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A Reflection on the Conservation of Waterlogged Wood: Do Original Artefacts Truly Belong in Public Museum Collections?

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Abstract

The last decade has seen a transformative advancement in computational technologies, enabling the precise creation, evaluation, visualization, and reproduction of high-fidelity three-dimensional (3D) models of archaeological sites and artefacts. With the advent of 3D printing, both small- and large-scale objects can now be reproduced with remarkable accuracy and at customizable scales. Artefacts composed of organic materials—such as wood—are inherently susceptible to biological degradation and thus require extensive, long-term conservation employing costly methodologies. These procedures often raise environmental concerns and lead to irreversible alterations in the wood's chemical composition, dimensional properties, and the intangible essence of the original artefact. In the context of public education and the dissemination of knowledge about historical technologies and objects, 3D replicas can effectively fulfill the same purpose as original artefacts, without compromising interpretative value or cultural significance. Furthermore, the digital data embedded in 3D surface and object models provides a wealth of supplementary information that cannot be captured, preserved, or documented through conventional techniques. Waterlogged wooden objects can now be thoroughly documented in 3D, enabling ongoing, non-invasive scientific analysis. Given these capabilities, it is imperative to revisit the philosophical and ethical foundations of preserving waterlogged wood and to adopt innovative strategies for the conservation and presentation of wooden artefacts. These new paradigms can serve educational, research, and outreach purposes—core functions of contemporary museums.

Keywords: conservation methodology; microbiology; restoration; preservation; computer vision; 3D technologies; museum interpretation

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Academic Editor: Marco Corradi

Received: 7 May 2025
Revised: 26 June 2025
Accepted: 1 July 2025
Published: 9 July 2025

Citation: Erič, M.; Stopar, D.; Guček Puhar, E.; Korat Bensa, L.; Saje, N.; Jaklič, A.; Solina, F. A Reflection on the Conservation of Waterlogged Wood: Do Original Artefacts Truly Belong in Public Museum Collections? *Heritage* **2025**, *8*, 273. https://doi.org/10.3390/heritage8070273

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1. Introduction

Wood has held deep significance throughout human history. The earliest references to its care appear in the 4000-year-old Epic of Gilgamesh [1], rooted in Babylonian–Sumerian tradition, where tar oil is mentioned as a protective agent for wood. Similarly, Sanskrit hymns from the Rigveda advise on the best season for tree felling to ensure longevity [2].

Early records of archaeology and conservation appear on a cuneiform tablet from Larsa (Iraq), detailing how Kings Nebuchadnezzar II and Nabonidus searched for traces

of earlier rulers. Nabonidus reportedly discovered inscriptions from King Hammurabi during a temple excavation. The Larsa tablet and a terracotta cylinder describe restoration work on the Temple of Shamash in Larsa between 555 and 539 BCE [3].

Remarkably, Princess Ennigaldi-Nanna, daughter of Nabonidus, collected and preserved artefacts—wooden ones included—making the Temple of Shamash the world's first museum [4].

In 2002 during archaeological investigations in the riverbed of the Ljubljanica near Sinja Gorica, a remarkable discovery was made among various remains—a small, handcrafted wooden point resembling Paleolithic stone tools. The point, made from yew wood (Taxus baccata), was subjected to dual radiocarbon dating (Oxford, Beta), which determined its age to be approximately 40,000 years. Owing to an unusual and fortunate series of events, the object was preserved in sediment with minimal physical, biological, or chemical interference that might have otherwise led to its deterioration [5,6].

2. Materials and Methods

This study employed comparative analysis of conservation methods using case studies, including the Paleolithic wooden point and a Roman barge. Three-dimensional scanning techniques such as CT and photogrammetry were used for documentation. Conservation outcomes were assessed through volumetric analysis and visual inspection.

However, reburial as a conservation strategy must be assessed on a case-by-case basis, since some agents of deterioration—especially certain bacteria and fungi—may persist or even thrive under specific anaerobic conditions [7]. Therefore, environmental characterization and risk assessment are essential before implementing reburial.

Therefore, our proposal should be regarded as a viable alternative and considered alongside existing conservation methods.

It was decided, unfortunately in our opinion, to conserve the Paleolithic wooden point using a conventional method—melamine resin treatment—based on standards established 40 to 60 years ago. Despite the passage of time, professional conservation practices have changed little. In contrast, digital documentation has progressed rapidly, now allowing for complete digital reconstruction and replication [8–12]. Section 5 provides a detailed analysis of how the melamine-based preservation process was carried out. Several 3D models of the wooden point were captured using a CT scanner before, during, and after the melamine conservation process, and were subsequently compared.

It is our professional and scientific responsibility to preserve cultural heritage for future generations. It is also our ethical and moral obligation to reconsider whether the continuation of traditional approaches to waterlogged wood conservation—which risk accelerated degradation or complete destruction—is justifiable, or whether we should instead embrace the opportunities offered by emerging technologies.

2.1. Properties of Waterlogged Wood Compared to Other Archaeological Materials

Waterlogged wood [13] is an organic, carbon-based composite that has undergone varying levels of biodegradation. It mainly consists of cellulose, hemicellulose, and lignin—components that differ in how easily they degrade. Cellulose and hemicellulose are highly susceptible to fungi and microorganisms, while lignin is more resistant, especially in waterlogged conditions.

Compared to stone, ceramics, metals, and bone, wood decays more readily—even underwater (see Figure 1). Once exposed to air, especially fluctuating temperature and humidity, degradation accelerates. Conserving organic materials like wood, leather, textiles, and paper is among the greatest challenges in heritage preservation, requiring expensive and specialized methods. Further complications arise because many museum climate

systems are designed for inorganic materials such as stone, ceramics, and metal, not for organic ones. For conservation purposes the parameter Umax is important. Wood's maximum dry weight (Umax) refers to the highest moisture content that wood can naturally hold in its green (freshly cut) state before drying begins. The maximum amount of water that wood can contain, is usually expressed as a percentage of its oven-dry weight. So, if a piece of green wood weighs 300 g and its oven-dry weight is 100 g, the moisture content is 200%. Umax is typically measured before conservation begins and varies by species and cellular structure. Umax helps conservators understand how degraded or waterlogged the wood is, which directly affects drying methods, risk of shrinkage or cracking, and suitability of conservation treatments (e.g., PEG, melamine resin).

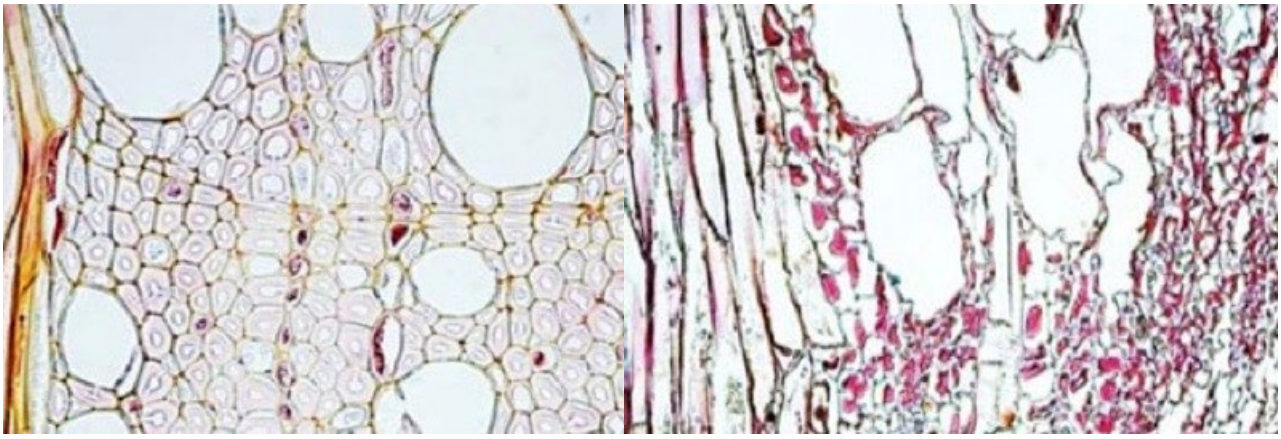


Figure 1. The cell structure of wood can be seen with transmitted light microscopy of recent *Fagus* spp. (beech) wood with less than 200% Umax (**left**) and the fragile cell structure of the flat-bottomed Roman barge from Sinja Gorica [14], extremely deteriorated up to 690% Umax (**right**). The photo on the right shows thinner cell walls, loss of cellulose, and loss of lignin. Photos taken with a microscope Nikon Eclipse E800 (digital camera Nikon DS-Fi1 and software NIS Elements B.r. 3.0) by Dr. Maks Merela, Chair of Wood Science, Department of Wood Science, Biotechnical Faculty, University of Ljubljana.

2.2. A Brief History of Waterlogged Wood Conservation

Wood preservation knowledge evolved over millennia. Studies of ancient Chinese temples have produced a continuous dendrochronological record from the ninth century CE to today. Traditional techniques included soaking fresh wood in salt water for three years and air drying for two—effective methods despite lacking synthetic materials [15].

With the rise of archaeology and museums in the 19th century, interest in wood conservation grew. In 1832, Kyan patented the first wood preservation method using a sublimate solution, launching modern waterlogged wood conservation. Over time, new techniques emerged, including creosote fumigation and zinc chloride treatments [16].

In 1860, Denmark's King Frederik VII founded the Society for Antiquarian and Archaeological Endeavours, promoting wood conservation practices. A notable early record from 1850 by Christian Jürgensen Thomsen mentions using "Potassium alum for wood, boiling"—suggesting standard conservation routines [16].

Christian F. Herbst, a society member, published a detailed 1861 account of using potassium alum to treat wood found in 1850 excavations at Viemos, Funen. Clear distinctions between dry and waterlogged wood conservation methods only emerged in the early 20th century (e.g., [4,17,18]).

2.3. Established Methods for the Conservation of Waterlogged Wood

In the mid-19th century, when systematic excavations began, knowledge of waterlogged wood conservation was virtually nonexistent. It was not until the early 20th century that serious study of preservation methods began.

Waterlogged wood is extremely fragile. Its cellular structure is often degraded, and the wood retains shape only because water fills the collapsed cells. As the water evaporates, structural collapse follows rapidly (see Figure 2). Simply storing such artefacts in tap or distilled water is insufficient, as microbial growth persists. Anaerobic environments slow biological decay significantly. Upon oxygen exposure, aerobic microorganisms accelerate deterioration. Therefore, artefacts must be transferred to an anaerobic aquatic environment immediately after excavation.

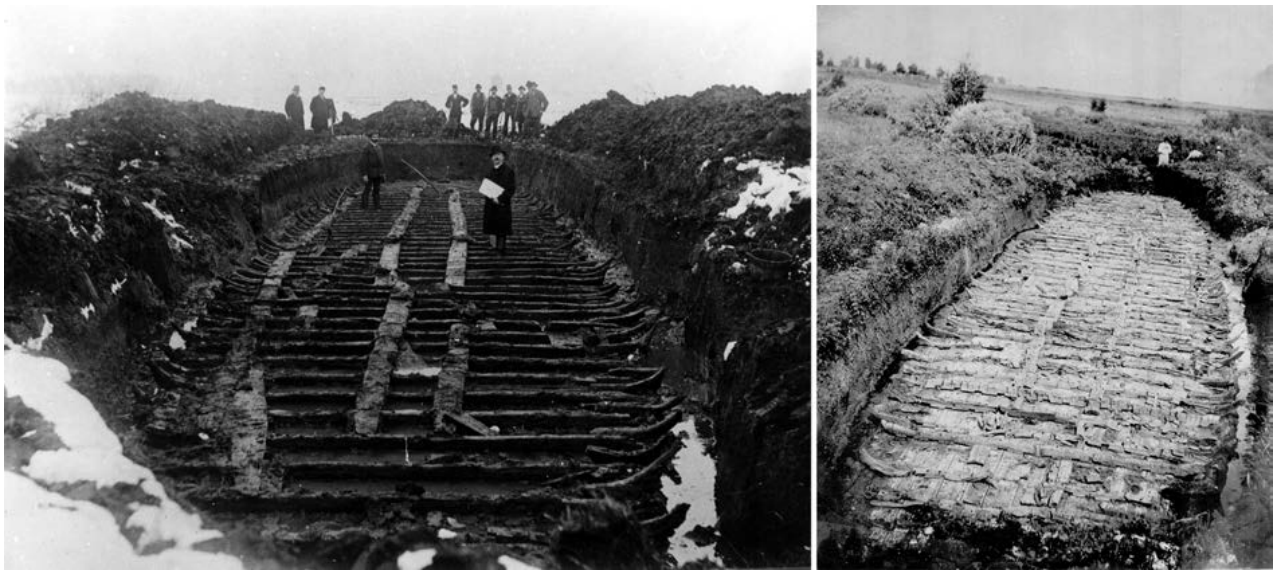


Figure 2. Alfons Müllner (on the **left** photo with the white table in his hand) was the curator of the Kranjski deželni muzej—Rudolfinum (Provincial Museum of Carniola—Rudolfinum) in Ljubljana and led the excavation of a flat-bottomed Roman ship from Lipe on Ljubljansko barje in November 1890 [19]. After measuring and documenting the ship, Müllner ordered the workers to cover the ship again with soil, but unfortunately, they failed to do so. After just several months (on the **right** photo), the exposed wooden remains of the ship severely deteriorated, and the ship was eventually destroyed. (Photo: archives of Kranjski deželni muzej—Rudolfinum.).

Upon exposure to atmospheric oxygen, waterlogged archaeological wood becomes vulnerable to aerobic microbial activity and oxidation processes, which can lead to degradation—particularly if relative humidity, temperature, and other environmental controls are not properly managed. However, archaeological wood may remain stable for extended periods under controlled environmental conditions, even in the absence of immediate conservation treatment [20].

Conservation methods aim to preserve the wood's shape and volume using organic or inorganic stabilizers [21]. Some techniques replace water in the wood's cells with substances that reinforce the structure. Others impregnate the wood with compounds that support the cell walls, minimizing collapse during drying. Some approaches combine both, or reduce surface tension to limit cell wall damage. Common treatments include polyethylene glycol (PEG) or sugars, often used with freeze-drying (lyophilization).

2.3.1. Potassium Alum–Glycerin–Linseed Oil Method

One of the earliest methods for conserving waterlogged wood was developed by S. W. Speerschneider in 1850, using wooden artefacts from Flensburg [16,22]. The process involved rinsing the wood, then boiling it in a potassium alum solution for several hours—repeating the procedure for larger items. After drying, the wood was treated with linseed oil and coated with varnish.

This low-cost method was approved by a state commission and adopted (with minor changes) by the Danish National Museum's workshop, becoming the standard treatment until 1958. Around 100,000 artefacts were conserved this way. Linseed oil was later replaced with shellac. However, after several decades, deterioration and defects emerged, leading to the method's eventual abandonment.

2.3.2. Polyethylene Glycol (PEG)

PEG is a water-soluble wax (e.g., [16,20,23–34] among others) and remains the most extensively studied and widely used method for conserving waterlogged wood.

Low-molecular-weight PEG variants, such as PEG 200 to PEG 800, penetrate deeply into the wood's cellular structure. Dimensional stabilization is achieved by replacing both free and bound water with PEG. The process involves immersing the wood in aqueous or alcoholic solutions, starting with low concentrations to enhance penetration via osmotic forces, followed by gradual increases until saturation.

A common variant combines PEG impregnation with freeze-drying [35,36]. The wood is soaked in a PEG solution—often 40%—before undergoing lyophilization. This technique remains standard practice in many museum conservation labs worldwide (see Figure 3).



Figure 3. Swedish royal ship Vasa, one of the world's most famous ships treated with the PEG method. (**Left**) Vasa during the early phase of conservation at the Vasa shipyard in January 1963 (photographer Holger Ellgaard CC BY-SA 3.0). (**Right**) The lower gun deck of the warship Vasa, on display at the Vasa Museum in Stockholm, Sweden. The picture was taken in December 2009 by photographer Peter Isotalo inside the ship looking forward (CC BY-SA 3.0).

2.3.3. Melamine: Arigal-C and Kaurin 800

(e.g., [4,21,37–41]). After thorough washing and desalination—especially for marine artefacts—waterlogged wood is impregnated with melamine-formaldehyde resin. The standard method involves soaking the object for up to 48 h in a 25% resin solution (in water or alcohol), then immersing it for up to 40 h in a 10% catalyst solution (urea) to initiate

curing. Before full hardening, the surface is rinsed with hot water, sealed in a polyethylene bag, and heated at 65 °C for 48 h. Final drying occurs at room temperature with relative humidity over 50%.

Variants reverse the order: the object is first soaked in a 2–5% catalyst solution, then treated with 15% resin at 10–15 °C. Drilling may be used to improve resin penetration [42].

Recent adaptations include post-cleaning with pH control, followed by soaking in a 25% resin solution enhanced with urea, triethylene glycol, and optionally triethanolamine for stability. The artefact is soaked for several months, polymerized at ~50 °C while wrapped in cellulose and polyethylene, then slowly dried within the wrapping [41].

2.3.4. Alcohol–Ether–Resin Method

This experimental method involves immediately immersing the excavated object in alcohol, which is then replaced with ether containing a mixture of dammar varnish, beeswax, carnauba wax, paraffin, and rosin. High temperatures aid penetration. Like PEG, this approach stabilizes the wood and reduces surface tension via alcohol or ether, preventing collapse. Several modified versions of this technique have since been developed [43].

2.3.5. Polybutyl Methacrylate

[44]. Following washing, the wood undergoes treatment in three successive baths: first with acetone, then butyl methacrylate, and finally a 1% benzoyl peroxide solution as a polymerization catalyst. The artefact is then oven-cured at 65–95 °C for up to nine hours. A variant uses polymethyl methacrylate with heating at 45 °C [22].

2.3.6. Acetone–Rosin Method

(e.g., [45,46]). The most commonly used solution is rosin dissolved in acetone. Numerous workshop-specific variations exist. After cleaning in water, artefacts are immersed in a 3% hydrochloric acid solution for a few days, then rinsed. Acetone is used for drying, followed by immersion for four weeks in a 67% rosin-acetone solution at 52 °C. The object is then rinsed with acetone and dried at room temperature. Experts regard this method as particularly suitable for softwood, charcoal, and small artefacts.

2.3.7. Electrokinetic Method

[47,48]. This is the only method applicable in situ. The object and surrounding soil are impregnated with an aqueous solution of sodium silicate and calcium chloride. Electrodes are placed around the artefact to form a closed electrical circuit, triggering hardening. However, subsequent lab tests failed to confirm its effectiveness.

2.3.8. Garrouste/Bouis Method

After washing, wood is immersed in hydrochloric acid and water, then impregnated with an aqueous solution of chromium acetate (sometimes with up to 20% sodium bichromate). Before final rinsing, the wood is immersed in sodium chloride solution. Post-drying, it is coated with wax, linseed oil, or synthetic resins [49].

2.3.9. Radiation-Induced Polymerization

(e.g., [50–52]). Developed in the United States, this method uses gamma radiation to polymerize monomer-impregnated wood. Initially, methanol replaces all water. Different labs use various monomers (styrene, methyl acrylate, methyl methacrylate, or 2-hydroxyethyl methacrylate). After impregnation, the object is irradiated with cobalt-60. Results show excellent dimensional stabilization (shrinkage < 1%, and sometimes even slight expansion up to 3% without damage), although these results were obtained under controlled lab conditions.

2.3.10. Hard Wax Mixture

(e.g., [22,53]). Though now largely replaced, this older method is still used in special cases, particularly with softwood. It employs a mixture of dammar varnish, raw carnauba wax, paraffin, and beeswax dissolved in toluene or xylene and heated to 80 °C. Impregnation begins as water is gradually replaced by toluene.

2.3.11. Sucrose Method

(e.g., [54–56]). This is one of the most cost-effective methods for waterlogged wood conservation. Sucrose does not discolor, evaporate, or pose toxicity risks, and is highly water-soluble [57]. Its reversibility is a major advantage. Comparative studies by the Vasa Museum tested PEG, salt, and sucrose [58,59], concluding that acceptable shrinkage must remain under 75% Anti-Shrink Efficiency (ASE). Sucrose yielded significantly lower shrinkage than other methods, though results in actual conservation settings often fall short of lab-reported ASE values (e.g., 92% ASE in controlled conditions, [55,60]).

2.4. Conservation Examples

Chinese archaeologists successfully raised an entire wooden shipwreck from the seabed using a specially designed support structure, enabling detailed investigation on land (Figure 4). At the 2017 International Symposium on the Discovery and Research of the Nanhai I Shipwreck, the paper "The Discovery and Research of the Nanhai I Shipwreck" was presented by Sun Jian, Chief Technology Officer of the Underwater Archaeology Unit (National Center for Underwater Cultural Heritage), and Cui Yong, Deputy Director of the Guangdong Provincial Institute of Archaeology.



Figure 4. Shipwreck Nanhai I during excavation in Maritime Silk Road Museum of Guangdong in Yiangjiang, China. (Details: [61]; photo: Miran Erič, 25 November 2017).

They reported that even under strictly controlled environmental conditions—temperature maintained at 18 °C and relative humidity (RH) between 70 and 80%, with automated water misting of the entire workspace seven times daily—significant changes still occurred. A full 3D scan of the entire working space was also performed daily. Despite these comprehensive conservation measures, the wooden structure experienced an average volumetric and dimensional deformation of up to 25% (Li et al. [61]).

3. Results

The 3D models captured before and after conservation revealed a significant volume loss (~20%) in the treated artefact. Comparative scans showed deformation, indicating that traditional melamine treatment may compromise structural integrity. Reburial proposals demonstrated reduced biological risk under anoxic conditions.

It is especially important to emphasize that the analyzed Paleolithic yew-wood point exhibited exceptionally well-preserved cellular structure, with water content below 300% of its maximum water saturation value (VVmax). Yet, despite meticulous handling, the conservation results were deeply disappointing.

3.1. Controversies Surrounding Current Methods of Waterlogged Wood Conservation

Debates persist around the most widely used methods for conserving waterlogged wood in museums today. The consequences of current practices are increasingly seen as unacceptable, prompting a fundamental reassessment of conservation goals, material understanding, and knowledge preservation.

Despite longstanding use, the chemical and biological interactions between wood, metals, and consolidants remain poorly understood—an ongoing shortcoming in current methods (see Figure 4) [62,63]. Major finds like boats often contain various wood species, which require different treatment methods in the conservation of waterlogged archaeological wood. This is due to several key factors that vary by species such as anatomical structure, chemical composition, degree of degradation, and shrinkage behavior [20].

Yet all modern techniques inevitably alter the wood, sometimes gradually—even under stable microclimates (e.g., [24,64–69]).

Wood shrinkage during drying remains a major issue (see Figures 3 and 5–7; [70–72]). In 1990, a 75% Anti-Shrink Efficiency (ASE) was acceptable; today, 90–95% is the standard. However, ASE is calculated under ideal lab conditions on uniform samples, while real artefacts vary widely in form and structure [10–12].

Environmental control is another key challenge. Sensitive artefacts require RH around 60% and 15 °C, yet most museum spaces are optimized for inorganic materials, with RH between 20 and 40%—conditions unsuitable for waterlogged wood. Microclimate stability is crucial for long-term preservation.

Current conservation methods are also cost-inefficient. The 2011 WreckProtect project [73] compared in situ shipwreck preservation with large-scale conservation [74]. Raising and conserving the Mary Rose (at 38 m depth) has cost EUR 65 million over 25+ years. In contrast, in situ protection of Burgzand Noord 10 (35 m depth) using geotextiles and gravel cost just EUR 70,000 ([73], pp. 43–44).

Due to growing recognition of these issues, a specialist working group was formed in 2017 in Bremerhaven. It monitors conserved shipwrecks and compares long-term practices. Members include researchers from major European maritime museums (Vasa, Mary Rose, Bremerhaven Cog, Vikingship Museum) and institutions like Lund University, ArcNucleart, and Slovenia's Restoration Centre.

The volumetric data and image changes are related to the phases of the artifact's conservation process with melamine resin. These are therefore artificial conditions that

were implemented in the laboratory from the beginning to the end of the conservation and up to the storage phase in the local museum collection.

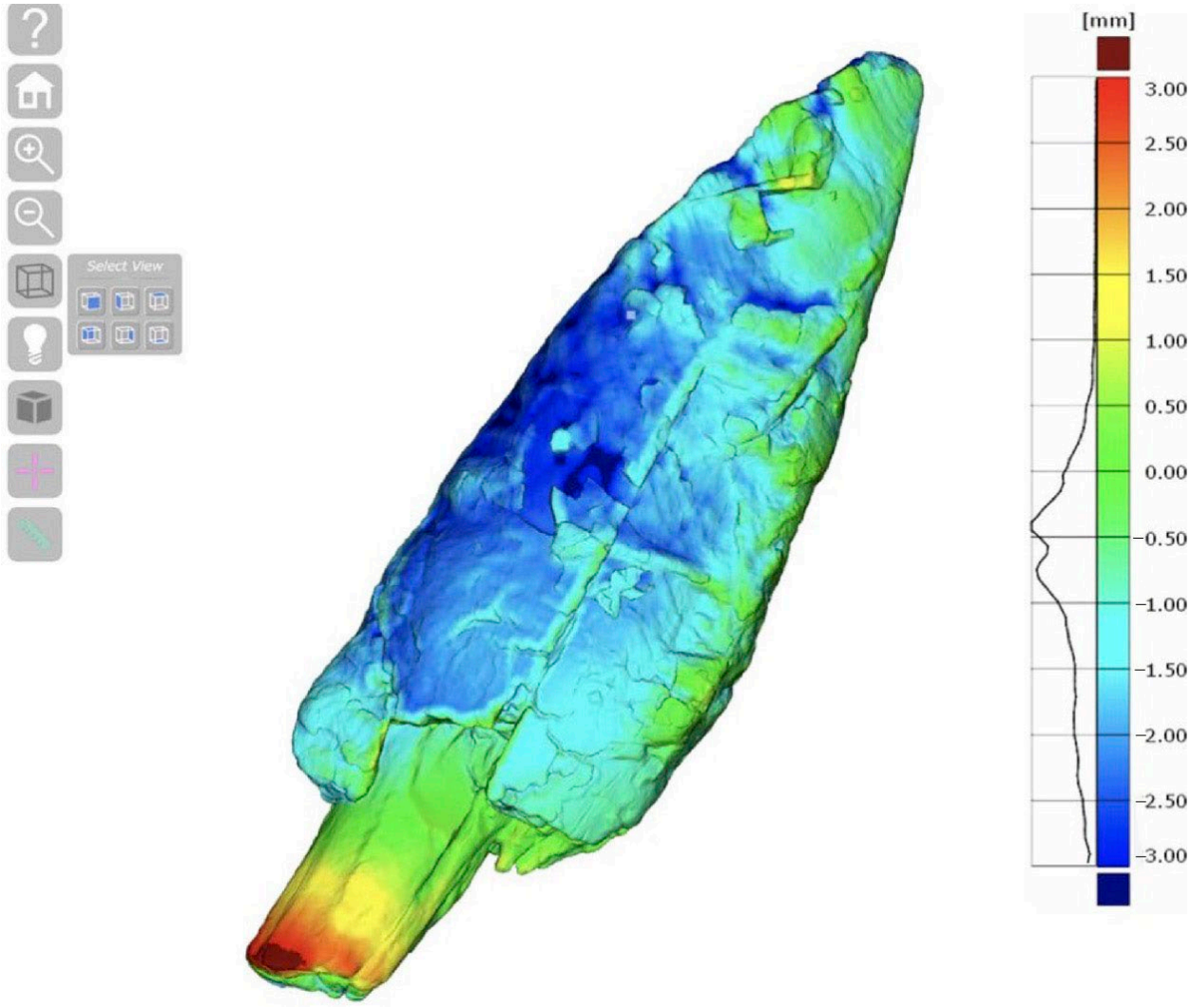


Figure 5. Volumetric analyses of Paleolithic wooden point [6]. During 2009–2018, two 3D models were measured before treatment with melamine (INTRI, Innovative Technologies and Solutions). Before and after conservation at the Römisch-Germanisches Zentralmuseum [13], Archaeological Research Institute (RGZM), Mainz—three more models were recorded. Subsequently, two more 3D models were recorded with micro CT by Lidija Korat Bensa at the Institute of Civil Engineering of Slovenia in Ljubljana. Comparative analyses were carried out by Enej Guček Puhar through ClaudCompare software [10–12]. Image: Enej Guček Puhar.

	PP-R2008	PP-2009	PP-2013	PP-2015	PP-2017	PP-2018
	0	1	2	3	4	5
	μm	μm	μm	μm	μm	μm
Length	160,000	155,606	160,958	152,709	151,768	150,435
Width	51,000 48,000	50,014	52,274	50,594	50,348	48,359
Thickness	25,000 24,000	25,579	28,810	23,856	23,585	22,689
	$+-\mu m$ / %	$+-\mu m$ / %	$+-\mu m$ / %	$+-\mu m$ / %	$+-\mu m$ / %	$+-\mu m$ / %
Length+–% (l)		α	+5352 +3.44%	–897 –1.86%	–3838 –2.47%	–5171 –3.3%
			α	–8249 –5.12%	–9190 –5.74%	–10,523 –6.54%
				α	–941 –0.62%	–2274 –1.49%
					α	–1333 –0.88%
Width+–% (b)		α	+2260 +1.41%	+580 +1.2%	+334 +0.68%	–1655 –3.31%
			α	–1680 –3.21%	–1926 –3.68%	–3915 –7.49%
				α	–246 –0.49%	–2235 –4.42%
					α	–1989 –3.95%
Thickness+–%		α	+3230 +12.63%	–1724 –6.74%	–1995 –7.8%	–2890 –11.3%
			α	–4954 –17.2%	–5225 –18.34%	–6121 –21.3%
				α	–217 –1.14%	–1167 –4.89%
					α	–896 –3.80%
	μm^3	μm^3	μm^3	μm^3	μm^3	μm^3
Volume		70,653.6	80,404.1	66,382.8	65,238.9	63,871.9
	$+-\mu m^3$ / %	$+-\mu m^3$ / %	$+-\mu m^3$ / %	$+-\mu m^3$ / %	$+-\mu m^3$ / %	$+-\mu m^3$ / %
Volume +–%		α	+9751 +13.80%	–4271 –6.05%	–5414 –7.66%	–6781 –9.60%
			α	–14,022 –17.44%	–15,166 –18.86%	–16,532 –20.56%
				α –6.05%	–1145 –1.72%	–2511 –3.78%
					α	–1367 –2.1%

Figure 6. Volumetric analyses of a Palaeolithic wooden point at different stages of the conservation process. Volumetric measurements and five 3D models support the hypothesis that the length, width, and thickness of the Palaeolithic point changed during the conservation process and that its volume decreased by approximately 20% when it was handed over to the museum. (The table was created by Enej Guček Puhar, author of ClaudCompare. 3D models 2009 and 2013 @INTRI; 2015 and 2017 476 @Römische-Germanische Shiffarts Museum, Mainz; 2018 @Lidija Korat, ZAG).

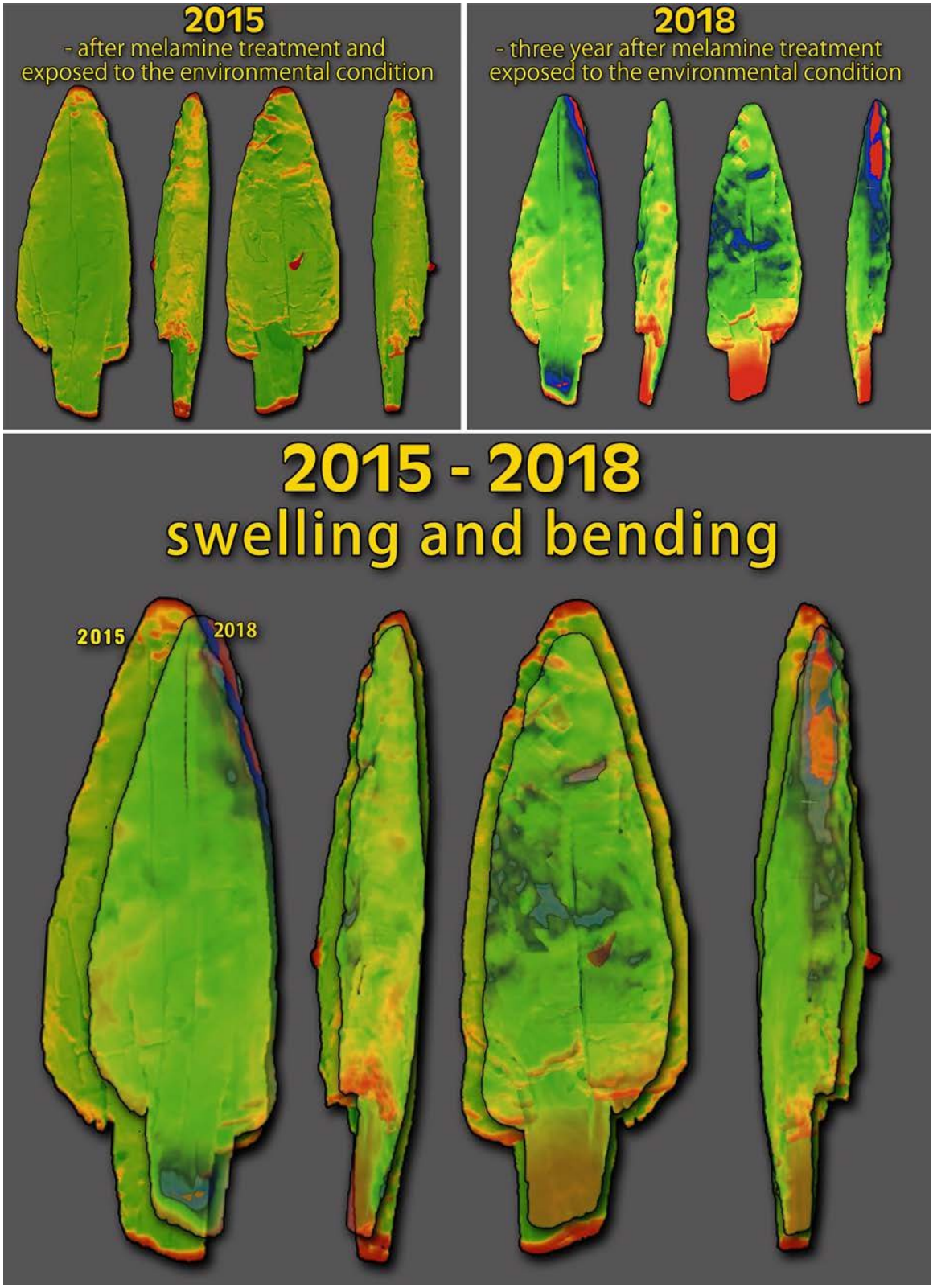


Figure 7. Volumetric analyses of a Paleolithic yew wooden point. Comparison models from 2015 and 2018 show a dramatic change in the volume and shape of the Paleolithic wooden points. Image: Enej Guček Puhar.

3.2. Fundamental Ethical Guidelines for the Protection of Underwater Cultural Heritage

The ethics of conserving archaeological finds from underwater sites are shaped by the Committee for Conservation, established in 1967 as part of the International Council

of Museums (ICOM-CC 2017). Over the past decade, several additional guidelines have been issued, including those by the Center for Maritime Archaeology and Conservation at Texas A&M University [75], the WreckProtect Guidelines for the protection of underwater wooden heritage [73], and the SASMAP Guidelines Manual 2 [76].

Ethical standards originally developed for the conservation of artworks can—and should—also apply to the preservation of underwater cultural heritage. Conservation and restoration ethics generally describe seven principles that can guide decision-making when selecting conservation methods and undertaking conservation actions [75]:

1. **Respect for the Integrity of the Object**

All professional actions by the conservator must be guided by unwavering respect for the object. Its value—including aesthetic, historical, archaeological, and physical integrity—must be carefully preserved, regardless of its condition. After conservation, the object should retain as many diagnostic features as possible.

2. **Competence and Capability**

It is the conservator's responsibility to work only within the boundaries of their professional knowledge and technical capacity when researching or treating historical objects.

3. **Uniform Standards**

A conservator must apply the highest and most rigorous treatment standards to every historical object, irrespective of their opinion of the object's value or quality. While practical circumstances may limit the scope of conservation, the quality of conservation should never be compromised.

4. **Appropriateness of Methodology**

A conservator should not perform or recommend any method unsuitable for preserving waterlogged wood. The necessity and quality of the method must outweigh any financial or institutional incentives. Methods that pose a risk to the object, or that involve extensive and time-consuming procedures, should be avoided. Decisions should not be driven by short-term or long-term goals alone, but by what is best for the object.

5. **The Principle of Reversibility**

Conservation should always aim to adhere to the principle of reversibility. The use of materials that might become impermeable or irreversible over time—and whose removal might endanger the object—should be avoided. Most current methods for conserving waterlogged wood do not meet the reversibility criterion. Techniques whose results cannot be reversed or corrected, even if later desired, should be abandoned. Ideally, all procedures should be reversible, assuming that current methods may later be improved upon.

6. **Limitations in Aesthetic Re-integration**

When compensating for damage or loss, a conservator may perform minimal or extensive aesthetic restoration but only based on prior agreement with the object's owner or custodian.

7. **Continual Self-Education**

It is the responsibility of every conservator to stay informed about current developments in their field and to continuously enhance their knowledge and skills to ensure best conservation practices.

8. **Oversight of Support Staff**

A conservator must always protect and preserve the objects under their care by supervising and guiding the work of all support personnel, interns, and volunteers under their professional authority.

3.3. Digital Technologies and Waterlogged Wood

Cultural heritage research now widely employs remote sensing technologies like airborne laser scanning (ALS), geo-electrical resistivity, ground-penetrating radar (GPR), magnetometry, electromagnetic conductivity, multi-beam sonar, and sub-bottom profiling. On-site methods such as terrestrial laser scanning (TLS) and photogrammetry are also standard. These techniques produce dense 3D point clouds for high-resolution documentation [77].

These datasets enable compelling visualizations. With photographic textures, interactive 3D models and virtual flythroughs can be created to support archaeological analysis and engage the public. Calibrated data allows for accurate measurements, which can be further processed using automated segmentation and modeling techniques [10–12,78].

Advanced 3D data capture is increasingly used underwater. However, most active 3D methods, like laser scanning and structured light, are not viable in aquatic settings. While sonar works well for larger objects, it lacks precision. Thus, the demand for accurate underwater 3D measurement is growing—especially in underwater archaeology.

Currently, photogrammetry remains the most effective method for producing detailed underwater documentation (e.g., [9,78–85]). The sustainability of long-term data preservation should also be addressed.

3.4. Photogrammetry and the Evolution of Underwater 3D Documentation

Although stereophotogrammetry was used in early underwater archaeology during the 1960s [86,87], it was too complex and expensive due to the difficulty of aligning underwater photographs and the labor-intensive manual feature registration (e.g., [80,88,89]).

When at least three matching points are identified across three consecutive images, it becomes possible to compute their relative 3D positions and derive the camera's optical parameters, eliminating the need for prior calibration. Since 2010, many commercial and open-source tools have been developed [90], producing dense 3D point clouds that can be textured using the original photos.

Images must overlap by about 70% for effective 3D reconstruction. Underwater, divers can manually capture photos or video, which is faster and more cost-effective than traditional methods, reducing dive time and increasing safety [9].

Underwater imaging challenges like low light, refraction, and scattering can be managed with extra effort. Visibility limits image distance: even in clear water, it rarely exceeds 30 m, and in murky environments, often less than 1 m. This necessitates close-range imaging and many high-quality images to ensure sufficient point identification.

Wide-angle lenses are commonly used to capture larger areas from close distances. Importantly, even low-cost compact cameras or consumer-grade video cameras can perform as well as high-end DSLRs for underwater photogrammetry [9,80,83].

Three-dimensional documentation should not invalidate the importance of rigorous human observation of relevant details for the study of elements, although details can easily be overlooked if the point clouds are only optically observed [91].

4. Discussion

Our findings highlight the benefits of digital documentation and replication over traditional chemical treatments. In situ conservation, supported by 3D scanning, offers a viable alternative for long-term preservation. However, the approach is limited by environmental variability and logistical challenges of reburial. Further research is needed to standardize reburial methods and develop reliable biodegradable containers.

4.1. Photogrammetry and Ethical Practice in Underwater Archaeology

Most published studies on underwater photogrammetry focus on documenting shipwrecks (e.g., [9,79,80,89,92–94]). Multi-view photogrammetry offers highly precise in situ 3D modeling of underwater artefacts.

Organic materials like waterlogged wood are highly sensitive to handling and environmental shifts, often deteriorating rapidly [8,95].

As a result, physically recovering waterlogged artefacts has become ethically contentious. When needed, laser and structured light scanners, as well as microscopic techniques, support post-processing. CT and micro-CT are also used to examine internal structures.

Once digitized, objects made of wood, metal, stone, resin, or plastic can be replicated through 3D printing [96,97] or subtractive methods like robotic carving [98] both increasingly common in heritage conservation. Robotic milling using CNC-equipped robotic arms—fed by high-resolution 3D scans—has become a common and effective method in heritage conservation. It is used to create highly accurate replicas of stone sculptures (including Renaissance-era works like those by Michelangelo) from marble, wood, or resin, enabling widespread display and minimizing damage to the fragile originals [99].

Digital models remain unchanged in virtual form, but proper long-term preservation and access standards must be observed [100]. Beyond meeting ethical standards, digital technologies offer powerful tools for presenting and interpreting heritage—whether as interactive virtual models or physical replicas.

4.2. Appropriate Solutions for the Protection of Waterlogged Wood

Uncertainty remains about what to do with newly discovered waterlogged wooden artefacts once they have been digitally documented. The most suitable solution is physical in situ protection, which can take several forms depending on the environmental conditions and the specific risks involved [73].

Specifically, the financial, environmental, and ethical implications of deploying massive protective structures should be carefully weighed against the costs and benefits of alternative conservation strategies—such as excavation, removal, and controlled curation in museum environments. The construction of concrete installations costing millions of euros raises serious questions about resource allocation, long-term site accessibility, and the reversibility of conservation actions. Moreover, the presence of such heavy infrastructure on the seabed may not only hinder future scientific access to the site but could also pose a physical risk to the underlying archaeological materials, potentially contributing to their gradual compression or destruction (Figure 8).

In light of these considerations, a broader discussion is warranted—one that includes stakeholders from archaeological, environmental, and policy-making communities—to assess whether such interventions truly represent the most responsible and sustainable path for underwater cultural heritage management.

In less trafficked waters, protective casings made from fiberglass or metal panels, mounted on modular frames and anchored at the site, can be employed. These structures can be reinforced with metal cages and sand/gravel fill. This approach is especially suitable for sites still under investigation. In cases where shipwreck sites are attractive to looters, such protection allows for monitorable preservation and even visitor access. According to heritage authorities in the Republic of Croatia, the best protection for exposed underwater sites is provided by metal cages secured to the seabed with concrete weights or stakes. These structures are equipped with double lockable doors, allowing for controlled access and safe diving inside the cage (see Figure 9; [101,102]).

In locations where treasure hunting is not a threat, but aggressive bottom trawling is, large multi-ton concrete pyramids can be deployed. These can be equipped with obstacle signaling systems to deter fishing activity and protect the site.

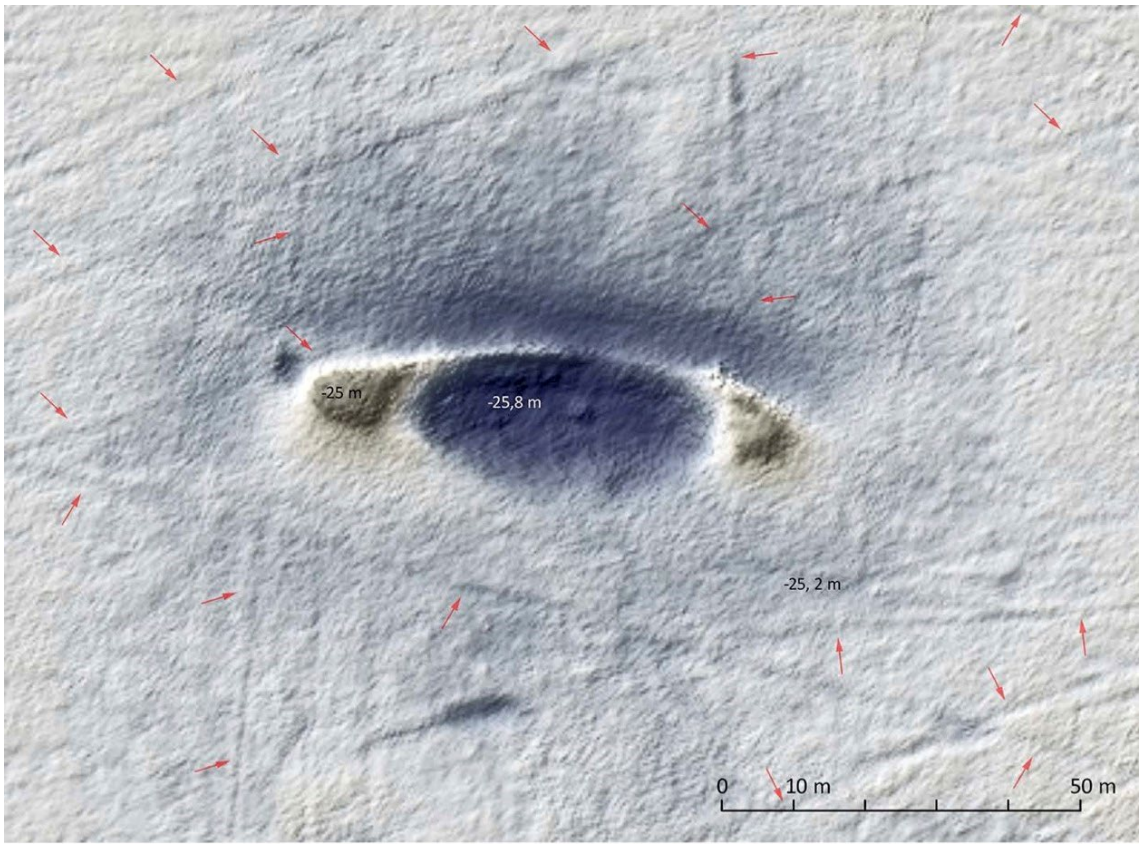


Figure 8. Anchor traces in the immediate vicinity of the Stojanov Bark [103] shipwreck as revealed by bathymetric surveys. Image: Sašo Poglajen.



Figure 9. Shipwreck from the third to fourth century AD protected with a cage. Photo: ICUA.

4.3. Public Presentation and Educational Value of Documented Shipwrecks

Once a shipwreck has been fully documented and researched, it is both reasonable and beneficial to present the recovered artefacts, structural remains of the vessel, or even the entire wreck site to the public—due to its educational, promotional, and economic value. In combination with the recent in situ preservation policies for underwater cultural heritage sites, there is great potential to develop a new form of cultural tourism in the shape of underwater parks and museums, incorporating various underwater and surface-level trails.

For individuals unable to physically visit submerged sites, 3D documentation can be used in virtual reality (VR) environments within more traditional museum settings or as augmented reality (AR) applications at heritage locations. These digital experiences could help raise awareness of the rich archaeological heritage hidden beneath the water's surface.

The added value of such virtual museums lies in the ability to integrate comprehensive scientific data related to a particular site—not only archaeological information but also interdisciplinary layers from geology, biology, ichthyology, ecology, and more. Information centers could be established in nearby ports, cities, communities, and tourist areas, featuring scaled 3D models of relevant shipwrecks, anthropogenic underwater landscapes, and surrounding marine environments. These spaces could serve as aesthetic and educational elements within contemporary urban architecture.

Such models would be accessible and engaging for children, blind and visually impaired visitors, and other vulnerable groups. Global best-practice examples include submerged glass walkways that allow on-site viewing of wooden remains, or unique aquarium installations that exhibit underwater heritage in an immersive setting.

4.4. What Should Be Done?

The conservation and restoration research community working in the field of organic material preservation—particularly that of waterlogged wood—should reconsider the continued use of established methods for preserving artefacts made from organic materials. Despite efforts to maintain appropriate microclimatic conditions (i.e., relative humidity, temperature, and lighting), exposing wood impregnated with consolidates to altered environments remains costly, ineffective in the long term, and, given current digital advancements, increasingly unacceptable.

The conditions in which the artefact was discovered may offer relatively favorable circumstances for the long-term preservation of waterlogged wood. These natural conditions enabled its survival until today. Therefore, we propose that, following precise 3D modeling—which captures the object's form and texture—and internal structural analysis, artefacts and shipwrecks should be reburied (in situ reburial) for their long-term conservation.

However, this raises an important point. While the archaeological find remains submerged, this alone does not guarantee an anaerobic environment. For conditions to be truly anaerobic, all oxygen must be excluded—something that water alone cannot ensure. Anaerobic conditions typically occur in fine, compacted sediments like mud or sand, which are saturated with water and dense enough to block oxygen diffusion. Therefore, submersion without such sediment does not necessarily create an anaerobic environment. This distinction is very important!

In recent decades, there has been growing development of methodologies for in situ reburial as a means of protecting underwater cultural heritage sites. Examples of good practice include the following:

- The SASMAP project [73,76].
- The Baiheliang Underwater Heritage Site [104].
- The ancient harbor of Alexandria [105].

- The Croatian protective cage project [101,102].
- UK guidelines for waterlogged wood [106].
- The Amsterdam Museum approach [107] (Figure 10).

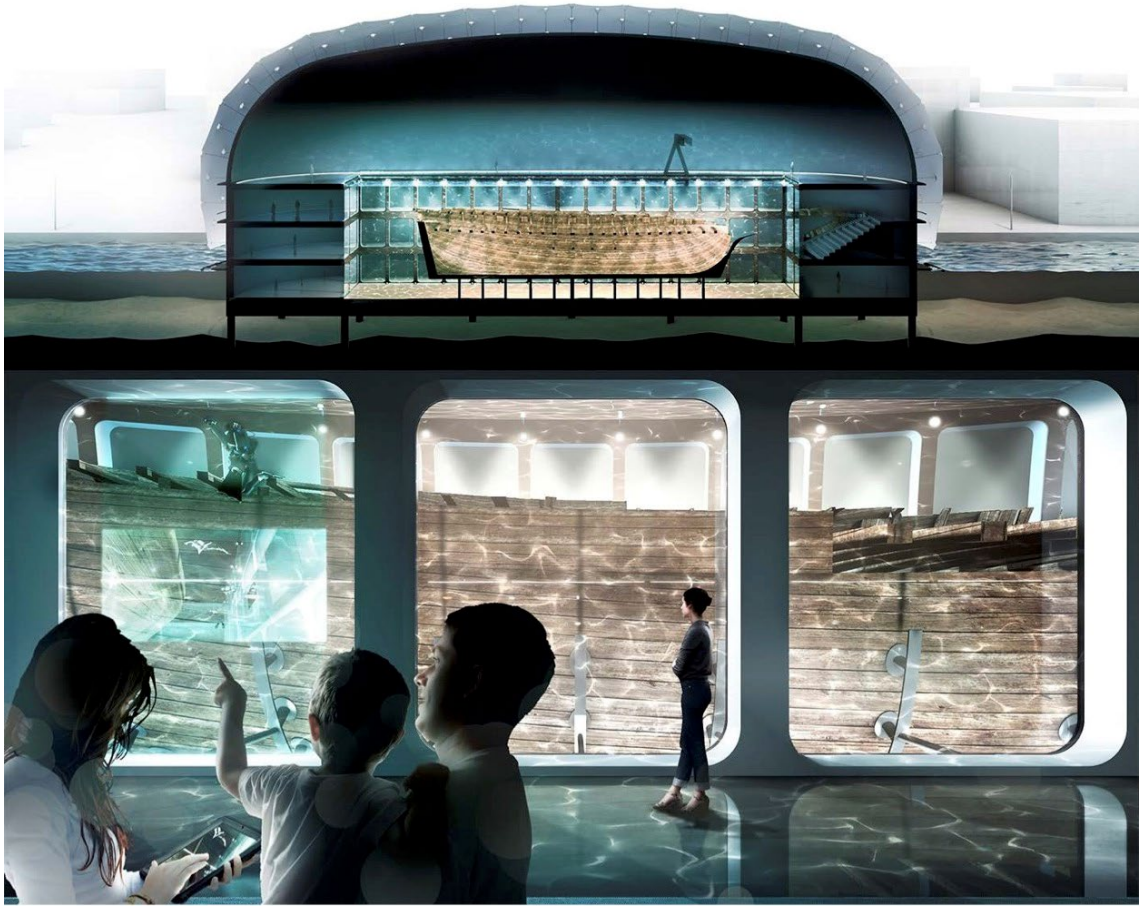


Figure 10. A museum in Amsterdam where the ship is preserved in a controlled aquatic environment. (**Top**) Longitudinal section of museum. (**Bottom**) Overview inside levels.

4.5. Toward a Responsible and Sustainable Approach to the Protection of Waterlogged Wood

TECTONIC's goal is to promote an interdisciplinary framework for developing solutions and establishing new standards for the sustainable in situ conservation of underwater cultural and natural heritage by 2030 [108]. It pays particular attention to the implementation of Sustainable Development Goal 11.4 from the UN General Assembly Resolution (25 September 2015), titled A/RES/70/1—Transforming our world: the 2030 Agenda for Sustainable Development. The project is financially supported by the Horizon Europe 2020 research and innovation program and involves partners from six EU countries (Italy, Greece, Croatia, Czech Republic, Spain, and France) as well as Argentina.

New technologies in 3D modeling and innovative conservation approaches have already been implemented in three pilot sites.

Greater attention should be directed toward studying diverse environments—such as wetlands, freshwater, and marine contexts—as well as distinctions between shallow and deep waters, local geographic conditions, and the stability of different types of organic materials and tree species.

In cases where in situ storage of sensitive and valuable small artefacts is not feasible—due to looting risks or adverse environmental conditions—there is a need to establish "controlled natural depositories." These could also be in urban environments, within buildings where continuous monitoring is more easily implemented. Such facilities must

support the measurement of physical, biological, and chemical parameters, enabled by the latest in digital and sensing technologies. Simultaneously, systems should be in place for the automatic tracking and recording of vital changes in the physical appearance, microbiological activity, and chemical processes affecting the artefacts.

A significant indication of changing attitudes in Europe is the planned exhibition of an 18th-century shipwreck in the new Amsterdam Museum, opening in 2025 [107]. The ship will be displayed in a large pool with a monitored aquatic environment, surrounded by four levels of walkways for public viewing (Figure 10), fully embracing the latest knowledge in the conservation of waterlogged wood.

Multiple levels of underwater protection can be applied depending on the importance of the find. In expert committees tasked with evaluating an artefact's significance and selecting protection methodologies, the decision of the lead conservator must take precedence over local political or institutional ambitions. In exceptional cases, extraction and display for museum purposes may be appropriate—but only if they do not compromise the long-term preservation of waterlogged wood.

At present, three viable solutions are available.

4.6. Three Viable Solutions for the Protection and Presentation of Waterlogged Wooden Artefacts

1. Reburial for Non-Museum-Priority Artefacts

If conservation and museum professionals determine that a find is not of sufficient significance for museum display but is nonetheless at risk due to environmental or human factors, a reburial strategy can be employed. In this case, the artefact is relocated to deeper waters. A sufficiently large and deep trench is excavated. The object is then wrapped in biodegradable geotextile, placed into the trench, and covered with sediment or sand.

2. Remote Presentation for Cost-Constrained Finds

If the find is of moderate interest and merits at least partial public presentation, but the costs of conservation or museum integration are too high, alternative methods exist. The object can be placed within a protective cage equipped with underwater cameras. A large screen can be installed along a coastal promenade, allowing visitors to observe the artefact in its natural aquatic environment. To enhance engagement, interactive content can be programmed, such as educational media, historical context, and a rotating 3D model and digital reconstruction of the find. This solution provides an attractive public experience while keeping the artefact safely submerged.

3. Museum Display of Exceptional Finds in a Controlled Aquatic Environment

If the conservation and museum community agree that a find is truly exceptional and warrants formal educational display, a more advanced solution is available. A specialist working group should be assembled, composed of:

- A conservator–restorer from a national conservation center.
- An architect to assist in the design of the aquatic display chamber and its integration into museum spaces.
- A computer scientist to implement automated environmental monitoring using sensors.
- A microbiologist to guide the creation of a closed aquatic system.
- An aquarist to advise on the development of the water chamber.
- A mechanical engineer to support water flow optimization using cavitation-based methods [85].
- A museum curator from the institution where the artefact would be housed.

This team would collaboratively design a customized conservation and presentation plan, resulting in an AI-regulated aquarium-like water chamber that is visitor-friendly and scientifically robust.

Traditional conservation of waterlogged wood using consolidates is a prolonged and expensive process, often taking over 20 years and requiring dedicated space, equipment, expertise, and ongoing financial investment (Table 1). For small artefacts, the conservation may take several months to 1–2 years, for large structures (e.g., shipwrecks) it can take 5–20 years or more (e.g., the Mary Rose took over 19 years) [25].

Table 1. This table summarizes the procedures and conditions under which waterlogged archaeological wood can avoid long-term degradation following exposure to atmospheric oxygen, based on current conservation practices and literature [20].

Procedure/Storage Method	Stabilization Required	Environment Type	Expected Longevity	Risk of Degradation	Notes/Examples
PEG treatment + Controlled Drying	Yes	Dry, RH 50–60%, temp < 18 °C	Long term (decades)	Low	Industry standard (e.g., Oseberg, Mary Rose); prevents shrinkage and microbial decay
Sugar/Alcohol Impregnation (e.g., lactitol)	Yes	Same as above	Long term	Low	Alternative to PEG; less used but promising
Anoxic Storage (sealed containers or chambers)	No/Optional	Oxygen-free, sealed	Long term	Very low	Imitates burial conditions; high cost; used in sensitive or high-value artefacts
Refrigerated Wet Storage	No	Water-saturated, 4–10 °C	Medium–long term (up to decades)	Low–medium	Useful as interim; risk increases over time without treatment
Controlled RH Storage (untreated wood)	Optional	RH 50–60%, temp stable	Medium–long term	Medium	Works for some dry-stored finds; used in Scandinavian reserves
Air-Drying Without Pre-treatment	No	Ambient air	Short term	High	Causes collapse, cracking, decay; not recommended
Reburial in Anoxic Sediment	No	Anaerobic, waterlogged	Long term (potentially indefinite)	Low	Depends on site chemistry; effective in peat, clay, silt

In contrast, constructing a water chamber could be completed in a much shorter time frame, offering substantial cost savings. More importantly, the public would gain immediate, visually compelling access to the artefact, while the new methodology would preserve the wood without volumetric changes or deformation in a museum setting.

For generations, researchers have sought to preserve waterlogged wood for museum display or storage in air-exposed environments. Although guided by the conservation standards of their time, many of these efforts have ultimately failed. Even today, we cannot confidently ensure the long-term survival of waterlogged wooden artefacts beyond a few centuries.

Polymer-based consolidants like PEG, melamine, and acrylates, while widely used, remain insufficiently tested for long-term durability and may not guarantee sustained preservation. In contrast, recent advancements in in situ underwater measurement, 3D printing, and digital engagement offer promising alternatives for developing new conservation methods.

We now have the capability to create precise digital and physical replicas of organic artefacts for display and education, allowing the originals to remain in the environments that preserved them for centuries. This copy-based conservation approach is gaining acceptance in other cultural heritage fields [109].

It is the ethical responsibility of conservators and researchers to protect waterlogged wooden heritage to the best of our ability. Future generations will likely develop superior technologies, but we must act now to establish standardized, reliable methods that enhance the longevity of these fragile objects [48].

By preserving the natural conditions that enabled their survival, we expand the window for study and appreciation. The necessary technology exists—so why not use it?

5. Conclusions

This study advocates a paradigm shift in waterlogged wood conservation—prioritizing digital documentation and in situ strategies over traditional consolidation. This not only preserves artefact integrity but also aligns with ethical and sustainable practices. Controlled digital preservation ensures future accessibility and scientific study.

Novel contributions of this article are as follows:

- Propose a new reburial strategy using 3D scanning and biodegradable containment.
- Demonstrate ethical and environmental benefits of avoiding invasive chemical treatments.
- Apply comparative volumetric analysis to evaluate conservation impact.
- Limitations of the proposal are as follows:
- Case studies are limited to specific artefacts and environments.
- Reburial feasibility varies with site accessibility and legal restrictions.
- Lack of long-term reburial trial data under monitored conditions.

Author Contributions: Conceptualization, M.E. and F.S.; methodology, M.E.; software, E.G.P. and A.J.; investigation, D.S. and N.S.; data curation L.K.B., writing—original draft preparation, M.E.; writing—review and editing, F.S.; project administration and funding acquisition, F.S. Authors M.E. and N.S. passed away prior to the publication of this manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge financial support by the Slovenian Research agency (ARRS) for the research program "Computer Vision" (P2-0214).

Data Availability Statement: There were no datasets generated or used during this research.

Conflicts of Interest: The author Enej Guček Puhar works for a company. The authors declare no conflicts of interest.

References

1. Kovacs, M.G. *The Epic of Gigamesh*; Stanford University Press: Redwood City, CA, USA, 1989.
2. Gonda, J. *A History of Indian Literature 1, Veda and Upanishads, Fasc. 1, Vedic Literature (Samhitas and Brahmanas)*; Otto Harrassowitz: Wiesbaden, Germany, 1975; ISBN 9783447016032.
3. Banks, E.J. Senkereh, the Ruins of Ancient Larsa. *Biblic. World* **1905**, *25*, 389–392. [CrossRef]
4. Farnoux, A.; Schnapp, A. La conquête du passé. aux origines de l'archéologie, 1993. *Topoi Orient-Occident.* **1994**, *4*, 223–230.
5. Erič, M.; Gaspari, A. Sinja Gorica: Poročilo o Arheološkem Podvodnem Pregledu Struge Reke Ljubljanice na Območju Zavarovanja Desne Brežine ob Sinjegoriških Ribnikih. Ljubljana: Zavod za Varstvo Kulturne Dediščine Slovenije, 2009. Available online: https://plus.cobiss.net/cobiss/si/sl/bib/290297#full (accessed on 3 July 2025).
6. Gaspari, A.; Erič, M.; Odar, B. A Palaeolithic wooden point from Ljubljansko barje, Slovenia. In *Submerged Prehistory*; Benjamin, J., Ed.; Oxbow Books: Oxford, UK, 2011; pp. 186–192.
7. Broda, M.; Hill, C.A.S. Conservation of Waterlogged Wood—Past, Present and Future Perspectives. *Forests* **2021**, *12*, 1193. [CrossRef]

8. Lobb, M.; Krawiec, K.; Howard, A.; Gearey, B.; Chapman, H. A New Approach to Recording and Monitoring Wet-preserved Archaeological Wood Using Threedimensional Laser Scanning. *J. Archaeol. Sci.* **2010**, *37*, 2995–2999. [CrossRef]
9. Erič, M.; Kovačič, R.; Berginc, G.; Pugelj, M.; Stopinšek, Ž.; Solina, F. The impact of the latest 3D technologies on the documentation of underwater heritage sites. In Proceedings of the 2013 Digital Heritage International Congress, Marseille, France, 28 October–1 November 2013; Alonzo, C.A., Ed.; IEEE: Marseille, France, 2013; pp. 281–288. [CrossRef]
10. Guček Puhar, E.; Erič, M.; Kavkler, K.; Cramer, A.; Celec, K.; Korat Bensa, L.; Jaklič, A.; Solina, F. Comparison and deformation analysis of five 3D models of the Paleolithic wooden point from the Ljubljanica River. In Proceedings of the 2018 Metrology for Archaeology and Cultural Heritage (MetroArchaeo), Cassino, Italy, 22–24 October 2018; pp. 449–454. [CrossRef]
11. Guček Puhar, E.; Erič, M.; Solina, F.; Jaklič, A.; Korat Bensa, L. Anatomical-morphological analysis of a volumetric 3D model of an archaeological object. *Archeol. Calc.* **2021**, *32*, 197–208. [CrossRef]
12. Guček Puhar, E.; Korat, L.; Erič, M.; Jaklič, A.; Solina, F. Microtomographic analysis of a Paleolithic wooden point from the Ljubljanica River. *Sensors* **2022**, *22*, 2369. [CrossRef]
13. Wittkopper, M. *Der Aktuelle Stand der Holzkonservierung mit Melamin/Aminoharzen am Römisch-Germanischen Zentralmuseum AdR, 2 (Gruppe 8)*; RGMZ: Mainz, Germany, 1998.
14. Čufar, K.; Merela, M.; Erič, M. A Roman barge in the Ljubljanica river (Slovenia): Wood identification, dendrochronological dating and wood preservation research. *J. Archaeol. Sci.* **2014**, *44*, 128–135. [CrossRef]
15. Organ, R.M. Carbowax and Other Materials in the Treatment of Water-logged Paleolithic Wood. *Stud. Conserv.* **1959**, *4*, 96–105. [CrossRef]
16. Christensen, B.B. *The Conservation of Waterlogged Wood in the National Museum of Denmark with a Report on the Methods Chosen for the Stabilization of the Timbers of the Viking Ships from Roskilde Fjord and a Report on Experiments Carried out in Order to Improve upon These Methods*; National Museum of Denmark: Copenhagen, Denmark, 1970.
17. Walsh-Korb, Z.; Janeček, E.-R.; Hodgkinson, J.; Sedlmair, J.; Koutsioubas, A.; Spring, D.; Welch, M.; Hirschmugl, C.; Toprakcioglu, C.; Nitschke, J.; et al. Multifunctional supramolecular polymer networks as next generation consolidates for archaeological wood conservation. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 17743–17748. [CrossRef]
18. Mühlethaler, B.; Barkman, L.; Noack, D. *Conservation of Waterlogged Wood and Wet Leather*; ICCROM, Eyrolles: Paris, France, 1973.
19. Gaspari, A. Pontonium iz Lip na Ljubljanskem barju. *Arheol. Vestn.* **1998**, *49*, 187–224.
20. Hoffmann, P. On the Stabilization of Waterlogged Oakwood with PEG. II. designing a Two-Step Treatment for Multi-Quality Timbers. *Stud. Conserv.* **1986**, *31*, 95–117. [CrossRef]
21. Jenssen, V.; Murdock, L. Review of the Conservation of Machault Ships Timbers: 1973–1982. In Proceedings of the ICOM Waterlogged Wood Working Group Conference, Ottawa, ON, Canada, 15–18 September 1981; Grattan, W.D., McCawley, J.C., Eds.; International Council of Museums (ICOM): Paris, France, 1982.
22. Christensen, B.B. Developments in the Treatment of Waterlogged Wood in the National Museum of Denmark During the Years 1962–69. *Stud. Conserv.* **1971**, *16* (Suppl. S2), 27–44. [CrossRef]
23. Albright, A.B. The Preservation of Small Water-Logged Wood Specimens with Polyethylene Glycol. *Curator* **1966**, *9*, 228–234. [CrossRef]
24. Carlee, E. What Do We Know About PEG? 2009. Available online: https://ellencarrlee.wordpress.com/2009/04/ (accessed on 3 July 2025).
25. Hoffmann, P. On the stabilisation of waterlogged oakwood with PEG—Molecular size versus degree of degradation. In *Waterlogged Wood: Study and Conservation, Proceedings of the 2nd ICOM Waterlogged Wood Working Group Conference, Grenoble, France, 29–31 August 1984*; Centre dÉtude et de Traitement des Bois Gorgés d'Eau: Grenoble, France, 1985; pp. 95–117.
26. Hoffmann, P. The Bremen Cog sails a new course. *Int. J. Naut. Archaeol.* **1986**, *15*, 215–219. [CrossRef]
27. Morén, R.; Centerwall, B. The Use of Polyglycols in the Stabilizing and Preservation of Wood. Meddelanden Fran Lunds Universitets Historiska Museum. Mooch Domsjö Aktiebolag. 1961. Available online: https://books.google.si/books?id=tkdAHAAACAAJ (accessed on 3 July 2025).
28. Mortensen, M.; Egsgaard, H.; Hvilsted, S.; Shashoua, Y.; Glastrup, J. Characterisation of the polyethylene glycol impregnation of the Swedish warship Vasa and one of the Danish Skuldelev Viking ships. *J. Archaeol. Sci.* **2007**, *34*, 1211–1218. [CrossRef]
29. Munnikendam, R.A. Conservation of waterlogged wood using radiation polymerization. *Stud. Conserv.* **1967**, *12*, 70–75. [CrossRef]
30. Müller-Beck, H.; Haas, A. Holzkonservierung mit Arigal C (CIBA). *Jahrb. Bernischen Hist. Mus. Bern* **1957**, *37*, 260–271.
31. Parrent, J.M. The conservation of waterlogged wood using sucrose. *Stud. Conserv.* **1985**, *30*, 63–72. [CrossRef]
32. Scopigno, R.; Cignoni, P.; Pietroni, N.; Callieri, M.; Dellepiane, M. Digital Fabrication Techniques for Cultural Heritage: A Survey. *Comput. Graph. Forum* **2017**, *36*, 6–21. [CrossRef]
33. Seborg, R.M.; Inverarity, R.B. Preservation of Old, Waterlogged Wood by Treatment with Polyethylene Glycol. *Science* **1962**, *136*, 649–650. [CrossRef]

34. Seinturier, J.; Riedinger, C.; Mahiddine, A.; Peloso, D.; Boï, J.-M.; Merad, D.; Drap, P. Towards a 3D Based Platform for Cultural Heritage Site Survey and Virtual Exploration. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXIV International CIPA Symposium, Strasbourg, France, 2–6 September 2013; pp. 1–6.
35. Rosenqvist, A.M. Experiments on the conservation of waterlogged wood and leather by freeze drying. *Marit. Monogr. Rep.* **1975**, *16*, 9–23.
36. Rowley, J.; Hartley, R. *Organizing Knowledge: An Introduction to Managing Access to Information*, 4th ed.; Routledge: London, UK, 2017. [CrossRef]
37. Müller-Beck, H.; Haas, A. A Method for Wood Preservation using Arigal C. *Stud. Conserv.* **1960**, *5*, 260–271. [CrossRef]
38. Müller-Beck, H. and Haas, A., Ein neues verfahren zur konservierung von feuchthoelzern. *Z. Fuer Museumstechnik* **1961**, *1*, 157–168.
39. Müller-Beck, H.; Thieme, J. Zur reinigung und festigung mittelalterlicher holz–und gewebefunde. *Neue Museumkunde* **1966**, *9*, 63–75.
40. Neumüller, M.; Reichinger, A.; Rist, F.; Kern, C. 3D Printing for Cultural Heritage: Preservation, Accessibility, Research and Education. In *3D Research Challenges in Cultural Heritage. A Roadmap in Digital Heritage Preservation*; Ioannides, M., Quak, E., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 119–134. [CrossRef]
41. Cesar, T.; Danevčič, T.; Kavkler, K.; Stopar, D. Melamine polymerization in organic solutions and waterlogged archaeological wood studied by FTIR spectroscopy. *J. Cult. Herit.* **2017**, *23*, 106–110. [CrossRef]
42. Haas, A.; Müller-Beck, H.; Schweingruber, F. Erfahrungen bei der Konservierung von Feuchthölzern mit Arigal C. *Jahrb. Bernischen Hist. Mus. Bern* **1963**, *62*, 41–42.
43. Christensen, B.B. Om Konservering af Mosefundne Trögenstande. In *Aarborger for Nordisk Old Kyndighed og Historie 1950–1951*; Nabu Press: Charleston, SC, USA, 1951; pp. 22–55.
44. Opała-Owczarek, M.; Owczarek, P.; Rahmonov, O.; Niedzwiedz, T. The First Dendrochronological Dating of Timber from Tajikistan—Potential for Developing a Millennial Tree-Ring Record. *Tree-Ring Res.* **2018**, *74*, 50–62. [CrossRef]
45. McKerrell, H.; Roger, E.; Varsanyi, A. The Acetone/Rosin method for conservation of waterlogged wood. *Stud. Conserv.* **1972**, *17*, 111–125. [CrossRef]
46. Bryce, T.; McKerrell, H.; Varsanyi, A. The Acetone-Rosin Method for the Conservation of Waterlogged Wood and Some Thoughts on the Penetration of PEG into Oak. *Natl. Marit. Mus. Monogr.* **1975**, *16*, 35–43.
47. Cebertowicz, R.; Jasienski, D. Elektrokinetyczna Methoda Petryficacji Drewna Oraz Mumifikacji Matewki z Prehistorycznego Wykopaliska w BISKUPINIE. Prace 1 Sesji Nankowei Politechniki Gdanskiej. Gdansk, 1951.
48. Williams, E.; Peachey, C. *The Conservation of Archaeological Materials: Current Trends and Future Directions*; BAR Publishing: Oxford, UK, 2010.
49. Bouis, J. Principes de conservation et de restauration des bois antiques immerges. *Reun. Mixte Comete L'ICOM Trait. Peint.* **1960**, *67*, 6–13.
50. Murray, H. The Conservation of Artefacts from the Mary Rose. In Proceedings of the ICOM Waterlogged Wood Working Group Conference, Ottawa, ON, Canada, 15–18 September 1981; Grattan, W.D., McCawley, J.C., Eds.; International Council of Museums (ICOM): Paris, France, 1982.
51. Karpov, V.L.; Serenkov, V. Radiation Makes Better Woods and Copolymers. *Nucleonics* **1960**, *18*, 88–90.
52. De Guichen, G.; Gaumann, T.; Mühlerthaler, B. Methode de Conservation des Bois Provenant de Cites Lacustres par Diffusion d'un Monomere et Polymerisation par Rayons Gamma. Ecole Polytechnique Federale de Lausanne, 1966.
53. Pang, J.T.T. The treatment of waterlogged oak timbers from 17th century Dutch East Indiaman, Batavia, using polyethylene glycol. In Proceedings of the ICOM Committee for Conservation, 6th Triennial Meeting, Ottawa, ON, Canada, 21–25 September 1981; Grattan, D.W., McCawley, J.C., Eds.; Preprints; International Council of Museums (ICOM): Paris, France, 1981; p. 13.
54. Remondino, F.; Del Pizzo, S.; Kersten, T.P.; Troisi, S. Low-Cost and Open-Source Solutions for Automated Image Orientation—A Critical Overview. In Proceedings of the International Conference on Cultural Heritage, EuroMed, Limassol, Cyprus, 29 October–3 November 2012; Springer: Berlin/Heidelberg, Germany, 2012; pp. 40–54. [CrossRef]
55. Hoffmann, P. Sucrose for waterlogged wood. not so simple at all. In Proceedings of the ICOM Committee for Conservation, 11th Triennial Meeting, Wet Organic and Archaeological Materials 2, Edinbourgh, Scotland, 1–6 September 1996; Bridgland, J., Ed.; ICOM Committee for Conservation: Edinbourgh, Scotland, 1996; pp. 657–662.
56. Stamm, A.J. Treatment with Sucrose and Invert Sugar. *Ind. Eng. Chem.* **1937**, *29*, 833–835. [CrossRef]
57. Tahira, A.; Howard, W.; Pennington, R.; Kennedy, A. Mechanical strength studies on degraded waterlogged wood treated with sugars. *Stud. Conserv.* **2017**, *62*, 223–228. [CrossRef]
58. Barkman, L.; Oddy, W.A. The preservation of the warship Wasa. In *Problems in the Conservation of Waterlogged Wood*; Barkman, L., Ed.; National Maritime Museum: Greenwich, UK, 1975; pp. 65–66.

59. Barkman, L.; Bengtsson, S.; Håfors, B.; Lundvall, B. Processing of waterlogged wood. In Proceedings of the Pacific Northwest West side Wood Conservation Conference, Neah Bay, WA, USA, 19–22 September 1976; Grosso, G.H., Ed.; Makah Graphic Arts: Neah Bay, WA, USA, 1976; pp. 17–26.
60. Bjurhager, I.; Halonen, H.; Lindfors, E.-L.; Iversen, T.; Almkvist, G.; Gamstedt, K.; Berglund, L. State of Degradation in Archeological Oak from the 17th Century Vasa Ship: Substantial Strength Loss Correlates with Reduction in (Holo)Cellulose Molecular Weight. *Biomacromolecules* **2012**, *13*, 2521–2527. [CrossRef]
61. Li, R.; Guo, J.; Macchioni, N.; Pizzo, B.; Xi, G.; Tian, X.; Chen, J.; Sun, J.; Jiang, X.; Cao, J.; et al. Characterisation of waterlogged archaeological wood from Nanhai No. 1 shipwreck by multidisciplinary diagnostic methods. *J. Cult. Herit.* **2022**, *56*, 25–35. [CrossRef]
62. Fors, Y.; Sandström, M. Sulfur and iron in shipwrecks cause conservation concerns. *Chem. Soc. Rev.* **2006**, *35*, 399–415. [CrossRef] [PubMed]
63. Helms, A.C.; Martiny, A.; Hofman-Bang, J.; Ahring, B.; Kilstrup, M. Identification of bacterial cultures from archaeological wood using molecular biological techniques. *Int. Biodeterior. Biodegrad.* **2004**, *53*, 79–88. [CrossRef]
64. Almkvist, G.; Persson, I. Degradation of polyethylene glycol and hemicellulose in the Vasa. *Holzforschung* **2008**, *62*, 64–70. [CrossRef]
65. Almkvist, G.; Persson, I. Fenton-induced degradation of polyethylene glycol and oak holocellulose. A model experiment in comparison to changes observed in conserved waterlogged wood. *Holzforschung* **2008**, *62*, 704–708. [CrossRef]
66. Björdal, C.; Nilsson, T.; Daniel, G. Microbial decay of waterlogged archaeological wood found in Sweden Applicable to archaeology and conservation. *Int. Biodeterior. Biodegrad.* **1999**, *43*, 63–73. [CrossRef]
67. Brassel, J. Das färben von Arigal-C konservierten feuchthölzern. *Jahrb. Bernischen Hist. Mus. Bern* **1960**, *39*, 438–440.
68. Sawada, M. Some problems of setting of PEG 4000 impregnated in wood. In *Waterlogged Wood: Study and Conservation, Proceedings of the 2nd ICOM Waterlogged Wood Working Group Conference, Grenoble, France, 29–31 August 1984*; Centre dÉtude et de Traitement des Bois Gorgés d'Eau: Grenoble, France, 1985; pp. 117–124.
69. Wielicka, M. Prace e konserwacja drewna pochodzacego z wykopalisk w Bi-skupinie i Gdansku (Research for the protection of wood from the excavations in Biskupin and Gdansk). *Wiad. Archeol.* **1960**, *25*, 288–296.
70. Trockmorton, P. Oldest Known Shipwreck Yields Bronze Age Cargo. *Natl. Geogr.* **1962**, *121*, 671–696.
71. Grattan, D.W. A practical comparative study of several treatments for waterlogged wood. *Stud. Conserv.* **1982**, *27*, 124–136. [CrossRef]
72. Grattan, D.W.; McCawley, J.C.; Cook, C. The potential of the Canadian winter climate for the freeze-drying of degraded waterlogged wood: Part II. *Stud. Conserv.* **1982**, *25*, 118–136. [CrossRef]
73. Manders, M.R. *Guidelines for Protection of Submerged Wooden Cultural Heritage*; WreckProtect: Amersfoort, The Netherlands, 2011.
74. Gregory, D.; Jensen, P. The importance of analysing waterlogged wooden artefacts and environmental conditions when considering their in situ preservation. *J. Wetl. Archaeol.* **2006**, *6*, 65–81. [CrossRef]
75. Ford, B.; Hamilton, D.L.; Catsambis, A. (Eds.) *The Oxford Handbook of Maritime Archaeology*; Oxford University Press: Oxford, UK, 2013.
76. Gregory, D.; Manders, M. (Eds.) *Best Practices for Locating, Surveying, Assessing, Monitoring and Preserving Underwater Archaeological Sites, SASMAP Guideline Manual 2*; National Museum of Denmark: Copenhagen, Denmark, 2015.
77. De Reu, J.; De Smedt, P.; Herremans, D.; Van Meirvenne, M.; Laloo, P.; De Clercq, W. On Introducing an Image-based 3D Reconstruction Method in Archaeological Excavation Practice. *J. Archaeol. Sci.* **2014**, *41*, 251–262. [CrossRef]
78. Jaklič, A.; Erič, M.; Mihajlović, I.; Stopinšek, Ž.; Solina, F. Volumetric models from 3D point clouds: The case study of sarcophagi cargo from a 2nd/3rd century AD Roman shipwreck near Sutivan on island Brač, Croatia. *J. Archaeol. Sci.* **2015**, *62*, 143–152. [CrossRef]
79. Drap, P. Underwater Photogrammetry for Archaeology. In *Special Applications of Photogrammetry*; Da Silva, D.C., Ed.; IntechOpen: London, UK, 2012; pp. 111–136. [CrossRef]
80. Erič, M.; Berginc, G.; Kovačič, R.; Pugelj, M.; Solina, F. Successful use of temporary underwater 3D documenting methodology: Early Roman barge from Ljubljanica river, Slovenia. In Proceedings of the IKUWA V International Congress on Underwater Archaeology, Heritage for Humanity, Cartagena, Spain, 15–18 October 2014; Negueruela Martínez, I., Castillo Belinchón, R., Recio Sánchez, P., Eds.; Ministry of Education, Culture, and Sports: Madrid, Spain, 2016; pp. 259–274.
81. Mahiddine, A.; Seinturier, J.; Peloso, D.; Boulaassal, H.; Boï, J.-M.; Merad, D.; Drap, P. Validating Photogrammetric Orientation Steps by the Use of Relevant Theoretical Models. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXIV International CIPA Symposium, Strasbourg, France, 2–6 September 2013; Volume XL-5/W2, pp. 1–6. [CrossRef]
82. McCarthy, J. Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *J. Archaeol. Sci.* **2014**, *43*, 175–185. [CrossRef]

83. McCarthy, J.; Benjamin, J. Multi-image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach. *J. Marit. Archaeol.* **2014**, *9*, 95–114. [CrossRef]
84. Menna, F.; Agrafiotis, P.; Georgopoulos, A. State of the art and applications in archaeological underwater 3D recording and mapping. *J. Cult. Herit.* **2018**, *33*, 231–248. [CrossRef]
85. Širok, B.; Dular, M.; Petkovšek, M. *Postopek Čiščenja Odpadnih Voda s Hidrodinamsko Kavitacijo*; Fakulteta za Strojništvo, Univerza v Ljubljani, Laboratorij za Vodne in Turbinske Stroje: Ljubljana, Slovenia, 2013.
86. Bass, F.G. *Archaeology Under Water*; Praeger: New York, NY, USA, 1966.
87. Unger, A.; Unger, W. *Holzkonservierung. Schutz und Festigung von Kulturgut aus Holz*; VEB Fachbuchverlag: Leipzig, Germany, 1990.
88. Canciani, M.; Gambogi, P.; Romano, F.G.; Cannata, G.; Drap, P. Low cost digital photogrammetry for underwater archaeological site survey and artifact insertion. The case study of the Dolia wreck in Secche della Meloria—Livorno—Italia. In *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIV 5/W12*; ISPRS: Hannover, Germany, 2003; pp. 95–100.
89. Erič, M.; Berginc, G.; Kovačič, R.; Celec, K. A short review of the application of 3D documentation methods on selected UW heritage sites in Slovenia and the Adriatic: The need for changes in methodology. In Proceedings of the N.E.R.D. New European Researches and Discoveries in Underwaterarchaeology Conference, Kiel, Germany, 21–23 November 2014; Marijana, C., Enzmann, J., Jürgens, F., Steffensen, F., Ulrich, J., Wilkes, F., Eds.; UPA Series: Bonn, Germany, 2016; pp. 10–18.
90. Ricca, M.; Alexandrakis, G.; Bonazza, A.; Bruno, F.; Petriaggi, B.D.; Elkin, D.; Lagudi, A.; Nicolas, S.; Novák, M.; Papatheodorou, G.; et al. A Sustainable Approach for the Management and Valorization of Underwater Cultural Heritage: New Perspectives from the TECTONIC Project. *Sustainability* **2020**, *12*, 5000. [CrossRef]
91. Erič, M.; Guček Puhar, E.; Stopinšek, Ž.; Jaklič, A.; Solina, F. The significance of detailed analysis of 3D cloud points which include data that the human eye can overlook. the case of a flat-bottomed ship from the Ljubljanica river. *SKYLLIS Z. Marit. Limnische Archäologie Kult.gesch.* **2019**, *19*, 29–40.
92. Balletti, C.; Beltrame, C.; Costa, E.; Guerra, F.; Vernier, P. Underwater Photogrammetry and 3D Reconstruction of Marble Cargos Shipwreck. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL5-W5, Underwater 3D Recording and Modeling, Piano di Sorrento, Italy, 16–17 April 2015. [CrossRef]
93. Diamanti, E.; Georgopoulos, A.; Vlachaki, F. Geometric Documentation of Underwater Archaeological Sites. In Proceedings of the XXIII CIPA Symposium, Prague, Czech Republic, 12–16 September 2011; pp. 1–9.
94. Yamafune, K.; Torres, R.; Castro, F. Multi-Image Photogrammetry to Record and Reconstruct Underwater Shipwreck Sites. *J. Archaeol. Method Theory* **2017**, *24*, 703–725. [CrossRef]
95. Antlej, K.; Erič, M.; Šavnik, M.; Zupanek, B.; Slabe, J.; Battestin, B. Combining 3D technologies in the field of cultural heritage: Three case studies. In Proceedings of the VAST 2011—The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, Short and Project Paper Proceedings, Prato, Italy, 18–21 October 2011; Dellepiane, M., Niccolucci, F., Serna, S.P., Rushmeier, H., Van Gool, L., Eds.; The Eurographics Association: Goslar, Germany, 2011; pp. 1–4. [CrossRef]
96. Nogid, I.; Pozdnjak, A. *Natural Organic Dyes Used in Russia for Dyeing Fabrics*; Muhlethaler, B., Barkma, L., Noack, D., Eds.; Edition Eyrothes: Paris, France, 1973.
97. Molloy, B.; Milić, M. Wonderful Things? A Consideration of 3D Modelling of Objects in Material Culture Research. *Open Archeol.* **2018**, *4*, 97–113. [CrossRef]
98. Seborg, R.M.; Inverarity, R.B. Conservation of 200-year-old Water- logged Boats with Polyethylene Glycol. *Stud. Conserv.* **1962**, *7*, 111–120. [CrossRef]
99. Barreau, J.-B.; Jouneau, J.; Charlet, C.; Ferré, G.; Robert, J. Digitization, Virtual Reality and Robotic Sculpture for the Preservation and Enhancement of the Public Heritage of the Sculpted Rocks of Rothéneuf. *J. Comput. Cult. Herit.* **2023**, *15*, 70. [CrossRef]
100. Sandström, M.; Jalilehvand, F.; Persson, I.; Gelius, U.; Frank, P.; Hall-Roth, I. Deterioration of the seventeenth-century warship Vasa by internal formation of sulphuric acid. *Nature* **2002**, *415*, 893–897. [CrossRef]
101. Bekić, L. *Conservation of Underwater Archaeological Finds*; ICUA: Zadar, Croatia, 2014.
102. Bekić, L.; Igor, M. *Istraživanje Podvodne Kulturne Baštine u Hrvatskoj*; ICUA: Zadar, Croatia, 2009.
103. Erič, M.; Poglajen, S. Seriously endangered maritime underwater heritage in Slovenia: Management options. In Proceedings of the IKUWA IV International Conference of Underwater Archaeology, Managing the Underwater Cultural Heritage, Zadar, Croatia, 29 September–2 October 2011; Boerker, B., Ed.; DEGUWA: Bubenreuth, Germany, 2014; pp. 200–210.
104. Joy. Chongqing: The First Underwater Museum in China Has Been Built and Opened. 2009. Available online: https://www.watermuseums.net/network/chongqing-baiheliang-underwater-museum (accessed on 3 July 2025).
105. Donahue, M.Z. An Underwater Museum in Egypt Could Bring Thousands of Sunken Relics into View. Smithsonian Magazine. 2015. Available online: https://www.smithsonianmag.com/innovation/underwater-museum-egypt-could-bring-thousands-sunken-relics-into-view-180957645/ (accessed on 3 July 2025).
106. Jones, D.M. *Waterlogged Wood: Guidelines on the Recording, Sampling, Conservation and Curation of Waterlogged Wood*; English Heritage Guidelines; English Heritage: London, UK, 2010.

107. Crook, L. ZJA to Create Museum Around Underwater 18th-Century Shipwreck. 2020. Available online: https://www.archdaily.com/953211/zja-designs-underwater-museum-for-a-shipwreck-in-amsterdam (accessed on 3 July 2025).
108. Rosenqvist, A.M. The Stabilizing of Wood found in the Viking Ship of Oseberg—Part I. *Stud. Conserv.* **1959**, *4*, 13–22.
109. Christensen, M.; Kutzke, H.; Hansen, F. New materials used for the consolidation of archaeological wood–past attempts, present struggles, and future requirements. *J. Cult. Herit.* **2012**, *13* (Suppl. S3), S183–S190. [CrossRef]

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