Executive Summary

Project title: MODELRISK- Ecosystem models to support Environmental Risk Assessment of marine ecosystems under HNS spills

Development period: 01/05/2021- 30/06/2023

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Problematic and goal

The Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC-HNS) emerged, in 2000, as the international framework to address pollution incidents caused by chemicals (IMO; Neuparth et al., 2012). However, only three of the twelve EU members that ratified the protocol claimed to have specialized knowledge to respond to HNSspills (IMO; Soares et al., 2020). The behaviour and effects of Hazardous and Noxious Substances (HNS) on the marine environment remain largely unknown and poorly understood (Soares et al. 2020, Cunha et al., 2015), which narrows mitigation actions and suitable responses to HNS spillages at sea. A full preparedness protocol that effectively guides authorities and otherintervening agents in case of HNS spills must take into account the specific behaviour of the HNS,its dispersion trajectory and concentration pattern in seawater, and the potential effects on surrounding marine ecosystems. Yet such a complex process should be translated into a simpler framework that would allow straightforward mitigation actions by competent authorities. Building on work previously developed by CIIMAR researchers, the goal of the MODELRISK project was to develop ecosystem models for Atlantic marine ecosystems to predict and quantify the effects of HNS spills on the composition and function of those ecosystems. Due to the ecological relevance and socio-economic importance of its marine ecosystems, the Azores region was used as a case study. Furthermore, the Azores archipelago is located on one of the busiest marine routes of the planet, thus, prone to incidents with HNS spillages.

Workflow

The project's goal was attained by developing a numerical framework that incorporates a database and several different models, specifically: i) the HNS online database previously developed by CIIMAR was augmented to include toxicological data of HNS on marine organisms; ii) the Regional Ocean Modeling System (ROMS) was calibrated for the area within the North Atlantic ocean encompassing the selected deep-sea ecosystems (34.3°/40.8°N, -36°/-28°W); iii) following an hypothetical incident with HNS spill at the summits of the seamount and of the vent field, HNS dispersion trajectories and concentrations were simulated using the OceanDrift from the open source OpenDrift software package; iv) an ecosystem model that includes a food web model of a typical North Atlantic seamount was simulated with the open source AQUATOX model (US-EPA); and v) a food web model of an Atlantic deep-sea hydrothermal vent was simulated with the open source Ecopath with Ecosim model (EwE) (Fig. 1A).

Based on their different behaviour, four HNS were selected: 4-nonylphenol (4NP), a persistent floater with potential strong effects on pelagic communities; tetrachloroethylene (PCE), a sinker with potential strong effects on benthic communities; aniline (AN), a floater/dissolver with potential strong to medium effects on pelagic and benthic communities; and nitrobenzene (NTB), a sinker/dissolver with potential strong to medium effects on pelagic and benthic communities.

The two selected ecosystems in the Azores oceanic region within the area calibrated for ROMS, were the *Seamount 10*, due to a lower depth location of the summit (413 m), and the *Menez Gwen vent field*, also due to a lower depth location (850 m).

Seamounts are hotspots of biodiversity and important habitats for commercial relevant species (e.g., tuna), whereas deep-sea hydrothermal vent field are chemosynthetic fuelled ecosystems sustaining iconic endemic species (e.g., vent mussels).

For each different HNS spill, it was assumed an incident at sea encompassing 100 containers with a volume of 76 m^3 each, which sank to the bottom and reached the summits of Seamount 10 (S10) and Menez Gwen (MG). A total volume of 7600 m^3 (100 containers x 76 m^3) leaked for five days (120 h) from the containers and distributed uniformly around S10 and MG. For each HNS incident, a winter and a summer scenario were simulated.

In both the AQUATOX seamount model and the EwE vent field model, HNS effects were accounted by acute toxicity (LC50). Nonetheless, due to the lack of data regarding the toxicity of the selected HNS on the food web species of both deep-sea ecosystems, in most cases, proxy species had to be considered.

The effects of HNS were simulated assuming the maximum HNS concentrations outputted by the circulation and Lagrangian models at the summit of the seamount and the vent field.

Main findings

According to the ocean circulation and Lagrangian model simulations, the concentrations of HNS are always higher at MG compared to S10, which is related to different circulation patterns affecting the two deep-sea habitats.

From the four considered HNS, PCE (the sinker) attains the highest concentrations at MG, both in winter (PCE=1.180 mgL^{-1}) and summer (PCE= 1.432 mgL^{-1}).

Results regarding the variation of abiotic parameters in the seamount ecosystem model, such as water temperature and salinity, were very well represented. However, nutrients, especially nitrate, were underestimated, possibly due to the fact that the model does not account for the upwelling of deeper nutrient-enriched waters. The seamount food web model accounts for 14 functional groups, amongst which, seven correspond to different fish groups (pelagic fish, demersal fish, mesopelagic fish, tunas, bathypelagic fish, pelagic sharks, deep and benthic sharks and rays), where some correspond to commercially important species (e.g., *Thunnus obesus*). Simulations indicate a GPP (gross primary production) of 42 g O_2 d^{-1} (equivalent to 1312.5 mmole O_2 d^{-1}), a P/R of 0.88, and a total biomass of 3.83 t DW km^{-2}.

Despite the sinking behaviour of PCE and NTB, in terms of recovery time, it was AN that revealed the longest recovery period (~7 years). This is probably related to specific physico-chemical properties of AN that highly influence its consequent breakdown in the system, with further consumption of dissolved oxygen, leading to anoxic conditions and further mortality. Indeed, although unexpectedly, AQUATOX predicts a decrease in oxygen concentration promoted by the breakdown of the four HNS, which in turn leads to the mortality of biotic groups that are strongly limited by dissolved oxygen concentrations, particularly, at higher depths. Although these results require validation, the indirect effect of pollutants degradation on oxygen depletion with depths cannot be ruled out in case of HNS spills at sea.

According to EwE simulations, the food web structure of the MG hydrothermal field is rather simple, including only three trophic levels, with low predation pressure, with free-living bacteria and vent mussels playing major roles in shaping the ecosystem. Network analysis suggests a system under development that has not yet reached maturity. The simulations of the hypothetical spills of 4NP, AN, and NTB, at the MG, had no observable impacts on the local benthic community. Otherwise, the PCE accidental spill induced concentrations that surpass the acute toxicity levels for two functional groups in the MG trophic web, namely, vent gastropods and vent mussels, with a consequent reduction of 50% in their biomass, which subsequently led to several impacts on higher and lower trophic levels. Nonetheless, according to these preliminary results, the MG ecosystem would recover its initial state after ~ 20 years.

The results of the effects of the four HNS on the two studied deep-sea ecosystems must be regarded cautiously and, at this point, only as a theoretical exercise. In fact, if a protection factor of 100, 1000, 10.000 would be used to set the LC50 as frequently recommended in case of toxicity data gaps (Soares et al., 2020), the effects of the studied HNS on both the seamount and the vent field ecosystems would be much stronger, potentially, leading to the extinction of deep-sea communities. On the other hand, some of these organisms are adapted to extreme environmental conditions, including metal-enriched environments as is the case of the Atlantic deep-sea mussel (*Bathymodiolus* sp), and have developed mechanisms to cope with such extreme conditions (e.g., metallothioneins) (Company et al., 2007). We do not know if these adaptions would confer them some kind of protection against other type of pollutants.

Final remarks and recommendations

Developing the MODELRISK project allowed us to assemble and calibrate a numerical framework encompassing several different models, from circulation and Lagrangian dispersion models, to toxicology, food web and ecosystem models of Atlantic deep-sea ecosystems, to respond to HNS accidental spills at Sea. While innovative and timely, the presented framework requires further calibration and validation before it can be used as a decision-support tool in spill response. Most of the current limitations of the MODELRISK framework rely on knowledge gaps (Fig. 1B), namely:

- The absence of a numerical tool that describes the chemical transformations of HNS in the water column (horizontally and vertically), while describing their dispersion (the first version of a model that describes pollutants fate in the water has just been released-ChemicalDrift by OpenDrift - Aghito et al., 2023);
- Available ecosystem models are not, in general, appropriate to simulate chemosynthetic ecosystems and habitats (i.e., where energy is not produced by photosynthesis);
- There is a deep knowledge gap regarding chronic and acute toxicity of the most frequently transported HNS on marine and deep sea species;
- Available knowledge regarding the ecology and physiology of some marine species and most deep-sea species is rather limited.

Hence, we recommend that future research may tackle the aforementioned points. Subsequently, modellers can improve the calibration, verification and, ultimately, the validation of the MODELRISK framework, allowing it to be used as a support tool in HNS spill response at Sea.

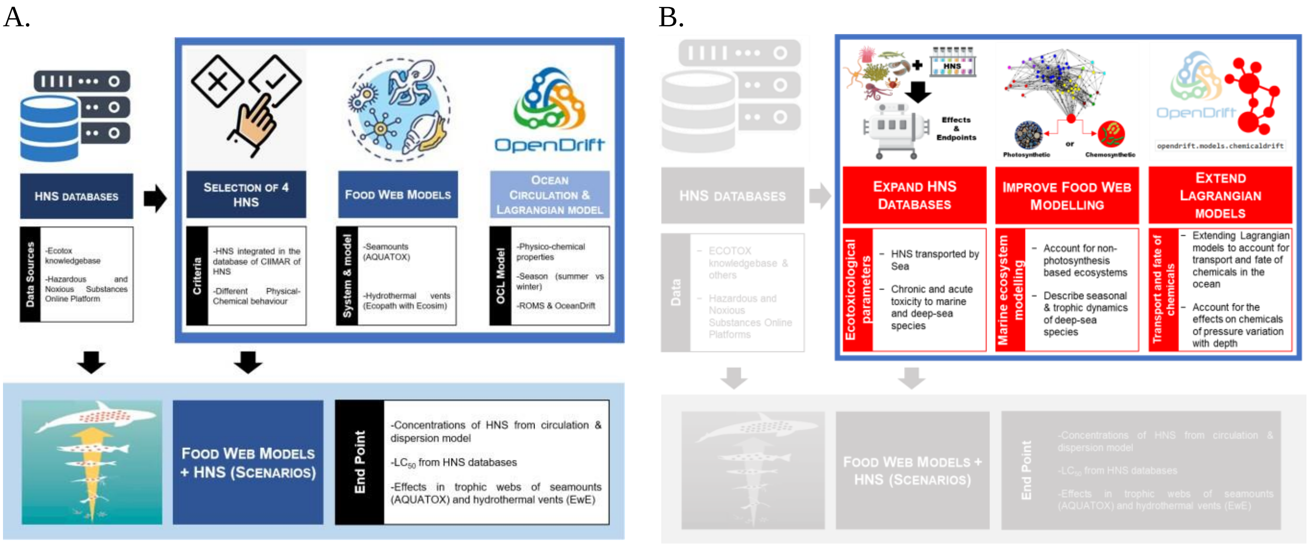

Fig.1 – A. Workflow; B. Recommended research efforts to tackle the limitations identified.

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