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Underwater Rescue Management in Flooded Areas Using Wireless Sensor Networks: An Overview

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Review Paper

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Abstract:

Floods are among the most destructive natural disasters, causing extensive loss of life, property damage, and displacement of populations. Traditional search and rescue (SAR) operations in flood-affected areas face significant challenges due to adverse conditions such as deep waters, fast-moving currents, low visibility, and lack of communication infrastructure. To address these challenges, this paper explores the potential of Wireless Sensor Networks (WSNs) in enhancing underwater rescue management in flooded environments. WSNs, consisting of distributed sensor nodes that collect and transmit real-time environmental data, offer unique advantages for monitoring and coordinating rescue efforts in disaster-stricken areas. By deploying various sensors such as acoustic, pressure, temperature, and motion detectors, WSNs can provide continuous situational awareness, track victims, assess flood dynamics, and support real-time decision-making. However, the deployment of WSNs in underwater rescue operations is not without challenges, including communication limitations, sensor node durability, and energy constraints. This paper discusses these challenges and highlights technological innovations that can improve the reliability and effectiveness of WSNs, such as hybrid communication systems, energy harvesting, and autonomous underwater vehicles (AUVs). Ultimately, the integration of WSNs into flood rescue operations has the potential to significantly improve response times, enhance rescue efficiency, and reduce the risks to human rescuers, offering a promising approach for disaster management in flooded regions.

Keywords: Flood Rescue, Wireless Sensor Networks (WSNs), Underwater Rescue, Search and Rescue (SAR), Disaster Management, Acoustic Sensors, Autonomous Underwater Vehicles (AUVs)

1. Introduction

Floods are among the most frequent and catastrophic natural disasters globally, capable of causing widespread destruction in a matter of hours or days [1]. The impacts of flooding are multifaceted, leading to not only significant loss of life but also severe economic, social, and environmental consequences. Floods often displace thousands of people, submerge homes and critical infrastructure, and disrupt essential services such as healthcare, education, and transportation. In the most severe cases, floods can result in the collapse of bridges, roads, dams, and buildings, further complicating rescue and recovery efforts [2]. The aftermath of a flood often leaves affected areas isolated, with limited access to emergency services or external support.

In such catastrophic events, the need for rapid and efficient search and rescue (SAR) operations becomes paramount [3]. Time is of the essence when lives are at risk, and the window of opportunity for successful rescues can be narrow. The challenges faced by rescue teams are compounded by the very nature of flood-affected environments. These include deep and fast-moving waters, submerged debris, and often unpredictable currents [4]. The visibility in these environments is typically poor, making it difficult for rescuers to locate survivors or navigate safely [5]. Traditional SAR methods that rely on human rescuers, helicopters, boats, and divers, while effective in certain situations, are often hindered by these adverse conditions, slowing down response times and reducing the overall effectiveness of the mission [6].

In recent years, advancements in technology have provided new avenues for improving SAR operations. One of the most promising innovations in this space is the use of WSNs. WSNs consist of spatially distributed sensor nodes that collect data from their environment and communicate wirelessly with each other or to a central command center. These networks have been successfully deployed in a wide range of applications, including environmental monitoring, disaster management, and industrial monitoring, among others [7]. What makes WSNs particularly well-suited for flood rescue operations is their ability to function in challenging environments, providing continuous monitoring and data collection in real-time. WSNs offer a variety of benefits in the context of flood rescue operations. They provide a means to monitor a flood-affected area in a way that is not possible with traditional methods. WSNs can be used to track water levels, monitor water quality, detect underwater currents, and even detect the presence of survivors or rescuers [8]. Equipped with a range of sensors, such as temperature, pressure, motion, and acoustic sensors, these networks can capture critical data about the underwater environment. This data can then be transmitted wirelessly to a central command center, where it can be analyzed and used to make informed decisions in real-time, thus enhancing the speed and accuracy of rescue operations.

For example, during a flood, WSNs could help locate survivors by detecting acoustic signals from distress calls or monitoring motion in the water to identify areas where individuals may be trapped. Additionally, these networks can provide detailed information about the flood's behaviour, such as the rise and fall of water levels, current velocities, and the potential for further flooding, which would allow rescue teams to adapt and respond more effectively. Moreover, WSNs enable remote monitoring of underwater environments, which can reduce the need for human rescuers to enter dangerous or submerged areas [9]. This reduces the risk to human lives and makes it possible to gather valuable information without endangering rescue personnel [10].

The integration of WSNs into underwater rescue management is a relatively novel approach and promises to revolutionize the way disaster response is handled. However, despite their potential, several challenges remain in deploying WSNs effectively in flooded areas. These challenges include issues related to the communication infrastructure in underwater environments, the energy limitations of sensor nodes, and the difficulty of maintaining network stability in a dynamic and often harsh physical environment [11]. For instance, acoustic waves, which are commonly used for communication between nodes in underwater WSNs, face significant limitations in terms of range, bandwidth, and susceptibility to interference from water noise or other sources. Additionally, sensor nodes need to be robust enough to withstand the harsh conditions of a flooded area, including high pressure, corrosion, and the risk of physical damage from debris [12].

Despite these challenges, ongoing advancements in sensor technologies, energy-efficient systems, and communication protocols continue to make WSNs more viable for underwater rescue operations. Researchers are developing new approaches to address the limitations of underwater communication, such as hybrid communication systems that combine acoustic and optical methods, and energy harvesting techniques that can prolong the life of sensor nodes. In addition, the use of autonomous vehicles (e.g., drones or autonomous underwater vehicles - AUVs) equipped with WSNs is becoming an increasingly popular solution for deploying and maintaining sensor networks in flood-affected areas. These vehicles can autonomously navigate through hazardous environments and deploy sensors at strategic locations to monitor key data points.

This paper aims to explore the role of WSNs in enhancing underwater rescue management during floods. It will examine the potential applications of WSNs in flood rescue, discuss the challenges that must be addressed for their effective implementation, and highlight the technological innovations that can overcome these challenges. Through a comprehensive analysis, this paper seeks to demonstrate how WSNs can provide critical support in improving the speed, safety, and effectiveness of flood rescue operations, ultimately contributing to saving lives and mitigating the impact of flooding on communities around the world.

2. Background and Motivation

Flooded areas present one of the most challenging environments for search and rescue (SAR) operations. These areas are typically characterized by unpredictable and dynamic water conditions, which include varying depths, fast-moving currents, fluctuating water levels, poor visibility, and the presence of debris such as fallen trees, buildings, and other obstructions. Such conditions make it extremely difficult for human rescuers to navigate and perform their tasks effectively [13]. In addition to these environmental challenges, flood-prone regions often lack adequate infrastructure, such as roads, power supplies, and communication networks, further complicating rescue efforts. In many cases, traditional SAR teams rely on boats, helicopters, or divers, all of which can be hindered by the murky waters, hazardous debris, and unpredictable behaviour of the floodwaters [14].

Given the high risks to human life in flood zones, there is a clear need for innovative technologies that can support and augment SAR operations. Traditional methods, while valuable, are often limited in their effectiveness under such harsh conditions. As such, there is a growing interest in utilizing WSNs to assist in rescue operations in these environments.

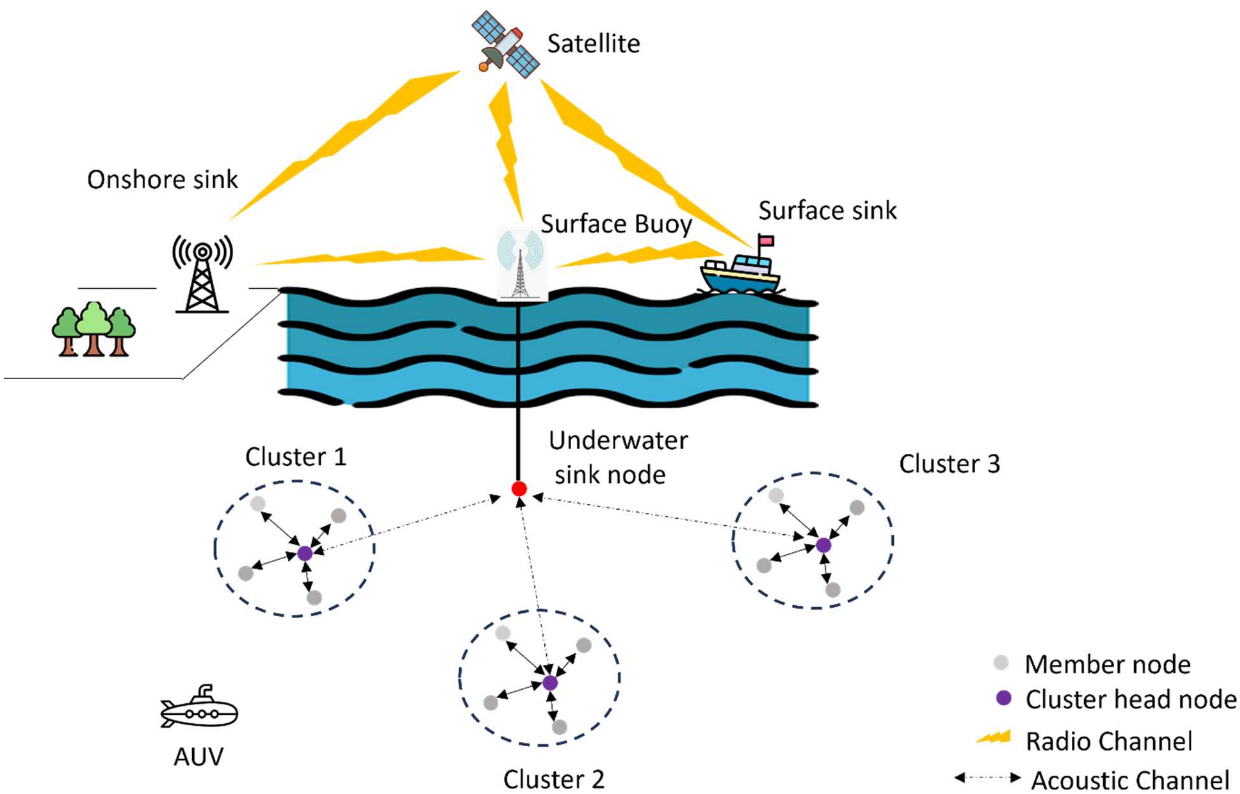

Figure 1: Schematic of underwater WSN system

WSNs consist of networks of distributed sensor nodes, each equipped with various sensing devices such as temperature, pressure, depth, acoustic, and motion sensors. These sensor nodes can be deployed in the flood-affected areas to gather data about the environment and communicate wirelessly with a central processing unit or command center [15]. The key advantage of WSNs is their ability to provide real-time environmental monitoring and data collection, even in challenging conditions where human intervention might be too risky or impractical.

The motivation behind deploying WSNs in underwater rescue operations is multifaceted. By providing continuous monitoring, these networks can help assess water conditions, track the movement of victims, and identify potential hazards that rescuers might face. This capability can significantly enhance decision-making and operational efficiency during SAR missions.

3. Advantages of Using WSNs in Underwater Rescue Operations

3.1 Real-time Monitoring:

WSNs enable the continuous tracking of environmental conditions such as water levels, temperature variations, and flow rates. This data can help identify changes in conditions that might pose risks to rescuers or victims [16]. For instance, sudden increases in water flow or a rise in water levels can trigger early warnings, enabling rescue teams to adjust their strategies or evacuate certain areas. Continuous monitoring can also help track the progress of the floodwaters, providing valuable information for long-term recovery efforts.

3.2 Autonomous Deployment:

One of the primary challenges of rescue operations in flooded environments is the difficulty and danger of deploying personnel into such areas. WSNs can be deployed autonomously via robotic vehicles or drones, including Autonomous Underwater Vehicles (AUVs) [17]. These vehicles can navigate through the floodwaters, placing sensor nodes in key locations without putting human lives at risk. Autonomous deployment also reduces the time and effort required for initial setup, allowing the rescue operation to begin much faster.

3.3 Data Fusion and Communication:

WSNs integrate data from a variety of sensors, creating a comprehensive understanding of the underwater environment [18]. For example, combining depth sensor data with acoustic sensor data can provide more accurate localization of survivors or submerged objects. This fused data can be transmitted wirelessly to command centers or rescue teams, ensuring that all involved parties have access to up-to-date, accurate information. The ability to transmit data in real-time via wireless communication reduces the dependency on traditional communication infrastructure, which may be damaged or absent in flood-affected areas.

3.4 Improved Decision-Making and Resource Allocation:

By providing accurate and real-time data, WSNs enable better situational awareness, allowing SAR teams to make informed decisions quickly [19]. This data can assist in prioritizing areas for rescue operations, directing teams to the most critical locations based on water conditions, potential victim locations, and hazards. The real-time feedback allows for more agile decision-making, ensuring that resources are allocated effectively and efficiently. This rapid decision-making can be the difference between life and death during a flood disaster.

3.5 Reducing Human Risk:

Perhaps one of the most important advantages of integrating WSNs into rescue operations is the reduction in risk to human rescuers. Deploying sensor networks, drones, and AUVs into flooded areas reduces the need for human personnel to enter hazardous conditions [20]. For example, sensors placed in strategic locations can monitor areas that are too dangerous for human intervention, such as rapidly moving waters or submerged structures, thereby minimizing the exposure of rescuers to extreme risks.

3.6 Long-term Monitoring for Recovery:

Beyond the immediate rescue phase, WSNs can continue to play an essential role during the recovery and rehabilitation phases [21]. Continuous monitoring can assess the impact of the flood on local infrastructure, track water quality, and help identify areas still at risk of further flooding or landslides. This data is invaluable for long-term recovery planning and ensures that the area is fully assessed before rebuilding efforts are launched.

4. Key Components of WSNs for Underwater Rescue

WSNs have become an invaluable tool for enhancing underwater rescue operations in flood-affected areas. These networks comprise several critical components that work synergistically to gather, process, and communicate real-time data from dynamic and often hazardous environments [22]. The following sections describe the key components of WSNs that make them effective for underwater rescue operations:

4.1 Sensor Nodes

Sensor nodes are the foundational elements of any WSN. They are responsible for capturing data about the underwater environment, processing it locally, and transmitting relevant information to the network for further analysis [23]. In an underwater rescue scenario, these sensor nodes need to be specifically designed to endure the extreme conditions present in flooded areas, including high-pressure environments, temperature fluctuations, and high humidity. They are typically equipped with various types of sensors tailored to monitor environmental parameters critical for rescue missions. Some common sensors include:

- **Acoustic Sensors**: Acoustic sensors detect underwater sounds, which can include human distress signals, the noise produced by moving objects, or the vocalizations of survivors [24]. These sensors can help identify the presence of trapped victims or distinguish between different sources of sound, providing valuable insight into the state of the rescue operation. Since sound travels well in water, acoustic sensors are commonly used for communication and detection in underwater environments.

- **Pressure and Depth Sensors**: These sensors monitor the depth of the water and the surrounding pressure conditions. Rapid changes in water depth could indicate potential hazards such as a sudden surge in water level or the collapse of structures [25]. Monitoring pressure also helps to understand the structural integrity of submerged areas, alerting rescuers to areas where there may be a risk of collapse or flooding.

- **Temperature and Humidity Sensors**: These sensors monitor changes in water temperature and humidity levels [26]. Temperature fluctuations can influence the behavior of floodwaters, while changes in humidity levels may be indicative of environmental instability or contamination. In rescue operations, such data is important for assessing the safety of divers, the condition of survivors, and planning appropriate rescue strategies.

- **Motion Sensors**: Motion detection is crucial for tracking both rescuers and victims [27]. These sensors can detect movement within a given range, helping to pinpoint the location of individuals in need of assistance or to monitor the movement of rescuers in dangerous zones. They can also detect the presence of underwater debris, which could pose a danger to both rescuers and victims.

4.2 Data Processing Unit (DPU)

The Data Processing Unit (DPU) is a central component that aggregates and processes data collected from the various sensor nodes. In an underwater environment, where communication with surface units can be challenging due to signal attenuation, the DPU helps filter and process the raw data in real time [28]. By performing initial data analysis locally on the sensor nodes or at the DPU, unnecessary data can be discarded, and only the most relevant information is transmitted to the command center.
The DPU is responsible for:

- Filtering noise from the data.
- Aggregating data from multiple sensor nodes.
- Performing basic analysis to detect anomalies (e.g., rapid changes in water depth, sudden temperature shifts, or distress signals).
- Sending relevant processed data to the command center for further decision-making.

By reducing the amount of data transmitted and focusing on actionable insights, the DPU enhances the efficiency of the network and ensures faster, more accurate decision-making.

4.3 Wireless Communication Network

In flooded areas, traditional communication infrastructure is often disrupted or non-functional due to water damage or the absence of reliable connectivity. This is where the wireless communication network within a WSN becomes critical. WSNs primarily rely on two types of communication methods in underwater environments: acoustic communication and radio frequency (RF) communication [29]. These methods are tailored to the specific constraints of underwater environments, where sound and electromagnetic waves behave differently than in air.

- **Acoustic Communication**: Acoustic signals are the most commonly used method for wireless communication in underwater networks. They can transmit data over relatively long distances, especially in shallow or moderately deep waters. Acoustic communication is highly effective for real-time data transfer between sensor nodes and the central system [30]. However, it has limitations such as low bandwidth, high signal attenuation with increasing depth, and interference from environmental noise. Despite these drawbacks, acoustic waves remain the most reliable option for underwater communication.
- **Radio Frequency (RF) Communication**: RF communication is typically used for shorter distances, such as within nodes closer to the water surface or in shallow areas [31]. RF waves can suffer from significant attenuation in water, limiting their usefulness in deeper or murkier waters. However, they are useful in applications where the sensor nodes are closer to the surface or where hybrid communication systems (using both RF and acoustic methods) are employed.

A robust communication network ensures the continuous flow of real-time data between sensors, rescue robots, and the command center, despite the challenges of underwater signal transmission.

5. Rescue Robots/Autonomous Underwater Vehicles (AUVs)

Rescue robots and Autonomous Underwater Vehicles (AUVs) are critical technological tools that play an essential role in improving the efficiency and safety of underwater rescue operations in flood-affected areas [32]. These vehicles are designed to operate autonomously or be remotely controlled, providing a means to conduct complex tasks in hazardous and submerged environments where human intervention is either too dangerous or impractical [33]. AUVs are increasingly deployed in flood scenarios due to their ability to perform tasks with precision, flexibility, and speed, all while minimizing the risks to human rescuers [34].
Here are several key roles that AUVs play in underwater rescue operations:

5.1 Deploying Sensor Nodes

One of the primary functions of AUVs in rescue missions is the autonomous deployment of sensor nodes in strategically important areas. The ability to autonomously place sensors in flood-affected zones, including deep or fast-moving waters, provides several advantages:

- **Reduced Risk to Human Rescuers:** Traditional methods of sensor deployment often require human divers or operators to venture into hazardous floodwaters, which exposes them to significant risks, including strong currents, submerged debris, and poor visibility. AUVs eliminate the need for direct human involvement in such environments, thereby enhancing safety.

- **Accelerated Setup Process:** In many rescue operations, time is of the essence. AUVs can swiftly navigate floodwaters and deploy sensors in pre-determined or dynamically chosen locations. This reduces the setup time for the sensor network, allowing for quicker initiation of monitoring and real-time data collection.

- **Strategic Placement:** AUVs can be equipped with advanced navigation systems and algorithms that allow them to identify optimal locations for sensor deployment. For example, they may choose areas with high survivor likelihood, such as pockets of calm water or near buildings or infrastructure that are submerged but still intact.

5.2 Surveying the Environment

AUVs are also crucial for surveying the environment in flooded areas, particularly when human access to certain locations is impossible or too risky [35]. These vehicles are often equipped with an array of sensors that allow them to gather detailed data about the state of the floodwaters and submerged structures.

- **Real-Time Imaging:** AUVs can be outfitted with cameras, sonar systems, or LiDAR sensors to provide real-time imaging of submerged areas. This gives rescue teams a visual representation of the flood's impact, such as detecting the locations of survivors, identifying submerged debris, and assessing the integrity of underwater structures.
- **Detailed Mapping:** In addition to visual imaging, AUVs can produce detailed maps of the flooded areas, capturing data such as the topography of the underwater landscape, water depth, and flow patterns. This data is invaluable for understanding the flood dynamics, planning effective rescue strategies, and identifying safe routes for human rescuers to follow.
- **Hard-to-Reach Areas:** AUVs are especially valuable in hard-to-reach or dangerous zones. For example, they can access deep or narrow crevices where human divers might struggle or where physical obstacles prevent access. These vehicles can provide a thorough survey of areas that would otherwise remain unexplored, thereby improving the overall situational awareness of the command center.

5.3 Supporting Data Collection

Beyond deploying sensors, AUVs are essential for ongoing data collection during rescue operations. They are capable of retrieving data from submerged or remote sensors, ensuring that the network remains operational and up-to-date throughout the mission [36].

- **Data Retrieval:** In flood situations, sensors may become displaced, malfunction, or lose power over time. AUVs can be dispatched to retrieve data from these sensors, relocate them, or replace them with new ones if necessary. This ensures that the sensor network remains effective and that rescue teams continue to receive accurate, real-time information.
- **Data Integration:** AUVs can also assist in integrating the data gathered from various sensors across the flood-affected area. This data can include information from temperature sensors, motion detectors, pressure sensors, and acoustic devices. AUVs can help compile and transmit this data back to the command center, where it can be analyzed and used for decision-making.
- **Remote Locations**: Certain areas may be too dangerous for humans to reach, such as locations where the water is contaminated or the risk of structural collapse is high. AUVs can navigate these hazardous zones, ensuring that vital data from these hard-to-reach locations is still collected and communicated back to the rescue teams.

5.4 Enhancing Safety and Speed of Rescue Operations

The primary advantage of integrating AUVs into underwater rescue missions is their ability to reduce the need for human intervention in dangerous environments, thus significantly improving the safety of rescue operations [37].

- **Minimized Human Exposure to Danger:** By utilizing AUVs to perform tasks like sensor deployment, environmental surveying, and data collection, human rescuers are kept out of harm's way. In the event of a submerged or unstable building, for example, AUVs can inspect the structure before humans enter, alerting teams to potential risks such as collapse, submerged electrical hazards, or hazardous materials.

- **Faster Data Collection and Analysis:** AUVs can operate around the clock, providing continuous data collection without the need for rest or recovery. This constant flow of real-time information allows for faster analysis by the command center, which can then deploy rescue teams more effectively based on the most current information.
- **Increased Operational Efficiency:** The autonomous nature of AUVs allows them to work efficiently in hazardous areas that would be difficult or dangerous for humans to access. As a result, they can cover a larger area in a shorter amount of time, thereby improving the overall efficiency of the rescue mission.

5.5 Command Center

The Command Center serves as the central hub in any underwater rescue operation, especially in flood-affected areas [38]. It is where data from various sources such as sensor networks, Autonomous Underwater Vehicles (AUVs), and rescue robots is aggregated, analyzed, and utilized to coordinate all rescue efforts. Equipped with advanced data analysis, visualization tools, and real-time communication systems, the command center plays a crucial role in ensuring that rescue operations are carried out effectively, efficiently, and with minimal risk to human personnel.

The command center's core function is to act as the decision-making and operational nerve center for the entire rescue mission. It not only monitors the ongoing situation in real-time but also provides critical insights into flood dynamics, victim location, and environmental hazards. The integration of real-time data feeds, predictive algorithms, and machine learning models empowers the command center to make informed decisions that can significantly impact the outcome of the rescue operation.

Key Functions of the Command Center

1. **Real-time Monitoring**

The command center provides continuous monitoring of the situation, keeping track of real-time updates from all deployed sensor nodes, AUVs, and other environmental monitoring devices [39]. Real-time data includes information such as:

- **Water depth:** Monitoring the changing levels of floodwaters to assess flood dynamics.
- **Current speeds:** Tracking the velocity of moving water, which helps determine areas that may be at greater risk or harder to reach.
- **Temperature and environmental data:** Keeping an eye on water temperatures, humidity, and environmental conditions that could impact both rescuers and survivors.
- **Motion and detection of distress signals:** Identifying the movement of victims, or tracking distress signals from survivors using acoustic or motion sensors.

The continuous monitoring of these parameters allows operators to stay updated on the status of the operation and adapt quickly to changing conditions. Operators can pinpoint high-risk areas where immediate rescue actions are necessary, adjusting strategies in real-time based on the most current data.

2. **Data Analysis**

The command center is equipped with powerful data processing and analysis tools. As data is collected by the sensor network, it undergoes real-time processing to detect patterns, trends, and anomalies. This analysis helps in making crucial decisions regarding rescue operations. Key aspects of data analysis include:

- **Water dynamics analysis:** Real-time monitoring of water flow, depth, and temperature helps in predicting potential hazards such as water surges, submerged structures, or blocked pathways.
- **Survivor detection:** Data from acoustic sensors and motion detectors can be analyzed to locate the position of survivors. Machine learning algorithms can be used to predict areas where people are likely to be trapped based on sensor data patterns.
- **Trend identification:** Continuous analysis of environmental data helps identify trends such as rising water levels or increasing current speeds. By tracking these trends, the command center can forecast future conditions, which aids in planning rescue operations.
- **Predictive algorithms:** Advanced algorithms, including machine learning models, can be deployed to anticipate dangerous conditions, such as the likelihood of floodwaters reaching certain critical areas or predicting the movement of survivors in the water. Predictive models can also assist in estimating the best time window for rescue missions, taking into account factors such as weather forecasts and water flow patterns.

Data analysis not only assists in identifying immediate risks but also helps the command center anticipate future challenges, allowing the rescue teams to stay one step ahead in the mission.

3. Mission Coordination

The command center coordinates all aspects of the rescue mission based on the analysis of incoming data. The center's operational responsibility includes the strategic allocation of resources and deployment of rescue teams to the most critical areas. Key functions related to mission coordination include:

- **Resource Allocation:** Based on the data received from sensors and AUVs, the command center makes real-time decisions on the allocation of rescue teams and equipment. This involves directing personnel to areas with the highest likelihood of finding survivors, focusing on zones with the most urgent needs, or clearing paths that are obstructed by debris.
- **Team Deployment:** The command center oversees the deployment of human rescuers, drones, and AUVs. By continuously analyzing environmental data, the center can ensure that rescue teams are deployed to areas that are not only most likely to have survivors but also those that are safe from imminent threats (e.g., rising water levels or debris).
- **Directing AUVs and Robots:** The command center can communicate directly with AUVs and other autonomous robots, providing them with new tasks or directing them to specific areas that require attention. For example, it can instruct AUVs to survey flooded structures, deploy additional sensors, or retrieve data from malfunctioning sensor nodes.
- **Real-time Communication:** The command center maintains communication with all deployed teams whether they are human rescuers in boats or underwater, or autonomous vehicles. This ensures that all units are working toward the same objectives, with the latest information available at every step.

Mission coordination ensures that rescue efforts are not only efficient but also optimized for the most critical needs of the situation, maximizing the chances of saving lives.

4. Situational Awareness

Situational awareness is the ability to understand and interpret the environment in which rescue operations are unfolding. The command center is tasked with integrating and analyzing a variety of data sources to maintain a comprehensive understanding of the situation at all times. Key aspects of situational awareness include:

- **Environmental Mapping:** The integration of real-time data from AUVs, sensors, and rescue robots allows the command center to create detailed environmental maps. These maps can highlight flooded zones, submerged infrastructure, potential obstacles, and the locations of survivors.
- **Continuous Data Integration:** Data from sensor nodes, AUVs, motion sensors, and cameras are continuously integrated and updated. This creates a dynamic picture of the operational environment, with situational changes being detected and responded to quickly.
- **Risk Assessment:** The command center assesses the risks posed to both rescuers and survivors based on real-time environmental data. It can evaluate factors such as water current strength, the stability of submerged structures, the likelihood of water surges, and more. This real-time analysis helps make critical safety decisions for human rescuers and assets.

Effective situational awareness helps operators make the right decisions quickly, ensuring the safety of rescuers, optimizing resource deployment, and improving the chances of successful rescues.

6. Applications of WSNs in Underwater Rescue Management

WSNs have found critical applications in underwater rescue management, especially in flood-affected areas where traditional rescue methods are often inefficient, dangerous, or impractical. By providing real-time monitoring, hazard detection, and enhanced situational awareness, WSNs enable rescue teams to work more efficiently, safely, and effectively [40]. Below are key applications of WSNs in underwater rescue operations:

6.1 Search and Rescue Operations

Search and rescue (SAR) operations in flooded areas face significant challenges due to poor visibility, strong currents, and the vast coverage area often involved. Traditional methods often require human rescuers to manually search through these conditions, which is both time-consuming and risky. WSNs, however, can significantly enhance the efficiency and effectiveness of these operations by:

- **Continuous Monitoring of Target Areas:** WSNs can be deployed in areas with high chances of containing trapped victims, such as buildings, submerged vehicles, or narrow water channels. The sensor nodes collect real-time data on environmental conditions and movement within these zones, alerting rescuers to potential locations where survivors may be found.
- **Data Analysis for Victim Localization:** Data collected from sensors, such as acoustic sensors, motion detectors, and temperature sensors, can be analyzed to identify areas of high activity or distress signals, helping to pinpoint the exact locations of victims. By combining this data with known flood patterns and environmental conditions, WSNs provide valuable insights that assist rescue teams in narrowing down search areas.
- **Reduced Search Time:** By focusing efforts on the most likely victim locations identified through sensor data, SAR teams can reduce the overall search time, allowing for faster rescues and more lives saved.

6.2 Hazard Monitoring and Risk Assessment

Flooded areas pose numerous risks, including the collapse of infrastructure, underwater currents, hazardous debris, and toxic chemical exposure. The dynamic and unpredictable nature of floodwaters makes real-time hazard monitoring essential for ensuring the safety of both victims and rescue teams. WSNs contribute to hazard monitoring and risk assessment in the following ways:

- **Continuous Hazard Detection:** WSNs can be equipped with a range of sensors (e.g., pressure, motion, and temperature sensors) to monitor environmental conditions, such as changes in water pressure, water flow velocity, and the presence of submerged obstacles. These sensors can detect dangerous fluctuations in water levels or fast-moving currents that might pose risks to rescuers or survivors.

- **Structural Integrity Monitoring:** In flood situations, the risk of infrastructure collapse such as the failure of bridges, dams, or buildings increases significantly. WSNs can be used to assess the structural health of critical infrastructure by deploying sensors that monitor for signs of stress, cracks, or material failure. These sensors can detect minute changes in the structure that may signal imminent collapse, enabling the command center to prioritize rescue efforts based on the structural integrity of various areas.

- **Early Warning Systems:** By integrating data from multiple sensors, WSNs can identify emerging hazards and provide early warnings to rescuers, enabling them to take appropriate actions before a situation becomes life-threatening. For example, if an underwater sensor detects unusual pressure shifts indicating the potential collapse of a building, the system can alert nearby rescue teams to evacuate or avoid certain zones.

6.3 Environment and Infrastructure Monitoring

The environmental impact of floods extends beyond the immediate threat to human lives. Floodwaters can cause significant damage to infrastructure, leading to long-term complications for recovery efforts. WSNs can be applied to monitor both environmental conditions and the health of key infrastructure in flooded areas. Some specific use cases include:

- **Monitoring Flooded Infrastructure:** Many critical infrastructures, such as bridges, dams, and power stations, are vulnerable to damage during floods. WSNs can be used to assess the structural integrity of these facilities by deploying sensors that monitor vibrations, stress, and strain on the structures. This helps determine which structures are safe to access and which ones pose a significant risk of collapse.

- **Environmental Data Collection:** WSNs can also gather important environmental data, such as water quality, temperature, and pH levels. This data helps rescue teams assess whether floodwaters are contaminated with hazardous chemicals or pollutants, and it can inform decisions about when and where to deploy human rescuers to reduce exposure to dangerous substances.

- **Waterway Monitoring:** In addition to monitoring infrastructure, WSNs can track water levels in rivers, reservoirs, and canals. By tracking changes in water flow and predicting potential floods or breaches, WSNs provide early warnings to communities and rescue teams. They also allow for the real-time mapping of submerged areas, which is useful for planning rescue routes and identifying accessible paths for evacuation.

6.4 Victim Tracking and Localization

One of the most challenging aspects of underwater rescue in flooded areas is locating and tracking victims who may be trapped or displaced by the rising waters. WSNs, with their network of sensors, provide an innovative solution to this problem by offering a means to track victims in submerged environments, even under low-visibility conditions.

- **Acoustic Sensors for Victim Detection:** Acoustic sensors embedded in the WSN can detect underwater sounds, such as the voices of trapped victims or distress signals. By analyzing the frequency and intensity of these signals, the system can triangulate the victim's position, even in areas where visibility is near zero.

- **Motion Sensors for Victim Movement Tracking:** Motion sensors, including accelerometers and gyros, can detect the movement of people or objects in the water. These sensors help in tracking the location and movement of victims, particularly those who may be swept away by currents or displaced to different parts of the flooded area. The system can send real-time alerts to rescuers, guiding them to the exact location of the victim.

- **Enhanced Localization with GPS and Sensor Fusion:** In some cases, a combination of GPS, sonar, and motion sensors can provide highly accurate location data for victims. For example, WSNs equipped with GPS receivers can provide rescuers with precise coordinates, while sonar systems can detect objects or individuals in deeper, murkier waters. Sensor fusion techniques can combine multiple sources of data to pinpoint victim locations with greater accuracy, even in challenging environments.
- **Zero-Visibility Operations:** One of the key advantages of using WSNs for victim tracking is the ability to operate in zero-visibility conditions, which are common in flood situations. Unlike visual-based technologies, acoustic and motion-based sensors can function effectively underwater, allowing rescuers to locate victims even when visibility is severely limited by murky water or debris.

7. Communication Challenges in Underwater WSNs

While WSNs hold significant potential for underwater rescue management, their implementation in flooded or submerged environments is fraught with several challenges [41]. These challenges stem from the unique characteristics of underwater communication, which differ significantly from terrestrial environments [42-44]. Below are some of the most critical communication challenges faced by underwater WSNs:

7.1 Signal Propagation

One of the most significant challenges in underwater communication is signal propagation. Unlike air or land, water is a highly attenuating medium for most types of wireless signals. Here are some key issues:

- **Attenuation of Radio Waves:** In underwater environments, radio waves (used in traditional wireless communication systems) are absorbed and scattered quickly by water, especially at greater depths. This leads to a sharp decline in signal strength, limiting the range and effectiveness of traditional wireless communication methods like radio frequency (RF) signals.
- **Optical Signal Limitations:** Optical signals (e.g., light) also face substantial attenuation in water, especially as water turbidity and particulates increase. Light-based communication methods, such as visible light communication (VLC), offer high bandwidth but suffer from significant limitations in terms of range and reliability in murky or deeper waters.
- **Acoustic Communication**: To overcome the attenuation problem, acoustic signals are commonly used in underwater WSNs. While acoustic communication is effective over longer distances compared to radio and optical methods, it comes with its own set of challenges:
    - **Noise Interference:** Underwater environments often have significant background noise, including natural sources like waves, marine life, and water currents, as well as artificial sources such as ships and underwater equipment. This noise can interfere with signal transmission, leading to reduced communication quality and data loss.
    - **Limited Bandwidth:** Acoustic communication typically offers lower bandwidth compared to RF or optical signals. This constraint makes it difficult to transmit large volumes of data quickly and can result in delays in real-time communication and monitoring.

Due to these challenges, underwater communication systems must use specialized protocols designed to handle signal degradation, noise, and bandwidth limitations while maximizing reliability.

7.2 Network Topology

The dynamic nature of underwater environments poses significant challenges for maintaining a stable network topology:

- **Fluid and Changing Terrain:** Flooded areas are constantly changing due to water currents, rising or falling water levels, and shifting debris. This makes the static placement of sensor nodes or communication devices problematic. For instance, sensor nodes deployed on the seafloor may shift due to strong currents or be buried under sediment, leading to network instability and gaps in coverage.

- **Node Failures:** Underwater networks are also subject to frequent node failures due to physical factors:
    - **Corrosion:** The harsh underwater environment accelerates corrosion in electronic components, especially for nodes left deployed for extended periods.
    - **Damage from Debris:** Floating or submerged debris in floodwaters can physically damage sensor nodes, causing them to fail or become inactive.
    - **Battery Depletion:** The limited lifespan of batteries on sensor nodes poses a significant issue for long-term missions. Once the battery is depleted, the node stops functioning, which may lead to gaps in data collection or loss of critical information.

These dynamic and often unpredictable environmental factors necessitate adaptive network topologies that can reconfigure as needed, ensuring continuous coverage and communication. This could involve the use of mobile sensor nodes, autonomous underwater vehicles (AUVs), or multi-hop communication systems that adapt to changing conditions.

7.3 Energy Efficiency

In underwater WSNs, energy efficiency is a crucial concern. Most sensor nodes are battery-powered, and long-term operations in submerged environments exacerbate the challenge of maintaining power. Several factors contribute to the energy efficiency challenge:

- **Limited Battery Life:** The batteries in sensor nodes are typically small, and their capacity is limited. Given the need for continuous monitoring and transmission of data in underwater rescue operations, the energy consumption of these devices must be carefully managed.

- **Continuous Data Transmission:** Sensor nodes in underwater environments must often transmit data continuously to a central processing unit or command center for real-time analysis. However, maintaining a constant data transmission rate significantly drains the battery, especially when using energy-intensive acoustic communication.

To address these challenges, energy-efficient algorithms and power management strategies are essential:

- **Data Compression:** Algorithms that compress data before transmission can help reduce the amount of energy consumed during communication by reducing the data size.

- **Duty Cycling:** By implementing duty cycling, where nodes operate in periodic active and sleep cycles, energy consumption can be reduced. Nodes only transmit or collect data at specific intervals, which extends battery life.

- **Energy Harvesting:** In some cases, the use of energy harvesting techniques, such as converting the movement of water or using solar panels (for surface-based sensors), can help recharge sensor batteries, prolonging network lifetime.

Balancing the trade-off between power consumption and data transmission requirements is critical for maintaining operational efficiency in underwater WSNs.

7.4 Real-Time Data Processing

Underwater rescue operations require real-time data processing for effective decision-making. However, several factors hinder the speed and efficiency of data processing in WSNs deployed in underwater environments:

- **Limited Computational Resources on Sensor Nodes:** Sensor nodes in underwater WSNs are typically small, lightweight, and low-cost devices, meaning they often have limited processing power and memory. This limitation restricts their ability to process large volumes of data locally and perform complex computations, such as image processing or machine learning tasks.

- **Communication Delays:** Due to the challenges of underwater communication, including signal attenuation and noise interference, there can be significant delays in transmitting data to a central processing unit (e.g., a command center). This results in latency, which can be detrimental in high-stakes rescue operations where timely responses are critical.

- **Data Fusion and Aggregation:** In many underwater rescue scenarios, multiple sensors (acoustic, pressure, motion, etc.) are deployed to gather data. The challenge here lies in data fusion—the process of combining data from multiple sensors to form a comprehensive picture of the underwater environment. This requires both significant processing power and bandwidth, which may be difficult to achieve under the constraints of underwater WSNs.

To overcome these issues, some strategies can be employed:

- **Edge Computing:** Performing data processing at the sensor node or close to the data source can reduce the amount of raw data that needs to be transmitted, thus reducing communication delays and conserving bandwidth.

- **Collaborative Processing:** Some WSNs use a distributed approach where nodes collaborate and share their processing tasks, allowing for more efficient data aggregation and decision-making without overloading any single node.

- **Efficient Communication Protocols:** Using specialized communication protocols designed to reduce latency and optimize bandwidth usage is essential. Protocols like Delay-Tolerant Networks (DTNs) or low-power wide-area networks (LPWANs) are examples of systems that can handle intermittent connectivity and long-range data transmission more efficiently.

8. Technologies and Solutions for Improving WSNs in Underwater Rescue

Underwater WSNs have vast potential in improving the efficiency and effectiveness of rescue operations in flooded or submerged environments [45]. However, to overcome the numerous challenges inherent to underwater conditions, several innovative technologies and solutions can be employed to enhance their performance. Below are key approaches that can improve the capabilities of WSNs for underwater rescue management:

8.1 Hybrid Communication Approaches

One of the most significant challenges in underwater WSNs is the limited range and reliability of communication due to the unique properties of water [46]. As discussed earlier, acoustic communication is the most commonly used method, but it suffers from limitations like noise interference, signal attenuation, and low bandwidth. Combining acoustic communication with other techniques such as optical communication or magnetic induction can help mitigate these issues and improve communication reliability.

- **Acoustic-Optical Hybrid Systems:** Optical communication, though limited in range, offers high bandwidth and can be effective in clear, shallow waters. By integrating optical communication for short-range high-bandwidth data transfer and using acoustic communication for long-range, low-bandwidth transmission, a hybrid system can provide more robust and reliable communication.
- **Magnetic Induction:** Magnetic induction-based communication is another promising alternative, especially for short-range, high-reliability communication in underwater WSNs. It is less affected by water turbidity and can be used in environments where acoustic signals may not be viable.
- **Adaptive Switching:** Hybrid systems can incorporate adaptive switching mechanisms where the communication system dynamically selects the best communication mode based on the environmental conditions (e.g., choosing optical communication when water clarity allows, and switching to acoustic communication in murkier waters).

By integrating multiple communication modalities, WSNs can ensure a more reliable and efficient communication network, enhancing the overall robustness of the system in real-time rescue operations.

8.2 Distributed Data Processing

In underwater WSNs, data transmission to a centralized command unit can be delayed due to factors like signal degradation, long transmission distances, and network congestion [47]. To mitigate these issues and enable quicker decision-making, distributed data processing is a promising solution.

- **Edge Computing:** Instead of sending raw data to a central processor, sensor nodes can process data locally through edge computing techniques. By filtering and aggregating data at the node level, only relevant information is transmitted, reducing the amount of data sent over the network and lowering the associated communication overhead.
- **Data Fusion on the Node Level:** Sensor nodes can also use data fusion techniques, where information from multiple sensors is combined at the local node level to create more accurate and meaningful results. This reduces latency and allows for faster local decision-making.
- **Decentralized Decision-Making:** In cases of network failure or if the command center is unreachable due to environmental factors, distributed processing enables sensor nodes to make autonomous decisions based on local data. This is particularly valuable in real-time rescue operations, where quick responses are critical.

By decentralizing data processing, WSNs can operate more efficiently, reducing response times and enhancing the effectiveness of rescue operations, especially in large, dynamic environments like flooded areas.

8.3 Energy Harvesting Techniques

One of the major challenges for underwater WSNs is the limited battery life of sensor nodes, which significantly impacts long-term operations [48]. Energy harvesting techniques provide a sustainable solution by utilizing ambient energy sources to power sensor nodes, reducing the reliance on traditional battery replacements.

- **Solar Energy:** For nodes placed near the water's surface or in shallow, clear waters, solar energy harvesting can be effective. Solar-powered sensors can recharge their batteries during the day, reducing the need for frequent manual interventions. However, solar energy is less effective in deep or murky waters.

- **Thermal Energy:** Thermoelectric generators can harvest energy from temperature differences between the water and the surroundings. This can be particularly useful in deep-sea or underwater environments, where there is a consistent thermal gradient between the ocean's cold depths and warmer surface waters.
- **Kinetic Energy:** Piezoelectric or electromagnetic harvesting methods can capture energy from water movement, such as tides, waves, or currents. Sensors can be designed to convert mechanical energy from water motion into electrical power, thus prolonging their operational lifetime.

Energy harvesting can significantly reduce the logistical burden of replacing or recharging batteries in underwater networks, enabling more prolonged and sustainable underwater rescue operations.

8.4 Advanced Localization Techniques

Accurately localizing victims and rescuers in submerged environments with low visibility or rapidly changing conditions is one of the most challenging aspects of underwater rescue operations [49]. Advanced localization techniques, combined with machine learning algorithms, can significantly improve the tracking and positioning of both victims and rescue teams.

- **Acoustic Localization:** By using arrays of acoustic sensors, it is possible to triangulate the position of individuals or objects underwater. Advanced signal processing and multi-sensor fusion can improve the accuracy of this method, even in environments with high background noise.
- **Sonar-Based Imaging:** Combining sonar systems with localization algorithms allows rescuers to create real-time maps of the underwater environment. By analyzing sonar data, WSNs can offer detailed, real-time imagery of submerged objects or victims, even in zero-visibility conditions.
- **Machine Learning for Enhanced Localization:** Machine learning (ML) [50] and artificial intelligence (AI) [51] can be employed to enhance localization accuracy. By training models on sensor data from different environmental conditions, ML algorithms can predict the most likely locations of victims or rescuers based on historical data, current conditions, and sensor inputs.

By integrating multiple data sources and advanced computational techniques, WSNs can achieve highly accurate and reliable localization in complex, underwater rescue scenarios.

8.5 Robust Sensor Design

Given the harsh and demanding environment in which underwater WSNs operate, the design of the sensors themselves must be tailored to withstand extreme conditions. A robust sensor design ensures long-term operational capability in submerged environments, enhancing the reliability of the entire system.

- **Corrosion-Resistant Materials:** Sensors should be constructed with corrosion-resistant materials such as titanium, ceramics, or specially treated metals. This ensures that sensors can survive prolonged exposure to saltwater and other corrosive substances, reducing the need for frequent maintenance or replacement.
- **Pressure-Resistant Housing:** Sensors must be designed to withstand the high-pressure conditions encountered at significant depths. This requires durable, pressure-sealed casings that protect the internal electronics while maintaining sensor performance.
- **Durability against Debris and Sedimentation:** The harsh underwater environment may contain floating debris or silt that can physically damage or obstruct sensor nodes. By using shock-resistant and debris-resistant designs, sensor nodes can continue to function effectively even in turbulent waters or when submerged in sediment-heavy environments.

- **Self-Diagnostics and Self-Healing:** Advanced sensor designs can incorporate self-diagnostics and self-healing capabilities. For instance, sensors may be able to detect malfunctioning components and automatically recalibrate or reroute data to maintain system functionality.

A robust sensor design ensures that WSNs can operate effectively in the challenging conditions of flooded or submerged environments, increasing the reliability and longevity of the entire system.

9. Conclusion

Underwater rescue management in flooded areas presents a significant challenge, but the application of WSNs offers promising solutions. By leveraging real-time data collection, efficient communication, and advanced sensor technologies, WSNs can vastly improve the efficiency, safety, and success of search and rescue operations in such environments. However, challenges related to signal propagation, energy efficiency, and data processing need to be addressed through advanced technologies and strategic deployment. Future research should focus on overcoming these challenges to make WSNs an integral part of disaster response in flood-affected areas. By combining WSNs with other emerging technologies like robotics, AI, and machine learning, the potential for underwater rescue operations will continue to expand, ultimately saving more lives and reducing the impact of floods on affected communities.

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