A Salience-Based Framework for Terrain Modelling: From the Surface Network to Topo-Contexts

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Abstract

Twenty years after Mark and Smith's seminal paper, *a Science of Topography*, we revisit some of their fundamental questions about how landforms are recognised by people and how they can be automatically extracted or delimited from representations of topographic surfaces. Many approaches and tools, essentially based on *GeoOBIA*, can extract objects associated with landforms from image data. But, they cannot relate these objects to the topology and topography of the terrain. Yet, geo-scientists can easily recognise landforms, considering terrain characteristics and other factors composing the context of appearance of those landforms. Revisiting *Gestalt Theory*, we propose a salience-based approach fostering a holistic view of the terrain which fits with the geoscientists' ability to recognise landforms using the topographic and hydrologic contexts. The terrain is represented as an *extended surface network* (ESN), a graph composed of elementary saliences (peaks, pits, saddles, thalweg and ridge networks) and obtained from raster data. The ESN combines both the surface and the drainage networks in a sound topological representation of the terrain. A skeletonisation technique of the ESN's thalweg and ridge networks is proposed to geometrically and topologically characterise landforms, as well as ensembles of landforms. On this basis and to represent the context of appearance of landforms, geo/topo-contexts are introduced as structures grounded in the properties of the ESN and using the skeletonisation technique. We give an illustration of how a geomorphologist can apply our approach and tools, using the depressions and drainage basins as examples of useful geo/topo-contexts.

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1 Introduction

Geomorphological mapping plays an essential role in earth sciences and is based upon the integration of multidisciplinary information from the field and remotely-sensed data. On a topographic map, the terrain is modelled as an elevation field, while topographic objects are represented by geometrical shapes or symbols. This representation is efficient for digital processing using a Digital Terrain Model (DTM) since fields and objects describe well physical properties. However, it does not apply to the human perception of topography. People perceive and reason about the geographic space mostly qualitatively [18]. Hence, many challenges remain and geomorphologists emphasise the complexity of: 1) deterministically characterising landforms and other geomorphological units/entities; 2) establishing comprehensive taxonomic schemes; 3) performing geomorphological mapping at various scales [6].

In their seminal paper, *A science of Topography*, Mark and Smith [33] set the stage for the next decades of research on the understanding, representation and automatic identification of landforms. Their goal was to "establish an ontology of landforms and of terrain of the sort that human beings employ when dealing with natural environments". They raised several

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fundamental issues that still hold today. Two of them are most relevant to our research: 1) Which kinds of landforms do people recognise, reason about, store, retrieve and process? 2) Which computer processing methods can be used to extract and delimit landforms from representations of topographic surfaces? We are particularly interested in examining how these issues have been addressed to support the geomorphologist's work.

A landform is a physical feature of the terrain with its own recognisable shape. Its definition is usually qualitative and inherently vague. Geomorphologists are trained to recognise landforms and to identify their prominent characteristics (i.e. saliences) in the field, on maps and on 3D representations of the terrain. The notion of salience has been investigated in cognitive research on visual attention [56], in neurosciences [31] and in linguistics [9]. For our purpose, salience can be informally defined as "an emphasis of an element or of a set of elements distinguishable from the whole" [32], characterized by "relatively distinct, prominent or obvious features compared to other features" [11]. Salience is a central notion when modelling/generating route directions and developing services for wayfinding [11] as well as for landscape descriptions [32]. However, only few works have considered the concept of salience when modelling landforms [25], although the geomorphologist's work obviously relies on recognising salient features of landforms in the landscape [10]. From a topographic point of view, a number of important terrain saliences can be identified in the surface network, a planar graph obtained from a DTM and formed by critical points (i.e. peaks, pits, saddles) and critical lines (i.e. ridge lines and valley lines) of the terrain [55].

Long ago, geomorphologists acknowledged the importance of the semantic modelling of landform structures [16] and geospatial semantics [29] has taken an increasing importance since then. Moreover, there is an important difference between how people describe landforms and how their definitions can be represented in a machine: this has been called the *qualitative-quantitative divide* [33]. The user has specific goals and cognitive abilities (spatial perception, interpretation and reasoning), which are not easily interpreted in terms of system variables and implemented in algorithms. Reflecting this gap, one can distinguish qualitative and quantitative approaches for landform identification [17].

In qualitative approaches, landform descriptions are formalised using ontologies. Geospatial ontologies [12] provide strong bases to model the semantics of geospatial information and to support interoperability through spatial data infrastructures and web geo-services [41]. They are useful to semantically structure the geomorphological knowledge and require appropriate elicitation approaches [30]. Moreover, a difficulty arises when trying to take into account the vagueness of the geomorphologist's landform perception/description, which is difficult to formalise in data structures used for the semantic web. Minimally, geospatial ontologies need to be enhanced to incorporate terrain models and topology in order to support automated landform identification and mapping [41].

Quantitative approaches aim at developing computational methods to recognise landforms from terrain data; the terrain being represented as a continuous field of elevation [48]. These approaches are data-centred and depend on the data structures (usually raster) chosen to characterise the topography. The terrain is segmented into homogeneous regions (called "landform elements") based on some parameters such as the slope gradient and the curvature; and landforms are defined as an aggregation of these landform elements, called objects when performing *Geographic Object-Based Image Analysis* (GEOBIA), a popular approach for terrain analysis from imagery [8]. Quantitative methods can identify land surface objects that are valuable for geomorphometric analysis, but they do not provide any topological information between the identified objects/areas.

Moreover, geographers emphasised that the study of the relationships among features (i.e. the terrain topology) is of particular importance for terrain analysis and to effectively identify topographic features [14]. But, compared to feature extraction from digital imagery (i.e. GEOBIA), researchers have given less attention to the topological relationships among topographic features. Thus, the authors [14] offered an in-depth review of historical and contemporary works on the surface network (SN), which is the most common way of representing the topology of terrain features. The geographers' interest in the SN and its ability to represent terrain topology converges with [24]'s claim that there is a real advantage to study landforms according to their topographic saliences extracted from a SN. Doing so, the landform models can be enriched with topological properties that image-analysis approaches (such as GEOBIA) cannot capture.

Indeed, landforms are salient (i.e. "recognisable by people") individual entities which are topologically distinct and can be related to (i.e. "have spatial relations with") other landforms [20, 33]. Landforms can even be embedded in other landforms (i.e., a mountain can be part of a mountain range). Hence, there is a need for approaches capable of identifying landforms as areal objects that are topologically related. The use of ontology design patterns was proposed to specify complex topographic features/objects, thought of as "assemblages of multiple components with functional relations to each other, to outside systems, and to the surrounding topography" [52].

In 2013, a group of researchers [42] advanced the vision of *Linked Topographic Data*, an approach to make topographic datasets accessible and interoperable through semantic web technologies. They observed that terrain surface datasets (based on continuous field data models), cannot be shared on the semantic web which needs discrete objects for assigning URIs. Moreover, they advocated for the use of SN to share information about surfaces on the semantic web. Indeed, a SN is a graph composed of topologically connected sets of critical points, lines and surfaces. These elements can be efficiently stored and shared on the web and may be linked to other data (URIs, gazetteers, etc.). An ontology design pattern, the SNODP, was proposed to capture the semantics needed to create a topologically consistent surface network. This conceptual solution aimed at advancing the vision of Linked Topographic Data, but we are not aware of any implementation of the SNODP. Moreover, [42] noted that the Linked Topographic Data vision also aligns well with the efforts of various national mapping organisations to develop topographic map ontologies, while being challenged by the need to integrate field and object topographic data models.

Another ODP, the SWFODP was proposed for surface water features [45]. Notably, a fundamental distinction was made between landscape features that act as containers (e.g., stream channels, basins) and the bodies of water (e.g., rivers, lakes) that occupy those containers. The SNODP and SWFODP have been integrated in the Landform Reference Ontology (LFRO) which was proposed as a domain reference ontology for knowledge representation and reasoning about landforms [41].

In [25], the authors proposed an approach based on an ODP to model elementary and complex landforms. A landform is defined by its salient characteristics and geometrically characterised by a skeleton. Skeletons are topological structures joining some critical points and lines of the terrain. They can be extracted from a SN and provide the support for a topological structure connecting landforms together. Using this conceptual model, their approach proposes an ODP to support the semi-automatic identification of landforms and of their components. This ODP helps in translating the skeleton definitions so that the proper structures can be obtained from a DTM. As an illustration, the approach was applied to identify submarine canyons from bathymetric data.

In recent years, significant progress has been achieved on the generation and manipulation of surface networks [22] and on the extension of the SN structure to embed the drainage network, allowing for the use of a common topological data structure for both terrain analysis and hydrology [23]. In this paper, our goal is to show how such an enhanced view of a SN provides a computational foundation for the development of salience-based approaches for terrain modelling and for the contextual identification of landforms. This is a possible answer to the question raised in [33]: *Which computer processing methods can be used to extract and delimit landforms from representations of topographic surfaces?*

The paper is organised as follows. Section 2 presents the SN as a tripartite graph structure of elementary terrain saliences (peaks, saddles, pits, ridge lines and thalweg lines) obtained from a DTM. It is shown that the SN is a topologically correct representation of the terrain grounded on the properties of a *Morse-Smale complex*. In Section 3, an extension of the SN is presented in the form of an *Extended Surface Network* (ESN) in which the drainage network is fully integrated in the surface network, capturing the topographic and hydrologic main features of the terrain according to [23]. In Section 4, *Gestalt Theory* is invoked to revisit the geomorphologist's cognitive ability to identify landforms and their main salient terrain features on topographic maps. Building on the properties of the thalweg and the ridge networks of the ESN, a skeletonisation approach is proposed to geometrically and topologically characterise important landforms, as well as ensembles of landforms. Gestalt Theory also shows that objects are not observed in isolation, but in context: this is confirmed by the practice of earth scientists. The notion of geo-context is thus introduced to represent the context of appearance of landforms: it is used to structure the salience-based representation of the terrain. In Section 5, a topo-context is defined as a refinement of a geo-context grounded in the properties of the ESN. Important characteristics (i.e. ring, skeleton), properties (i.e. adjacency, containment) and operations (i.e. fusion) of topo-contexts are formally defined. Several examples (i.e. depressions, basins) are given to illustrate this important notion and its use to partition the terrain and to help locate landforms. Section 6 illustrates how this approach and the associated software can be used by a geomorphologist. Section 7 concludes the paper by summing up the main contributions of this work and evoking future works.

2 Towards the integration of the surface network and the drainage network

Clarke and Romero's review [14] presents the numerous works related to surface theory and to terrain modelling using graph representations of critical points (pits, peaks and saddles) and their associated (ridge and valley) lines. Of particular interest is the mathematical theory that Morse [35] proposed to analyse the topology of "sufficiently smooth manifolds" using what are called now the *Morse functions*. This theory led to the formal definition of the so-called *Morse-Smale complex* (MSC) connecting all critical elements of a Morse function. In the case of terrain modelling, [39] introduced the concept of SN relying on the MSC theory to describe terrain morphology [55].

A SN is defined as a topological data structure modelled by a tripartite graph in which critical lines (ridges and thalwegs) are edges connecting critical nodes (pits, peaks and saddles). The ascending cell of a pit is an area where all flows converge to the pit, forming a depression. It is surrounded by a set of ridges. The descending cell of a peak is an area that contains all the flows issued from the peak, forming a hill. The surface network provides a full partition of the terrain into ascending cells (the ascending manifold) and another partition into descending cells (the descending manifold). The intersection of a descending

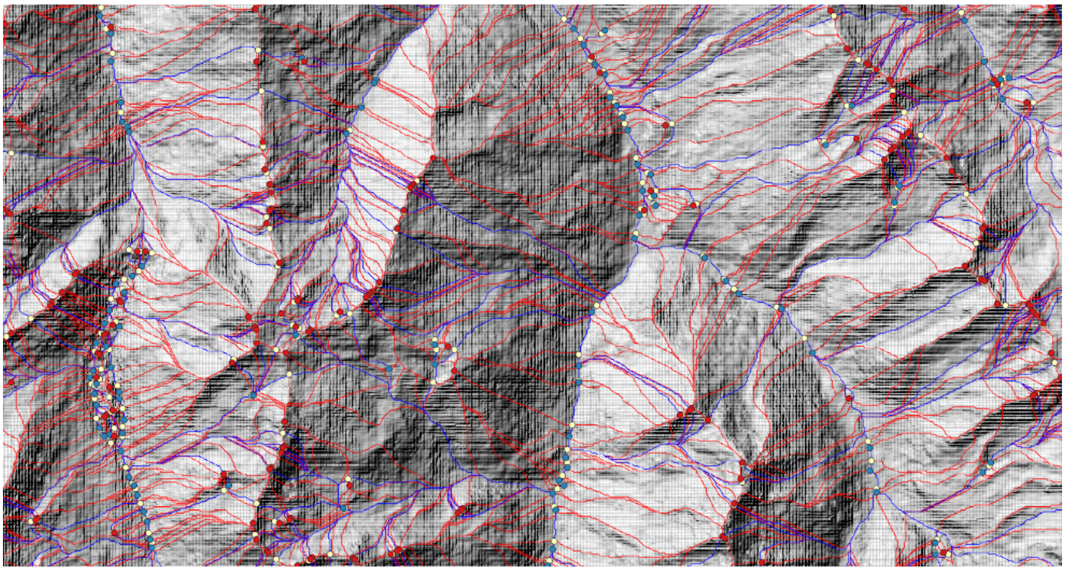

Figure 1 Portion of the study area. Thalwegs (blue lines), ridges (red lines), peaks (red nodes), pits (blue nodes) and saddles (white nodes).

cell and an ascending cell forms a *Morse-Smale cell*, a cell that contains all the flows starting from a peak and reaching a pit. The network obeys certain rules that ensure its topological consistency. For example, saddles are connected to pits by a thalweg and to peaks by a ridge, and ridges and thalwegs cannot intersect, except at saddles [55].

On raster DTMs, surface networks are usually calculated by first detecting saddles, and then by initiating ridges and thalwegs at each saddle point by following the steepest slope upward to a peak or downward to a pit. [22] proposed a new approach for the SN construction that ensures the topological consistency for DTMs represented by a raster grid. This new algorithm does not require any pre-set parameter and includes a coherent partitioning of the terrain into ascending and descending cells.

Considering terrain modelling and landform recognition, it is clear that people can easily identify peaks, passes, ridges, hills and depressions when observing a landscape. Trained people can even easily identify such salient features on topographic maps. Hence, we consider that the *elementary salient features* that characterise the morphology of a terrain are modelled by the critical points (pits, peaks, saddles) and the critical lines (ridge lines, thalweg lines) of its SN.

Indeed, geomorphologists are not able to distinguish all the salient points and lines in a topographic map or in a DTM. That is where the SN and the tool that we use [22] provide an invaluable support to automatically extract the fine-grained salience structure of the terrain in a form that captures the “topology of the topography”, providing a solution to some of the challenges set in [14].

As an illustration, we present in this paper some examples of the application of our approach and software to the drainage bassin of the Rhône river upstream the Léman lake in Switzerland. Source DTM is a SRTM image with a pixel size of 26 m. Figure 1 presents a small part of the SN generated by our system, displaying peaks, pits, saddles, the ridge network and the thalweg network.

Geomorphologists and hydrologists mainly rely on the computation of the drainage network to explain the features on a surface, especially in fluvially eroded terrains. The drainage network (DN) is composed of streams that form a directed, hierarchical graph. Tributary streams connect to main streams at *confluence points* and their hierarchical position can be defined by an order such as the *Strahler order* [47].

Traditional approaches obtain the DN by computing the flow direction and the flow accumulation directly on a raster DTM for each pixel [37]. Accumulation values higher than a certain threshold are considered as streams and a drainage network is vectorised from these pixels. The flow direction is also used to compute drainage basins, formed by pixels whose flows contribute to the same outlet. Limits of drainage basins correspond to drainage divides.

The SN in the form of a MSC cannot be directly used to generate a DN because it is an undirected graph; and since there is no hierarchy in the network, no flow accumulation can be defined. Nonetheless, the SN and the DN share similarities. Thalwegs and streams are both defined as lines of converging flow. Ridges in a SN are lines of diverging flow, similarly to drainage divides in a DN. However, traditional drainage network extraction methods do not consider several important topographical characteristics of the terrain. There is a loss of important topological relations in these methods: 1) ridges and streams are disconnected and do not form a connected graph; 2) when computing a drainage network, saddles are not considered at all, although they are important critical elements of the SN.

With the goal of making the SN and DN topologically compatible, [23] recently proposed an extension of the SN structure of [22] called the *Extended Surface Network* (ESN). This structure yields several advantages [23], mainly 1) the ESN includes ridges and streams in the same structure; 2) the ESN provides a common structure that can be used both in topography and in hydrography. Thus, the ESN enables new processing capabilities exploiting topographical and hydrological features. The current work capitalises on these advantages which are discussed in the next section.

3 The extended surface network (ESN)

We explain here some of the main technical characteristics of the ESN [23]. In the ESN, the ridge definition is extended to include drainage divides. Figure 2 presents a portion of the ESN with nodes (peak, pits, saddles) as in the SN, and with new nodes (confluence, junction, outlet) that are used to integrate the drainage network. In addition to the SN edges (ridges and thalwegs), divides are also displayed. Now, considering thalwegs connecting at a point, ridges should be traced in order to separate the areas that contribute to each thalweg. This means that at a node, one should initiate as many ridges as there are thalwegs connected to this node.

For example, in Figure 2 left, three thalwegs join at a confluence: two coming from saddles, and one going to the pit. Thus, three ridges are initiated at this node. Similarly, three ridges are initiated at the pit. Because of the less restrictive connection rules between critical nodes and lines, the ESN is not a tripartite graph anymore. This new definition leads to the ESN containing twice as many ridges as thalwegs [23].

In the ESN, ridges do not delineate depressions centred on pits. Instead, they delineate dales centred on thalwegs. *Dales* are defined for each thalweg by all the flow lines that run into the thalweg. Hence, each thalweg is associated with a dale in a one-to-one relationship (Figure 2 left) and the dale is connected to both ends of the thalweg. Consequently, a thalweg partitions a dale into two sub-areas called slopes. A *slope* is also obtained by intersecting a hill and a dale. The ESN is still a simplicial complex and can be decomposed into a hill

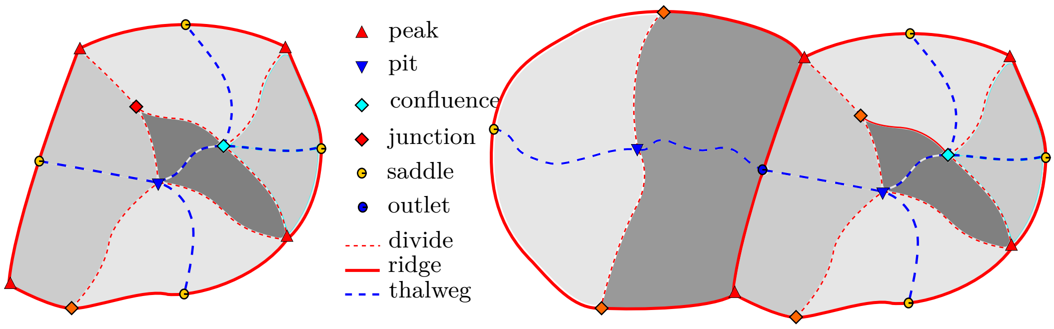

Figure 2 Left: Ascending cell partitioned in dales (in different shades of grey). Each dale contains a thalweg and is bounded by ridges. Right: two adjacent ascending cells sharing a common outlet.

complex where hills are delineated by thalwegs, and into a dale complex where dales are bounded by ridges [23]. The hill complex provides the same decomposition as the descending manifold of the SN. An ascending cell is partitioned in several dales (Figure 2, left) and the dale complex provides a decomposition in smaller cells than the ascending manifold of the SN.

To determine the drainage network, the thalweg network needs to be transformed into a weighted directed graph from which one can define the flow direction and compute flow accumulation. Both operations are performed on the ESN directly and do not require the DTM anymore. In the ESN, each thalweg corresponds to a potential stream segment and the flow can simply be defined by directing each thalweg from its higher end to its lower end. However, as with traditional flow accumulation methods, the flow can be interrupted along the thalwegs by spurious pits that usually correspond to some local minima found in nearly flat parts of the terrain. These depressions are considered in [23] as "puddles" from which the flow should come out through an outlet. A *puddle* contains at least a pit, marking the depression, and a saddle marking the outlet. Since a puddle may flow into another puddle, our system aggregates puddles recursively until an uninterrupted flowpath can be found. Thalwegs in each puddle are then directed towards the outlet. When all thalwegs are directed, springs can be identified in the thalweg network as nodes where no flow converges.

In a drainage network, the flow accumulation of a point along a stream is the amount of water that flows through this point from above. Notably in the ESN, flow accumulation is computed not per pixel (as in traditional hydrological approaches) but per thalweg. The flow accumulation of a thalweg is given by the flow coming from all connected thalwegs upstream and the flow within its dale. The flow in a dale is simply equated to the dale area while the flow coming from upstream is the accumulation measured at thalwegs directly above. Thus, flow accumulation is computed recursively as the sum of the areas of all dales located upstream and is recorded by the system as a thalweg attribute.

Because the ESN already provides the flow direction and the flow accumulation of each thalweg, the drainage network is computed by defining an accumulation threshold and by selecting all the thalwegs having a higher accumulation. This threshold is set by the user, depending on the type of flow regime considered in the analysis. The Strahler order which defines a hierarchy between streams is computed from this network, where thalwegs with an accumulation below the threshold are assigned an order of 0.

In the ESN, the thalweg being the basic stream unit, a drainage basin is the surface of all flows converging to a thalweg and is computed in a similar way as the flow accumulation: it is the union of all the dales located upstream of a thalweg. Basin calculation makes use of the

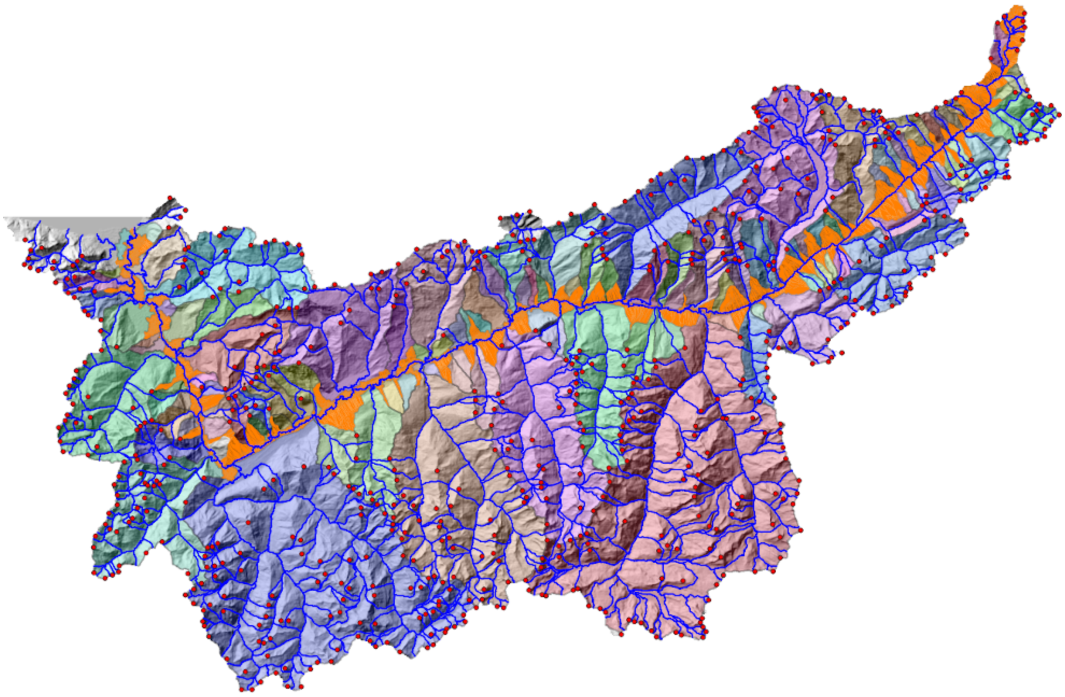

Figure 3 Drainage basins (coloured surfaces). The limit of the hill around each summit (red dot) is marked by a thalweg ring (blue lines). Orange surfaces delineate OwnCatchement areas of the Rhône river (see Section 5).

dale partition of the terrain to avoid geometrical calculations. Hence, the ESN guarantees the topological consistency between all elements of the drainage system and can be used to retrieve the drainage network and/or drainage basins at any level of detail.

As an illustration, Figure 3 displays the drainage basins of tributaries of the Rhône river, obtained from the ESN and shows major elevations depicted here by their summits and the thalwegs marking their limits.

To conclude, the ESN and associated algorithms provide a powerful framework to generate a drainage network fully integrated in a surface network. We think that this fully implemented integration can support well the ontology design patterns SNODP [42] and SWFODP [45] that were proposed to capture the semantics needed to create a topologically consistent surface network. Hence, such a solution may provide a good foundation to the vision of Linked Topographic Data [42].

4 Cognitive foundations of our approach: saliences and geo-contexts

Let us now examine the cartographer's cognitive ability to recognise landforms. Notably, the perception and recognition of forms have been studied by the German Gestalt School of Psychology. These researchers who developed the *Gestalt Theory*, theoretically and experimentally established fundamental principles of visual perception which are applied in many disciplines that deal with form recognition and creation, both by humans and machines [36]. Of particular interest to us is the guiding principle asserting that the result of form perception is a global and unified sensation in which the parts are inseparable from the whole: people do not see isolated parts, but relations that form the perceived object [1]. This principle is particularly important when considering the salient characteristics of an object [28] and applies well when considering topographic saliences and landform recognition.

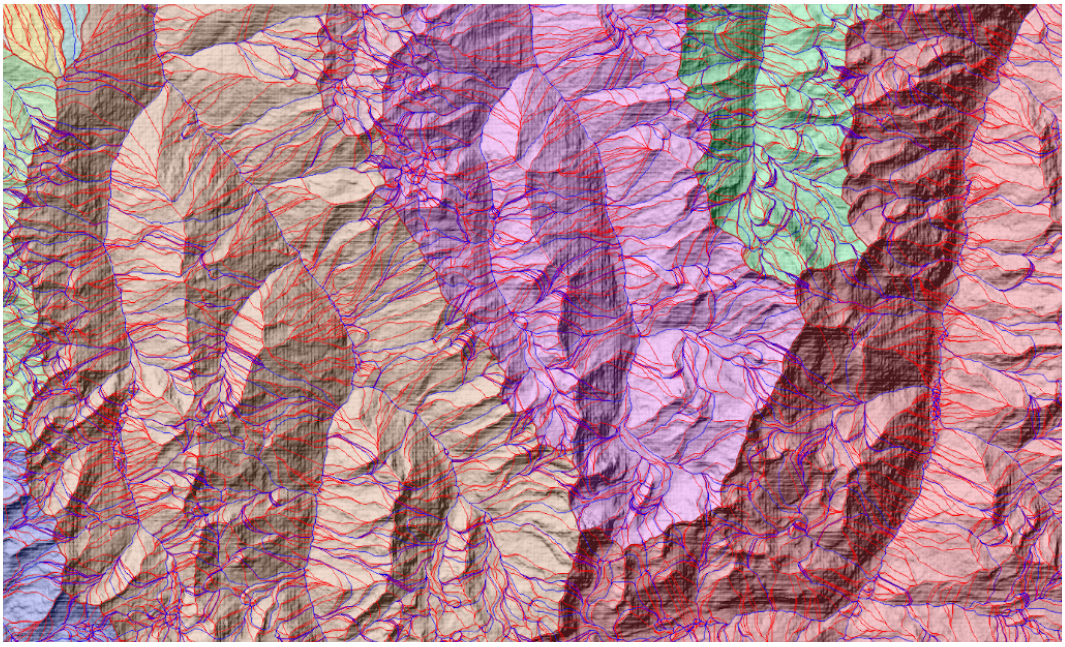

Figure 4 Ridge (red lines) and thalweg (blue lines) networks and drainage basins (coloured areas).

As we previously mentioned, the SN of a terrain is composed of elementary topographic saliences (i.e. critical points) and their salient relations captured by the thalweg and the ridge networks. Moreover, and well in line with Gestalt principles, one can identify more global saliences that are typical of a terrain/landscape shape. This is the case for terrain skeleton lines (i.e. valley and ridge lines) that geographers consider to be important and inseparable parts of topographical maps [26]. Although topographic skeletonisation has been proposed to represent nested sub-catchments and hillslopes [5] and to automatically delineate drainage basins from contour elevation data [34], we are not aware of its practical use for landform characterisation.

In our approach, terrain skeleton lines are considered to be important salient features of topographic maps. Considering the ESN data structures, a *skeleton line* is defined as a portion of either the thalweg network or the ridge network. According to Gestalt Theory, we hypothesise that a large number of landforms can be characterised by such skeleton lines. The ESN data structures allow for geometrically representing landforms characterised by a skeleton, a “salient region” and a “boundary region” as proposed in [25]. The salient and boundary regions are used to handle vagueness and indeterminacy of the landform location in a similar way as in [7]. Skeleton lines can also provide a topological structure connecting the landforms together, and hence they can be used to characterise and identify an ensemble of landforms. As presented above, the ESN is used to determine the thalweg networks that are the skeletons of the hydrological network. In this case, a drainage basin is the boundary region of a hydrological area that is characterised by a skeleton (the portion of the thalweg network contained in the basin) and delimited by drainage divides (the portion of the ESN ridge network enclosing the basin). As an illustration, Figure 4 presents a portion of the thalweg and the ridge networks of the Swiss Rhône valley. The coloured areas correspond to different drainage basins generated by our system using the ESN.

Gestalt Theory also shows that objects are not observed in isolation, but in context [36]. Notably, this principle is exploited in image analysis approaches for the detection of so-called “salient regions” [57] and for the identification of object shapes [51]. Indeed, geomorphologists are trained to consider the global context (i.e. topographic, geologic) when identifying landform shapes and typical ("salient") regions where the landforms can be found. In [6] the authors emphasise the importance of considering contextual information based on spatial topological relationships. In [10] the authors claim that, when "reading a landscape, settings, observations and analyses of landscapes must be framed in relation to several contextual considerations such as the climate, the geology and the topography".

In our approach we emphasise the importance of the context of appearance of landforms, that we define as follows.

> Considering 1) that a landform is the result of past geomorphological processes or of ongoing processes; and 2) that a landform can only appear in places where these processes occur(red); we define the **geo-context** of a landform to be a region of the surface of the earth where these conditions of appearance are met and where the landform can be found.

Geo-contexts may have different spatial extensions. For example, a geomorphologist interested in the influence of glacier erosion in our study area in Switzerland, may consider the map of the LGM: the Last Glacial Maximum [13]. We call *LGMAlpGeo-context*, the area where glaciers covered the Alps during the LGM [46]. Indeed, our study area is itself a geo-context included in the *LGMAlpGeo-context*. Hence, a geomorphologist will expect to detect typical glacial landforms in this area such as U-shaped valleys, glaciers, glacial cirques, drumlins and different kinds of moraines. We need to note that the kinds of expected landforms depend on the level of detail of the observation (i.e. the map scale and resolution). Hence, geo-contexts need to be considered at different levels of detail in accordance to cognitive studies [49]. Moreover, it is indicated in [50] that: 1) the representation of a spatial object at different levels of resolution leads to a hierarchical representation; 2) space is often conceived as a container; 3) Containment forms a transitive relation, which leads to a hierarchy of containers; 4) Aggregation along a container hierarchy respects spatial neighbourhood.

Indeed, in our approach, geo-contexts are such spatial containers (i.e. regions) that are hierarchically organised at different levels of detail thanks to the containment relation.

For a long time, partitioning the geographic space has been recognised as an important practice in earth sciences [19, 38]. Hence, the hierarchical representation of geo-contexts should ideally have two fundamental properties: 1) at each level of the hierarchy, the geo-contexts provide a partition of the geographic space; 2) any geo-context can be partitioned into embedded geo-contexts.

As an illustration, we present here a geo-context-based partitioning of the geographic space based on streams' catchment areas. We consider a portion of a stream *StrP* defined in the ESN by a directed thalwegline bounded by an upstream node called *Inlet(StrP)* and a downstream node called *Outlet(StrP)*. The catchment area *CatAr(StrP)* is defined as the union of all the dales whose flow converges towards *StrP*. Considering all the tributaries of *StrP*, the ESN provides the set *Bas(StrP)* of the drainage basins, as well as the drainage network of *StrP*. Let us consider the set of dales that are not part of *Bas(StrP)* and are directly providing a flow to *StrP*. This set is called *OwnCatchment* of *StrP* and denoted *OwnCat(StrP)*.

The set *OwnCat(StrP)* and the drainage basins of *Bas(StrP)* form an exact partition of the catchment area *CatAr(StrP)*. In Figure 3, the *OwnCatchment* areas of the Swiss portion of Rhône River are displayed in orange.

Such a partitioning applies well in mountainous and hydrologically eroded landscapes where the thalweg and the ridge networks are prominent. Moreover, geomorphologists and geoscientists may consider a large variety of factors (i.e. topographic, geologic, climatic, ecologic) to characterise the geo-contexts in which they expect to find certain types of landforms. Such geo-contexts have to be defined according to the expert's needs, and all of them may not have the nice mathematical properties of the partition based on drainage basins and OwnCatchment areas. Moreover, for a long time, GIS systems have provided functionalities and data structures to model the geographic space by means of spatial partitions that form categorical coverages derived from chosen thematic classifications [21]. Hence, when considering various coverage factors in relation to the topography, it is recommended to preserve a spatial partitioning, as much as possible.

5 Topo-contexts and landforms

Since topography is certainly the most obvious and essential way to characterise the earth surface, we suggest that a fundamental way of defining geo-contexts is to consider the terrain topographic characteristics. We define a *topo-context* as a particular sub-category of geo-context that is based on the terrain topography. We shall emphasise that all the following definitions are grounded on the properties of the ESN considered as a simplicial complex, notably on the properties of the thalweg and the ridge networks.

Formally, a **topo-context** (TContext for short) is an area defined by a dale (resp. by a hill) or an aggregation of adjacent dales (resp. adjacent hills) in the ESN; the aggregation criterion depending on the type of topo-context. We note that the dales (resp. the hills) are the elementary building blocks of the topo-context and that the aggregation of adjacent dales (resp. hills) preserves the ESN topological properties[1].

Two important components of a TContext, the *ring* and the *skeleton*, are needed to formally express the characteristics of TContexts, considering that they are portions of the ESN. The ***ring*** of a TContext is defined as the closed thalwegline or ridgeline that marks the periphery of the TContext's spatial area. According to the ESN properties, we can now define two generic categories (*protusion* and *cavity*) of TContexts to provide some foundations of an ontology of TContexts. If the ring of a TContext TC is a thalwegline, TC is said to be a *Protrusion*. Conversely, if the ring of a TContext TC is a ridgeline, TC is said to be a *Cavity*.

The ***skeleton*** of the TContext is defined as the portion of the ridge network or of the thalweg network contained within the area delimited by the ring of a TContext. According to the ESN properties, a *Protrusion* has a skeleton composed of connected ridges. Conversely, a *Cavity* has a skeleton composed of connected thalwegs.

A number of TContexts correspond to salient regions of the terrain, regions that have recognizable topographic characteristics. For instance, an *ElementaryHill* is a TContext which covers a single hill containing a peak node in the ESN. In this case, the peak can be considered as the salience of the *ElementaryHill* TContext. Similarly, a dale defines an elementary TContext where the skeleton is a single thalweg segment.

A fundamental property of TContexts is the ***adjacency***. Two TContexts are said to be adjacent if they share either a ridgeline or a thalwegline. This property is useful to define the important *fusion* operator that builds a larger TContext from smaller TContexts. The ***fusion*** of two adjacent TContexts $TC1$ and $TC2$ of the same type (e.g. *Protrusion* or

[1] Recall that the ESN is a simplicial complex which can be decomposed into a hill complex containing the thalwegs, and a dale complex containing the ridges. The set of dales of the ESN compose a spatial partition of the terrain. Since a dale is an elementary area centered on a thalweg, it is partitioned into two sub-areas, called slopes, whose intersection is the thalweg; the periphery of the slopes being composed of ridges. Hence, the aggregation of adjacent dales preserves the ESN topological properties.

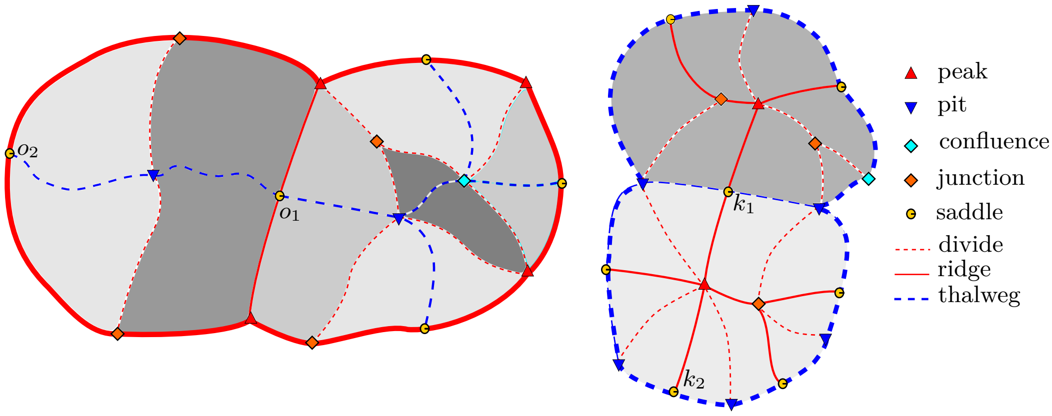

Figure 5 Left: aggregation of two *Depressions*. o_1: outlet common to both depressions before merging. o_2: outlet of the merged depression. Right: aggregation of two *Hills*. k_1: key saddle common to both hills before merging. k_2: key saddle of the merged hill.

Depression) consists in creating a new TContext $TC3$ which is the union of $TC1$ and $TC2$ such that: 1) $TC3$ has the same type as $TC1$ and $TC2$; 2) the skeleton of $TC3$ is the merge of the skeletons of $TC1$ and $TC2$; 3) the ring of $TC3$ is the merge of the rings of $TC1$ and $TC2$.

It is important to note that: 1) the two above mentioned merge operations are different and defined according to the type of TContext; 2) Some conditions may need to hold in order to authorise the fusion.

As an illustration, we consider the Cavity TContexts that form depressions of different extents holding the waterflow. We define an *ElementaryDepression* as a TContext characterised by its pit (as a salience) and by its associated ridge ring. Another salient point of this elementary TContext is the **outlet**, which is the lowest node on its ridge. It is the node through which the water would flow. While most depressions are spurious, some, such as lakes or reservoirs, are relevant and are located in larger TContexts that we call Depression TContexts.

Larger *Depression* TContexts are obtained by merging smaller *Depressions* starting from *ElementaryDepressions*. The condition to authorise the fusion of two depression TContexts is that they share the same outlet. For example, in Figure 2 right, there are two adjacent *ElementaryDepressions* such that: 1) each has a portion of the thalweg network as a skeleton; 2) the adjacency between these TContexts is the ridgeline which contains an outlet node (blue node). The result of the fusion is displayed by the thick red line outlining the ring of the fused *Depression* and the new outlet (Figure 5 left).

Similarly to *Depressions*, *Hill* TContexts can also be merged to form larger hills. In this case, the merging condition can be that the Hill rings share the same **key saddle**, that is the highest node on the thalweg ring. Figure 5 right illustrates the fusion between two *ElementaryHills*.

This operation of fusion of TContexts can be recursively applied (i.e. TContexts are "growing") until the fusion condition cannot be verified anymore. All operations are performed automatically by our system. An example of *Depression* TContext obtained by recursive fusion is displayed in Figure 6 left. The thick red line marks the ring of the fused TContext. Figure 3 provides another example: each *Hill* TContext (marked by a red peak and surrounded by a blue thalweg ring) results from the fusion of elementary hills.

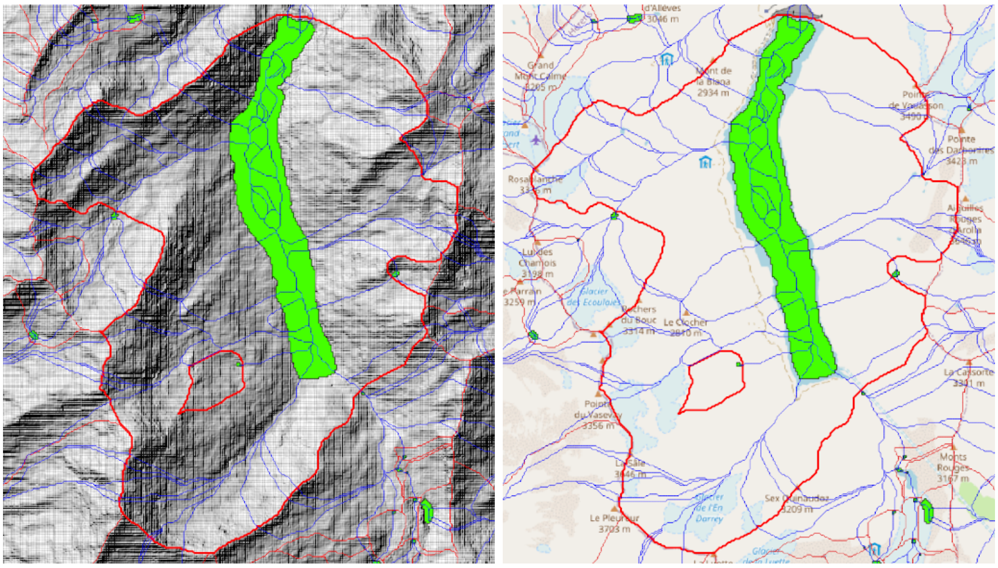

Figure 6 Left: A *Depression* with its limit (thick red lines) and its core (in green). Right: the *Depression* with OSM data in the background.

As a way to handle vagueness and indeterminacy of locations, Bittner [7] located vague objects using a spatial partition of three regions: the core, the wide boundary and the exterior. Similarly, we define the **core region** of a TContext TC to be an area such that: 1) the core region is contained in TC; 2) there is a good probability to find in the core region the salient features (points, lines, surfaces) that are typical of TC and of the landform enclosed by TC [25].

In the case of a *Depression TContext* D characterised by its outlet o, we define its core region as an area such that: 1) it is contained in D; 2) it contains all the points of D that have a lower elevation than o. As an example, in Figure 6 left, we display a *Depression TContext* identified by our system in the ESN: its ring is marked by the thick red line. Its core region is the green area. We can expect to find in it a lake or a reservoir. We checked that by displaying data from Open Street Map (OSM) in the background (Figure 6 right). We observe that the green area almost perfectly covers the light blue area that is a reservoir, the Lac des Dix. Figure 7 displays a larger part of our study area with the thalweg network (thin blue lines) and the ridge network (thin red lines). The system has automatically identified a number of *Depression* TContexts (shown by their rings marked by thick red lines) and their core regions (green surfaces).

Drainage basins are also TContexts, called ***Basin TContexts***. As previously shown, the ESN provides a decomposition of the terrain into drainage basins associated with the underlying hierarchical structure of the drainage network. A *Basin TContext* B is an area such that: 1) a node called *outlet* of B is part of the thalweg network such that it is a salient node with the lowest elevation of all the nodes of B; 2) the skeleton of B is the portion of the thalweg network that is embedded in B and converges towards the basin outlet); 3) B has a ring composed of the ridge lines that enclose the basin.

The ***OwnCatchment*** area of a stream portion $StrP$ is also a TContext. In Section 4, we showed that the drainage basins of $StrP$ and its *OwnCatchment* area provide a partition of the whole catchment area of $StrP$. These kinds of TContexts can be used to partition catchment areas at any level of detail. It may be useful for a variety of applications such as hydrology [27] and ethnophysiography [53] by providing a complete partition of the catchment area of any stream and the topological relation with the topography.

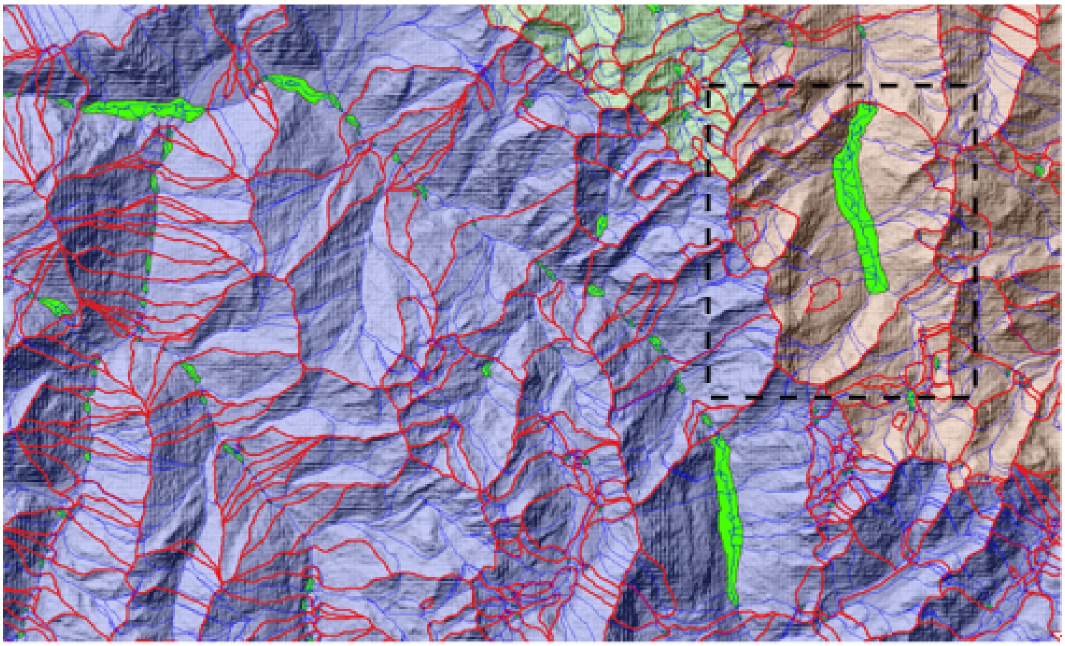

Figure 7 Larger portion of the study area with core regions in green. The dashed rectangle is the area displayed in Figure 6.

The types of TContext share common characteristics and can be structured hierarchically to provide an ontology of TContexts. Figure 8 displays a UML class diagram of the main TContext types mentioned in this paper.

6 The geo-context workspace

Although the automatic identification of individual landforms is a difficult (and maybe an impossible) task, we think that the automatic determination of topo-contexts (and ideally of geo-contexts) can be an invaluable tool for geomorphologists and earth scientists, to locate landforms. Moreover, since we can count on all the properties of the ESN-based determination of geo-contexts and topo-contexts (geo/topo-contexts for short), we suggest to *shift the emphasis of the automation process from landforms to topo-contexts.*

Technically, geo/topo-contexts need not be recorded with the ESN data structures since they depend on the user's goals and needs: they are recorded in a user's workspace that we call a *geo-context workspace*. For example, since drainage basins can be computed for any thalweg, they are only relevant at confluences or at points of particular interest to the user. They are easily extracted any time from the ESN and are recorded in the user's geo-context space, when needed. In accordance with the well-established practice of hierarchical geomorphological mapping [15] and of partitioning [19, 38], geo/topo-contexts are organised hierarchically in the geo-context space such that: 1) the *StudyArea* is at the top of the hierarchy; 2) embedded geo/topo-contexts are related by the containment relation. As shown in Section 5, since the geo/topo contexts are areal objects, the containment relation is the most natural relation to organise this hierarchy. In this way, the user's study area contains all the geo/topo contexts of the first level that are relevant to the study. In its turn, each of these geo/topo contexts can be associated with other geo/topo contexts which are spatially contained within it. A similar refinement of the embedded geo/topo contexts

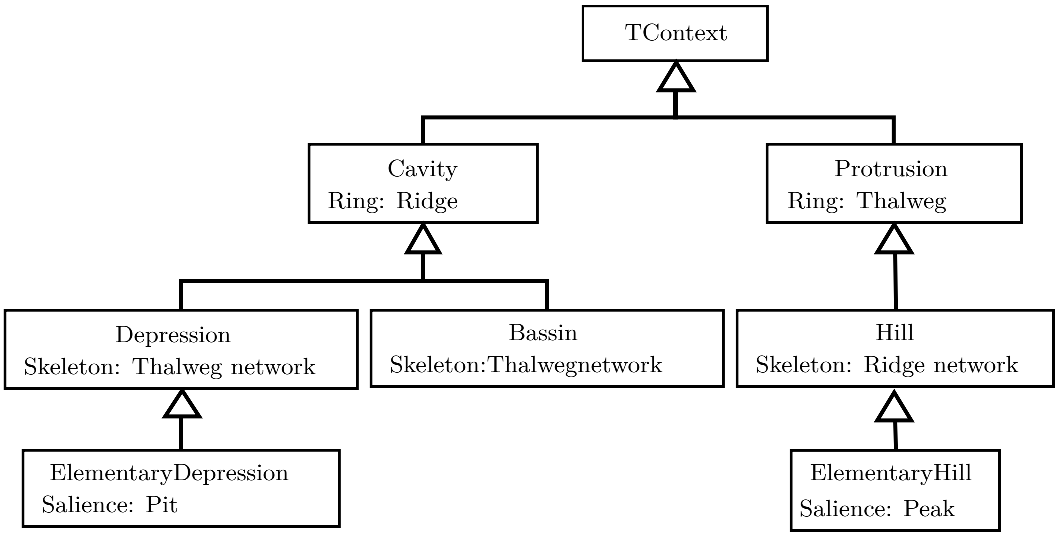

Figure 8 Hierarchy of TContext types.

can be performed at any level of detail according to the user's needs and observations. At any level, a geo/topo context may contain any kind of geo/topo context that is deemed important by the user. A geo/topo context may also contain any relevant element of the ESN: critical points, critical lines, surfaces, portions of the ridge or the thalweg networks, as well as partitions such as the partition of catchment areas (Section 5).

A geo-context workspace is truly a workspace that can be used for various tasks from recording field data to carrying out various analyses: it provides a useful tool for reading and studying the landscape [10]. An important contribution of our approach and tool is that every element contained in the geo-context space is specified using the ESN: this provides a sound salience-based topographic and topologic structure generated from the raster data set that the user has chosen as a study area. Hence, the user, being aware of the precision/resolution of the input raster data, can easily assess the precision of the various elements contained in the ESN and in his/her geo-context workspace.

As an illustration of the use of the geo-context workspace, suppose our geomorphologist friend Jeff is interested in identifying glacial landforms in our Swiss study area for which the ESN has been previously generated. After inspecting the map displaying drainage basins, the positions of the main summits and ridge lines (Figure 3), Jeff decides to concentrate on the south-eastern part and on the basin of Borgne river. He first displays the LaborgneBasin TContext with OpenStreetMap in the background (Figure 9 left) along with the Depression TContexts and their core regions (green surfaces). Jeff notes that glaciers (light blue surfaces) are concentrated in the south eastern part of Borgne drainage basin. He also uses the system to generate the sub-basins of Borgne river (Figure 9 right) to get an idea of the main rivers draining the region. His attention is drawn to the large elongated core region of a Depression TContext marked by the dashed rectangle (Figure 7). He decides to zoom on this Depression TContext (Figure 6 left). He puts the OSM data in the background and finds out that this accumulative depression marks the location of a notable landmark: the reservoir (Figure 6 right). A quick search with Google Maps shows that this is Lac des Dix near the summits Aiguilles Rouges d'Arolla and Cassorte (Figure 10 left). Jeff can even get photos of different points of view on the lake (figure 10 right). Jeff is happy! He has successfully used our

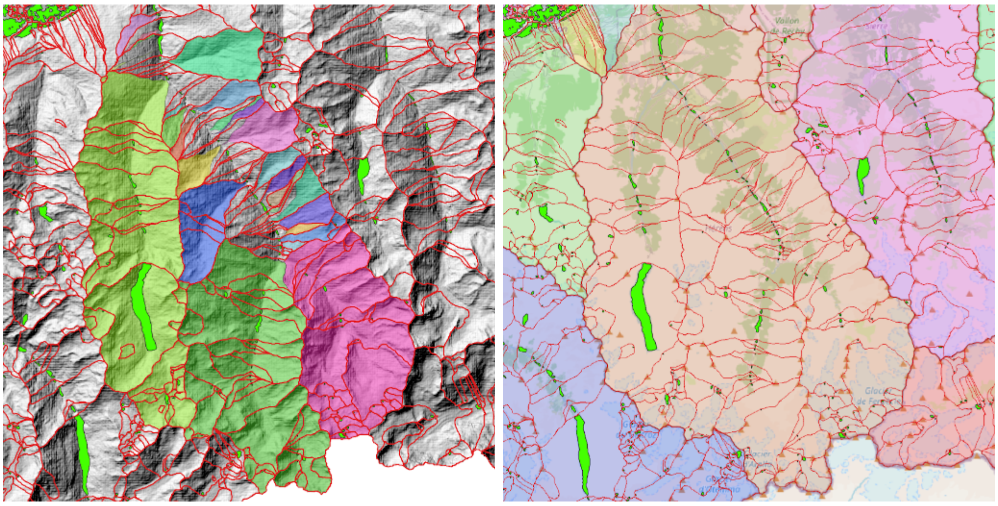

Figure 9 Left: depressions (red lines) with cores (green polygons) and Borgne river subbasins. Right: Depressions and Borgne river basin on OSM background.

ESN-based framework to locate a landform. For lack of space we stop here following Jeff. He has identified many more depression cores to explore in La Borgne basin and in its western neighbour basin (Figure 7).

Our goal in this section was to show how the geo-context workspace can provide a useful tool to geomorphologists and earth scientists in their exploration of the terrain using geo/topo contexts and ESN-based topographic saliences (i.e. summits, passes, ridge and valley lines), seeking landforms and other salient features.

7 Conclusion

[44] emphasised the difficulty to establish a universal ontology for "common sense categories" (i.e. mountain, lake, or valley) and their instances because the category definitions depend on the context (i.e. on various aspects of language, culture, individual's mental model, situation, geography). Indeed, the automatic identification of landforms is still a difficult

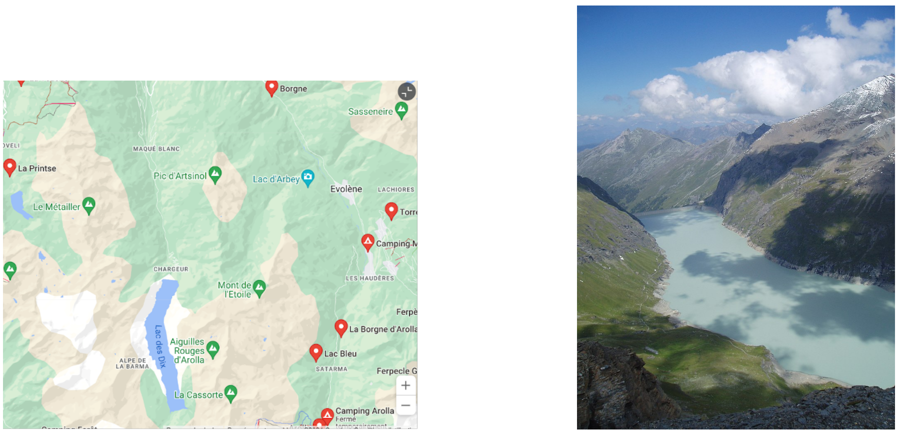

Figure 10 Left: Google Maps view. Right: View on lac des Dix (CC BY-SA 3.0 Gfalquet).

and complex task [4, 43]. In fact, as shown in this paper, it seems easier to automatically generate a computational model of the topographic context in which one can identify salient features (typical points, lines and/or surfaces) that may help a specialist recognise landforms. Moreover, our salience-based approach fosters a holistic view of the terrain which may be a good fit with the geoscientists' practice of observation and analysis of the terrain/landscape as well as with their cognitive ability to recognise landforms in the topographic and hydrologic contexts. To sum up, this paper extends the fundamental contribution of [22] and [23]: the theoretical and implemented demonstration that elementary topographic saliences can be captured from a DTM as sets of critical nodes (peak, pits, saddles) and critical edges (thalweg lines, ridge lines) to create an Extended Surface Network (ESN) that fully integrates the surface network and the drainage network in a sound topological representation of the terrain.

Laying down the foundations of a salience-based approach of landform delimitation grounded on the ESN, the new contributions of this paper are:

1. The proposal of a skeletonisation approach applied to the ESN ridge and thalweg networks to geometrically and topologically characterise important landforms, as well as ensembles of landforms.
2. The introduction of the geo-context, a new notion used to structure the salience-based representation of the terrain in order to capture the context of appearance of landforms.
3. The introduction of the topo-context as a refinement of a geo-context that is grounded in the properties of the ESN and is obtained using our skeletonisation approach; it is shown that topo-contexts can be used to partition the terrain and to help locate/delineate landforms.
4. The illustration of how this approach and the associated tools can be practically used by a geomorphologist, taking-into-account the topographic and hydrographic contexts.

We also showed how this proposal may provide a good foundation to the vision of Linked Topographic Data [42] and support the implementation of the SNODP [42] and SWFODP [45] ontology design patterns. A number of research avenues are opened by this work. Using the ESN-based topo-contexts and the skeletonization approach, we are currently investigating how to associate topo-contexts with named places (such as mountains and mountain ranges, ridges, plains and valleys) found in databases and gazetteers such as OSM, GNIS and GeoNames. This would provide a topologically sound solution to the challenge of associating boundaries with terrain features recorded in GNIS [4] and other gazetteers. When looking at the context of appearance of landforms, geomorphologists often consider a number of factors called "structural elements" (such as soil characteristics, geology and morphometry) that are typical of geomorphological processes creating the landforms: these factors jointly provide a contextual understanding of the terrain [40]. Topo-contexts may provide a good approach to associate such structural elements with a sound topographic and topologic salience-based structure; hence facilitating landform localisation and identification.

Another research direction worth exploring is how the ESN-based geo/topo contexts may complement GEOBIA studies of the terrain/landscape. Indeed, the ESN provides a sound topographic and topological background on which one could project objects obtained from image-based analyses. This would support efforts to pair such objects with semantics [3] grounded in a salience-based description of the terrain. Currently, our system uses terrain data in the form of a DTM or a digital elevation model. We are considering to develop an alternative input module to directly process point cloud data [54], the ESN creation workflow being unchanged. This would permit the exploitation of national topographic LIDAR data sets such as the Canadian *LiDAR Point Clouds* and the US *Nationwide Point Cloud* [54].

Doing so, our salience-based approach and ESN-based tool would provide strong topographic and topological grounds for new applications such as the three-dimensional documentation of natural and cultural geosites [2].

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