# Structuring the Underwater Environment: A Taxonomy of Aquatic Landmarks

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**Abstract**

Effective navigation in aquatic environments relies on the perception and use of environmental cues, or landmarks, that provide spatial orientation and facilitate wayfinding. While much research has focused on terrestrial and urban landmarks, comparatively little is known about underwater landmarks and how divers perceive and use them. Thirty-eight participants completed an online survey and provided information on the use and perception of underwater landmarks. Rock formations and caves, seabed features, and wrecks are the most frequently selected underwater landmarks, with no significant differences observed between recreational and professional divers or among different experience levels. Based on the results of the survey, we develop a data-driven taxonomy of aquatic landmarks comprising three top-level classes: Natural Landmarks, Artificial Landmarks, and Environmental Conditions. The taxonomy provides a structured framework for understanding underwater spatial orientation and serves as a foundation for future research, cognitive mapping studies, and the development of navigational aids in aquatic settings.

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## 1 Introduction

Effective navigation in aquatic environments relies on the perception and use of environmental cues, or landmarks, that provide spatial orientation and facilitate wayfinding. While extensive research has focused on terrestrial landmarks [15, 26], comparatively little is known about underwater landmarks and how they are perceived by divers. Developing structured conceptual frameworks for underwater landmarks is crucial for applications ranging from recreational diving to marine research, ecological monitoring, and safety operations.

Landmarks in terrestrial and urban environments have been extensively categorised using ontologies and taxonomies, often based on visual salience, spatial location, and functional relevance (e.g., [23, 17, 21, 19]). In aquatic settings, however, landmarks differ fundamentally: the underwater environment presents unique perceptual constraints, including reduced

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visibility, variable light conditions, and dynamic water movement. These factors influence which landmarks divers attend to and rely upon for orientation, and they highlight the need for a dedicated, empirically grounded taxonomy of aquatic landmarks.

Frameworks for aquatic environments remain largely unexplored, motivating our effort to fill this gap by developing a data-driven taxonomy of aquatic landmarks. Using the results of an online survey we identify the landmarks most commonly used and map them to structured groups, drawing on a prior framework for landmarks [21] adapting it to the underwater context. This approach incorporates natural landmarks, artificial structures, and environmental conditions, ensuring that the taxonomy reflects both the perceptual realities of diving and the practical needs of navigation. The remainder of the paper is organised as follows: Section 2 reviews existing conceptual frameworks, Section 3 describes the methods employed, Section 4 presents the results, and Section 5 concludes with a discussion and outlook on future work.

## 2 Conceptual Frameworks for Landmark Representation

Urban landmarks have been categorised in various ways to capture their structural and functional characteristics. Common distinctions include global and local landmarks [23], two-dimensional and three-dimensional landmarks [17], as well as on-route and off-route landmarks, depending on whether they are located at a decision point [14]. Several taxonomies have been proposed to conceptualise the functional roles of landmarks in navigation tasks. Chan and colleagues [5] differentiate between objects serving as visual beacons indicating a nearby en-route target location, objects functioning as associative cues linked to a navigational action, objects acting as visual cues to maintain or regain orientation, and objects used as elements of an environmental reference frame. Similarly, Sadalla and colleagues [20] model the contextual role of landmarks within a hierarchical taxonomy, distinguishing landmarks used in routing tasks, orienting tasks, and memorising tasks. Furthermore, Hansen and colleagues [12] introduce an eight-level taxonomy, with each level describing a specific functional aspect of landmarks within route instructions.

While these classifications provide important structural and functional perspectives, they largely emerge from terrestrial and predominantly urban navigation contexts. As a result, they often assume stable, permanent, and visually salient environmental features [3, 22]. Research on human wayfinding has shown, however, that orientation practices are strongly shaped by environmental conditions, sociocultural needs, and available sensory cues [4, 24, 18]. Research on non-urban landmarks has led to ontology-based approaches tailored to specific environmental contexts. Sarjakoski and colleagues [21] present an empirical study conducted in a national park during both winter and summer seasons. Based on recognised and categorised forest landmarks, they develop a hiking ontology comprising eight landmark groups: structures, passages, trees and parts of trees, waterways, land cover, rocks, signs, and landforms. More recently, Olteanu-Raimond and colleagues [19] propose a lightweight ontology, characterised by relatively low complexity and the absence of formal constraints, designed to support mountain rescue operations by describing different landmark types.

These context-specific approaches demonstrate that wayfinding environments fundamentally influence which features become salient for orientation and how they are conceptualised. This becomes particularly important in marine and underwater environments, where many assumptions underlying terrestrial navigation no longer hold. Unlike urban settings, underwater environments present unique challenges such as low visibility, extreme lighting conditions, dynamic currents, and the unpredictable nature of underwater terrain [11, 10]. Despite the breadth of existing work, a dedicated conceptual model for water landmarks remains absent from the literature. Tenbrink and Dylla [25] investigate water-related navigation by examining how people talk about space in sailing. Their study shows that sailors rely on specific spatial concepts and specialised jargon such as port and starboard, windward, leeward, or into the wind instead of everyday directional terms. This highlights that common spatial language is insufficient for describing orientation and movement in sailing contexts [25]. However, they do not propose a formal taxonomy or ontology. Their findings nevertheless indicate that marine navigation relies on spatial concepts and orientation strategies that differ fundamentally from those typically assumed in terrestrial landmark research.

## 3 Methods

This study investigates which landmarks divers use underwater through an online survey. This section provides an overview of the participants who completed the survey (Section 3.1), describes the procedure (Section 3.2), and summaries the statistical analyses employed (Section 3.3).

### 3.1 Participants

Thirty-eight participants completed an online survey and provided information on the use and perception of underwater landmarks. We recruited participants through diving schools and diving clubs in Germany and France. All participants provided informed consent for participation prior to accessing the questionnaire.

Of the participants, 29 identified as recreational divers and 9 as professional divers. Among recreational divers, years of diving experience ranged from 1 to 50 years (mean = 16.53, SD = 13.23), with the number of completed dives ranging from 31 to 4000 (mean = 728.72, SD = 1002.34). Professional divers reported between 8 and 35 years of experience (mean = 21.11, SD = 9.96) and between 400 and 5000 completed dives (mean = 2473.33, SD = 1893.52).

Six participants are classified as beginners, while the remainder are categorised as advanced or expert divers. Diver classification is based on both years of experience and total logged dives, as some divers may have started years ago but completed relatively few dives. Beginners have 1–5 years of experience or fewer than 100 dives, advanced divers have 6–10 years and at least 100 dives, and experts have more than 10 years and at least 100 dives.

### 3.2 Procedure

We employ an online survey to investigate which landmarks divers perceive and utilise in aquatic environments. We implemented the questionnaire using SoSci Survey [13] and made available in German and French. A native speaker translated and reviewed the French version. The university's ethics committee approved the procedure. We sent invitation emails containing the survey link in April 2024.

Core questions on use and perception of underwater landmarks asked participants to select from predefined landmark groups including rock formation/caves, distinctive marine fauna, distinctive marine flora, seabed features, corals or sponges, coast, natural coastal landmarks, artificial coastal landmarks, floating buoys, marked dive routes, wrecks, underwater installations, and guide ropes. Participants could also report additional landmarks with an open-ended response.

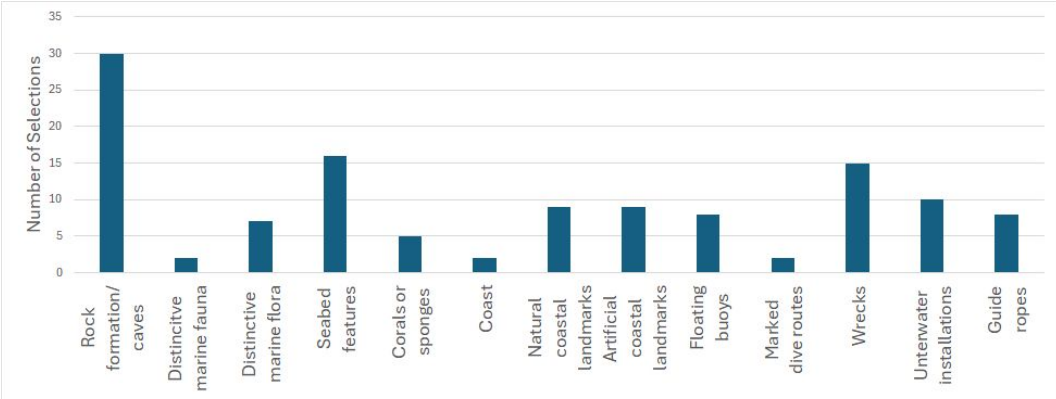


**Figure 1** Selections of landmark groups.

### 3.3 Statistical Analyses

To examine whether the frequency of selection differs across landmark groups within participants, we apply Cochran's Q test [6]. This test is appropriate for detecting overall differences in proportions across more than two related binary variables. When the omnibus test indicates significant differences, post hoc pairwise comparisons are performed using McNemar's tests [16] with Bonferroni adjustment [1] to control for inflated Type I error due to multiple testing.

To explore potential differences between recreational and professional divers in the selection of individual landmarks, we employ Fisher's exact tests [8]. This test is chosen because of small sample sizes and sparse cell counts, which violate the assumptions of chi-square tests. Odds ratios are calculated to estimate the magnitude and direction of group differences. Because multiple landmark groups are tested independently, false discovery rate (FDR) correction [2] is applied to adjust p-values and reduce the risk of Type I error inflation. Finally, to examine associations between diver experience levels and landmark selection across groups with more than two groups, we use the Fisher–Freeman–Halton exact test [9]. This extension of Fisher's exact test is suitable for contingency tables larger than $2 \times 2$ and is particularly appropriate for small samples and uneven distributions. All statistical analyses are conducted using an alpha level of 0.05 to determine significance. This threshold is applied consistently across all tests to maintain uniform criteria for evaluating results.

## 4 Results

In this section we investigate the details by investigating the frequency and patterns of underwater landmark selection (Section 4.1). Furthermore, we propose a data-driven taxonomy of aquatic landmarks (Section 4.2).

### 4.1 Frequency of Underwater Landmark Selections by Divers

Results indicate that rock formations and caves ($n = 30$), seabed features ($n = 16$), and wrecks ($n = 15$) are the most frequently selected landmarks (Figure 1). Less frequently selected landmarks included distinctive marine fauna ($n = 2$), the coast ($n = 2$), and marked dive routes ($n = 2$). Participants selected an average of 4.10 landmark groups ($SD = 1.77$).

**Table 1** Taxonomy of Underwater Landmarks.

| Class | Subclass | Landmark Type |
|---|---|---|
| Natural | Geological Landmarks | Cliff; Rock formations; Caves; Holes |
| | Seabed Cover | Sandy area; Stony area |
| | Marine Flora | No details given |
| | Marine Fauna | Fish; Octopus; Moray eels; Corals; Sponges |
| Artificial | Structures | Wrecks; Submerged car; Underwater installation; Statues; Mine; Wooden cross |
| | Floating Structures | Boats; Floating buoys |
| | Navigation Aids | Guide ropes; Spools; Arrows |
| Environmental | Water Conditions | Depth; Tides; Currents; Visibility |
| | Celestial | Sun |

Cochran's Q test revealed significant differences in selection frequencies across landmark groups ($Q(12) = 107.71$, $p < .001$). Post hoc Bonferroni-adjusted pairwise McNemar tests indicated that rock formations and caves are selected significantly than the other landmarks. Beyond this dominant group, only a few pairwise differences remain significant: distinctive marine fauna versus seabed features, seabed features versus coast, seabed features versus marked dive routes, and marked dive routes versus wrecks.

We observe no significant differences between recreational and professional divers or among different experience levels. Divers did not differ in their selection of underwater landmarks. All associations, tested with Fisher's exact and Fisher–Freeman–Halton exact tests and corrected for multiple comparisons using FDR, are non-significant (all $p > 0.05$).

We analyse open-ended responses thematically. Participants reported using permanent or distinctive landmarks such as buoys, sunken cars, statues, boats, or wooden crosses, especially in areas with low tidal variation or in narrow channels, where proximity to the banks aids navigation. They highlighted visually salient and memorable landmarks, including contrasting sandy and rocky zones, coral formations, and holes or crevices where octopuses and moray eels hide. Environmental conditions, particularly poor visibility in lakes, influenced participants' ability to recognise surroundings, prompting them to follow the group leader closely and rely on navigation aids such as spools and arrows in wrecks or caves. Some also mentioned sunlight and current direction as navigational cues, and certain specific sites, such as the Torpedoversuchsanstalt Tollensee, are referenced as landmarks.

## 4.2 A Data-Driven Taxonomy of Aquatic Landmarks

Based on the results of the survey, we develop a data-driven taxonomy of aquatic landmarks (Table 1). Analyses reveal no perceptual differences between recreational and professional divers, nor among divers with varying levels of experience. Consequently, we develop a single unified taxonomy for all participants.

The final taxonomy for aquatic landmarks consists of three top-level classes: Natural Landmarks, Artificial Landmarks, and Environmental Conditions, subdivided into thematic subclasses (e.g., Geological Landmarks, Marine Flora). Each subclass contains specific landmark types (e.g., Cliff, Rock formation, Caves) (Table 1). To ensure a data-driven taxonomy, we include only terms that participants were exposed to or explicitly named.

The following paragraph details how each subclass is defined and adapted based on survey responses and environmental considerations. We adopt the groups of Sarjakoski and colleagues [21] (structures, passages, trees, water, land cover, rocks, signs, and landforms) and map the observed landmarks to these groups wherever appropriate. Landmarks that are rarely selected by participants (distinctive marine fauna, n = 2; coast, n = 2; marked dive routes, n = 2) are considered for inclusion with caution, and coast and marked dive routes are excluded due to low selection frequency. However, open-ended responses frequently referenced fish, octopus, moray eels, and corals, motivating the addition of a *Marine Fauna* subclass. Because terrestrial land cover does not translate directly to underwater environments, we refine this group into a *Seabed Cover* subclass. To capture non-living solid formations, we introduce a *Geological Landmarks* subclass encompassing both landforms and rocks. Recognising the absence of trees in marine environments, we incorporate a *Marine Flora* subclass to include landmarks such as seagrass, kelp, and algae fields. Although participants selected the class Natural Coastal Landmarks, they did not provide any specific details, and therefore no corresponding landmark type is included in the taxonomy. Within artificial landmarks, we divide the original Structures class into *Structures* (fixed man-made objects, e.g., wrecks, statues, submerged vehicles) and *Floating Structures* (e.g., boats, floating buoys) to account for differing dynamics and mapping properties. Since participants did not report conventional signs such as informational boards or warning markers, we do not include a Signs class. All navigational cues, including markers such as spools and arrows, are included in a newly defined *Navigation Aids* subclass. Finally, we create two additional subclasses to capture environmental and dynamic conditions: *Water Conditions*, which includes depth, current, and visibility, and *Celestial Conditions*, capturing landmarks such as the sun.

## 5 Discussion and Outlook

The taxonomy provides a structured framework for understanding underwater spatial orientation and serves as a foundation for future research. Rock formations and caves, seabed features, and wrecks emerged as the most salient landmarks. Objects such as the coast, marked dive routes, and distinctive marine fauna are rarely selected. Interestingly, we find no statistically significant differences between recreational and professional divers, nor among divers with varying experience levels. This suggests that the identification of key underwater landmarks may be largely universal, governed by perceptual and environmental constraints rather than training or skill. This finding also justifies the development of a single, unified taxonomy for all divers, rather than separate frameworks for different user groups.

Some of the adapted groups from Sarjakoski et al. [21] required refinement to suit the underwater context: terrestrial land cover became Seabed Cover, trees are replaced with Marine Flora, and Geological Landmarks are created to encompass rocks and non-living solid formations. Artificial Landmarks are divided into Structures and Floating Structures, and Navigation Aids are added to capture orientation cues. Environmental conditions, including Water Conditions and Celestial Conditions, are also included to reflect dynamic factors affecting navigation. These adaptations illustrate the importance of contextualising landmark groups to the specific affordances of the underwater environment.

While the taxonomy is data-driven and grounded in participant observations, some groups are informed by open-ended responses rather than frequency counts, which may introduce subjective interpretation. Additionally, the sample size is modest, particularly for professional divers, which may have limited the ability to detect subtle experience-based differences. Future studies could expand the participant pool, examine landmarks across different aquatic environments, or investigate how dynamic factors such as currents, visibility, or moving fauna influence navigational strategies.

Future work will explore underwater landmark modalities beyond vision, with a particular focus on acoustics. Sound is the most efficiently transmitted radiation underwater, creating a complex "soundscape" of natural, biological, and anthropogenic sources that may serve as navigational cues for marine life [7]. Investigating how divers could perceive or utilise these acoustic landmarks may provide new insights into orientation strategies and inform the design of non-visual navigational aids.

Overall, this work contributes both empirical and conceptual insights. It confirms that underwater navigation relies on landmarks, highlights the consistency of landmark perception across diver experience, and provides a structured, data-driven taxonomy that can serve as a foundation for future research, cognitive mapping studies, and the development of navigational aids in aquatic settings.

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