity. Class and property names of the SWO NHD described in this study omit the prefix of the namespace and use just the colon before the resource name, as in:flow, to indicate that SWO NHD is the default ontology being referenced. Class names begin with uppercase letters and property names begin in lowercase letters.

The surface water feature concept is defined by two general parts: topography, meaning the solid earth, and surface waterflow. When a drop of rainwater falls on the land, it flows downslope toward a singular water feature accommodated on and within the terrain, such as a stream. Surface water then flows downstream; no matter what juncture it comes to, the stream continues along the most straightforward channel. SWO NHD accommodates feature classes at this general level of the NHD and the included WBD. A characteristic of the NHD is that it includes many earth surface-type classes, such as :Diversion, a channel. The WBD centers data on nested hydrologic unit, such as a basin, subbasin, or watershed. Modifications of the earth surface that affect the collection of water as NHD features are indicated by a class called :HU_Mod, indicating a type of modification to natural overland flow such as :UrbanArea or :SpecialCondition subclasses such as :Glacier or :Karst. The terrain features described in this study will be the NHD surface features, and not those of the WBD.

BFO class definitions were used to reorganize the surface water concepts along ontology principles (Figure 7.2). The results were subgroups that encompass a large number of hydrologic feature types and properties. These classes include the earth surface formations indicated as :Feature (equivalent to bfo:MaterialEntity) with subtypes :Object and :ObjectAggregate. Surface water is indicated as :Flow (equivalent to bfo:Process), including standing water and hydrological events such as damming. The class :SpatialExtent (related to bfo:SpatialRegion) includes :SpatialQuality, :SpatialRelation, and :SpatialMeasurementUnit subclasses. :Temporality (equivalent to bfo:TemporalRegion) has subclasses :Ephemeral, :Intermittent, :Perennial, :Regulated, and :Status. SWO NHD includes bfo:Function, a class for socially defined areas serving a role by virtue of their dispositions (not depicted in Figure 7.2). This class was included to link to separate but related graphs, such as for land use or the role of surface water in other ontologies. These superclasses include many subclasses in the digital file that are too numerous to include in this article, though some specific examples are discussed in the following sections.

Figure 7.2 indicates the solid material components that are characterized by form and spatial extents (continuants) and fluid materials that are characterized by processes and temporal change (occurrents). This distinction is not completely disjoint, in that solid materials that interface with water are not completely static. Debris flows, landslides, and glaciers are examples of solid earth change affected by surface water. This specific interaction is not described in the SWO NHD.

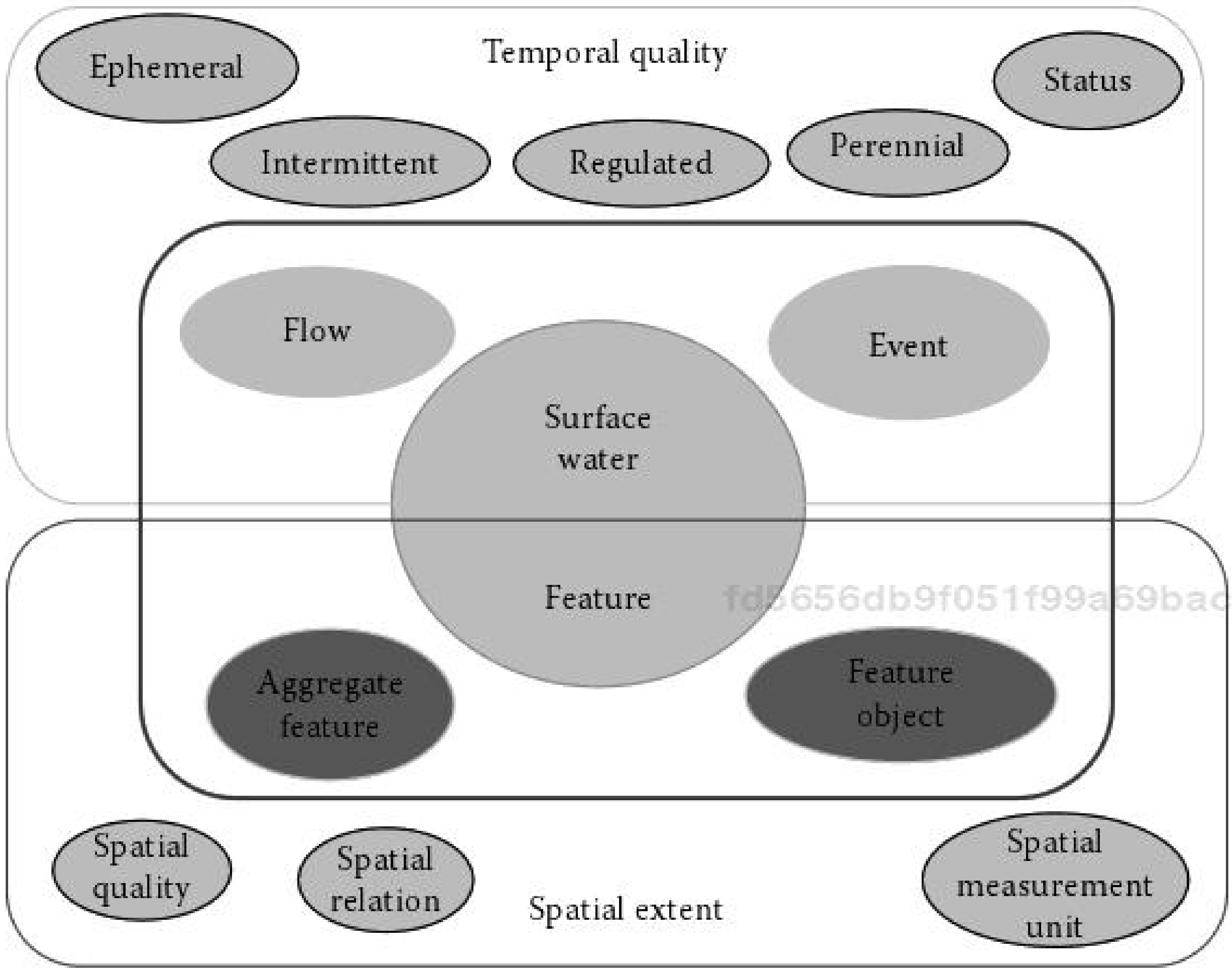


**FIGURE 7.2 (See color insert.)**
Top-level surface water ontology classes for land cover.

Ontology models allow for greater specification of feature qualities, roles, and relative spatial positions. In determining these specifics, a common problem was identifying the primitive terms that were combined in NHD attribute names to specify two or more classes at once, such as, areaAcres (area in acres) or DEDEM10 (Drainage-enforced 10 m Digital Elevation Model). A balance was struck between splitting such terms whenever possible to increase the reuse of classes and to reduce database redundancy and maintain attribute names for linking to NHD data (USGS 2014c).

### *7.4.2.1 Feature*

Geographical or geospatial feature type is a term that is widely used in geospatial analysis literature, standards, and database design (Usery 2015). A feature is a relatively stable entity and so for the SWO NHD, the term is classified as equivalent to the structures that support the collection and flow of water, such as terrain or engineered channels and basins. The class :Feature is a subclass of bfo:Material Entity and conceptualizes a real-world material object in time and space, but infers additional semantics from the geographical literature. Feature type class semantic specifications apply to its subclasses :Object and :ObjectAggregate, a distinction that also appears in SUMO. These Feature subclasses allow for distinctions to identify material objects that are normally separated by spatial gaps, such as one single stream channel from others, from aggregates of objects, such as rocks of a reef or an area of complex channels. Object instances have cardinality normally restricted to one. :ObjectAggregate instances could have a restriction allowing for one group or many members. This distinction between an object and aggregated object allows, for example, the differentiation between a single-dredged channel and other nondredged channels of a braided stream river. Though bfo:FiatObjectPart was not used, the meronymy property :partOf, which allows objects such as a bay or inlet with a bona fide or fiat separation from an otherwise singular entity such as a sea, was added to the class of object properties.



#### *7.4.2.2 Spatial Extent*

Surface water often involves spatial extent as a criterion for classification. The class :SpatialExtent is related to bfo:SpatialRegion, but bfo:SpatialRegion is represented by spatial coordinates, and :SpatialExtent includes relative and qualitative spatial representation; the SWO NHD class for spatial coordinates is called :Geometry within the instance gazetteer. Upper ontologies lack broad guidelines of spatial and geographic theory for spatial extents that can be found in geographic information science literature. The subclasses devised for :SpatialExtent are :SpatialQuality, such as :Area or :Length; :SpatialRelation, such as :Elevation; and :SpatialMeasurementUnit, such as :Acre.

A distinction was drawn between spatial qualities of objects and spatial measurements. If a term was a spatial dimension of an object, such as length, this class or property was treated as a quality. If a spatial relation exists between objects whose computation is based on spatial coordinates, such as distance, then that entity was classified as a spatial relation. The actual measurement is a specific value for each instance and is documented in the gazetteer. The :SpatialQuality class includes geometric dimension classes, :Length and :Area, that are applied to features in general. :SpatialMeasurementUnit includes :Acre, :Kilometer, :SquareKilometer, :Meter, and :SquareMeter. These subclasses are available in commonly used ontologies and can serve as links to broader and widely used ontology modules. :SpatialRelation subclasses, indicating certain vertical and horizontal relations between features and representations as real-world entities and as measurements, such as a :SoundingDatumLine, include :Direction, :Elevation, :RelationshipToSurface, :Route, :SoundingDatumLine, :Route, :Stage, and :VerticalRelationship. :RelationshipToSurface and :Stage have several subclasses, such as :Underground or :AboveWater, and :FloodElevation or :NormalPool (Figure 7.3). Other topological relations are defined by the GeoSPARQL standard and applied to geospatial feature geometry objects in the instance gazetteer (Perry and Herring 2012).

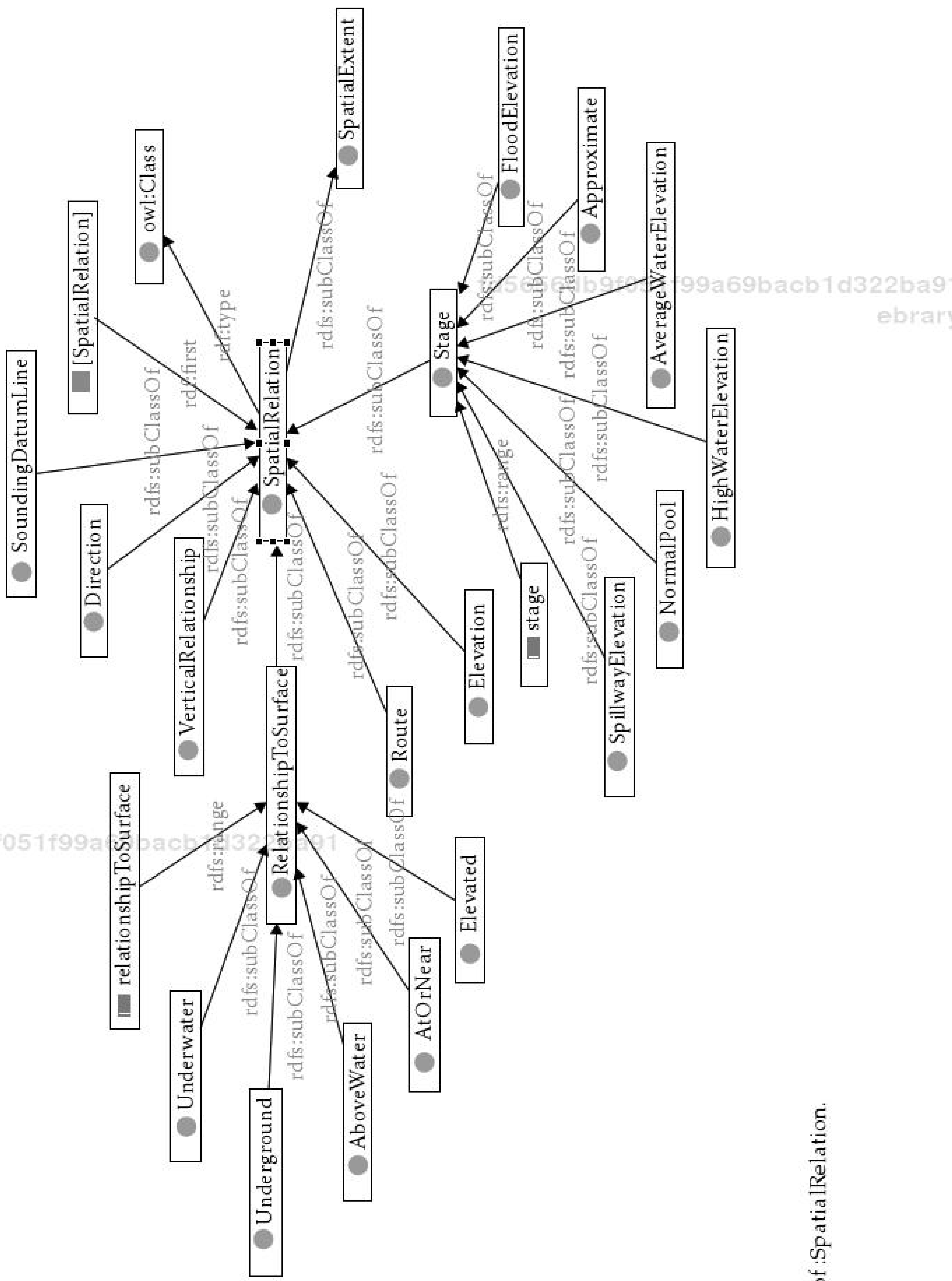


**FIGURE 7.3**
Subclasses of :SpatialRelation.

Surface water features have physical qualities that can lead to socially defined functions and roles, perhaps particularly true for engineered features designed and built for a purpose. A class called :Function is related to bfo:RealizeableEntity, with criteria that if a particular feature bearing a quality, role, disposition, or function is removed, the feature may be changed, but continues to exist. The SWO NHD :Function class links to classes such as NHD :HazardZone or :SpecialUseZone, found in a separate graph.

:Feature and :SpatialExtent classes focus on hydrographic entities of temporal endurance, relative to the more changeable temporality of surface water. The qualities of surface water and temporality are discussed in the following section.



#### *7.4.2.3 Flow and Temporality*

The :Flow class was designed separately from the :Feature class for modeling temporal processes such as :Waterbody and :Event. BFO defines bfo:Process as a bfo:Occurrent, an entity with temporal parameters that for some time is dependent on some material-entity participant to play itself out, that in this case is the water. Processes are weakly modeled in GIS relative to continuant entities defined primarily by their spatial ranges, so relations between these classes were drawn more from surface water science domain knowledge.

:Flow is the class of features consisting of water and flow dynamics. :Event is a subclass of :Flow consisting of hydrological monitoring types associated with particular features, such as :Dam or :Divergence. :Event is a class to integrate with possible hydrology ontologies. :Waterbody has subclasses for spatial parameters with regard to the terrain, such as :Rapids, :SinkOrRise, :SpringOrSeep, or :Waterfall. A much smaller number of such features are named compared to the number of :Feature subclasses. :Temporality, representing the temporal aspects of processes as defined in BFO, includes :Ephemeral, :Intermittent, :Perennial, :Regulated, and :Status, meaning a state of being.



### 7.4.3 Gazetteer Ontology

The gazetteer, or database, of the ontology consists of classes, but differs from the feature type taxonomy because categories are sets of instances and not subtypes. For example, the class :Name is a collection of instances of names, not a taxonomy of types of names. One characteristic of this difference is that subtypes of a parent class must be mutually exclusive, but instances may be members of more than one subclass.

A gazetteer consists of traditional categories: :Names (toponyms), :Geometry (spatial coordinates), and :Identifier, but added to these in the SWO NHD is the :Hydro_Net class, which is the entire coordinate geometry network created by all the combined geospatial features in the selected data set when a subset of the NHD is downloaded from the national database. Gazetteer classes, being sets of instances, and properties, relating to instances, were mostly taken directly from the GIS NHD ontology. The taxomony of surface water land cover required ontological reorganization that could be modeled as a graph, but once those classes were specified, sets of instances fell in place along the ontology design. This is a benefit of building "bottom-up," that is, starting the ontology with the GIS database. The feature type and gazetteer instance modules are interconnected using properties between classes. The gazetteer includes a great number of properties for instances. Most of the feature ontology properties are object properties, drawing relations between continuant entities, but the majority of properties in the gazetteer are datatype properties, storing specific values for instances. Though many triple model object resources of instances in the gazetteer ontology take the form of literals, the creation of an object class in the feature ontology is required to define them as instances of sets. For example, the :Geometry class contains the objects of the :hasGeometry property.

A class within the Hydro_Net called :HydroNetJunction is a set of NHD vector nodes forming junctions of different features in the geometry network. These junctions support surface water flow modeling. Flow modeling and watershed boundaries, forming nested hydrological units, have transitive properties that are compatible with inference. According to the Strahler Stream Order, if a first-order stream feeds to a second-order stream, and if the second-order stream flows to a third-order stream, then the first-order stream flows to the third-order stream (Strahler 1952). Within the WBD, subwatersheds are units contained within watersheds, and watersheds are contained within basins, then subwatershed are contained within basins. The inferred data from the Hydro_Net can be queried to trace a route along multiple stream segments and linkages from one point on the network to points downstream. These relations are calculated "on-the-fly" using GeoSPARQL topological relation analysis.

For the SWO NHD as a whole, the more specific the subclasses of those aligned with upper ontology, the more semantic specification is required. In addition to asserted classes, the effective use of inference is a key objective for the surface water domain ontology. Different methods are available for specifying semantics and inference; among these are formal proofs (Hitzler et al. 2010), graphic representations (Allemang and Hendler 2011), and an expressive language such as ISO Common Logic (ISO/IEC 2007). Although logical proofs capture the details of the algorithms and graphic representations do not, graphics were used for this study, as in examples shown below, because of their clarity for anticipating inference processes. Formalizations were left to the ontology, triplestore, and reasoning software.

## 7.5 Inference

Inference can be executed using the subsumption relation between owl:Class and rdfs:subClassOf, setting domain and range classes for properties, OWL axioms, defined classes using the property owl:equivalentTo, and using other restrictions such as cardinality. The top-level classes described in this study so far form a taxonomic hierarchy of primitive or asserted classes. A primitive class, using the subsumption (type-of) relation between parent and child classes, is defined in ontology as having necessary, but not sufficient conditions to support inference. Defined classes have necessary and sufficient conditions. This is indicated by specifying an equivalent-to relation between triple resources. For example, the :Flow subclass :Waterbody was converted to a defined class equivalent to the intersection of :Flow and one of the :Waterbody subtypes (The list of subtypes appearing below includes only a few of the eleven possible.)

:Waterbody owl:equivalentTo :Flow and (:Rapids or :SinkOrRise or :SpringOrSeep or :Waterfall)

After applying reasoning software to the ontology, new triples were defined, indicating class membership through the transitive property. The following triple for :Waterbody is inferred:

:Waterbody rdfs:subClassOf (:Waterbody or :Event)

Rather than adding taxonomic classes to the ontology to expand perceived distinctions, for example, engineered from natural feature types, the goal is to specify the formal semantics of each defined class to indicate the criteria by which subclasses vary. Feature types should cluster in the graph according to restrictions rather than additional taxonomic definitions. The number of classes was kept as small as possible to focus on key ontology properties. Nevertheless, the :FeatureObject class is particularly large, including engineered objects with operational parts, such as :LockChamber; natural objects with complex criteria, such as :SwampOrMarsh; and simple objects consisting of a single type of matter, such as :EarthenMaterial. The specifications for various defined classes are not fully established yet for the ontology as a whole, but some individual examples are described later. These limited semantics are partially to quickly complete initial drafts and will be addressed in later edits, and partially to facilitate sharing mutual natural language semantics with other hydrography data sets. As a result, many of the classes are simply terms for named entities and require further logic specification.

### 7.5.1 Feature Class Semantics

The SWO NHD has a greater number of triple resources to model than can be described in this study. This section presents models for two specific feature type classes, :InundationArea (Figure 7.4), defined by the NHD as "An area of land subject to flooding" and :AreaToBeSubmerged (Figure 7.5), defined as "The known extent of the intended lake that will be created behind a dam under construction" (USGS 2014c). These two classes are chosen because of their similar but slightly different semantics for :spatialExtent and :flow.

To model :InundationArea and :AreaToBeSubmerged, both were first identified as features. Features have certain dispositions based on internal physical qualities of the entities in question, as is so with :InundationArea and :AreaToBeSubmerged; flooding is possible only if the surface water height exceeds flood elevation. The two types of features differ in their external influences, which are uncontrolled natural forces or controlled human decisions and actions. With:InundationArea and with :AreaToBeSubmerged, a consequence is assumed, but for one site,

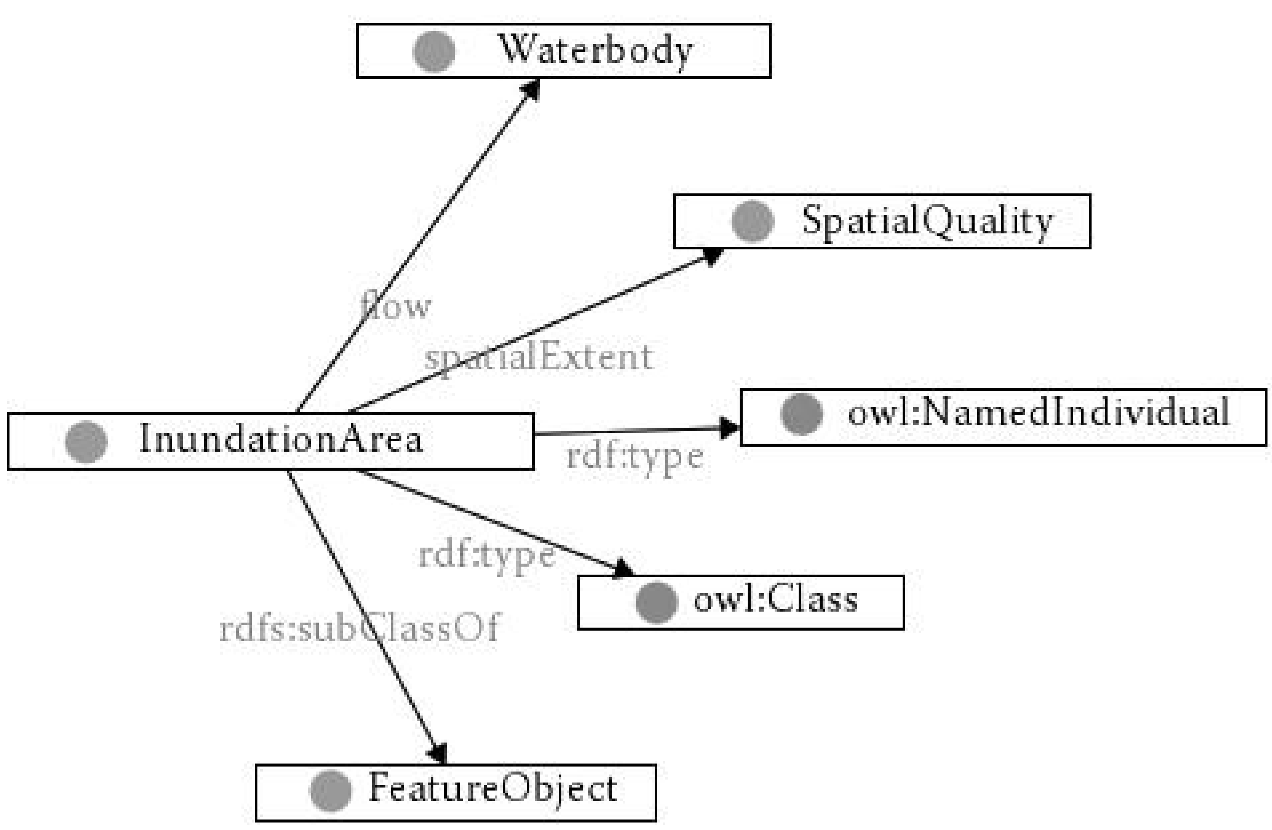




**FIGURE 7.4**
A semantic model for the class :InundationArea.

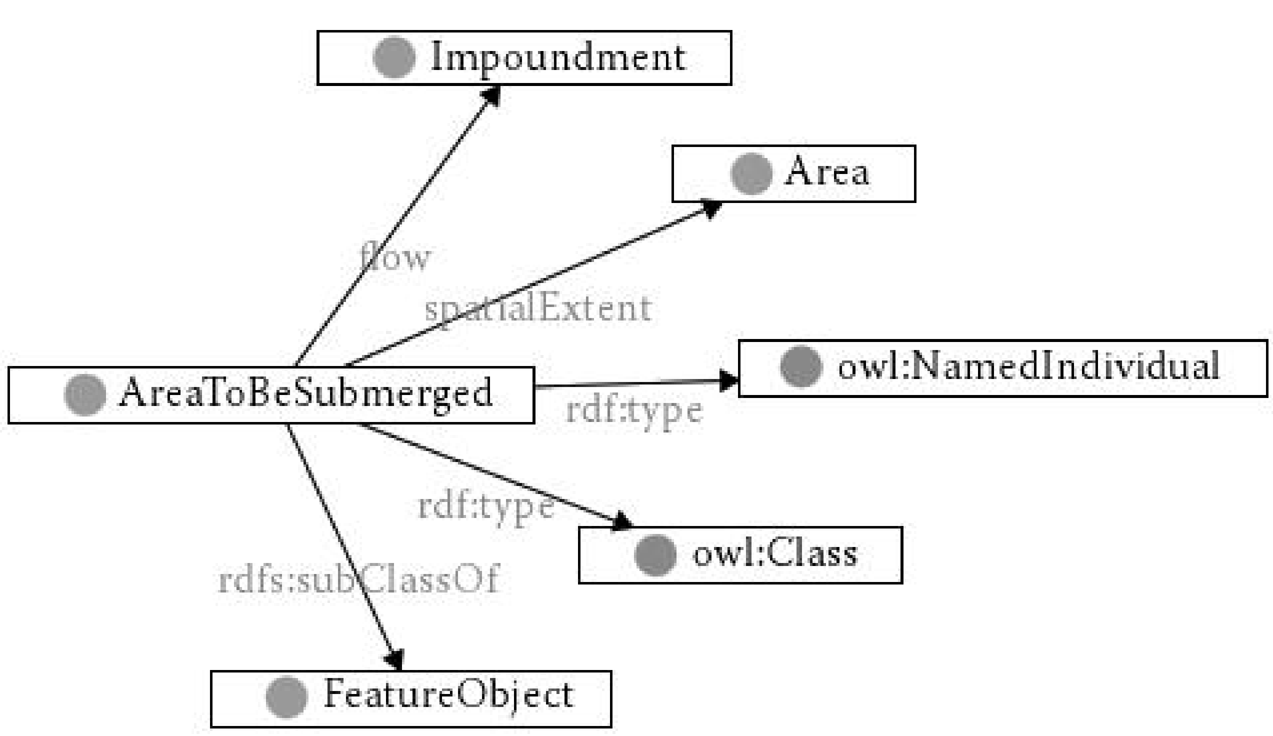


**FIGURE 7.5**
A semantic model for the class :AreaToBeSubmerged.

intermittent inundation from variable water flow, and for the other, permanent submersion from damming. For both models, the potential presence of surface water is assumed.

The two features have the same properties of rdf:type; rdfs:subClassOf; and :flow, meaning they are associated with surface water; and have :spatialExtent of their physical formation in common, though the objects of these properties are different. :Feature has a :flow property that is fulfilled by :Waterbody; :Waterbody has properties of :stage, :temporality, and :event (Table 7.1). For the class :InundationArea, which has a simpler set of criteria than :AreaToBeSubmerged, the property :flow has a wider range of possible object values and thus a more general range class. The range class of :AreaToBeSubmerged is a subclass of :Waterbody.



### 7.5.2 Inference on Asserted Classes

The inference engine executed using SWO NHD was SPIN. SPIN is a RDF vocabulary that formalizes constraints using SPARQL. SPIN is an expressive way to formalize rules that will apply to classes (Knublauch 2011). The results in Table 7.1 are inferred triples produced from asserted classes. Inferred triples based on the semantic graphs for :InundationArea (Figure 7.4) and :AreaToBeSubmerged (Figure 7.5) are included in the results listed in Figure 7.6, together with sibling and other classes of the SWO NHD. Inferencing at this step of ontology development demonstrates that some restrictions are declared by the RDF and RDFS vocabulary. For example, by declaring a domain and a range class for a property, several inferences are invoked. The subject of the statement will be inferred to be an instance of the class in the domain of the property, and the object of the statement will be inferred to be an instance of the class in the range of the property. However, if a property has more than one domain or range, the resource will be inferred to be an instance of both. As a result, the ontology will probably be more correct if fewer general classes are declared for domain and range than several



**TABLE 7.1**
Domain and Range Classes for Selected SWO NHD Properties

| Property | Domain | Range |
|---|---|---|
| :flow | :Feature | :Waterbody |
| :stage | :Waterbody | :Stage |
| :temporality | :Waterbody | :Temporality |
| :event | :Waterbody | :Event |
| :spatialExtent | [none] | [none] |

| | | |
|---|---|---|
| Aqueduct | rdf:type | Feature |
| AreaToBeSubmerged | rdf:type | Feature |
| Bridge | rdf:type | Feature |
| CanalOrDitch | rdf:type | Feature |
| ChannelDiversion | rdf:type | Feature |
| Coastline | rdf:type | Waterbody |
| Connector | rdf:type | Feature |
| Dam | rdf:type | Feature |
| Flume | rdf:type | Feature |
| Foreshore | rdf:type | Feature |
| Gate | rdf:type | Feature |
| Impoundment | rdf:type | Waterbody |
| InundationArea | rdf:type | Feature |
| LakeOrPond | rdf:type | Waterbody |
| Levee | rdf:type | Feature |
| LockChamber | rdf:type | Feature |
| Stage | rdfs:seeAlso | http://water.usgs.gov/e |
| StreamOrRiver | rdf:type | Waterbody |
| Waterbody | rdf:type | Waterbody |
| Watercourse | rdf:type | Waterbody |
| xsd:nonNegativeInteger | rdfs:subClassOf | rdfs:Literal |
| xsd:string | rdfs:subClassOf | rdfs:Literal |



**FIGURE 7.6**
Triples derived from :InundationArea and :AreaToBeSubmerged semantics.

specific classes. Declaring rdfs:domain and rdfs:range classes accomplishes one stage of creating an expanded graph of inferred triples.

The inferred triples in Figure 7.6 highlight two particular inference rules. Subclasses acquire the type relation to their parent class in addition to the subclass relation that was asserted in the class hierarchy. The property rdfs:subClassOf is used to state that all the instances of one class are instances of another class. The property rdf:type is used to state that a single instance of a class is an instance of another class. Second, a class is reflexive, meaning a class is a type of itself.



The transitive property of inference applies to properties as well. In the Dublin Core Metadata Initiative (DCMI) vocabulary terms, which uses the prefix "dcterms," the dcterms:partOf property is a subproperty of dcterms:relation (Dublin Core Metadata Initiative 2012). Through inference, a triple such as :BayOrInlet dcterms:partOf :SeaOrOcean will also lead to the creation of the triple :BayOrInlet dcterms:relation :SeaOrOcean. Subproperties have domain and range classes whose parent classes will be inferred for the parent property (TopBraid Composer 2011). If the parent property has domain and range classes, then additional triples, such as :BayOrInlet dc:terms:Relation :Waterbody, will result. Such inference expands the range of associated category types for a triple and supports information retrieval.

| | | |
|---|---|---|
| Impoundment | rdfs:subClassOf | Watercourse |
| Impoundment | rdf:type | Waterbody |
| Impoundment | rdfs:subClassOf | Dam |
| Impoundment | rdfs:subClassOf | AreaToBeSubmerged |

**FIGURE 7.7**
Triples derived from the defined class :Impoundment.

### 7.5.3 Inference on Equivalent Classes

Subsumption or taxonomic relations, indicating types or subsets, are frequently not sufficient to establish criteria for membership in a class. The application of restrictions, meaning conditions to which specific instances must adhere, creates defined classes that are considered to establish necessary and sufficient conditions for a class. The primary property for establishing restrictions is owl:equivalentTo. The property owl:equivalentClass converts an asserted class to a defined class. The owl:equivalentClass property exists in addition to rdf:subClassOf, not in place of it.

The class :Impoundment, defined as "A body of water formed by impoundment," was defined to be equivalent to :Watercourse and :Dam and :AreaToBeSubmerged. The conjunction "and" indicates the intersection of the three classes, one a :Waterbody (:Watercourse), an :Event (:Dam), and a :Feature (:AreaToBeSubmerged). Certain inference rules are invoked by these semantics for the defined class :Impoundment. The triples that result from running the inference engine, shown in Figure 7.7, indicate that the defined class :Impoundment is a subclass of each of the members of its equivalent class, meaning that members of the set of :Impoundment may be a member of the class :Watercourse, :Dam, or :AreaToBeSubmerged, but :Impoundment is not a type of these equivalent sets.

Establishing taxonomic classes, domain and range classes, properties and subproperties, and defined classes are basic ways of building semantics in graph databases. Other possible restrictions support other new inferred triples. The graph with the original and inferred triples from asserted and defined classes formed the basis of a triplestore for SPARQL queries.

## 7.6 Information Retrieval

An objective for the design and development of the SWO NHD is to see whether semantic technology eases information access. To explore this question, the use case method, which assumes the perspective of a system user, was selected for information retrieval executed with SPARQL queries (Wiegers 2003; Fox and McGuinness 2008). Three use cases are described in this section. The use cases have corresponding competency questions designed to demonstrate queries that would otherwise be complex to retrieve in GIS. GIS primarily uses Structured Query Language (SQL) for queries. SPARQL is similar to SQL, but the potential expression of potential SPARQL queries on RDF data is limited at this stage of its technical development (Patroumpas 2014).

The use case/competency question method involves scoping capabilities of the system for particular objectives. Parts of the scoping process are to ask questions and assess resources for relevant and acceptable results. The competency question method originated in human interviewing techniques to answer criteria-based questions and thus has a greater focus on the cognitive semantics. Competency questions are an important part of the use case approach because ontology formalizations are mediated with psycholinguistic semantics by users.



### 7.6.1 Use Case 1

Use Case 1 poses the task: retrieve classes of different types that are related to each other, such as surface water and terrain. Use Case 1 is designed to seek specific information given a general set of parameters. The competency question is stated as, What types of waterbodies are subject to inundation? The question must be reformulated to work with SPARQL. The following SPARQL Query specifies a variable to select called ?wb to stand for waterbody. The WHERE clause, which specifies the triple pattern to match against the data, is at the point of the query process at which the natural language question is formalized as a logic statement, reversing the order of the subject and object. :InundationArea represents the subject and "has type" is the predicate (the rdf:type property) and "waterbodies" represent the object. The subject is modified as "are subject to inundation" by virtue of the :InundationArea class definition.



```
Query:

SELECT ?wb                        Selects and displays all
                                  waterbodies that match the
WHERE {                           constraints of the WHERE clause
:InundationArea :flow ?wb.        Restricts triple results to
                                  waterbodies that have the
}                                 subject :InundationArea and
                                  property :flow

The results of this query submitted to the triplestore are
copied below.
  ?wb
  LakeOrPond
  Reservoir
  StreamOrRiver
  SwampOrMarsh
```

**TABLE 7.2**

Inundation Area and Waterbody Associations as Retrieved Using a GIS Attribute Table

| Feature | Waterbody |
|---|---|
| :InundationArea | :LakeOrPond |
| :InundationArea | :StreamOrRiver |
| :InundationArea | :StreamOrRiver |
| :InundationArea | :LakeOrPond |
| :InundationArea | :SwampOrMarsh |
| :InundationArea | :Reservoir |
| :InundationArea | :StreamOrRiver |
| :InundationArea | :StreamOrRiver |
| :InundationArea | :StreamOrRiver |
| :InundationArea | :LakeOrPond |
| :InundationArea | :Reservoir |
| :InundationArea | :SwampOrMarsh |
| :InundationArea | :Reservoir |
| :InundationArea | :SwampOrMarsh |



A similar query using GIS would filter the data first by one variable and then the second. The data retrieval results shown in Table 7.2 would return the entire columns of both. Though some software offers the additional option of identifying just the unique values, that step is not the basic way the tables function. SPARQL supports data retrieval as subgraphs of the graph being queried, but results such as those shown in Use Case 1 suggest that triplestores can also be used as a knowledge base of statements that answer information questions.



### 7.6.2 Use Case 2

Use Case 2 poses the following task: retrieve values from a category not directly related to a feature type; for example, to model the relation of objects to their temporal qualities. The competency question is, What is the temporality of surface water flow associated with particular terrain feature types? The SPARQL Query has a variable ?F for any type of feature class and ?T for any type of flow temporality, given that temporality is associated with processes, not objects. The query and results appear below.

```
Query:
SELECT ?F ?T               Select and display all values for
                           variables F and T
WHERE {                    that match the constraints of the
                           WHERE clause
    ?F :temporality ?T.    the variable F has temporality T
}
```

```
Results:

[F]                   T
 AreaToBeSubmerged    Regulated
 InundationArea       Intermittent
```

Though one-to-one relationships are easily modeled in GIS, a query such as this one will return the possible options within the database, not just a list of values within the cells of selected rows.

### 7.6.3 Use Case 3

Use Case 3 poses the following task: get more information about a concept. In this use case, the competency question could be, How can I get more information about the term :Stage in surface water studies? This query builds toward the development of triple data linkages to other information about a single entity, instead of an entire metadata document, as is common in GIS. ?I is the variable representing additional information.



```
SELECT ?I
WHERE {
Stage rdfs:seeAlso ?I.
}

Results:

?I
http://water.usgs.gov/edu/dictionary.html
```

Though ideally, URIs link to a specific gloss associated with the NHD class :Stage, in this instance, http://water.usgs.gov/edu/dictionary.html is a document with multiple glosses for an entire vocabulary; the specific gloss for :Stage must be manually sought.



The use cases demonstrate that triples can contribute semantic detail to any number of primitive entities or complex concepts without duplication that increases file size and visual complexity for the user. The implication of this is that the added semantic detail does not need to be specified for every instance because classes work as sets of instances.

## 7.7 Discussion/Conclusion

A surface water ontology was developed from an empirical base, organized in accordance with top-level ontology models, and formalized for basic inference using asserted, domain, range, and defined classes. Parts of the SWO NHD were validated through inferring new triples and querying the triplesstore within the parameters of use cases. The NHD data model structure was regrouped around related concepts, creating semantically a similar context for complex parts of the GIS database. For example, terrain categories were grouped together distinct from water flow processes and spatial and temporal qualities. The GIS data that were captured from the automated conversion aligned within classes and properties with identical URIs. The legacy data can be managed with minimal change to the SWO NHD because of the flexibility of the graph-based data model.

By developing the SWO NHD, feature classification was no longer based on geometric constraints of layer-based GIS, but on relations between concepts made more intuitive to the user through natural language. For example, GIS data layers were organized by feature geometry, which constrained water feature and flow modeling along Flowlines, modeled as linear features in one layer, through water bodies, modeled as polygons, formed as a separate layer. A class of objects called Artificial Paths was required to resolve the discrepancy between lines and polygon disconnect in layer-based NHD. With the SWO NHD, water flow is easily modeled along the surface water network in a way that more closely resembles the real world because coordinate geometry constraints are removed. Feature types, processes, and qualities were reorganized in semantic technology along guidelines consistent with cognitive understanding of real-world entities. The conclusion of this study is that though the ontology requires further refinement, it demonstrates the potential of semantic technology for advancing surface water data use.

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