REVIEW ARTICLE

UNMANNED MARINE SYSTEMS FOR MONITORING CHEMICAL WEAPONS SUNK IN THE BALTIC SEA – AN INNOVATIVE TOOL FOR PROTECTING HUMAN HEALTH AND THE ENVIRONMENT

Bezzałogowe systemy morskie w monitorowaniu broni chemicznej zatopionej na dnie Bałtyku – innowacyjne narzędzie dla ochrony zdrowia ludzi i środowiska

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Abstract

The Baltic Sea, one of the most congested seas in Europe, is particularly vulnerable to pollution due to its shallow depth and enclosed nature. After World War II, tons of German chemical weapons were dumped there on the orders of the Allied forces. It is estimated that around 40,000 tons of these weapons and munitions – including dangerous chemical agents such as sulfur mustard, tabun, and phosgene – now lie on the sea floor. These substances pose a serious threat to both marine life and human health, especially if leaks occur as a result of corrosion in the shells or containers in which the chemicals are stored. Regular monitoring of the condition of these containers is therefore essential. In this context, unmanned maritime systems – including underwater, surface, and aerial vehicles – play a crucial role in monitoring and neutralizing the threats posed by chemical weapons on the Baltic Sea floor. Working in collaboration, these systems can be used for detection, mapping, and environmental analysis to help minimize the risks associated with these substances.

Streszczenie

Morze Bałtyckie jest zbiornikiem wodnym szczególnie narażonym na zanieczyszczenia ze względu na swoją niewielką głębokość i zamknięty charakter. Po II wojnie światowej, w ramach operacji alianckich, została zatopiona w nim niemiecka broń chemiczna. Szacuje się, że na dnie znajduje się około 40 tysięcy ton chemikaliów, w tym niebezpieczne środki bojowe, jak iperyt siarkowy, tabun czy fosgen. Zatopione substancje stanowią poważne zagrożenie dla środowiska morskiego i zdrowia ludzi, zwłaszcza w przypadku uwolnienia ich np. na skutek korozji korpusów amunicji czy pojemników, których stan powinien podlegać stałej kontroli. W tym kontekście rosnące zainteresowanie bezzałogowymi systemami morskimi, w szczególności pojazdami podwodnymi, powierzchniowymi oraz powietrznymi, staje się kluczowy w monitorowaniu i neutralizacji zagrożeń związanych z zatopioną bronią chemiczną. Współdziałanie tych systemów może być wykorzystywane do wykrywania, mapowania oraz analizy środowiskowej w celu zminimalizowania ryzyka związanego z tymi substancjami.

Keywords: Baltic Sea; ecological safety; civil protection; chemical weapons; unmanned maritime systems

Słowa kluczowe: Morze Bałtyckie; bezpieczeństwo ekologiczne; ochrona ludności cywilnej; broń chemiczna; bezzałogowe systemy morskie

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Introduction

The history of chemical weapons sunk in the Baltic Sea is closely linked to the military operations of World War I and World War II. During that time, vast quantities of toxic agents were produced for filling aerial bombs, artillery shells, grenades, mines, and metal containers. It is estimated that between 1914 and 1918, around 180,000 tons of chemical warfare agents (CWAs) were produced [1]. The widespread deployment of chemical weapons during this period resulted in the poisoning of approximately 1.2 million people, with about 100,000 fatalities [2]. In the interwar period and during World War II, the production and development of chemical weapons continued. Previously used agents, such as sulfur mustard (yperite), lewisite, and adamsite, remained in military use, while new, more toxic organophosphorus compounds – including tabun and sarin – were developed. During the military operations in Europe, not all of the stockpiled weapons were used, which, after the war, created the problem of disposing of both chemical munitions and the CWAs themselves [1]. Various methods were employed to eliminate them: some were buried, others incinerated or neutralized, while vast quantities were dumped into seas and oceans. It was a widely accepted practice from the early 20th century until the 1970s, considered at the time to be the safest and cheapest way to dispose of chemical weapons. A key turning point in this matter was the Potsdam Conference in 1945, where the disposal of chemical weapons in the Baltic Sea was officially approved as part of Germany's demilitarization process [1, 3]. Today, it is estimated that within Poland's exclusive economic zone (EEZ), the risk of human exposure or contamination of ships by submerged chemical weapons exists across an area of approximately 340 km² (Fig. 1). The EEZ is an area of maritime waters under Poland's jurisdiction, granting it broad sovereign rights over resources and economic activities within 200 nautical miles from the

Figure 1. Official and unofficial chemical weapons transport routes and dumping sites within the Polish exclusive economic zone [1]

coastline. Within the Polish EEZ, Polish maritime authorities have designated six hazardous zones, which include: the area near Bornholm – at the border with the Danish EEZ, covering approximately 220 km² – as well as regions close to Dziwnów (88 km²), Kołobrzeg (8 km²), Darłowo (8 km²), Hel (8 km²), and the Gdańsk Deep (approximately 8 km²) [4, 5]. The estimated quantity of chemical munitions in these areas ranges between 10,000 and 12,000 units [4, 6].

In Polish maritime areas, the largest quantities of chemical weapons were dumped in the Gdańsk Deep. They were deposited there as a result of actions by Weimar Germany, Nazi Germany, Soviet forces, the GDR, and the USSR. It is estimated that around 60 tons of chemical munitions, mainly containing sulfur mustard (mustard gas), were dumped in these areas. An additional hazard comes from conventional munitions that were disposed of alongside chemical weapons [4]. Table 1 presents the characteristics of the areas within Polish maritime waters where there is a risk of contact with CWA, as well as the types of chemical weapons recovered from these areas.

Chemical munitions lying on the Baltic Sea floor become particularly hazardous if toxic substances are released into the water. This can occur due to the corrosion of metal containers or as a result of explosions during research, recovery, or operational activities. Such events can cause the rapid dispersal of CWAs in the form of an aerosol, suspension, or colloid, leading to environmental contamination [2]. Health risks to humans include direct exposure of fishermen to chemical munitions, consumption of contaminated fish, and beach pollution from containers washed ashore [7, 8].

In the first half of the 1950s, reports began to emerge of containers with sulfur mustard being washed ashore along the Polish coast, southwest of Bornholm, and along shipping routes leading to dumping sites in the Gotland Deep and Bornholm Deep [4]. Until 2012, incidents involving chemical weapons in the Baltic Sea were recorded by the Danish Navy on behalf of the Helsinki Commission (HELCOM). However, since 2013, Denmark has discontinued this practice, resulting in a lack of official data on such incidents after that date. Nevertheless, several incidents are still reported each year. Analysis of recorded events shows a decline in their number since 2000 (with the exception of 2003). Experts suggest this trend may be attributed to shifts in local fish stocks, reduced fishing activity in high-risk zones, and the use of modern fishing gear. Additionally, underreporting remains an issue – fishermen often fail to report retrieved hazardous objects if no one was harmed, which may skew the statistics downward [4].

It can be concluded that chemical weapons are dispersed over a much wider area than indicated in the reports prepared by the HELCOM CHEMU Working Group based on available archival documentation. Numerous cases of encounters with chemical weapons and leaked chemical warfare agents outside designated disposal zones suggest that weapons were frequently dumped *en route* to their intended sites, and that unauthorized disposal occurred in undesignated areas, many of which remain largely unmapped to this day. In light of the intensive exploitation of the Baltic Sea, which plays a key role in the European economy, there is a growing need to implement modern technologies, including unmanned marine systems, for monitoring and neutralizing contamination. Therefore, effective management of this issue requires not only a thorough analysis of existing threats, but also the implementation of innovative technological solutions that can safeguard this precious ecosystem from the consequences of past chemical weapons disposal activities.

Unmanned maritime systems

Unmanned vehicles, including aerial and maritime systems, are seeing increasingly widespread applications [9, 10]. Their potential is particularly evident in marine research and monitoring, where these advanced technologies offer new possibilities for both exploring and protecting the marine environment [11]. Unmanned maritime sys-

Table 1. Risk zones for chemical warfare agent exposure in Polish marine waters. Source: Fabisiak [4]

Region	Hydrogeological characteristics	Type of ammunition
Bornholm	• depth: 70–105 m • salinity: 7–16 PSU • temperature at the seabed: 5–6°C	bombs, artillery ammunition, mines, containers, and canisters with mustard gas and arsenic compounds
Dziwnów	• depth: 10–16 m • salinity: 7.5 PSU • temperature at the seabed: 5–6°C	artillery shells containing mustard gas and arsenic compounds
Kołobrzeg	• depth: 65 m • salinity: 7–16 PSU • temperature at the seabed: 5–6°C	bombs, artillery ammunition, mines, containers, and canisters with mustard gas and arsenic compounds
Darłowo	• depth: 90 m • salinity: 7–16 PSU • temperature at the seabed: 5–6°C	mustard gas bombs
Hel	• depth: to 117 m • salinity: low • temperature at the seabed: 5–6°C	bombs, artillery ammunition, mines, containers, and canisters with mustard gas and arsenic compounds
Gdańsk Deep	• depth: 80–110 m • salinity: 7–16 PSU • temperature at the seabed: 5–6°C	mustard gas bombs; conventional munitions were also dumped in the area.
PSU – practical salinity unit		

tems encompass a broad range of technologies. Based on their operational characteristics, they can be classified into three main categories: unmanned underwater vehicles (UUVs) [12], unmanned surface vehicles (USVs) [13], and unmanned aerial vehicles (UAVs) [14] used for maritime operations. Each of these systems offers distinct advantages and limitations, while their integrated operation can ensure optimal mission effectiveness.

Unmanned underwater vehicles are capable of operating in challenging deep-sea conditions where manned vessels cannot function, enabling the monitoring and exploration of otherwise inaccessible locations. Additionally, their long endurance allows them to carry out missions lasting many hours, or even days, without the need to return to the surface [12]. Equipped with advanced sensors and imaging systems, UUVs provide high-precision seabed mapping data, facilitating the identification of shipwrecks [15] and hazardous objects like chemical weapons [16]. On the other hand, their limitations arise from the challenges of underwater communication, which necessitate autonomous operation. This can lead to delays in responding to dynamic or rapidly changing situations. In addition, depth and variable conditions may limit the effectiveness of sensors, adversely affecting the quality of the collected data [12].

In contrast, unmanned surface vehicles maintain continuous contact with the base, allowing real-time data exchange and swift responses to changing conditions [17]. They also serve as support platforms for other unmanned systems, such as underwater vehicles and aerial systems, providing power and communication points. Their lower operating cost, compared to manned units, makes them more cost-efficient [10, 12, 14, 15]. However, USVs are vulnerable to changing weather conditions, which may impede their operation, and they offer limited mobility compared to aerial systems – a significant drawback when operating over large water areas [13, 17].

Unmanned aerial vehicles, on the other hand, are distinguished by their speed and agility, enabling them to rapidly cover long distances [10, 14]. This makes them particularly well-suited for immediate reconnaissance, large-scale monitoring, and rapid response to emerging threats. Equipped with advanced cameras and sensors, they provide real-time imagery and data to support decision-making processes in maritime operations. Additionally, their operational flexibility enables rapid deployment and retrieval of units as needed. However, limited flight time due to battery capacity necessitates frequent recharging or swaps, and their effectiveness can be significantly reduced by harsh weather conditions such as strong winds and rain, posing a major challenge during prolonged open-sea missions.

Each of the aforementioned unmanned systems has distinct strengths and limitations, but their combined deployment creates an optimal support framework. UUVs provide valuable deep-sea data, USVs serve as communication hubs and surface support platforms, while UAVs deliver real-time aerial surveillance.

Unmanned surface vehicles conduct detailed surface water monitoring and perform measurements in coastal zones. Aerial platforms provide extensive airborne surveillance coverage, enabling wide-area monitoring and identification of potential hazard zones. Meanwhile, diving drones conduct deep-water investigations, collecting direct seabed data and profiling threat-source environments. Data collected by these three types of platforms is transmitted in real time to a central analytical system. Leveraging advanced computing technologies such as artificial intelligence algorithms and 3D spatial modelling, the system performs multi-layered data analysis. Based on the obtained results, operational decisions are made in accordance with previously developed safety protocols. Thanks to this integrated architecture, the system enables precise mapping of sunken chemical weapons, assessment of potential threats, and rapid implementation of protective measures, minimizing the risk to the environment and humans (Fig. 2).

When integrated, these three categories of unmanned maritime systems complement one another, forming a comprehensive solution capable of addressing even the most demanding operational challenges.

Applications of unmanned maritime systems

The use of unmanned systems for monitoring and neutralizing chemical weapons sunk in the Baltic Sea includes:

- **Detection and mapping.** Unmanned underwater vehicles are equipped with advanced sensors, such as sonars, magnetometers, and imaging systems, which enable precise seabed mapping and identification of objects that may pose a potential threat.
- **Monitoring and environmental analysis.** Unmanned underwater and surface vehicles can be deployed to collect water and seabed sediment samples for chemical analysis and contamination assessment. Regular measurements allow for continuous monitoring of potential leaks and their impact on the ecosystem. Currently, due to technological limitations, direct on-site sample analysis is not feasible. Consequently, collected sediments, water, or fragments of objects must be transported to specialized laboratories for examination However, research is underway to develop sensors capable of performing direct analysis in the surveyed area. One promising innovation is a neutron analyzer, which would enable on-site identification of hazardous substances.
- **Threat neutralization.** Unmanned systems can also take part in threat neutralization operations, for example by precisely placing explosive charges for the controlled destruction of corroded chemical weapon containers.

Challenges related to the use of unmanned vehicles for monitoring the Baltic Sea floor

The advancement of unmanned maritime systems undoubtedly offers significant benefits, particularly in mitigating or eliminating hazards posed by dangerous submerged objects – such as chemical weapons – in seas and oceans. However, these systems also present certain limitations that should guide future technological developments. A primary concern is the safety of unmanned vehicle operations. Operations in chemical weapon dumping zones – characterized by highly dynamic conditions – are

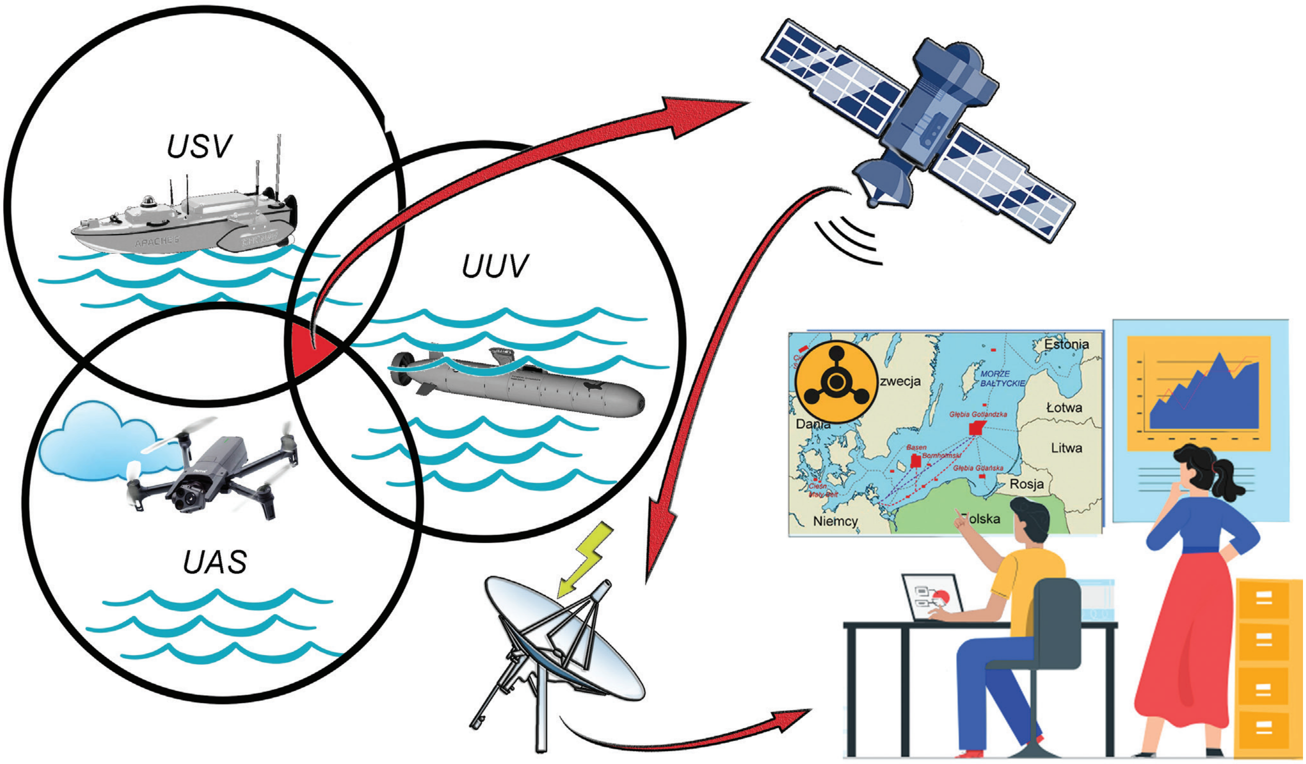

Figure 2. Integrated support system using unmanned platforms for monitoring chemical weapons hazards on the Baltic seafloor. USV – unmanned surface vehicles; UUV – unmanned underwater vehicles; UAS – unmanned aircraft system

extremely hazardous, require rapid response capabilities, and carry a high risk of serious accidents if mistakes occur [18]. Moreover, operations in the Baltic Sea often require cooperation between multiple countries, which can be complicated due to differences in legal regulations, operational procedures, and levels of technological advancement [19]. To minimize risks associated with such operations, several preventive measures should be considered. First and foremost, before commencing operations, a detailed risk analysis should be conducted to identify potential hazards and develop contingency plans. Drone operators should undergo regular training, including crisis simulations, to prepare for various scenarios. It is also essential to ensure that personnel operating unmanned maritime vehicles are well-trained in data analysis and in carrying out activities without endangering or obstructing traffic in the Baltic Sea. This type of training should cover topics related to hazard identification, procedures for handling emergency situations, operation of specialized equipment, evacuation protocols, as well as principles for minimizing the impact of operations on the marine environment and navigational safety. Therefore, it is essential to develop and implement strict safety procedures for working with unmanned maritime systems, particularly in areas classified as hazardous.

Another challenge lies in the technological limitations associated with operating equipment in the difficult conditions of the Baltic Sea, such as high pressure, low temperature, limited visibility, and the presence of other vessels [20–22]. For this reason, it is essential to develop an information system that integrates and supports the operation of various types of unmanned vehicles – including underwater, surface, and aerial systems. The development of such systems should deliver comprehensive and complementary data, enabling precise detection and mapping, as well as facilitating environmental analyses related to chemical weapons and toxic agents located on the Baltic Sea floor.

Another factor that should not be overlooked is the high cost of purchasing, maintaining, and operating advanced unmanned systems, which can be a barrier to their widespread adoption. The Baltic Sea is an international body of water, which is why the development of a monitoring program and the sharing of its costs should be a shared responsibility among all Baltic states. It is necessary to agree on a joint financing strategy for unmanned maritime systems to monitor threats related to submerged chemical weapons.

The role of Polish science and numerous academic centers in Poland, which monitor and study the ecological safety of the Baltic seabed, is also very important. Adequate funding for Polish science is essential, as it can drive significant progress in developing information systems that enhance the ergonomics, performance, and energy efficiency of unmanned vehicles. Equally important is the involvement of biologists analyzing ecological changes caused by chemical weapons submerged on the Baltic seabed [23, 24].

Conclusions

Unmanned maritime systems hold significant potential for enhancing the mapping, monitoring, and neutralization of hazards related to chemical weapons in the Baltic Sea. The development of advanced technologies can significantly improve ecological and health safety in this region. Further efforts are needed to integrate individual unmanned systems and improve cooperation between them. This requires investment in technology development and the creation of comprehensive strategies and procedures to enable effective and safe management of the threat elimination process.

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