An Ontological Framework for Characterizing Hydrological Flow Processes

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Abstract

The spatio-temporal processes that describe hydrologic flow – the movement of water above and below the surface of the Earth – are currently underrepresented in formal semantic representations of the water domain. This paper analyses basic flow processes in the hydrology domain and systematically studies the hydrogeological entities, such as different rock and water bodies, the ground surface or subsurface zones, that participate in them. It identifies the source and goal entities and the transported water (the theme) as common participants in hydrologic flow and constructs a taxonomy of different flow patterns based on differences in source and goal participants. The taxonomy and related concepts are axiomatized in first-order logic as refinements of DOLCE's participation relation and reusing hydrogeological concepts from the Hydro Foundational Ontology (HyFO). The formalization further enhances HyFO and contributes to improved knowledge integration in the hydrology domain.

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1 Introduction

Much progress has been made towards formal semantic representation of concepts in the water domain, though mostly by representing static physical and spatial hydrogeological features (e.g., rock bodies, water bodies, voids) while neglecting important dynamic aspects, such as the transport of water between the various stages of the water cycle and different places where water is stored. One of these dynamic aspects is movement of water via hydrological flow processes on the surface of the earth (such as runoff and stream flow), in subsurface rock formations (such as percolation), as well as movement of water between surface and subsurface entities (such as infiltration). The presented work is a step towards filling this gap by laying out an ontologically rigorous formal framework of hydrological flow processes that spans surface and subsurface flow and links the two. The framework distinguishes different kinds of hydrological flow processes based on their participants and organizes them taxonomically. The taxonomy is formalized using semantic participatory roles, which are played by different hydrogeological entities in the different kinds of flow processes, as refinements of DOLCE's participation relation. The participating static hydrogeological entities are expressed using concepts from the work towards the Hydro Foundational Ontology (HyFO) [4, 13, 14, 16] as a domain reference ontology for the water domain.

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Hydrological flow consists of several spatio-temporal components that describe the movement of water above, on, and below the surface of the earth, and these are individually influenced by physical phenomena such as gravity, porosity and permeability of the soil zone, and capillary pressure. Existing standards for the hydrology domain model flow of water at general levels without refining them according to their participants, and focus on flow either in surface or ground water systems. However, the water cycle is a constant physical interaction between surface and subsurface water features, for example, surface water bodies may be fed from or discharge water to aquifers beneath and surface water may infiltrate the ground to become groundwater. These interactions, which are flow processes themselves and have properties in their own right (e.g., flow volume or speed), must be explicitly represented and thus require a unifying representation of surface and subsurface water flow. Their formal representation would benefit a range of applications, such as assessing hydraulic connectivity between surface streams and groundwater bodies, or determining flow paths between aquifers within aquifer systems or seepage of water through confining beds. Representation of flow processes also informs regional, agricultural, and urban planning, where information about where water comes from and where it flows to is required to maintain adequate water supplies and trace the path of water-born pollutants. Future incorporation into HyFO will improve HyFO's overall utility for analyzing, refining, and integrating flow concepts across existing hydro ontologies. For example, because of the lack of a flow concept in HyFO, GWML2's flow module [3], which models the flow of groundwater, was the only GWML2 part that could not yet be ontologically analyzed and logically specified using HyFO concepts [16].

Objective. The specific objective of this work is to ontologically analyze and categorize different flow patterns in the hydrological domain and to formally represent them as an extension to HyFO. In the process, we aim to at least partially address a number of challenging ontological questions about the nature of hydrological flow, including: What precisely are hydrological flow processes? What is common to all of them? How do they differ? Can they be clearly delineated? How are they related to hydrogeological entities? What are their spatial and temporal properties?

Scope. We limit our study to flow processes that (1) occur directly on or below the surface of the Earth and that (2) do not involve physical changes in the state of water matter, thus excluding other hydrological processes that transport water, such as precipitation, condensation, evaporation, and evapotranspiration. The aim is to represent spatio-temporal dynamic aspects of flow, leaving aside qualities and quantifiable properties that flow processes might exhibit, such as water pressure in an aquifer, or the speed or volume of flow, though the representation should be extendable by such parameters in the future. As such, the ontology is not intended to serve as a mathematical model for calculating flow quantities, but rather to express interactions between water bodies contained in different rock bodies and to capture the general physical pattern of different hydrological flows, including how flow processes are physically manifest in the different hydrogeological units/zones.

Approach. Each occurrence of a flow process manifests itself in specific hydrogeological entities from and to which water flows. Based on DOLCE's upper level classification, *hydrological flow* (HF) is modeled as a *perdurant* that can have temporal parts (e.g., sub-processes) and that is related to physical endurants, such as rock formations and water bodies, via DOLCE's time-indexed *participates* relation $PC(x, y, t)$. This approach permits different entities to participate at different times during the duration of a flow process.

We gather common kinds of flow processes from the hydrological literature and identify their participating hydrological and geological endurants and associated physical aspects, such as the spatial configuration and connectivity of geological formations or their porosity (the presence of connected voids), which capture minimal requirements for where and when different kinds of flow can occur. We then use Fillmore's case roles [5] to identify three types of participants common to all hydrological flow processes and formalize them as refinement of DOLCE's participation relation. They are subsequently used to develop a taxonomy of hydrological flow processes, each indicating what static hydrogeological entities – selected from HyFO's hydrogeological entities and newly axiomatized hydrological *subsurface zones* – must or can participate in each of the roles. In addition, basic temporal constraints between the participants are identified and formalized.

Sec. 2 surveys how flow is represented in existing hydro ontologies and Sec. 3 reviews HyFO's hydrogeological entities and DOLCE's participation relation as basis for our formalization. A preliminary analysis of flow processes leads to a unifying high-level pattern for hydrological flow and participatory roles in Sec. 4, which is formalized more fully in Sec. 5.

2 Related Work

Devaraju and Kuhn advocate in [6] a process-centric approach to relate processes to observable properties. While not the focus of their work, the authors highlight the benefits of identifying the entities that participate in processes to distinguish different types of processes (e.g., infiltration and percolation) and to identify processes that only differ in label (e.g., surface runoff and overland flow), which we pursue more systematically here. The formalization in [6] focuses on the hydrological processes of precipitation and evapotranspiration rather than the flow processes that we are concerned with.

Most closely related to our work is [9]. It identifies hydrogeological entities (e.g., sources, sinks, channels) that participate in flow processes and relates them to perdurant processes via BFO's [21] *involvement* relation, which is the inverse of DOLCE's *participation* relation. The identified processes include seven basic kinds of flow processes [9]: *overland flow*, *channel flow*, *infiltration*, *return flow*, *through flow*, *percolation* and *base flow*. Certain flows are identified a aggregate processes, which are a composition of these seven processes. However, no formal analysis to constrain the endurants that can participate in different processes is undertaken, neither is a full taxonomy of flow processes developed, nor are different participatory roles in hydrological flow processes formally distinguished.

Existing hydrology-related data models and ontologies include the Groundwater Markup Language (GWML2) [3], INSPIRE's data specification on hydrography [17], HY_Features [8], the hydrogeology extension to SWEET (SWEET-HG) [23], and the surface water ontology pattern (SWOP) [20]. HY_Features [8] and INSPIRE's hydrography specification [17] do not model flow processes at all. The others model hydrological flow to varying extents, but either model abstract flow paths rather than processes with spatio-temporal properties (e.g., GWML2, SWOP), or concentrate only on properties of flow, such as transported amounts of water or volumetric rates of flow, rather than hydrological or hydrogeological participants (e.g., SWEET-HG). Moreover, the data models tend to represent flow only within the surface (e.g., SWOP) or subsurface water domains (e.g., GWML2, SWEET-HG), leaving out important flow concepts, such as infiltration, that cross the surface-subsurface boundary. SWEET-HG [23] further models some kinds of flow (e.g., recharge and interflow) as processes, and others (e.g., baseflow) as phenonema, but all of them lack sufficiently detailed representations and none explicitly model the participants.

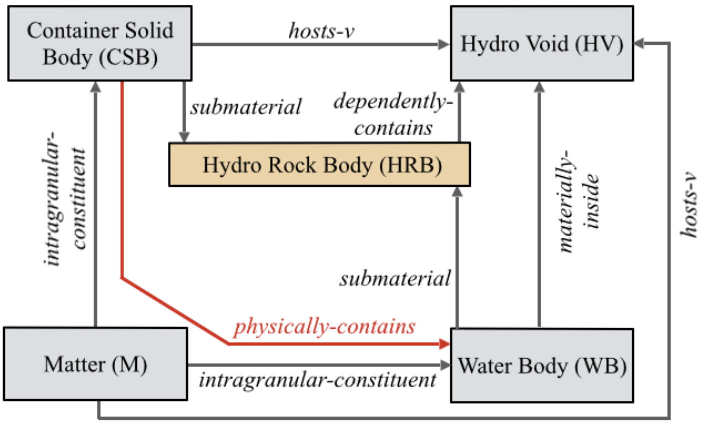

Figure 1 Key HyFO concepts and the physical relationships between them.

3 Background

The formalization that we present in Section 5 builds on prior work on the Hydro Foundational Ontology (HyFO), on DOLCE's upper ontology, and on Allen's interval algebra.

HyFO. HyFO is an effort to develop a domain reference ontology for the hydrology domain that represents key semantics of surface and ground water concepts in a unified framework in first-order logic [4, 13, 14, 16]. At the highest level, it describes the following five types of hydrogeological entities, depicted in Figure 1, and their interrelationships:

- **Physical containers** such as rock formations constituted of solid material and containing empty spaces (voids).
- **Physical void** such as a depression or channel in the ground surface, or microscopic pores between grains of solid matter.
- **Bodies of water** that are either *surface water bodies* (SWB), or *subsurface water bodies* ($SSWB$) [16] typically located in the voids of physical containers.
- **Rock and water matter** that constitute container and water bodies, respectively.
- **Hydro rock bodies** that are rock bodies with water bodies therein (i.e., physical containers with contained water bodies), such as aquifers (a geological unit + the stored water) or rivers (a riverbed + the river's water). *Hydrologic units* (HU) and *hydrogeo units* (HGU) (following GWML2 terminology) are its surface and subsurface variants (see Figure 3)

These hydrogeological concepts are specialized *physical endurants* (using DOLCE's PED concept) and are assigned abstract spatial locations (*space regions*, S, in DOLCE) using the $\mathrm{r}(x)$ function. The configuration of the spatial regions is described using mereological and topological relations from [15, 12] similar to the RCC and 9-intersection relations. The new axioms presented in this work only make use of the relations of parthood $P(x, y)$ (i.e., x is a spatial part of y) and partial overlap $PO(x, y)$ (i.e., x and y share some spatial part), and the intersection operation $(\cdot)$ that identifies the spatial region shared by two regions. HyFO axiomatically relates the hydrogeological entities using foundational physical relations: physical containment [14], constitution, and hosting a void [13]. Most relevant to the work here is $submaterial_t(x, y, t)$, which denotes that at time t, x is a physical part of y whose removal would alter y (i.e., x and y are materially-spatially interdependent). It is a temporally indexed variant of the physical containment relation $submaterial(x, y)$ from [14].

Relevant DOLCE Concepts: Processes and the Participation Relation. Upper-level ontologies such as DOLCE [19] or BFO [21] help ground domain ontologies in formal ontological distinctions and can facilitate interoperability across ontologies [4, 16]. A key distinction in DOLCE is between *endurants* (called *continuants* in BFO) that are wholly present at any time they exist (e.g., the hydrogeological entities from HyFO) and *perdurants* that are necessarily temporally extended objects such as processes or events (called *occurents* in BFO). Perdurants are characterized by the endurants that *participate* in them and by temporal characteristics, such as when an instance of a perdurant starts, pauses or terminates. This is captured by DOLCE's time-indexed *participation* relation $PC(x, y, t)$ that expresses that an endurant x participates in a perdurant y at time t (AD-33 from [19]), further implying that the perdurant y occurs, among other times, at time t. Other types of participation, such as *constant participation* and *temporary participation* are also defined in DOLCE but are of lesser importance here.

(Ad-33) $PC(x, y, t) \rightarrow ED(x) \wedge PD(y) \wedge TR(t)$ ***(x participates in y during t)***

In this paper, we treat hydrological flow processes as perdurants and, more precisely, as processes rather than events in line with [11], assuming that they occur fairly steadily (though possibly variable over seasons), that is, they are typically not time-bounded and can be decomposed spatially or temporally into smaller processes of the same kind (e.g., infiltration over a longer period of time consists of many shorter lasting infiltration processes). We do not consider specific water-related events, such as a specific time-bound event of flooding associated with a specific hurricane or with intense rainfall in a confined location.

Temporal Relations. The temporal parameter in the participation relation refers to instances of DOLCE's temporal region concept $TR(x)$, which encompasses both extended time intervals as well as time points. To temporally compare temporal regions, we rely on $beforeEq(t1, t2)$ as the only temporal relation. It denotes that $t1$ occurs entirely before or at the same time as $t2$, which is satisfied by any of the three qualitative relations "precedes", "meets", or "equals" from Allen's interval algebra [2]. The relation equally applies to time intervals and time points (as special kind of intervals with the same start and end), but is most useful when – as we assume – the start and end of each interval is a time point. Then the existence of overlapping intervals requires the existences of start times that can be properly ordered temporally.

4 Analysis of Physical Endurants in Hydrologic Flow Processes

As a process, hydrological flow specializes DOLCE's concept of a perdurant (HF-A1). Next we analyze common hydrological flow processes discussed in the literature to develop refined participation relations that deal with key hydrological participants.

(HF-A1) $HF(x) \rightarrow PD(x)$ ***(Hydrological flows are perdurants)***

4.1 Kinds of Hydrologic Flow Processes

Fundamental to designing ontologies is identifying key concepts and their intended semantics. Here, refined *hydrological flow* concepts are based on the terminology frm USGS coupled groundwater and surface water model (GSFLOW model) [18] and related models, including the Integrated Water Flow Model (IWFM) [7]. GSFLOW models hydrological flow within and between three coarse geophysical regions: (1) the *ground surface*, which encompasses the topsoil zone and is a mix of rock and organic matter; (2) *water bodies* contained or supported by the *ground surface*, represented in HyFO as *surface water bodies* that includes both standing and flowing water bodies; (3) subsurface zones, including *zones of unsaturation* and *saturation*. The following summarizes the most important types of hydrological flow identified from these models that will guide our analysis and formalization.

Runoff is movement of water above the *ground surface*, typically caused by precipitation or melting of snow and ice. It may take the form of surface runoff, channel flow, or subsurface runoff.

Infiltration is the vertical movement of water through the *ground surface* or the groundwater table.

Overland flow is movement of water where it travels between two points on the *ground surface* without infiltrating the *ground surface*.

Percolation is the movement of water through pores and voids in *subsurface zones* driven by gravity and capillary forces.

Throughflow is the downhill percolation of water through the *zone of unsaturation* under the influence of gravity until it infiltrates the water table.

Channel flow is the movement of water within a river channel.

Recharge and Discharge is the movement of water between two *water bodies*, such as the flow of water from a tributary into another stream segment.

Interflow is the flow of water from the *zone of unsaturation* into a *water body*.

Baseflow is the flow of water from an aquifer into a connected *surface water body*.

Leakage is water moving from a *surface water body* into the connected subsurface rock unit or a *subsurface water body*.

4.2 Modeling Physical Participants in Hydrological Flow Processes

Hydrological endurants evolve continually during hydrological flow processes, e.g., water levels change and containers erode. Despite such physical changes, each flow process relies on a specific set of participating entities. Different kinds of flow processes can be discriminated based on how and what kinds of hydrogeological endurants can participate. This is formalized using semantic roles, which capture and distinguish participants based on their function within events or processes. Semantic roles were originally developed to assign participatory roles to language predicates in English grammar, but more generally identify domain independent thematic roles for endurants that participate in perdurants [10]. We utilize Fillmore's case roles [10] as summarized in [1, p. 93] but other semantic role frameworks, such as Sowa's thematic roles [22], would yield similar formalizations.

Out of the nine semantic roles from [1, p. 93], we have identified the following four as relevant for describing how hydrogeological entities participate in flow processes:

Theme participant is the moving entity that continuously participates throughout the flow process' duration. It always is some amount of water matter, but may include other, smaller amounts of matter, such as sediments, organic materials, or pollutants.

Source participant is the entity from which water moves, such as a subsurface water body from which water seeps into a surface stream.

Goal participant is the entity where the water is moved to, such as the surface water body that receives water from a baseflow process.

Locative participants are physical endurants where a process occurs and that undergoes change in physical or spatial qualities. All source and goal participants are locative participants as well.

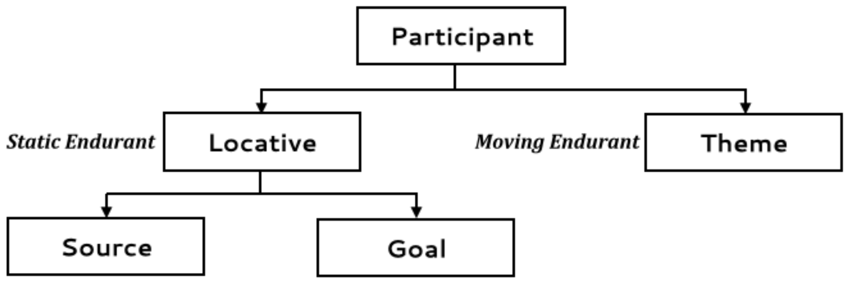

Figure 2 Kinds of participants in hydrological flow derived from Fillmore's case roles.

The reviewed kinds of hydrological flows all transport of water from some source entity to a goal entity. For example, infiltration is a flow process that transports water from the ground surface to some subsurface entity (e.g., a zone of unsaturation or a hydrogeo unit). For example, the infiltration process can consist of distinct temporal stages identified by different participating endurants, such as percolation of water matter through the zone of unsaturation, followed by percolation through a physical container, and followed by entry into a subsurface water body. As such, hydrological flows are inherently spatial processes where water changes location from a *source* to a *goal* participant, both refining the more general concept of a *locative participant*. The transported water matter itself is the *theme* of any hydrological flow process. Temporal aspects in participation arise from the spatial ones and do not need to be modeled separately. Furthermore, hydrological flow generally does not involve intentional agents, except maybe for the designers of flow enhancing, altering, or impeding measures such as dams, culverts, or environmental engineering. But such agents are not directly involved in flow processes but rather in water planning processes.

5 Formalization

The first set of axioms (HPC-A1–10) captures the three kinds of specialized participation relations and ontological and temporal dependencies between them. Section 5.1 captures what static hydrogeological entities can fill the participant roles. Afterwards, the zones of saturation and unsaturation, which are not yet part of HyFO, are axiomatized. Subsequently, we formalize flow within a single hydrogeological entity (intraflow; Sec. 5.3) and across two distinct entities (interflow[1]; Sec. 5.4). All axioms for the ontology in this paper are expressed in full first-order logic, and are available at `https://github.com/gruninger/colore/tree/master/ontologies/hyfo_flow` encoded using the ISO standard Common Logic.

Figure 2 presents the hierarchy of participants distinguished by their roles in *hydrological flow*. These roles are formalized as refined variants of the general participation relation (*PC* from DOLCE) as *TPC*, *SPC* and *GPC* (HPC-A1–3). The term *locative participant* is used to denote either *source* or *goal participants* (HPC-A4). HPC-A5–8 capture basic ontological dependencies between the participants: disjointness of the locative particpants from the theme participant (HPC-A5) and the existence of some source, goal, and theme participant for each flow process (HPC-A6–8), though at possibly different times. HPC-A9 and A10 express basic temporal constraints on the participants: some *goal participant* must exist at the same time or after any *source participant* (HPC-A9) and, vice versa, some *source participant* must exist at the same time or before any *goal participant* (HPC-A10). In reading

[1] This concept is distinct from the term **Interflow** described in Section 4.1.

these two axioms, let the reader be reminder that the temporal parameters denote either extended time intervals or time points, and any time interval at which a participation relation holds can be broken into many contained time points, for which the participation relation must also hold. Thus, HPC-A9 and A10 are satisfied if the last/earliest possible timepoint during a *source/goal participation* satisfies the axiom.

(HPC-A1) $TPC(x,y,t) \rightarrow PC(x,y,t) \wedge HF(y) \wedge PED(x)$ **(*Theme participation*)**

(HPC-A2) $SPC(x,y,t) \rightarrow PC(x,y,t) \wedge HF(y) \wedge PED(x)$ **(*Source participation*)**

(HPC-A3) $GPC(x,y,t) \rightarrow PC(x,y,t) \wedge HF(y) \wedge PED(x)$ **(*Goal participation*)**

(HPC-A4) $LPC(x,y,t) \leftrightarrow SPC(x,y,t) \vee GPC(x,y,t)$
(*Locative participation generalizes source and goal participation*)

(HPC-A5) $LPC(x,y,t) \rightarrow \neg TPC(x,y,t)$
(*Locative and theme participation are disjoint*)

(HPC-A6) $LPC(x,y,t) \rightarrow \exists z \, TPC(z,y,t)$
(*At any time when something locative participates in a hydrological flow process, then there must also be some theme participant*)

(HPC-A7) $HF(x) \rightarrow \exists y,t SPC(y,x,t)$
(*Any HF process has some source participant*)

(HPC-A8) $HF(x) \rightarrow \exists y,t GPC(y,x,t)$ **(*Any HF process has some goal participant*)**

(HPC-A9) $HF(x) \wedge SPC(y,x,t1) \rightarrow \exists z,t2[GPC(z,x,t2) \wedge beforeEq(t1,t2)]$
(*Any source participant has a goal participant at the same or a later time*)

(HPC-A10) $HF(x) \wedge GPC(z,x,t2) \rightarrow \exists y,t1[SPC(y,x,t1) \wedge beforeEq(t1,t2)]$
(*Any goal participant has a goal participant at the same or a later time*)

5.1 Hydrogeological Participants

Every *hydrological flow* process requires the involvement of some *source*, *goal* and *theme participants* (HPC-A7,8, together with HPC-A4,6). *Water matter* is the only entity that is transformed by virtue of being moved and becomes the sole *theme participant* (HPC-A11) of hydrological flow, while *geologic units* and *water bodies* stay in place. The movement of water from a *source participant* indicates that it must contain some amount of *water matter* at the beginning of the process (HPC-A13). The most common *source* and *goal participants* are *hydro rock bodies*, which are hybrid entities that consist of a surface or subsurface *water body* and a geologic unit that serves as the physical container. Other important *locative participants* are the *ground surface*, which is a layer of soil and rock and acts as a boundary between surface and subsurface flow (e.g., in infiltration and overland flow), and *zones of saturation* and *unsaturation*, which participate in subsurface flow, e.g., throughflow (HPC-A12). The *zone of saturation* lies within the region of a *hydro rock body* that is a *locative participant*, and is therefure not separately mentioned in HPC-A12.

(HPC-A11) $HF(x) \wedge TPC(y,x,t) \rightarrow WM(y)$
(*Water matter is always the theme participant in hydrological flow*)

(HPC-A12) $HF(x) \wedge [SPC(y,x,t) \vee GPC(y,x,t)] \rightarrow HRB(y) \vee GS(y) \vee ZOU(y)$
(*Source and goal participants in hydrological flow are a HRB, GS, or ZOU*)

(HPC-A13) $HF(x) \wedge TPC(y,x,t2) \rightarrow \exists s,t1[SPC(s,x,t1) \wedge submaterial_t(y,s,t1) \wedge beforeEq(t1,t2)]$ **(*Any water matter that is a theme participant is submaterial of the source participant at the same or an earlier time point*)**

5.2 Subsurface Zones

Hydrological flow can occur almost anywhere beneath the ground surface. As evident from Section 4.1, a complete categorization of subsurface flow processes requires a more detailed description of two hydrologically distinct regions, the *zones of saturation* and *unsaturation*. These have previously not been represented but can be described using existing HyFO concepts and relations from [16]. The presented formalization closely follows their informal descriptions from GWML2 [3].

The zone immediately below the soil surface containing pore spaces that can potentially accommodate *water matter* is called the *zone of unsaturation* (ZOU), often also referred to as zone of aeration or vadose zone. This zone includes the capillary fringe where the moisture content is less than saturation, that is, water may flow through this zone but does not reside there for extended periods of time. The *zone of saturation* (ZOS) is the zone that lies below the *zone of unsaturation* and is bounded at the top by the water table. The zone of saturation is the region of a *hydrogeo unit* whose void spaces are entirely filled with *water matter* (Z-A1). *Subsurface water bodies* such as those in aquifers are situated in this zone (Z-A2), but the zone excludes regions occupied by *confining beds* (Z-A3). *Zone of unsaturation* is the spatially complementary region of the *ZOS* within a *geologic unit* (Z-A4), meaning they may be spatially connected but do not overlap (Z-A5).

For completeness, we also refine the definition of a *ground surface* from [13] to describe it as a relevant part feature that is hosted by a *geologic unit*.

(Z-A1) $ZOS(z) \rightarrow HGU(z) \wedge \exists c, w[P(\mathrm{r}(z), \mathrm{r}(h)) \wedge CSB(c) \wedge submaterial(c, z) \wedge \neg ZEX(\mathrm{r}(z) \cdot con\text{-}voidspace(c)) \wedge WM(w) \wedge P(\mathrm{r}(z) \cdot con\text{-}voidspace(c), \mathrm{r}(w))]$

(***Zone of saturation is a hydrogeologic unit that includes some connected, non-empty voidspace in the unit's container – denoted as the intersection between the zone*** z ***and the container's connected voidspace – and the voidspace is completely filled with water matter***)

(Z-A2) $SSWB(x) \rightarrow \exists z[ZOS(z) \wedge P(r(x), \mathrm{r}(z))]$

(***Every subsurface water body is located in a ZOS***)

(Z-A3) $CB(x) \wedge ZOS(z) \rightarrow \neg PO(r(x), r(z))$

(***A*** ZOS ***does not overlap with any confining bed***)

(Z-A4) $ZOU(z) \rightarrow GU(z) \wedge P(\mathrm{r}(z), \mathrm{r}(h)) \wedge \forall y[ZOS(y) \rightarrow \neg PO(\mathrm{r}(z), \mathrm{r}(y))]$

(***Zone of unsaturation is a geologic unit that does not overlap a ZOS***)

(Z-A5) $GS(x) \wedge [ZOS(z) \vee ZOU(z)] \rightarrow \neg PO(\mathrm{r}(x), \mathrm{r}(z))$

(***Zones of saturation or unsaturation do not overlap the ground surface***)

(GS-A1) $GS(x) \rightarrow RPF(x) \wedge \exists y[GU(y) \wedge hosts(y, x)]$

(***Ground surface is a relevant part feature hosted by a geologic unit***)

5.3 IntraFlow

Our preliminary analysis in Section 4.1 suggests a classification based on whether the water flow is confined to a single entity or between entities. This results in the top-most refinement of *hydrological flow* based on whether the participating *source* and *goal participants* are distinct: (1) *intraflow* is flow within a single endurant object, and (2) *interflow* is flow between two endurant objects. Figure 4 illustrates the full taxonomy of the different types of *hydrological flow* processes along with the constraints that we use to hierarchically organize the concepts.

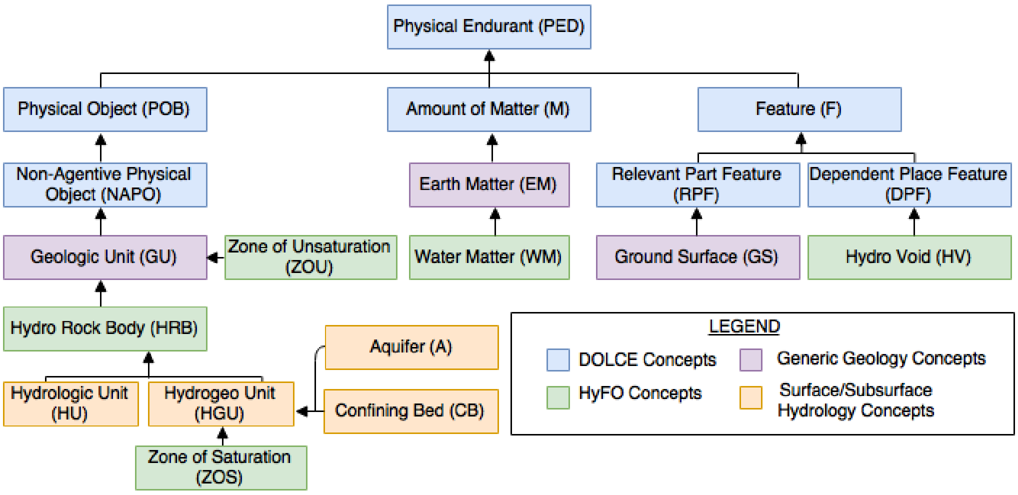

Figure 3 HyFO's geological and hydrogeological concepts that are relevant to hydrological flow.

Intraflow represents the flow of water within a single (hydro)geological endurant, hence the *source* and *goal participants* are identical (HF-A2). This high-level concept captures three types of water movement: (1) the (mostly horizontal) movement of water within the *ground surface*, (2) the movement of water within a single *water body* that is contained in a *hydro rock body*, and (3) the movement of water through the pores and fractures of a *geologic unit* that lacks a water body. Because *source* and *goal participants* are identical, any *water matter* that acts as a *theme participant* in an *intraflow* process remains submaterial of the static *locative participant* over the entire duration of the flow process (HF-A3).

(HF-A2) $intraFlow(x) \rightarrow HF(x) \wedge \forall y,t[SPC(y,x,t) \leftrightarrow GPC(y,x,t)]$
(***The source and goal participants are identical in intraflow***)

(HF-A3) $intraFlow(x) \wedge TPC(y,x,t) \wedge LPC(z,x,t) \rightarrow submaterial(y,z,t)$
(***The water that is the theme participant in an intraflow process is submaterial of the locative participant at any time t during the process***)

Surface-intraflow and ***subsurface-intraflow*** are distinct and disjoint subclasses of *intraflow* (HF-A4–A7), denoting flow processes that occur above/within the *ground surface* and below the *ground surface*, respectively.

(HF-A4) $surfaceIntraFlow(x) \rightarrow intraFlow(x)$ (***Specializing intraflow***)

(HF-A5) $surfaceIntraFlow(x) \wedge LPC(y,x,t) \rightarrow HU(x) \vee GS(x)$ (***The locative participant in surface-intraflow is either a surface HRB (a HU) or the GS***)

(HF-A6) $subsurfaceIntraFlow(x) \rightarrow intraFlow(x)$ (***Specializes intraflow***)

(HF-A7) $subsurfaceIntraFlow(x) \wedge LPC(y,x,t) \rightarrow HGU(y) \vee ZOS(y) \vee ZOU(y)$
(***The locative participant in subsurface-intraflow is either a subsurface HRB, a ZOS, or a ZOU***)

(HF-A8) $intraFlow(x) \leftrightarrow \neg surfaceIntraFlow(x) \vee \neg subsurfaceIntraFlow(x)$
(***Disjoint and exhaustive subclasses of intraflow***)

Overflow specifically describes the lateral flow of water on or within the *ground surface* (HF-A9,10) that does not infiltrate it. This includes surface runoff where flow precipitation or excess water from a surface *water body* flows over the Earth's surface.

(HF-A9) $overFlow(x) \rightarrow surfaceIntraFlow(x)$ ***(Specializing surface-intraflow)***
(HF-A10) $overFlow(x) \wedge LPC(y,x,t) \rightarrow GS(y)$
(The locative participant in an overflow process is the ground surface)

Water matter may move inside a *water body* or a *hydro rock body* that contains the *water body*. For example, water flows within a river and between different parts of a river (e.g., from one section of rapids to into a more even flowing section) until it eventually gets discharged at the river's mouth or at a junction with another river. This kind of flow occurs above and below the *ground surface*: ***surface-withinflow*** occurs within *water bodies* contained in a *hydrologic unit* (HU), which is a surface *hydro rock body* (HF-A11,12), while ***subsurface-withinflow*** occurs within a *subsurface water body* hosted by a *hydrogeo unit* (HGU), which is a subsurface *hydro rock body* (HF-A13,14).

(HF-A11) $surfaceWithinFlow(x) \rightarrow surfaceIntraFlow(x)$
(Specializing surface-intraflow)
(HF-A12) $surfaceWithinFlow(x) \wedge LPC(y,x,t) \rightarrow HU(y)$
(Locative participant in surface within flow is surface** HRB**, i.e., a HU)
(HF-A13) $subsurfaceWithinFlow(x) \rightarrow subsurfaceIntraFlow(x)$
(Specializing subsurface-intraflow)
(HF-A14) $subsurfaceWithinFlow(x) \wedge LPC(y,x,t) \rightarrow HGU(z)$ ***(Locative participant in a subsurface-withinflow is a subsurface HRB, i.e., a HGU)***
(HF-A15) $surfaceIntraFlow(x) \leftrightarrow overFlow(x) \vee surfaceWithinFlow(x)$
(Overflow and surface within flow are exhaustive classes of surface-intraflow)
(HF-A16) $\neg overFlow(x) \vee \neg surfaceWithinFlow(x)$
(Overflow and surface-withinflow are disjoint classes)

Through flow is a specialization of *subsurface-intraflow* (HF-A17) that represents flow of *water matter* through a *zone of unsaturation*. Once water infiltrates the *ground surface*, gravity and other forces cause it to move through the unsaturated zone until it eventually reaches the *zone of saturation* or a surface or subsurface *water body*, neither of which are themselves participants in the *through flow* process. This flow depends on the properties of the rock matter constituting the *zone of unsaturation*, such as porosity, permeability and hydraulic conductivity, necessitating that it occurs in porous *geological units*, that is, those with non-empty connected voidspace (HF-A18).

(HF-A17) $throughFlow(x) \rightarrow subsurfaceIntraFlow(x)$
(Specializing subsurface-intraflow)
(HF-A18) $throughFlow(x) \wedge LPC(y,x,t) \rightarrow ZOU(y) \wedge \exists z\,[\,GU(z) \wedge \neg ZEX(r(y) \cdot con\text{-}voidspace(z))]$ ***(Locative participant in through flow is zone of unsaturation that lies in some porous geological unit)***
(HF-A19) $subsurfaceIntraFlow(x) \rightarrow throughFlow(x) \vee subsurfaceWithinFlow(x)$
(Exhaustive subclasses of subsurface-intraflow)
(HF-A20) $\neg throughFlow(x) \vee \neg subsurfaceWithinFlow(x)$
(Throughflow and subsurface-withinflow are disjoint classes)

5.4 Interflow

In *interflow* processes, such as infiltration, baseflow, or leakage as described in Sec. 4.1, water flows between distinct *source* and *goal participants* (HF-A21). Often, such flow processes may consist of several heterogeneous temporal parts that are *inter-* or *intraflow* processes, but we epitomize them as single *interflow* processes as long as they occur in spatially connected *source* and *goal participants* (HF-A22). More complex *interflow* processes across multiple participants can be easily composed. The temporal constraints on source and theme participants from HPC-A13 are expanded to *goal participants* for *interflow* by stating that any *theme participant* will eventually become submaterial of a *goal participant* (HF-A23).

(HF-A21) $interFlow(x) \rightarrow HF(x) \wedge \forall s, g, t1, t2[SPC(s, x, t1) \wedge GPC(g, x, t2) \rightarrow s \neq g]$
(*Any source and goal participants in interflow are distinct*)

(HF-A22) $interFlow(x) \wedge SPC(s, x, t) \wedge GPC(g, x, t) \rightarrow C(r(s), r(g))$
(*Source and goal participants in an interflow process are spatially connected*)

(HF-A23) $HF(x) \wedge TPC(y, x, t1) \rightarrow \exists g, t2[GPC(g, x, t2) \wedge submaterial_t(y, g, t2) \wedge beforeEq(t1, t2)]$ **(*Any water matter that is a theme participant is submaterial of the goal participant at the same or a later time point*)**

Three specializations of *interflow* processes are identified: (1) *surface-interflow* where water moves between hydrogeological endurants above the Earth's surface such as surface *hydro rock bodies* or the *ground surface* (HF-A24); (2) *subsurface-interflow* where water moves between subsurface hydrogeological endurants such as *hydrogeo units* and *zones of saturation* (HF-A25); (3) *surface-subsurface-interflow* where water moves between a surface and a subsurface endurant (HF-A27).

(HF-A24) $surfaceInterFlow(x) \rightarrow interFlow(x) \wedge \forall l[LPC(l, x, t) \rightarrow (HU(l) \vee GS(l))]$
(*Surface-interflow is the flow of water between HU's or GS*)

(HF-A25) $subsurfaceInterFlow(x) \rightarrow interFlow(x) \wedge \forall l[LPC(l, x, t) \rightarrow (HGU(l) \vee ZOU(l))]$
(*Subsurface-interflow is the flow of water between HGU's or ZOU*)

(HF-A26) $surface\text{-}subsurfaceInterFlow(x) \rightarrow interFlow(x) \wedge \forall l[LPC(l, x, t) \rightarrow (HRB(l) \vee ZOU(l) \vee GS(l))]$
(*Surface-subsurface-interflow is the flow of water between HRB's, ZOU or GS*)

Prototypical *interflow* processes are *recharge* and *discharge* where water flows into or out of a *hydro rock body* and fills or drains the contained *water body*. Thus, in *recharge* the goal participant is a *hydro rock body* and in *discharge* the source participant is a *hydro rock body*.

6 Summary

The absence of a formal semantic representation for different kinds of *hydrological flow* processes inhibits an integrated view of how water moves and is stored above and below the surface of the Earth. This paper presents a general schema for analyzing *hydrological flow* patterns, identifying *water matter* as a definite participant, but with varying *source* and *goal participants* (see Figure 2). Thus, three refinements of DOLCE's participation relation are proposed to model this formally: the participation of the transported water as *theme participant* and two *locative participants*, namely the *source* and *goal participants* that indicate the hydrogeological entities that loose or gain water.

A taxonomy of common hydrological flow relations, depicted in Figure 4, is developed using the roles and the participating physical endurants as described by HyFO (see Figure 3). The highest-level distinction between hydrological flow patterns is based on whether water moves within a single *locative participant* (*intraflow*) or between two distinct *locative participants* (*interflow*). *Intraflow* is further specialized based on the single participant: whether it is the *ground surface* (e.g., overflow), a surface *hydrologic unit* (e.g., channel flow), a subsurface

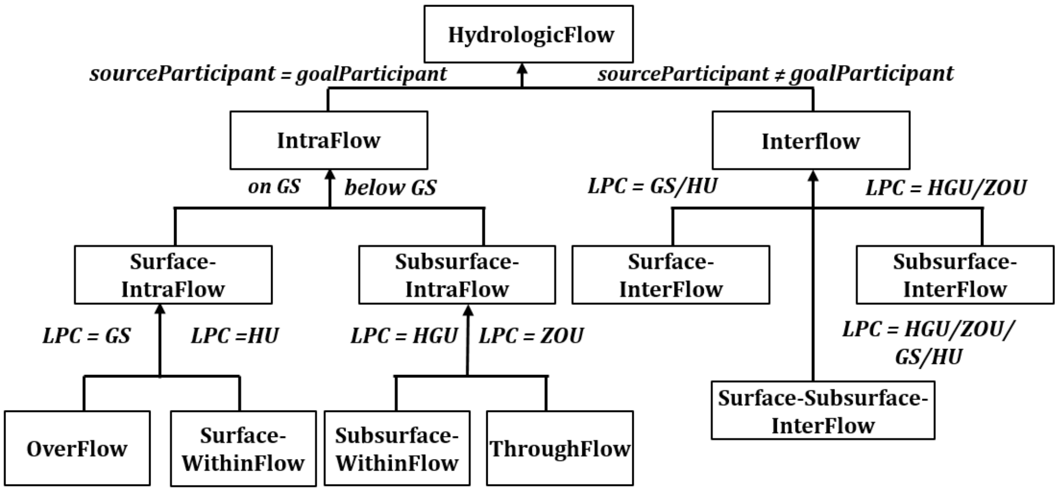

Figure 4 The taxonomy of *hydrological flow* concepts.

hydrogeologic unit (e.g., flow within an aquifer), or a subsurface zone (e.g., throughflow, percolation). Similarly, *interflow* can be distinguished based on three combinations of *source* and *goal participants*: (1) both are surface features (one possibly the *ground surface*), (2) both are subsurface features (a hydrogeological endurant or a zone), (3) one is a surface and the other is a subsurface feature (e.g., infiltration, leakage, and base flow).

The different flow processes have been formalized only to the extent necessary for communicating the taxonomy's basic distinctions and associated temporal constraints. It is a proof-of-concept that shows how one could extend HyFO with dynamic hydrological aspects. More work is required to complete the formalization of all discussed flow concepts and to test the formalization's internal consistency and its consistency with how hydrological flow is represented in related hydro data models and ontologies.

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