SDGS STUDIES REVIEW
e-ISSN: 2966-0548 | DOI: https://doi.org/10.37497/sdgs.v6istudies.46

PERSPECTIVE PAPER

SDG-13, Tsunamis: Causes, Impact, and Recovery Challenges

Rania Lampou
Greek Ministry of Education & Religious Affairs (Greece).

Rashmi Gujrati
Ludhiana Group of Colleges, (India).

Cemalettin Hatipoglu
Bandırma Onyedi Eylül University (Turkey).

ABSTRACT | Purpose: This paper explores the multifaceted causes, impacts, and recovery challenges associated with tsunamis, emphasizing their links to climate change, marine ecosystem degradation, and global sustainability efforts under SDG 13. **Design/Methodology/Approach:** The study adopts a qualitative and integrative review of scientific literature and institutional reports. It examines the physical mechanisms of tsunamis, their socio-economic and psychological consequences, and the role of technological and policy-based interventions in disaster recovery. **Findings:** Tsunamis, primarily triggered by underwater seismic events, are intensified by climate change through sea-level rise and coastal erosion. Beyond physical destruction, tsunamis disrupt social cohesion, livelihoods, and mental health, while marine debris exacerbates ecological damage. The paper identifies artificial reefs and mangrove restoration as key ecological strategies, complemented by policy frameworks such as Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP). Technological innovations, including early warning systems and marine debris recovery projects (Ocean Cleanup, Seabin, WasteShark), enhance disaster preparedness and resilience. Moreover, international cooperation and financial mechanisms, such as the Green Climate Fund, are critical to supporting long-term recovery, particularly in developing nations. **Practical Implications:** The importance of integrating ecosystem restoration, disaster risk reduction, and technology-based solutions into national and international resilience strategies. **Originality/Value:** By linking climate action, marine sustainability, and post-disaster governance, the paper contributes to an interdisciplinary understanding of sustainable recovery from tsunamis.

Keywords | Tsunamis; Climate Change; Disaster Risk Reduction; Marine Ecosystems; Sustainable Recovery

Received: 8 September 2024
Revised: 12 May 2025
Accepted: 25 September 2025
e-ISSN: 2966-0548

Corresponding Author: Rania Lampou – E-mail: rania.lampou@gmail.com

Editor in chief: Dr. Altieres Silva – ALUMNI IN (EUA).

How to cite this article: Lampou, R., Gujrati , R., & Hatipoglu, C. (2025). Tsunamis: Causes, impact, and recovery challenges. *SDGs Studies Review*, 6(studies), e046. https://doi.org/10.37497/sdgs.v6istudies.46

INTRODUCTION

Tsunamis are a great threat to coastal communities anywhere on the planet and they are mainly caused by underwater earthquakes and other similar events. They are exceptionally powerful waves, triggered by the sudden displacement of very large volumes of water and when they strike an area their effects include widespread destruction, numerous fatalities, and long-lasting environmental damage. Tsunamis affect the entire water column and they are thus able to travel vast distances at great speeds while conserving most of their vast energy and that is what makes the difference from regular waves. The acceleration of climate causes sea levels to rise and coastal erosion thus rendering coastal areas more vulnerable to tsunamis. The recovery process from tsunamis requires a multifaceted approach that will not just focus on immediate human needs but will also strive to repair the damage to marine ecosystems while improving long-term resilience. This paper will present the many ways in which tsunamis can affect coastal populations and ecosystems as well as sustainable strategies for recovery and increased resilience. The paper will also highlight both local and international policies, technological solutions, and global cooperation and their necessity for reducing future risks and fostering sustainable recovery (Edward Bryant, 2014).

THE IMPACT OF TSUNAMIS ON COASTAL COMMUNITIES

Tsunamis are gigantic and very catastrophic waves triggered by sudden and massive displacement of water, usually due to natural events, mainly seismic activities under the ocean. Tsunamis can also be caused by volcanic eruptions and underwater. The sudden displacement of great volumes of water causes large waves capable of traveling large distances at immense speeds while accumulating energy.

The energy associated with tsunamis is very different compared to that of regular ocean waves. Regular ocean waves are usually caused by wind and affect only the surface layers of the water, which means that their energy is contained within the upper 100 meters of the ocean. The impact of these waves is localized because their energy is not only reduced with depth, but it is also mostly contained in the surface. Regular waves tend to affect only boats, coastal structures, and beaches. Tsunamis on the other hand possess far greater energy and they affect the entire depth of the ocean, and this enables them to travel vast distances without any significant loss of strength, which in turn allows them to strike coastal areas located far from their point of origin (Murty, Aswathanarayana, Nirupama, 2006 & National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 2023).

Climate change is expected to increase the frequency and severity of tsunamis, since it has been associated with the rise of sea levels, increased coastal erosion, and various changes in ocean currents and seafloor conditions. The most important way in which climate change affects tsunami severity is the rise in sea levels. This phenomenon is caused by the melting of glaciers and the thermal expansion of seawater, rendering coastal regions more vulnerable to tsunamis and their catastrophic effects. Even if the height of a tsunami does not change, higher sea levels could enable it to reach further inland, resulting in widespread flooding and more damage. Furthermore, coastal communities that were considered safe from tsunamis could now be affected by them. Also, the rise of sea levels accelerates coastal erosion, making natural barriers to tsunamis such as sand dunes, mangroves, and coral reefs less effective. These natural barriers absorb the energy of tsunami waves and lessen their impact on coastal areas, which means that their erosion will make coastal communities that rely on them for protection against tsunamis more vulnerable to them (Carrington, 2025). Climate change could also affect ocean currents and seafloor conditions; however it is not yet clear how much these changes affect tsunami behavior. Changes in ocean temperature and circulation patterns could affect underwater geological processes, including tectonic movements and volcanic activity, which are known to be among the most important causes of tsunami formation. However, this connection is not well-understood, and further studies are necessary in order to determine if and how much these changes affect the occurrence of tsunamis (Pare, 2025). The consequences of tsunamis have been catastrophic for many nations, with Indonesia, Japan, and Sri Lanka being some of the countries most affected by them. The 2004 Indian Ocean tsunami devastated Indonesia. The Aceh province was struck the worst, with over 167.000 human fatalities and the almost complete annihilation of its infrastructure. Additionally, many local fishing villages were completely destroyed, which resulted in thousands of people losing their livelihood. Similarly, Japan's 2011 Tōhoku earthquake and tsunami devastated the northeastern coast of the country causing more than 15,000 deaths and a nuclear disaster at Fukushima. Japan suffered long-term economic consequences since its fishing and agricultural industries suffered great damages. In Sri Lanka, the 2004 tsunami caused more than 35.000 fatalities, serious issues to the tourism and fishing industries and destroyed entire coastal communities, the most important pillars of the country's economy (Kajikawa, 2009, Lloyd Parry, 2017).

Apart from physical devastation, tsunamis also cause significant psychological and social consequences on affected communities. They can cause the forced displacement of entire communities, since people are asked to flee to temporary shelters. This fragments social networks and reduces community cohesion. This sudden loss of familiar social structures can hinder the mental and emotional recovery of those affected by tsunamis. Additionally, the damage that they cause to infrastructure can result in the disruption of vital services like education, health services, and communication systems, leaving local authorities unable to respond to the destruction and hindering all recovery efforts. The economic strain after a tsunami often results in an increase of social inequalities because underprivileged groups may find the aid and resources necessary for them to rebuild their lives completely inaccessible. Additionally, shared trauma can either cause relationships in communities to become stronger but it could also lead to social tensions, depending on how well the affected population can cope with the stress and resource scarcity caused by the tsunami (Kajikawa, 2009, Lloyd Parry, 2017).

The presence of marine debris is another factor that can significantly hinder the recovery after a tsunami. Floating debris, such as plastics, metals, and wood, can have serious long-term effects on marine ecosystems. Coral reefs, essential for marine life, can be physically damaged by debris if it comes in direct contact with them or if it gets trapped in them. Mangroves, which are vital for the protection of coastlines and biodiversity, can also be uprooted or otherwise harmed by debris, which reduces their effectiveness as natural barriers against erosion and storm surges. Marine debris doesn't just destroy habitats, it also causes pollution which can be a great threat to marine life. Debris contains plastics and chemicals, which release toxic substances into the water contaminating the environment and harming marine life. Plastics degrade into miniscule particles known as microplastics, which can be eaten by marine animals and cause them long-term health problems while contaminating the food chain. Furthermore, some animals such as turtles and seabirds, can get caught in discarded fishing nets or eat small pieces of debris, resulting in injuries, starvation, or even death (John, Nandhini, Velayudhaperumal Chellam, Sillanpää, 2021).

On the other hand, restoring coastal ecosystems, such as mangroves, is vital for the protection of communities from tsunamis and other climate-related events. Mangroves also manage coastal erosion due to their dense root systems which stabilize the shoreline and stop the loss of land, thus offering protection against rising sea levels. Furthermore, mangroves are also natural barriers against storm surges, making the waves less intense and powerful and protecting coastal communities during extreme weather events. They also support local livelihoods by providing resources including wood, honey, and fruits. They are also nurseries for fish and crustaceans, which is important for sustainable fisheries. The restoration of mangrove ecosystems not only helps with the protection of communities from the consequences of tsunamis and storms but also makes them more resilient to climate change, ensuring their recovery from future disasters (Rhodes, 2025).

To conclude, tsunamis are powerful and extremely destructive natural events that can devastate coastal areas, both physically and socially. Tsunamis are primarily caused by underwater seismic activity, although other geological events are also thought to contribute to their creation.

The negative effects of tsunamis are only made worse by climate change, which is the main cause of the rise of sea levels, coastal erosion, and changes in oceanic and seafloor conditions. The psychological and social consequences of tsunamis on affected communities can be very severe since they cause serious issues such as forced displacement, economic strain, and the dissolution of social structures, which can severely delay recovery efforts. Furthermore, marine debris can also hinder recovery efforts by causing damage to vital ecosystems and contaminate the marine environment. However, the restoration of coastal ecosystems, particularly mangroves can offer protection from future disasters to communities while also reducing the consequences of tsunamis and making them more resilient to climate change. Effective preparedness, recovery strategies and ecosystem restoration are vital for the mitigation of the risks posed by tsunamis, and they also make coastal communities more resilient.

ARTIFICIAL REEFS, POLICY, AND TECHNOLOGICAL INNOVATION IN DISASTER RECOVERY

Artificial reefs are essential to the recovery and restoration of marine ecosystems since they can provide support to areas in which natural habitats have suffered serious damage. They can also play a significant part in ecosystem rehabilitation, particularly in areas whose coral reefs or seagrass beds have been devastated. Artificial reefs can offer new habitats which draw various marine organisms to them. Their surfaces can be colonized by marine life since they can provide shelter, food, and breeding grounds to various forms of marine life including fish, mollusks, and invertebrates. Furthermore, these structures foster biodiversity by increasing and improving the variety of marine life in the area. Artificial reefs can also attract local as well as migratory species, thus providing even more ecological diversity to the region (Mohanty, 2025).

Governments are vital for the promotion of sustainable recovery in the wake of a catastrophe like a tsunami. Their policies should not only focus on addressing immediate needs, but long-term resilience should also be their focus as well. Environmental restoration should be the main priority of sustainable recovery strategies and of all efforts to rebuild vital ecosystems. Disaster risk reduction (DRR) should be incorporated in coastal zone management strategies. In order for a coastal zone management policy to be effective it will need to include a complete and balanced approach which will include conservation, development, and disaster preparedness. Governments can also establish buffer zones along coastlines, which will offer protection to vulnerable areas by regulating development in high-risk areas. Furthermore, vital ecosystems such as mangroves and coral reefs can act as natural barriers against storms, and they can significantly mitigate the impact of future disasters (Singh, 2010, Bosher, 2008).

Disaster risk reduction policies should aim to eliminate vulnerabilities before disasters. Some of the strategies that countries can implement for the preparation of their vulnerable civilians from disasters include risk assessments and early warning systems. These systems can be combined with mitigation strategies to make coastal regions more resilient and safeguard both human life and the environment from future tsunamis and other natural disasters (Collins & Brown, 2017).

Marine spatial planning (MSP) is another strategy that is essential for mitigating the risks of future disasters as well as for ensuring that marine resources are managed in a sustainable manner. MSP is a methodical approach to marine and coastal spaces management, which focuses on establishing and maintaining a balance between environmental, economic, and social interests.

The identification of vulnerable coastal and marine areas enables MSP to propose land-use policies for the regulation of development in high-risk zones, in order to minimize exposure to future disasters. Additionally, MSP promotes the conservation and restoration of natural coastal defenses, including mangroves, coral reefs, and sand dunes, which protect coastal communities from storm surges and erosion. These ecosystems are essentially natural buffers which dissipate the energy of the waves and mitigate the impact of natural disasters.

The identification of safe zones for human activity is vital to disaster preparedness. The strategic planning of construction and other activities allow MSP to protect essential infrastructure by ensuring that it is not built in areas that are vulnerable to disaster. This significantly mitigates the possibility of serious damage and loss of life in the wake of extreme weather conditions or tsunamis (Intergovernmental Oceanographic Commission policy brief, 2025).

International cooperation is a crucial factor of the effectiveness of the response to large-scale marine disasters. Marine disasters, like oil spills, pollution caused by plastics in the sea, and the degradation of marine habitats know no borders and they can have negative effects in ecosystems and economies all over the world, because marine ecosystems are interconnected. This interconnectedness is caused by ocean currents and migration patterns of marine species which transfer the effects of a disaster in one region not just to its neighboring countries, but also to regions very far away from it. Because of the aforementioned interconnectedness, coordinated international approaches are essential for the effective management of the aftermath of disasters and the minimization of their consequences.

Thanks to international cooperation countries are able to share resources and expertise. Countries with more advanced technology, an abundance of financial resources, or specialized knowledge can share them with other countries, making disaster response more efficient and effective. For example, international teams with specialized equipment and experts from multiple countries often provide aid to countries affected by oil spills. Furthermore, when it comes to marine disasters, quick and coordinated actions are essential for the prevention and management of major environmental damage. International frameworks, such as the International Maritime Organization (IMO) and the United Nations Environment Programme (UNEP), specialize in rapid response coordination and allow nations to work in order to minimize the effects of such disasters as much as possible (International Maritime Organization, UN Environment Program).

Technological innovations, such as early warning systems, have been very effective in the mitigation of the damage caused by tsunamis. These systems can allow for timely evacuations, allowing coastal populations to reach higher ground or seek shelter before a tsunami strikes. Based on the epicenter of the earthquake and how far it lies from the coast, early warning systems can alert coastal populations a few minutes or even several hours before a disaster strikes. When a tsunami is caused by an offshore earthquake, seismic networks and tsunami buoys “sense” the event and start notifying experts and the authorities. These timely warnings enable the authorities to alert residents and order evacuations in order to safeguard human lives and properties from the tsunami. For instance, local tsunamis usually allow very little time for response, however an early warning system can detect the magnitude and the epicenter of the earthquake that caused a tsunami and send out a “tsunami watch” or “tsunami warning”. This warning can allow individuals and communities to prepare for the tsunami and seek shelter in safe areas, thereby significantly reducing the danger of loss of human life and property (UNESCO).To summarize, a multifaceted approach focusing on the restoration of ecosystems, the implementation of sustainable policies, and collaboration between several countries is essential for an effective recovery from tsunamis and other marine disasters. Artificial reefs are vital in marine ecosystem recovery since they enhance biodiversity by offering new habitats to marine fauna. Governments should implement integrated disaster risk reduction and coastal zone management policies in order to mitigate the impact of future disasters, while marine spatial planning can protect natural coasts by identifying and delineating areas which are safe for human activity.

Furthermore, effective response to large-scale marine disasters hinges on international cooperation which allows countries to share resources and expertise.

Finally, technological innovations, like early warning systems, are essential for the minimization or prevention of fatalities and property damage when tsunamis strike. These combined strategies are vital for the creation of coastal communities that will be able to successfully stand against tsunamis and other future disasters (UNESCO).

TECHNOLOGICAL SOLUTIONS AND GLOBAL PARTNERSHIPS IN MARINE AND ECOSYSTEM RECOVERY

Marine debris, such as plastics, poses a serious environmental challenge and innovative technological solutions are constantly being developed in order to manage or even overcome it. The main focus of these is the collection, recycling, and prevention of the accumulation of debris in the oceans. One of the most important ocean cleanup technologies is the *Ocean Cleanup Project (see Figure 1)*. This initiative uses large-scale passive systems, such as specially designed giant floating barriers, to trap plastic waste while it is being carried by ocean currents. The barriers consist of a floating arm and a specially designed skirt that reaches beneath the water's surface, allowing it to capture plastic without harming or hindering marine life. The trapped debris is then removed and recycled in a central location. This system is undergoing tests and trials in the Great Pacific Garbage Patch, where it aims to remove 90% of ocean plastic by 2040. If it proves successful, it will be a very important victory in the fight against marine pollution (Ocean Cleanup Project website).

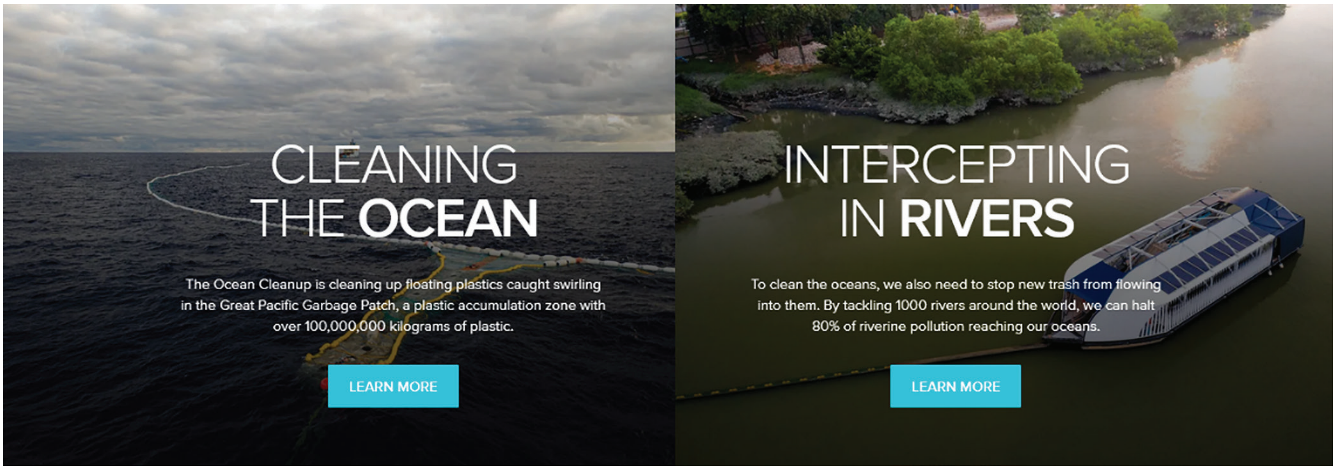

Figure 1. Cleaning the Ocean and Intercepting in Rivers (*The Ocean Cleanup Project*, 2025).

Another technology whose goal is the reduction of marine debris is the *Seabin Project (see Figure 2)*, which consists of specially designed floating trash bins strategically placed in harbors, marinas, and coastal areas. Seabins are like vacuum cleaners because they essentially draw in waste and capture it inside a mesh bag which can be emptied periodically. The main focus of this solution is the removal of smaller-scale debris such as plastics, oils, and detergents from urban or recreational waters. Its localized character makes it ideal for managing pollution in busy coastal areas (Seabin Project website).

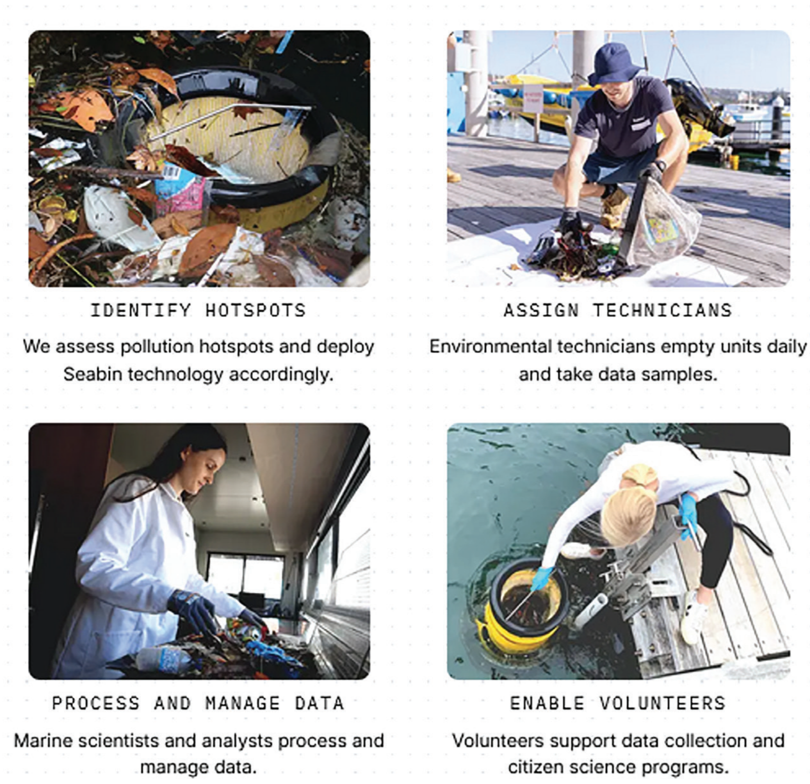

Figure 2. Identification of hotspots, technician operations, data management, and volunteer engagement (Seabin Project, 2025).

Another important initiative is the *WasteShark (see Figure 3)*. The Wasteshark is an autonomous, drone-like vessel which can collect floating debris from both freshwater and saltwater environments. The WasteShark can collect trash such as plastics and oils very effectively thanks to the fact that it can be deployed in rivers, lakes, and coastal areas. Its unique design includes a special mechanism resembling a mouth which essentially scoops up debris and collects it in a container from which it can then be easily removed and processed. These technologies are essential for managing or even solving the problem of marine debris since they can very effectively reduce pollution levels in coastal waters and inland waterways (The WasteShark website).

Figure 3. The WasteShark autonomous surface vessel for aquatic waste collection (*RanMarine Technology*, 2025).

Technological solutions not only provide solutions to the problem of marine debris but they also help restore coral reefs, which are vital ecosystems endangered by climate change, pollution, and human activity. Restoration techniques based on state of the art technology can prove essential to coral reef recovery. Recent advancements such as underwater robots, artificial reefs, and coral farming have been deployed with the aim of aiding the regrowth of coral populations in areas that have been seriously affected by bleaching or damage. These technologies increase the effectiveness of restoration efforts, they also make efforts for the rehabilitation of coral ecosystems more likely to succeed while making them more resilient against future environmental stressors (CSIRO, Commonwealth Scientific and Industrial Research Organization).

Financial support and insurance mechanisms also play a vital role in the recovery process following large-scale disasters like the 2004 tsunami. One of the biggest issues in the wake of this disaster was the raising of funds and other resources for rebuilding affected communities, especially those located in less-developed countries. In order to help solve this issue, the international community promised substantial financial aid, which came in the form of disaster funds and micro-insurance programs specially designed for vulnerable populations. These programs did not only aid with the immediate needs of recovery efforts, but they also made these communities more resilient to natural disasters. Financial tools, including insurance schemes, have played a vital role in the support of recovery efforts because they cover both the immediate and ongoing needs of affected communities (Climate Funds Update).

The 2004 tsunami showed that there was a significant lack in understanding tsunami behavior, and it also highlighted the limitations of prediction and monitoring systems. After the disaster, significant improvements to tsunami prediction capabilities, and regional monitoring systems were made. Tsunami warning systems in both the Indian Ocean and Pacific Ocean regions were expanded which greatly increased their capability to detect and predict tsunamis. This expansion also resulted in the collection of vast amounts of real-time data which was used to make predictions more accurate which in turn resulted in coastal communities being able to better prepare themselves for future tsunamis, and the minimization of the potential for loss of life and property damage (Frost, 2024).

Global partnerships are essential for long-term recovery of areas that have been affected by natural disasters and environmental degradation. Recovery efforts are often very complicated which means that they can only be successful through the coordinated collaboration of many different nations, organizations, and sectors. Global partnerships allow the sharing of resources, expertise, and knowledge, rendering recovery projects more effective and efficient. After the 2004 Indian Ocean tsunami, international organizations such as the United Nations and Red Cross, worked together with national governments for the effective recovery of the affected regions and they offered very valuable financial aid and technical expertise. These collaborations play a vital role in addressing the long-term needs of affected communities and ecosystems (Green Climate Fund, World Bank Group).

Additionally, global partnerships play a vital role in the financial support of areas that do not have access to the resources necessary for recovery following a disaster. Many developing countries find recovery after large-scale disasters or environmental damage to be extremely difficult or even impossible without international assistance. Partnerships with international organizations, donor countries, and financial institutions offer the necessary funding, grants, and investments for long-term recovery and sustainability. For example, the Green Climate Fund, established under the United Nations Framework Convention on Climate Change (UNFCCC), offers resources from developed nations to developing countries to help them withstand the effects of climate change. Without this financial aid, many countries would simply be unable to recover and protect themselves from future environmental challenges (Climate Funds Update).

To summarize, the recovery from marine pollution, natural disasters, and ecosystem degradation is a very complicate process that can only be successful through a holistic approach that incorporates technological innovations, financial support, and global cooperation. Technological advancements like the Ocean Cleanup Project, Seabin, and WasteShark, can provide solutions to the ever-growing problem of ocean pollution. These technologies reduce ocean debris and foster efforts in ecosystem restoration, including coral reefs. Additionally, financial tools such as disaster funds and insurance schemes, as well as international partnerships, are crucial for the support of both immediate recovery and long-term resilience in affected communities. Finally, continued research and collaboration on the global level are essential for the improvement of prediction systems as well as the organization and coordination of sustainable and effective recovery efforts from the effects of future natural disasters.

CONCLUSION

Tsunamis are among the most dangerous natural disasters for coastal communities, since their aftermath consists of long-lasting environmental, social, and economic consequences. However, a combination of sustainable recovery strategies, including ecosystem restoration, new disaster risk management policies, and technological advancements, can render communities more resilient to future tsunamis and other similar disasters. International cooperation and financial support are essential in order to ensure that recovery and rebuilding efforts will be successful, especially when it comes to developing countries. The integration of science, technology, and policies results in a holistic approach for recovery from tsunamis as well as the prevention and minimization of their consequences in the future. By fostering a collaborative, sustainable, and resilient approach, countries can improve the protection and resilience of their coastal environments and the livelihood of the communities that depend on them.

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