# A global approach to mapping the environmental risk of commercial harbours on aquatic systems


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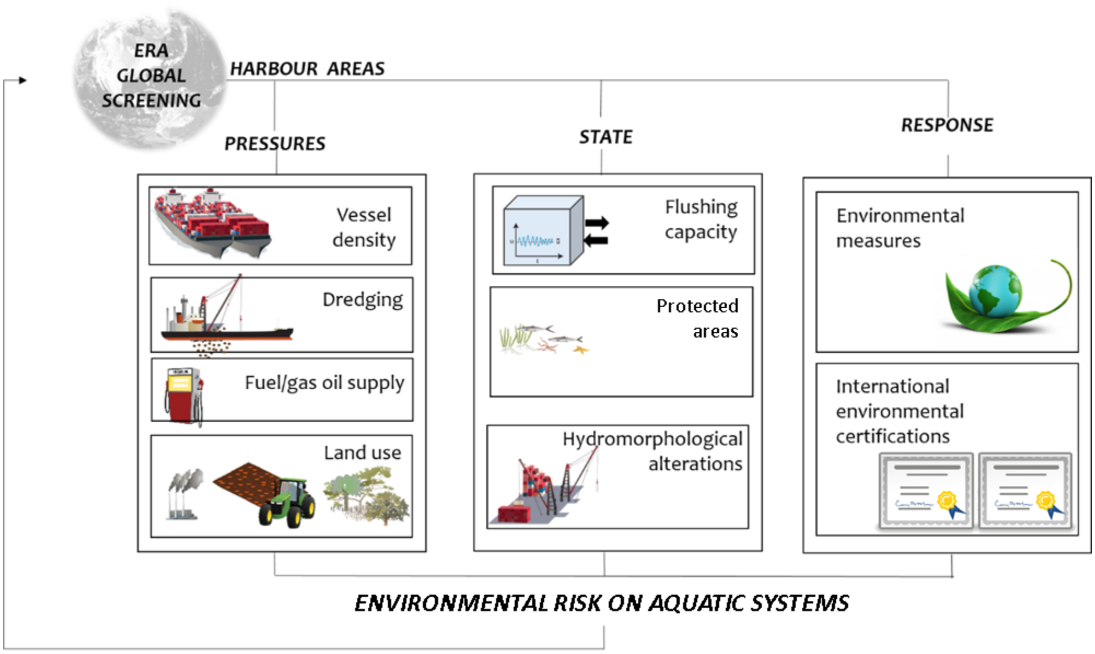
# A global approach to mapping the environmental risk of harbours on aquatic systems

## Highlights:

- A method is proposed to assess the environmental risk of ~~commercial~~ harbours on aquatic systems.
- The method is a tool to identify the factors of risk on harbour aquatic systems
- Results obtained from 15 globally distributed harbours are analysed
- Towards the creation of a global atlas of environmental risk of harbours on aquatic systems

## Graphical abstract:




## Abstract:

The goal of this paper is to propose a screening method for assessing the environmental risk to aquatic systems in harbours worldwide. A semi-quantitative method is based on environmental pressures, environmental conditions and societal response. The method is flexible enough to be applied to 15 harbours globally distributed through a multinational test using standardised and homogenised open data that can be obtained for any port worldwide. The method emerges as a useful approach towards the foundation of a global

environmental risk atlas of harbours that should guide the harbour sector to develop a more globally informed strategy of sustainable development.

**Keywords:** environmental risk assessment; global atlas; pressure-state-response model; harbour aquatic systems; harbour management; sustainable development.

## 1. INTRODUCTION

Shipping has an important role in moving about 90% of global trade, which is vital for the continuing and sustainable development of the world economy (ICS, 2018; 2019). The shipping sector is projected to continue to expand in the future with an estimated annual growth rate of 3.2% by 2017-2022 (UNCTAD, 2017). The relevance of this sector for world trade has placed this industry at the centre of a policy debate on globalisation, trade, development and environmental sustainability (UNCTAD, 2012). Harbours are continuing to expand to accommodate the infrastructure required to support growth in the shipping industry (UNCTAD, 2012). This growth increases the likelihood of environmental damage, which, to some extent, is being mitigated by harbour authorities embracing a sustainable development approach (EC, 2013). Shipping, alongside the many other marine activities, generates several threats of varying severity to marine ecosystems (Gómez et al., 2014; Knights et al., 2015; Valdor et al., 2017), and harbours themselves can be some of the most impacted habitats on Earth (Halpern et al., 2008).

The environmental sustainability of harbours needs to be focused on preventing the impoverishment of aquatic systems caused by pollution from commercial ships or other navigation activity. Harbours are guided and regulated by international legislation that aims to limit ecosystem exposure to harmful activities. International bodies, like the International Maritime Organisation (IMO), continue to develop legal frameworks to mitigate environmental harm as a result of commercial shipping (e.g. IMO, 2004; 2013; 2014 or Lethbridge, 1991), and they set the appropriate standards through international treaties and conventions. Others, such as the World Association for Waterborne and Transport

Infrastructure (PIANC), provide expert guidance (PIANC, 2019), recommendations (PIANC, 2011) and technical advice (PIANC, 2020) on environmental issues related to both recreational and commercial navigation activity (Brolsma, 2010). The maintenance of high-quality aquatic systems (e.g. by preventing marine pollution) is a permanent and universal goal of these conventions, guidelines and the research developed by these international organisations. Consequently, water quality has been one of the top 10 environmental priorities of the harbour sector over last years (2003-2009) (ESPO-ECOPORTS, 2019).

Scientific research that provides an evidence-based for decision-making related to environmental risk on harbour aquatic systems is conducted by projects like the World Harbour Project (WHP) (www.worldharbourproject.org, Steinberg et al., 2016). This project enhances research and management across major urban harbours. To develop resilient urban harbours, a global network of collaborating scientists works on different topics such as ecological engineering (Strain et al., 2019), environmental management (Valdor et al., 2019), accessible syntheses and summaries of current knowledge (e.g. Juanes et al., 2020). Thus, research programs should be responsible in developing science and communicating findings in an accessible way to a wide range of users to facilitate the design of global strategies. We suggest that global strategies are needed to ensure that harbour managers worldwide are able to assess the environmental risk on aquatic systems using an easy-to-apply and versatile method. In this context, one of the main objectives of global strategies is to provide standardised methods to analyse risk. In this way, data among different harbours are comparable, and their management can be adjusted to the best available practices regarding limiting environmental risk.

However, when global strategies are designed, the harbours' histories, the geomorphological and environmental contexts and the socio-economic settings are very different across the world (Steinberg et al., 2016) and thus may affect approaches to environmental management. In that context, the Environmental Risk Assessment (ERA) arises as a general management tool that is used worldwide to assess potential effects on the environment due to the exposure to disturbing agents derived from different human activities (e.g. fishery, industry, urban, agricultural or harbour activities, among others) (AENOR, 2008; Hope, 2006; Smith et al., 2007; Samhouri and Levin, 2012; Valdor et al., 2016). Using the ERA approach, the potential effects of environmental hazards on the quality of aquatic systems in harbour areas have been widely studied (e.g. Ronza et al., 2006; Grifoll et al., 2010; Gómez et al., 2015; Ondiviela et al., 2012; Parra et al., 2018), and methods to assess the environmental risks of harbour activities have been proposed (e.g. Gómez et al., 2015; Juanes et al., 2013; Ondiviela et al., 2012; Puig et al., 2015; Valdor et al., 2016). However, worldwide studies to assess the environmental risk of harbour activities on aquatic systems to support global strategies, such as Global Sustainable Development Goals (United Nations, 2015), have not been conducted.

Harbours around the world implement different environmental management methods that make use of different approaches to the characterisation of systems, use different analytical tools and databases, thus making it challenging to obtain standardised quantitative data globally (PIANC, 2019). For this reason, qualitative and semi-quantitative data analyses are more suitable alternatives when conducting an ERA study at a global scale (Gómez et al., 2019). Moreover, parameters, indicators, and assessment criteria should be carefully selected to integrate the singularities of each specific harbour (Darbra et al., 2005; Gupta et al., 2005). We suggest that, at the same time, the simplicity and low computing cost of the method should allow for wider applicability to harbours of different sizes, hydrodynamic characteristics, harbour uses and pressures or resources to assess environmental challenges.

The goal of this paper is to propose a method for mapping the assessment of the environmental risk of harbours on aquatic systems. This method will be: i) flexible enough to be applied to any harbour worldwide; ii) open-data dependent; and iii) implemented to lay the foundation to create a global atlas of environmental risk on aquatic systems of harbours.

The proposed method is tested by applying it to 15 harbours spread across five continents worldwide. The main contributions of this study are: (i) the development of a standard and unified ERA method to assess environmental risk of harbour activities worldwide on aquatic systems (Section 2); (ii) the implementation of the ERA method in 15 harbours around the world (Section 3); and (iii) the discussion of the proposed method and the results obtained in the implementation (Section 4).

## 2. MATERIALS AND METHODS

The semi-quantitative method providing an assessment of environmental risk on aquatic systems is based on the Pressure-State-Response (PSR) model defined by Gómez et al. (2019) for marinas. The method comprises the following three steps: i) identification of harbours and data collection; ii) estimation of the risk factors (environmental pressures of harbour activities on the aquatic system, environmental conditions and management responses); and iii) assessment of environmental risk.

### 2.1 Identification of harbours

Harbours are classified based on the typologies defined by the US National Geospatial-Intelligence Agency (2015) into: i) coastal natural harbours are harbours that are sheltered from the wind and sea due to their location within a natural coastline or occur in the protective lee of an island, cape, reef or other natural barrier, or harbours that are located along a river; ii) coastal breakwater harbours are harbours located behind a human-made breakwater that are constructed to provide shelter or supplement inadequate shelter already provided by natural resources; and iii) natural river harbours are harbours in which slips for vessels have been excavated in the banks obliquely or at right angles to the axis of the stream.

For this study, general data, hydro-morphological characteristics and environmental management information was gathered globally at all 15 harbours through a standardised form (Supplementary Data. Appendix A) and through other sources of information (e.g., official harbour webpages).

## 2.2 Estimation of environmental risk

Environmental risk assessment at the harbour level was based on three factors: i) Pressures from human activities exerted on the environment; ii) State, or the environmental conditions that relate to the quality of the environment; and, iii) Response, or the extent to which the harbour responds to environmental concerns (OECD, 2003) (Eq.1).

Accordingly and based on Gómez et al., (2019), environmental risk of harbours on aquatic systems was estimated through the following formulas:

$$Ri = Pti \times Sti + Rsi \quad \text{(Eq. 1)}$$

$$Ri = (NVi + HSi + HOi + CDi) \times (SUi + EVi + NAi) + (AMi + AIi) \quad \text{(Eq. 2)}$$

Where R is the environmental risk, Pt is the Pressure, St is the State and Rs is the Response of an *i* harbour. Pressure is estimated considering the navigation activity (NV), the harbour services (HS), the harbour operation (HO) and the coastal development around the harbour (CD). While, State is estimated by combining the susceptibility (SU), the ecological value (EV) and the naturalness (NA). Finally, Response was estimated through the adopted measures (AM) and the Adopted Instruments (AI).

Estimation of environmental risk was evaluated using a semi-quantitative assessment criteria that was based on a combination of specific indicators, representative of a number of selected parameters for each factor (Table 1).

Table 1. Parameters, indicators, metrics and criteria assessment to estimate each environmental risk factor. (i: a specific harbour; max: maximum value obtained for a parameter considering all harbours under study; ISO: International Organisation for Standardisation; EMAS: Eco-Management and Audit Scheme; PERS: Port Environmental Review System). Unless specifically indicated by appropriate references to the source paper indicators were originally developed here.

| Factor | Parameter | Indicator and metric (units) | Criteria assessment |
|---|---|---|---|
| ***Pressures*** | ***Navigation Activity (NV)*** | ***Density of trade vessels*** (vessels per year/$m^2$) by dividing vessels per year by the surface water area where the harbour activities take place. | $NV_i/NV_{max}$ [0-1] |

| | | | | |
|---|---|---|---|---|
| | ***Harbour Services (HS)*** | ***Harbour services:*** presence (1) or absence (0) of fuel oil and diesel oil supplies, major repair services and dangerous/hazardous goods handling within the area where the harbour activities take place (Valdor et al., 2016*)*. | $HS_i/HS_{max}$ [0-1] | |
| | ***Harbour Operation (HO)*** | ***Dredging probability,*** frequency of dredging operations. | Continual<br>Periodic<br>None | 1.0<br>0.5<br>0.0 |
| | ***Coastal Development (CD)*** | ***Land uses*** developed in a 1-km buffer distance around the harbour (worst case scenario) (Gómez et al., 2019). | Artificial<br>Agricultural<br>Natural - Other uses | 1.0<br>0.5<br>0.0 |
| ***State*** | ***Susceptibility (SU)*** | ***Flushing capacity*** of the water volume where harbour activities take place, combining hydrodynamic and morphological characteristics through the Complexity Tidal Range Index (CTRI*) (Gómez et al., 2017). | $CTRI^*_i/CTRI^*_{max}$ [0-1] | |
| | ***Ecological Value (EV)*** | Number of ***Protected areas*** (#) in a 1-km buffer distance around the surface water area where the harbour activities take place (Gómez et al., 2019). | $EV_i/EV_{max}$ [0-1] | |
| | ***Naturalness (NA)*** | ***Alteration by hydro-morphological pressures*** in a harbour's environment (harbour's typology) (US National Geospatial-Intelligence Agency, 2015) | Open Roadstead<br>Natural (Coastal or River)<br>Coastal Breakwater/ River Basin<br>Tide Gates (Coastal or River)/Canal or Lake | 1.0<br>0.75<br>0.5<br>0.0 |
| ***Response*** | ***Adopted Measures (AM)*** | Number of ***adopted measure***s (#) to reduce the pressure of human activities on the environment (garbage disposal, dirty ballast management, etc.) (Gómez et al., 2019). | $AM_i/AM_{max}$ [0-1] | |
| | ***Adopted Instruments (AI)*** | Number of ***adopted standards*** (#) to improve the environmental performance (ISO 14001, EMAS, PERS, others.) (Gómez et al., 2019). | $AI_i/AI_{max}$ [0-1] | |

$*CTRI_i = \left[1-\frac{4\times A}{\pi\times L^2}\right]\times\frac{e}{R}$ Where A is the surface water area where the harbour activities take place (m²), L is the diameter of the smallest circle enclosing the surface water area polygon (m), e is the minimum distance between the harbour's infrastructures or the natural elements that conform the harbour's entry (m) and R is the medium tidal range (m) (Gómez et al., 2017).

The range of the potential values of all parameters were normalised (varying from 0 to1) by dividing the observed value by the maximum value, after discarding outliers for each parameter with values greater than x □± 3·SD (Gómez et al., 2019).

### 2.3. Environmental Risk Assessment

To assess the environmental risk to the harbour's aquatic systems, the results of pressure and state factors were classified into four categories (1 to 4), while the response factor was categorised by assigning one of either values: 0 or 4 (Table 2, Eq. 2). Levels separating the different categories were established for all harbours under study using the 25th, 50th and 75th percentile values, with the 50th percentile value used as the threshold between optimal and insufficient response (Table 2).

Table 2. Criteria to assess Pressures ($Pr_i$), State ($St_i$) and Response ($Rs_i$) categories from study site results (VL: Very low; L: low; M: moderate; H: high; P25: 25th Percentile; P50: 50th Percentile; P75: 75th Percentile).

| Factor | Category | Criteria | Thresholds |
|---|---|---|---|
| **Pressures (Pr)** | VL (1) | Pri ⩽ P25 | Pri ⩽ 2.11 |
| | L (2) | P25 < Pri ⩽ P50 | 2.11 < Pri ⩽2.51 |
| | M (3) | P50 < Pri ⩽ P75 | 2.51 < Pri ⩽ 2.58 |
| | H (4) | Pri > P75 | Pri > 2.58 |
| | VL (1) | Sti ⩽ P25 | Sti ⩽ 0.95 |
| **State (St)** | L (2) | P25 < Sti ⩽ P50 | 0.95 < Sti ⩽ 1.10 |
| | M (3) | P50 < Sti ⩽ P75 | 1.10 < Sti ⩽ 1.37 |
| | H (4) | Sti > P75 | Sti > 1.37 |
| ***Response (Rs)*** | Optimal (0) | Rsi ≥ P50 | Rsi ≥ 0.75 |
| | Insufficient (4) | Rsi < P50 | Rsi < 0.75 |

Obtained scores at the factor level (Table 2) were used to estimate the environmental risk of each harbour through Eq. 1. Based on the environmental risk value (Eq. 1), each harbour was classified considering three categories: (i) high-risk harbour (Ri ≥ 12), (ii) moderate-risk harbour (6 ≤ Ri < 12), (iii) low-risk harbour (1 ≤ Ri < 6).

# 3. RESULTS

## 3.1. Identification of harbours

The twenty-seven partners of World Harbour Project network were invited to participate to test the developed ERA method (Steinberg et al., 2016). Fifteen WHP partners were able to encourage harbour managers from their respective cities to participate and to gather the needed information. WHP partners contacted harbour managers by email or phone, and meetings were conducted when necessary. The fifteen harbours, where the developed ERA method was tested, spanned Europe (Dublin, Heraklion, Plymouth, Santander, Ravenna and Vigo), Australasia (Ashdod, Auckland, Darwin, Hobart, Hong Kong, Qingdao and Sydney) and the Americas (Baltimore and Rio de Janeiro) (Figure 1). “Coastal natural harbour” was the typology best represented by seven harbours (Rio de Janeiro, Qingdao, Hong Kong, Santander, Vigo, Darwin and Sydney), followed by “coastal breakwater harbours” represented by four harbours (Ashdod, Dublin, Heraklion, and Ravenna) and “natural river harbours” represented by four harbours (Baltimore, Plymouth, Auckland and Hobart) (Figure 1).

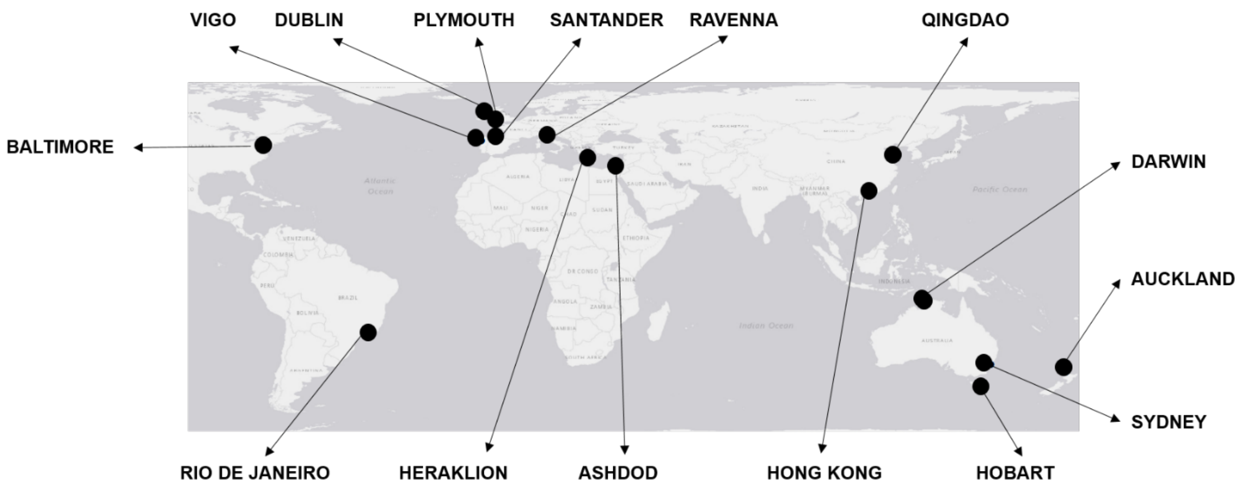



Figure 1. Harbours assessed using the ERA method.

The standardised form (Appendix A) was used to gather information from harbour managers. Harbour managers sent the filled-in form through email to their respective local WHP partner. In addition to consulting with harbour managers, where possible, data collected was cross-checked using global, national (e.g. puertos.es) and local resources or was specifically sourced from each harbour (e.g. the official web page of each harbour). Using these sources of information, a database of metrics was generated for each harbour.

### 3.2. Estimation of environmental risk

The environmental risk assessment process provided explicit information on the parameters of risk. To define the spatial scope, a polygon of the surface area of the water where harbour activities take place was first digitalized using ArcGIS software. Harbour managers were asked to approve the delimitation of these areas. The resulting polygons indicated harbour surface-water areas (Supplementary data. Appendix B). The tools "extract by mask" and "Clip" from the ArcGIS software were used to recognize both land uses and protected areas in 1-km buffer around each harbour, using Globe Land 30 (Chen et al., 2015) and World Database on Protected Areas (UNEP-WCMC, 2016), respectively. Mean tidal range (R, m), as a hydrodynamic characteristic, was calculated from the GOS dataset (Cid et al., 2014); morphological characteristics were estimated for each harbour using ArcGIS techniques, including area (A, $m^2$), applying the "calculate geometry" tool; length (L, m) and entrance width (e, m), using the "minimum bounding geometry" tool (Gómez et al., 2017).

*Pressures*: Normalised values of navigation activity (NV) were extremely variable among the studied harbours. Ashdod had the highest density of trade vessels (1), followed by Ravenna (0.18), Dublin (0.16), Qingdao (0.15) and Rio de Janeiro (0.11), while the other harbours showed normalised values lower than 0.07 (Figure 2, NV). Most harbour areas showed the maximum value of Harbour Services (HS), since 10 of the 15 study sites develop fuel oil and diesel oil supplies, major repair services and dangerous or hazardous goods handling activities (Figure 2, HS). Exceptions to this were Hobart and Plymouth, where fuel oil supply and major repairs are not developed, and Heraklion and Ravenna, where dangerous or hazardous goods handling is not carried out. Harbour Operation (HO) was estimated through dredging activities, which ~~is~~ are periodic ~~operation~~ in most of the harbours (0.5) apart from Ashdod and Hong Kong, where continual dredging operations are undertaken (1), and Hobart and Qingdao, where dredging operations are not carried out (Figure 2, HO). Normalised Coastal development scored 1 in nearly all the harbours, since the land use around the harbours was mainly artificial (urban, mining or industrial). Only one harbour (Darwin) presented natural land uses in its surroundings (Figure 2, CD).

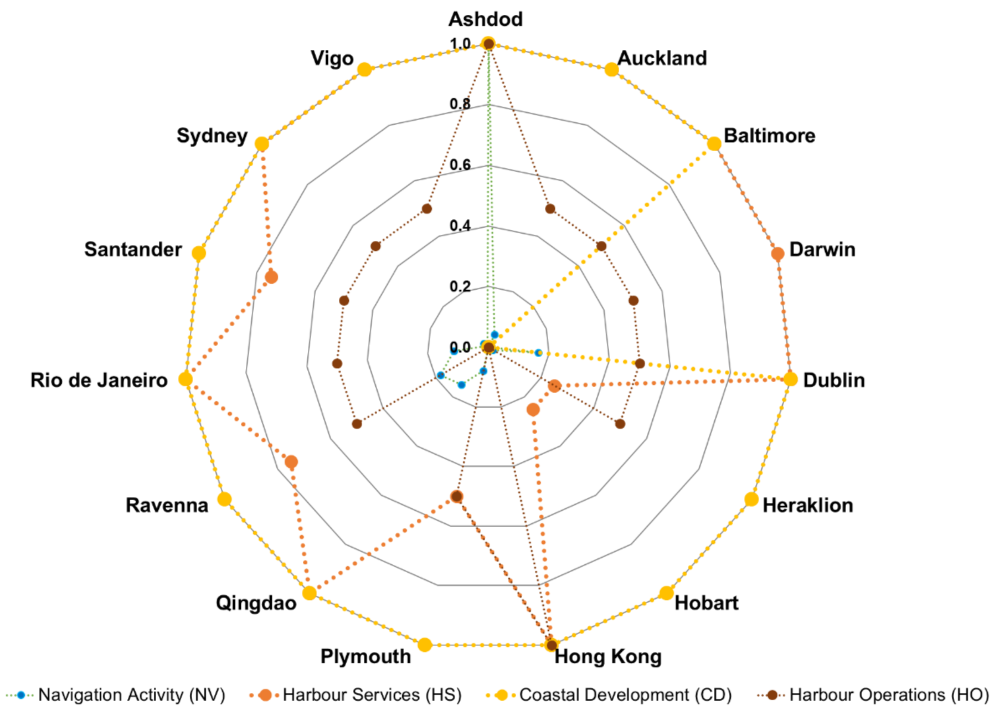



Figure 2. Representation of normalised values of the parameters applied for the estimation of the environmental pressures (Pressures) at each of the 15 studied harbours

*State*: Susceptibility (SU, a measure of flushing capacity) was the most variable parameter of State in all the 15 harbours studied (Figure 3, SU) as it is related to the cleaning capacity of the water volume, which combines hydrodynamic and morphological characteristics at the harbour level. The main characteristics of the harbours that were responsible for this variability were the differences in water surface area (~0.8 km$^2$ in Plymouth, to 36.73 km$^2$ in

Darwin), the minimum distance between the elements that conform the harbour's entry (~0.2 km in Ravenna to ~316 km in Darwin) and the variability in tidal ranges (microtidal in the Mediterranean to a 5 m tidal range in Plymouth). Regarding the Ecological Value (EV), the number of protected areas located in a 1-km buffer ~~distance~~ around the harbour's water surface area varied among the different harbours: 0 (five harbours), 1 (four harbours), 2 (two harbours), 4 (two harbours) and 6 (two harbours) (Figure 3, EV). Conversely, naturalness (NA) showed similar values at all harbours, with most of them (11) with a normalised NA value of 0.75 and only 4 harbours with 0.5 (Figure 3, NA).

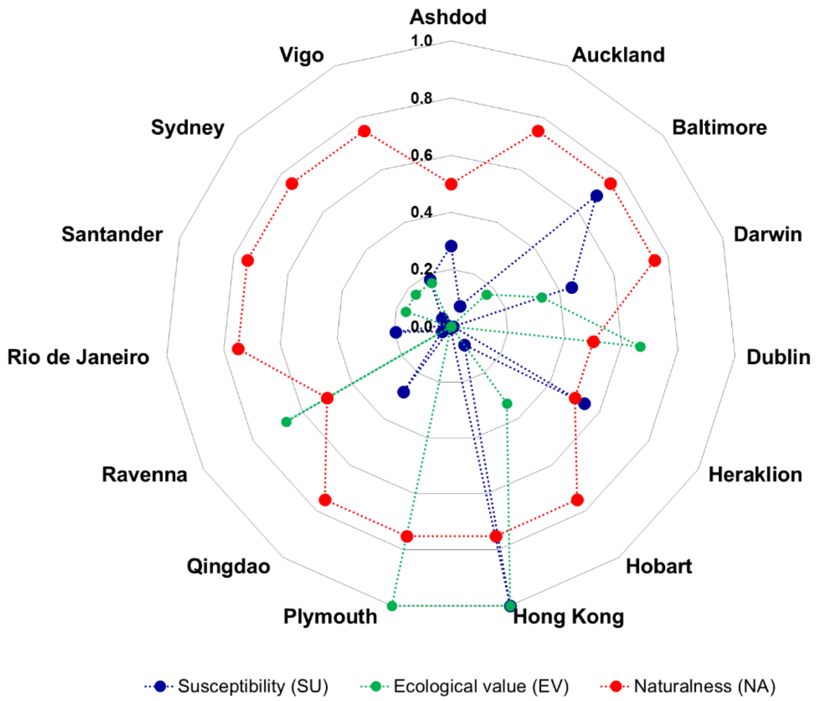



Figure 3. Representation of normalised values of the parameters applied for the estimation of environmental conditions (State) at each of the 15 studied harbours.

Response: All studied harbours implemented a minimum of 3 Adopted Measures (AM) to reduce the pressures of human activities on the environment (AM normalised value ≤ 0.5), with 8 being the maximum number of measures applied in Qingdao and Baltimore (1 AM normalised value) (Figure 4, AM). A higher variability was registered in the number of Adopted Instruments (AI), with eight harbours where no instruments to achieve international standards were applied, four harbours where 1 was adopted, two harbours where 2 instruments were applied and one harbour where 3 international instruments were applied (Figure 4, AI).

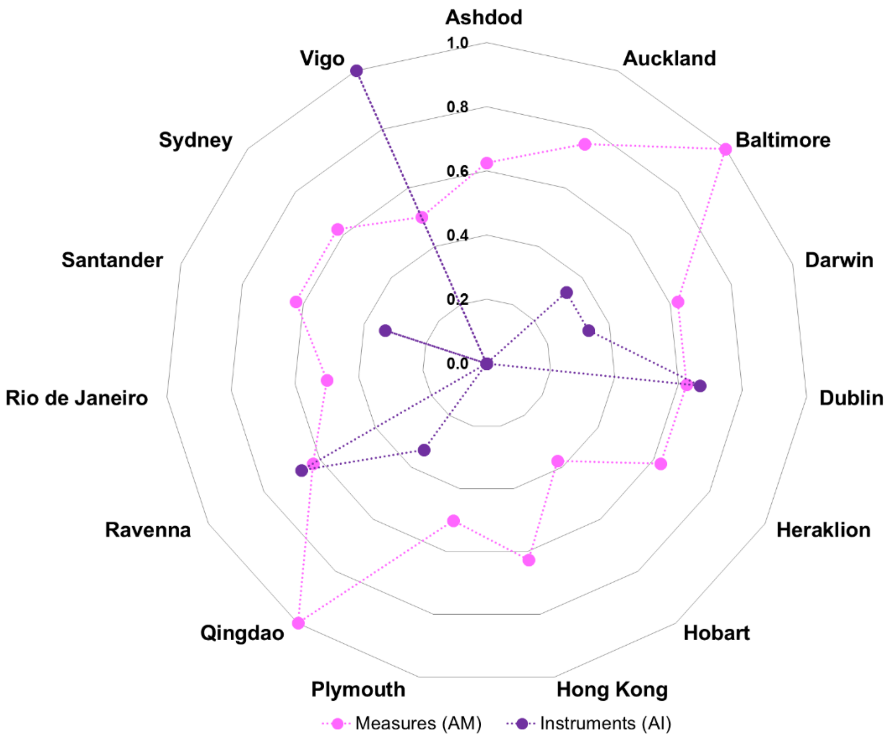



Figure 4. Representation of normalised values of the parameters applied for the estimation of level of response (Response), at each of the 15 studied harbours.

### 3.3. Environmental risk assessment

In terms of Pressure categories, two harbours were assessed to have high environmental pressure with four harbours assessed as being moderate. This was followed by a total of six harbours that were assessed as having low environmental pressures and, finally, three harbours with very low associated pressures (Figure 5, Pressures in blue bars). Regarding the State factor, four harbours were classified within the high category, with three harbours showing moderate environmental conditions and a total of eight harbours within the low and very-low categories (Figure 5, State in yellow bars). Finally, 7 of the 15 studied harbours showed insufficient environmental management, while 8 harbours presented an optimal level of management Response (Figure 5, Response in green bars).

The most frequent category of risk was moderate; 8 of the 15 harbours studied presented moderate risk, 5 harbours presented low risk, while 2 harbours presented a high environmental risk to aquatic systems (Figure 5, Environmental risk in red bars).

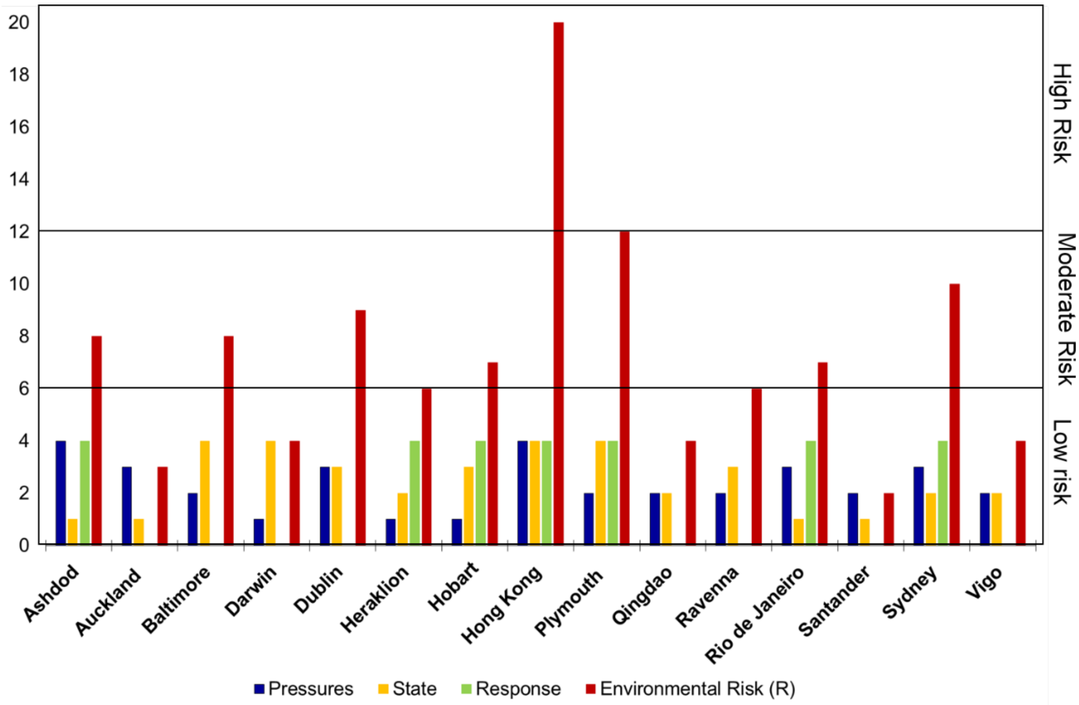



Figure 5. Graphical representation of categorised risk factors (Pressures, State and Response) and categorised environmental risk to aquatic systems at each of the 15 studied harbours.

Results of environmental risk to aquatic systems of harbours, based on this study's results are shown in Supplementary data Appendix B.

## 4. DISCUSSION

### 4.1 Why this ERA method?: The conceptual model

From a conceptual point of view, the Pressure-State-Response (PSR) model (OECD, 2003) is used as a framework to select indicators that assess environmental risk at the harbour level, based on Gómez et al., (2019). Moreover, the Driving force-Pressure-State-Impact-Response (DPSIR) model (EEA, 2005) is integrated in the PSR model to define specific indices of Pressure, State and Response. These indices group and classify a small number of indicators (Figure 6).

From a practical point of view, the selection of general-purpose indicators for global assessments was complex because of the need to obtain homogeneous, objective and systematic, open and publicly available data and information on a series of diverse parameters from analogous entities (harbours) that are under different socio-ecological contexts from all over the world. Indicators were selected based on: i) the complementarity and non-redundancy of indicators in their representation of risk factors; ii) the possibility of finding available and homogeneous data from harbours worldwide, and iii) state-of-the-art and previous studies.

Driving forces describe the social, demographic and economic development within a given harbour (EEA, 2005). Based on the conceptual model presented (Figure 6), indicators selected to estimate the environmental pressures include the four main driving forces relevant to the harbour areas (navigation, harbour services, harbour operation and coastal development). Navigation activity, estimated as the number of trade vessel visits per year by a water-surface area of a harbour, was selected, as it has been identified in previous works as a representative environmental stressor (Antão et al., 2016) and it is easily accessible from institutional statistics (e.g. Eurostat, or individual webpages of harbours). Regarding Harbours Services (HS), two indicators were selected: i) major repair services (shipyards, ship repair or painting, etc.) that generate chemical wastes (heavy metals, PAHs and antifoulants), which can pose a risk to aquatic organisms inhabiting harbour areas (Bebianno et al., 2015); and ii) dangerous/hazardous goods handling defined by IMO codes (IMO, 2014), which were previously considered in ERA mapping studies on harbour systems (e.g. Valdor et al., 2016). Furthermore, dredging, one of the most important operations and maintenance activities within harbours (PIANC, 2006), and dominant land use in the surrounding area, served as proxies of the external influences on water quality (Cornelissen et al., 2008).

Indirect or direct pressures are identified by each driving force (Gómez et al., 2019). The identified pressures produce impacts altering the state of the environment (Ondiviela et al., 2013; Petrosillo et al., 2010). State factor of risk considers three important aspects of the harbour's environment: susceptibility, ecological value and naturalness. From the eight pressure indicators proposed in the conceptual model (Figure 6), there are three related to quality of the aquatic system (chemical quality, physico-chemical quality and biological quality) that require periodic monitoring and systematic evaluation. Since each country applies different monitoring and evaluation systems (in terms of thresholds, frequency, etc.), the susceptibility to water and sediment contamination was considered as a standard representative indicator of the quality of the aquatic system of harbours worldwide, assuming a significant relationship between flushing capacity and water quality in littoral areas (Ferreira et al., 2005; Fortes and Silva., 2006; Gómez et al, 2014; Yin et al., 2000). This assumption was previously used for ERA in marinas (Gómez et al., 2017) and harbours (Gómez et al., 2015). The harbour's ecological value considered that the greater the protected area in the vicinity of the harbours is, the greater the biodiversity and ecological processes that maintain that system (Gómez et al., 2015; Langanke et al., 2005; Margulles and Usger, 1981). Finally, their 'naturalness' (Machado, 2004) was estimated using the harbour typology (US National Geospatial-Intelligence Agency, 2015) as a surrogate of number and dimensions of hydro-morphological pressures at the marina level typology (Gamito, 2008; Gómez et al., 2019).

The response factor to environmental risk was used to integrate the actions and reactions, intended to mitigate, adapt to or prevent human-induced negative effects on the environment that could be applied to minimize the impacts of driving forces and improve the state of aquatic ecosystems (OECD, 2003). Responses may arise from different sectors, such as those in social, technical or institutional (i.e. local, national or international administrations) realms (Figure 6). Among all of them, institutional responses are the option that integrates a greater number of fields involving social responses (awareness campaigns), institutional responses (policy and strategies) and technical responses (research). For this reason, the implementation of different kinds of well-known international measures (e.g., garbage disposal, oil recycling, ballast water management, among others) and international standards (e.g. EMAS, ISO, PERS, among others) was considered an appropriate indicator to estimate the response factor.

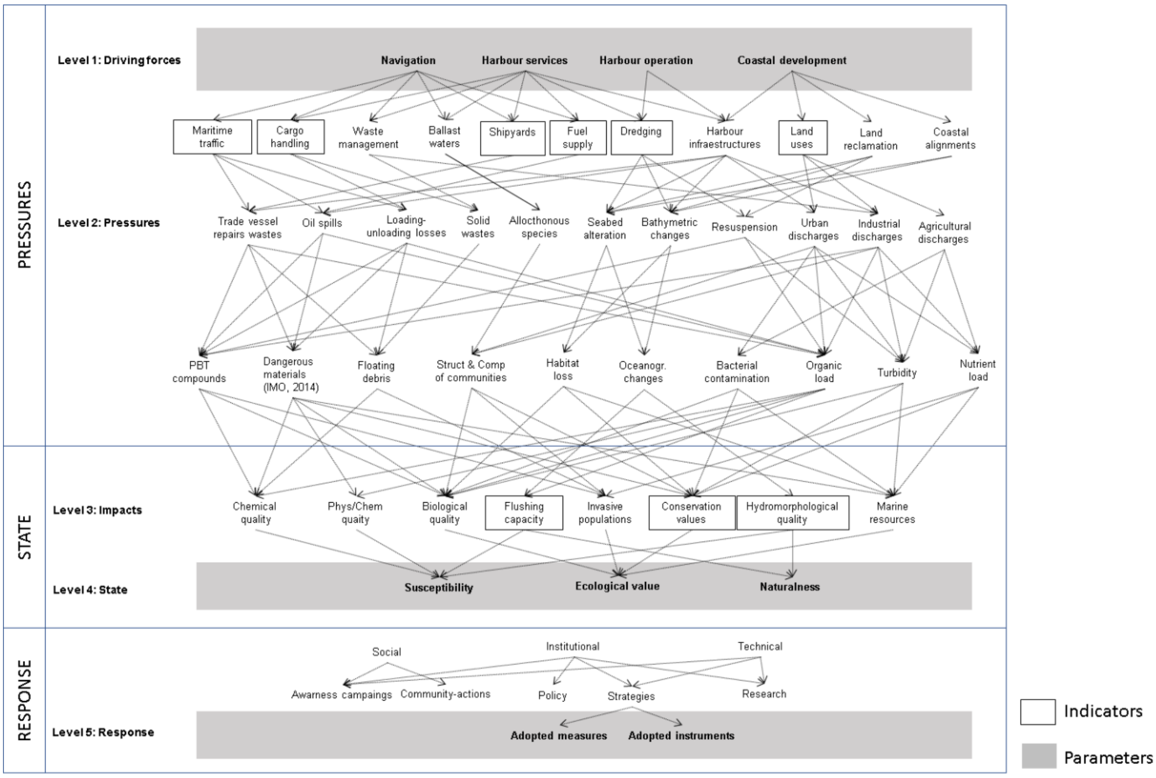



Figure 6. Conceptualisation of the causal links between main driving forces, pressures, impacts, state and response of aquatic systems in harbours.

**4.2 The global implementation**

Based on this study's results, the method used provides a tool to standardize the assessment of environmental risk to aquatic systems at a global scale (Supplementary data Appendix B). However, a question arose from this implementation: Are the PSR and DPSIR scenarios of the study sites representative of the environmental risks of harbours globally? ERA results showed that most of the study areas had a moderate risk but included significant variability of environmental pressures, environmental conditions and societal responses. However, results showed differences at the indicator level in those harbours within the same category of risk. For instance, Hobart showed a moderate environmental risk on the aquatic system due to a combination of high vulnerability (high naturalness but a moderate ecological value of the surroundings) with a high score of environmental management (due to the low number of adopted measures and none of the international standards implemented). Heraklion showed a moderate risk on the aquatic system even though they were adopting a good number of environmental measures (above the average) to reduce the pressure of human activities on the environment because no international environmental management instruments were applied. In other cases, the higher susceptibility (Baltimore) or the higher ecological value (Ravenna), were the parameters of risk that penalised the result for these harbours. Identification of such risk parameters allows for the targeted application of more preventive and corrective management actions to help reduce environmental risk to aquatic systems for those specific harbours.

Therefore, from a practical perspective, the environmental risk assessment method can be used as a tool to proactively identify the most important factors of risk on which to apply actions that allow for environmental improvements in each.

For this, expert knowledge on environmental risk is not strictly necessary, but a deep understanding on the environment harbour characteristics is needed. These data are controlled and known by harbour managers. In Section 2, practical steps are described considering parameters, indicators, metrics and criteria to estimate each risk factor. The pathway to apply the ERA method to an individual harbour include the collection of the information needed and the calculation of parameters for each risk factor. A standardized form to gather the information is provided in Appendix A and calculations described at Section 2 are easy to apply with a basic knowledge of spatial analysis using geographical information systems.

Once applied, the method can be used to detect which harbours should apply environmental measures or/and international standards to improve their management of aquatic systems, based on the highest standards of environmental quality applied around the world. An example of this is shown in Figure 7, which represents the hypothetical case in which the 15 harbours analysed for this implementation applying eight environmental measures (such as garbage disposal, dirty ballast management, waste management, bilge management, sewer pump-out, oil management) and 1 international standard (Figure 7). As all harbours apply the maximum number of environmental measures and standard certifications, the value of the response factor is 0 (optimal response) for all the harbours analysed. For this reason, the green bars are not observed in Figure 7.

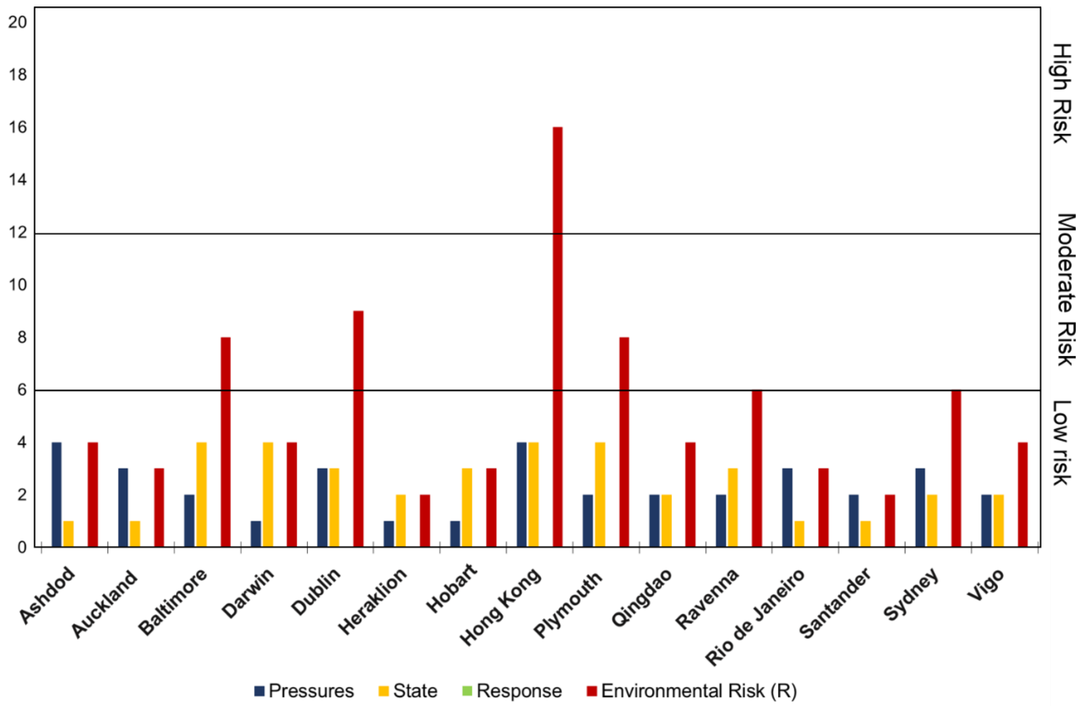



Figure 7. Graphical representation of a hypothetical situation at each of the 15 studied harbours with reduced categorised risk factors (pressures, state and responses) by the application of at least 4 environmental measures and 1 international standard and categorised environmental risk to aquatic systems.

In this case, one harbour continues to show high risk, five harbours show moderate risk while the other nine show a low environmental risk on the aquatic system. The screening capacity of this tool may address the global challenge of standardizing methods that produce comparable risk assessments of high-level entities (e.g. harbours) at large spatial scales. However, if the harbours applying the environmental measures and certifications do not obtain a low value of environmental risk, they should then focus their efforts on reducing the environmental risk factors that are penalizing the final value of environmental risk. This is the case in Hong Kong, which has high pressures due to the presence of intense navigation activity (NV), the harbour services (HS) provided in the harbour, the continual dredging activity (DG) in the harbour area and the Coastal development (CD) in their surroundings. Baltimore is also highly susceptible probably due to the morphological characteristics of the harbour area, which is very difficult to change from an environmental management standpoint. In these cases, socio-economic issues should also be incorporated into a long-term sustainability or management plan, which must assess the disadvantages and benefits that may result from modifying factors that penalized the final value of the environmental risk.

To the extent that harbours collaborate by providing the necessary information for the calculation of environmental risk, it will be possible to create a global atlas of risk. Collaboration by harbours will be feasible as long as the global atlas were understood as a participatory process towards the sustainability of aquatic systems, recalling the adoption of the 2030 Agenda and its Sustainable Development Goals (SDG, in particular SDG 14) and the more recent resolution of the UN on the Decade for Ocean Sciences (2021-30), which will provide a unifying framework across the UN system to enable countries to achieve all of their ocean-related Agenda 2030 priorities (IOC, 2017).

The global atlas developed by using the method presented herein would introduce valuable ~~bring the~~ elements of judgment to guide managers involved in decision-making (AENOR, 2008) towards the sustainability of aquatic systems in harbour areas, as well as to design the first global strategy for sustainability related to the water quality at a global level. Sustainable development goal (SDG) 14 in the UN 2030 Agenda requires to “conserve and sustainably use the oceans, seas and marine resources for sustainable development” (United Nations, 2015). Global Sustainable development goals require global analysis of the problems presented and definition of global strategies to resolve them. Many critical management and conservation challenges of aquatic systems in harbour areas are inherently spatial issues (Valdor et al., 2016). As new spatial data are collected on the distribution and intensity of harbour activities, this will allow for more flexible and adaptive environmental management processes to identify global environmental problems and possible sustainable solutions through an environmental risk assessment approach.

Future work could improve the current Atlas through the collection and comparison of more data from more harbours across the globe, and it also could test for the robustness of this approach. In addition, new indicators could be developed to improve the method proposed. For example, the navigation and docking of cruise ships or fishing vessels could serve as a complementary indicator for the parameter of risk related to navigation activity (NV), and an international connectivity index of harbours could be an indicator of the potential environmental risks from invasive species.

## 5. CONCLUSIONS

In this study, we present the first example of an Environmental Risk Assessment (ERA) screening approach to assess the environmental risk on aquatic systems in harbours at global scale. The method implemented in this attempt proposes a semi-quantitative ~~and simple~~ method to assess the environmental risk on aquatic systems in harbour areas worldwide. The implementation of the method to the 15 diverse harbours has provided sound evidence for the usefulness, versatility and adaptability of the proposed ERA method as a management tool. The method is flexible enough to be applied to any harbour worldwide using international open-databases. The implementation of this method to a wider number of study cases would allow identification of harbours that could improve their environmental management through the implementation of measures with specific indicators. The method lays the foundation of a global atlas for the sustainability of ~~commercial~~ harbours and it provides a powerful tool to facilitate the design of a strategy for the sustainability of the harbour sector at a global level.

# Acknowledgments

In Memoriam of Professor José Antonio Revilla Cortezón (Pepe), former leader of the Environmental Management Group of the University of Cantabria.

This work was supported by the World Harbour Project (www.worldharbourproject.org) and its supporters, including The Ian Potter Foundation, the NSW State Government and the SIMS Foundation. Authors would like to thank all the harbour managers worldwide who provided their time to complete the forms to gather relevant information for this study.


# Supplementary data

# Appendix A.

The appendix includes the standard form aimed to collected data from each harbour.

# Appendix B.

These data include the Google map (.kml) of the Atlas of environmental risk to aquatic systems in the 15 harbours analysed.

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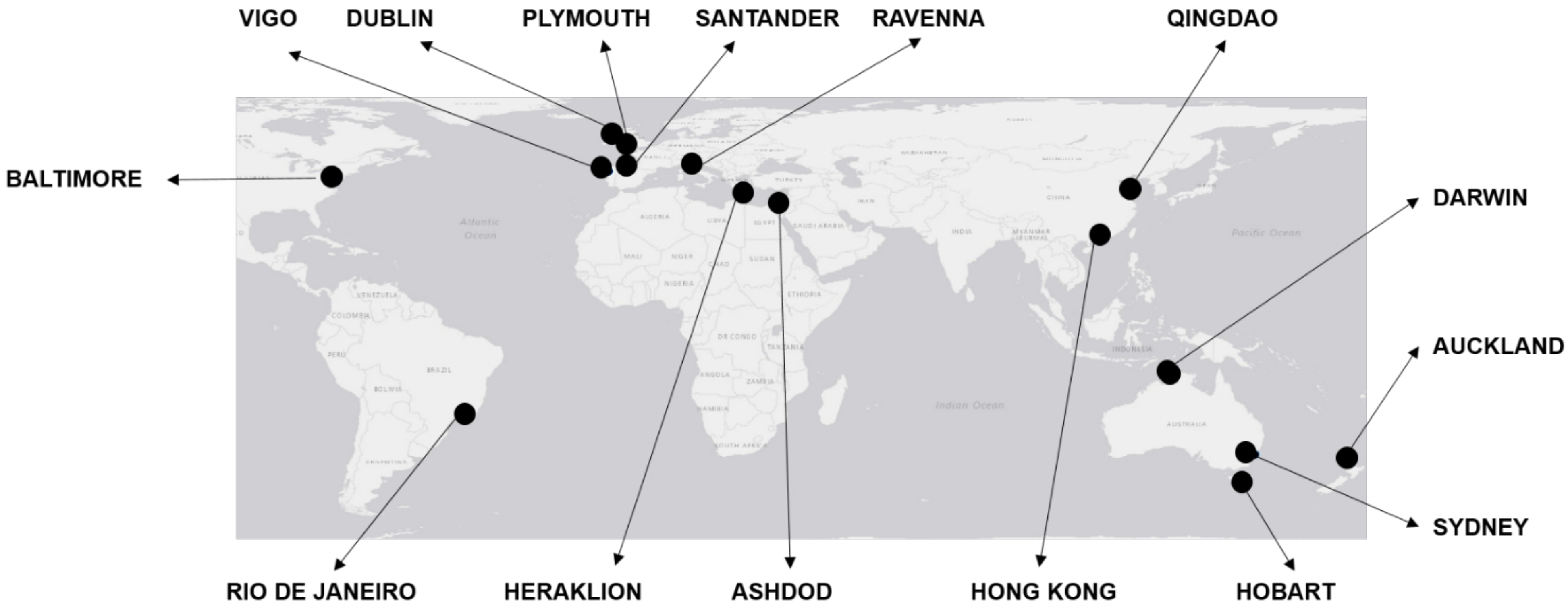
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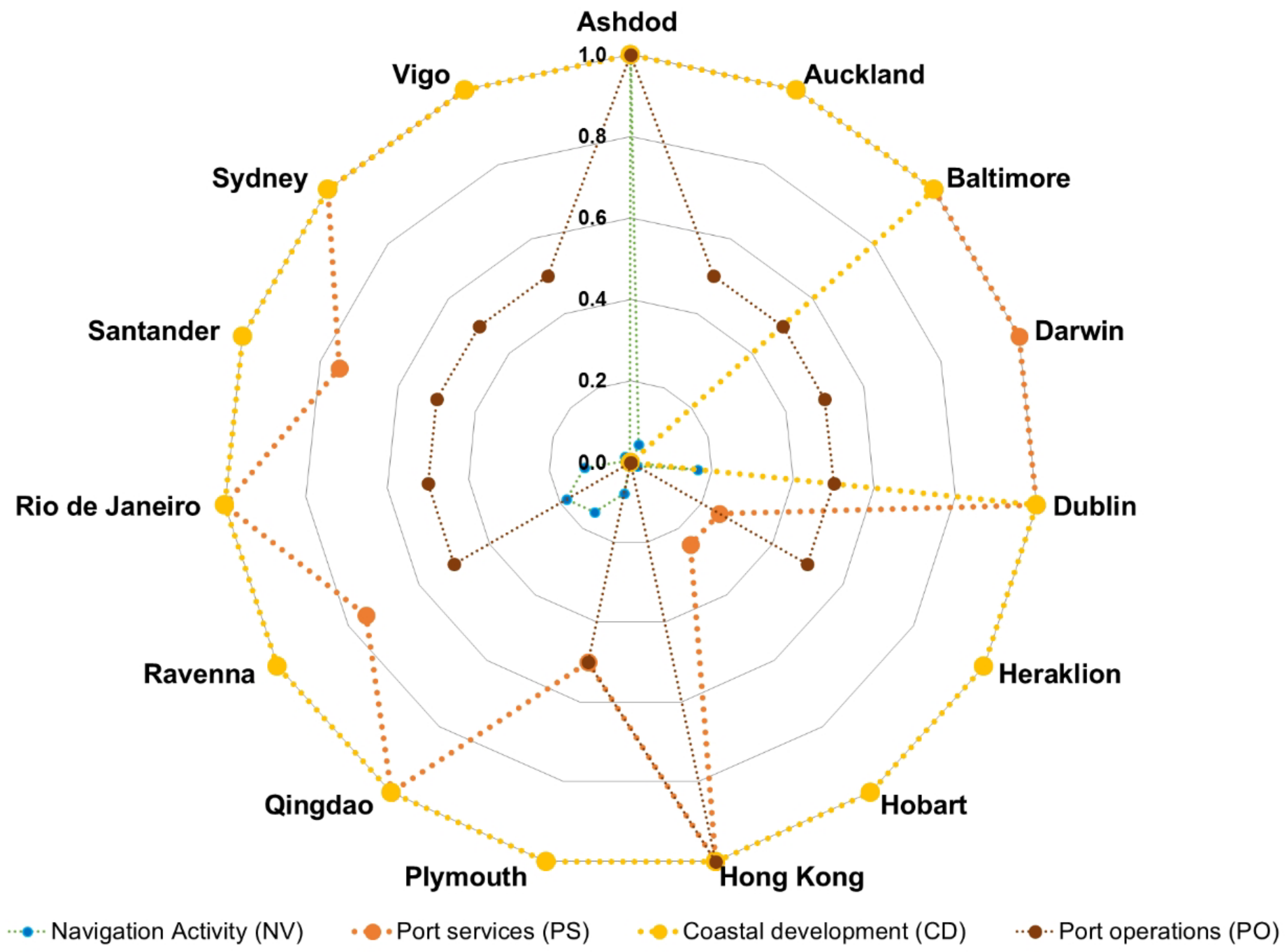

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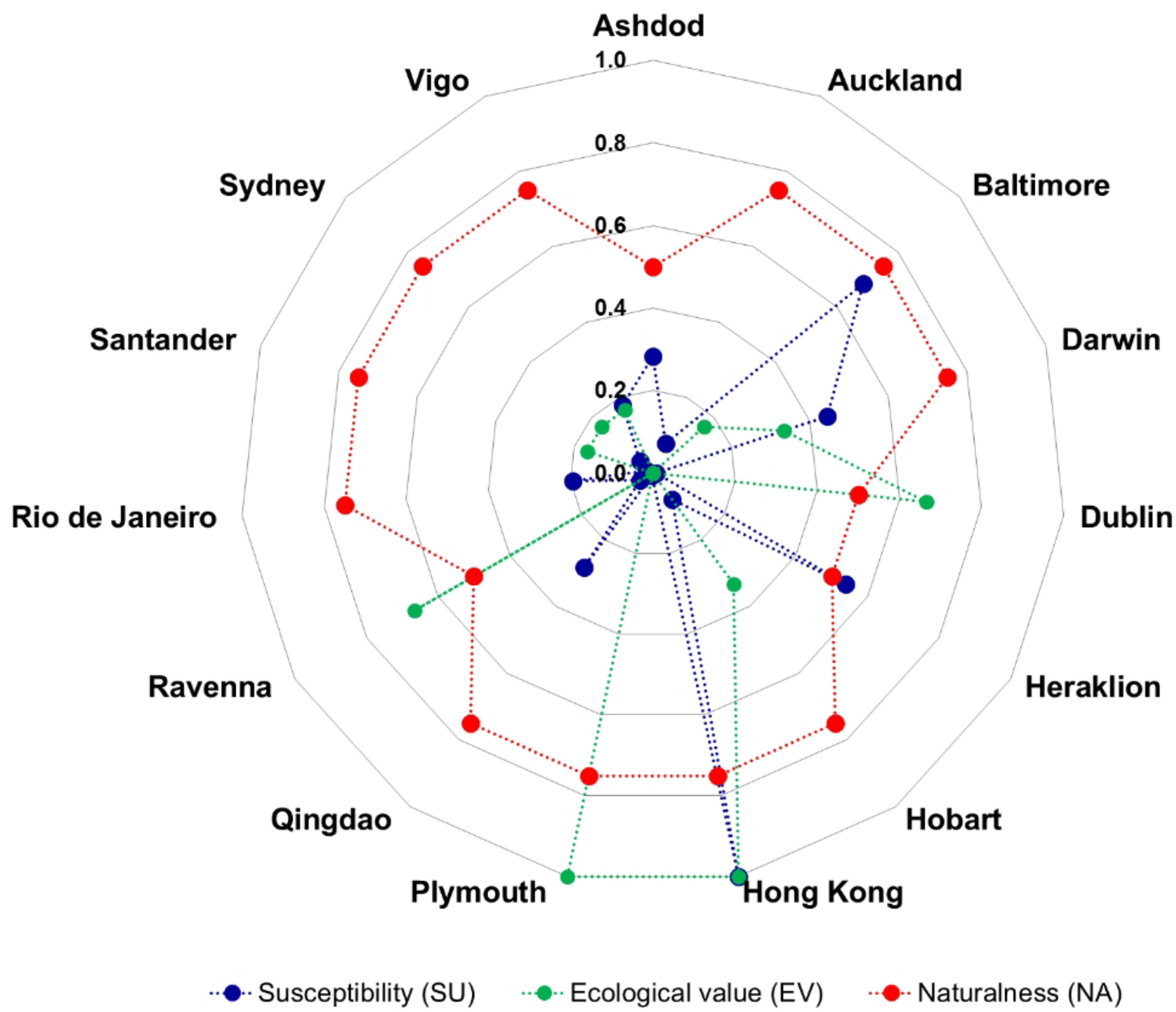

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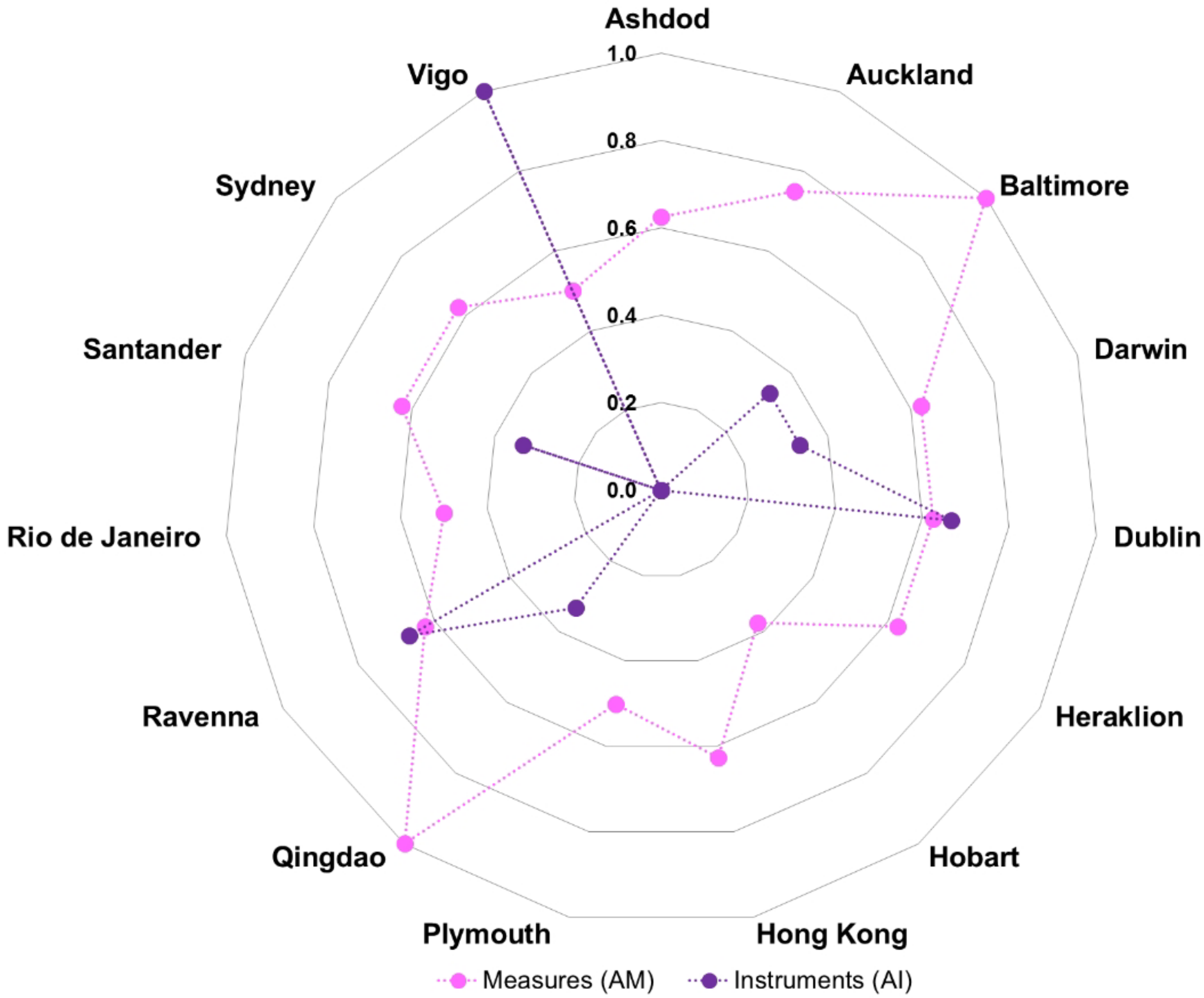
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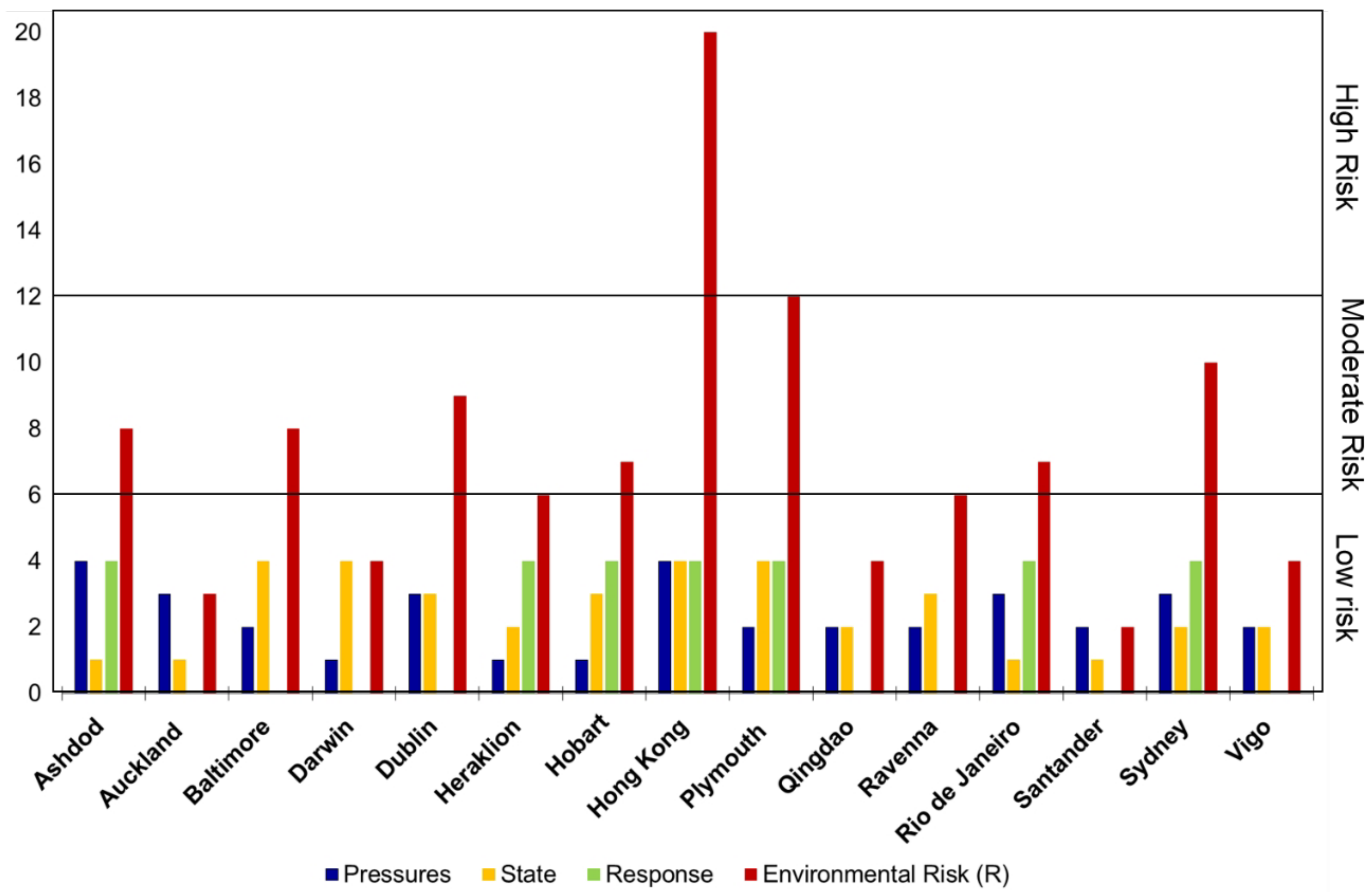
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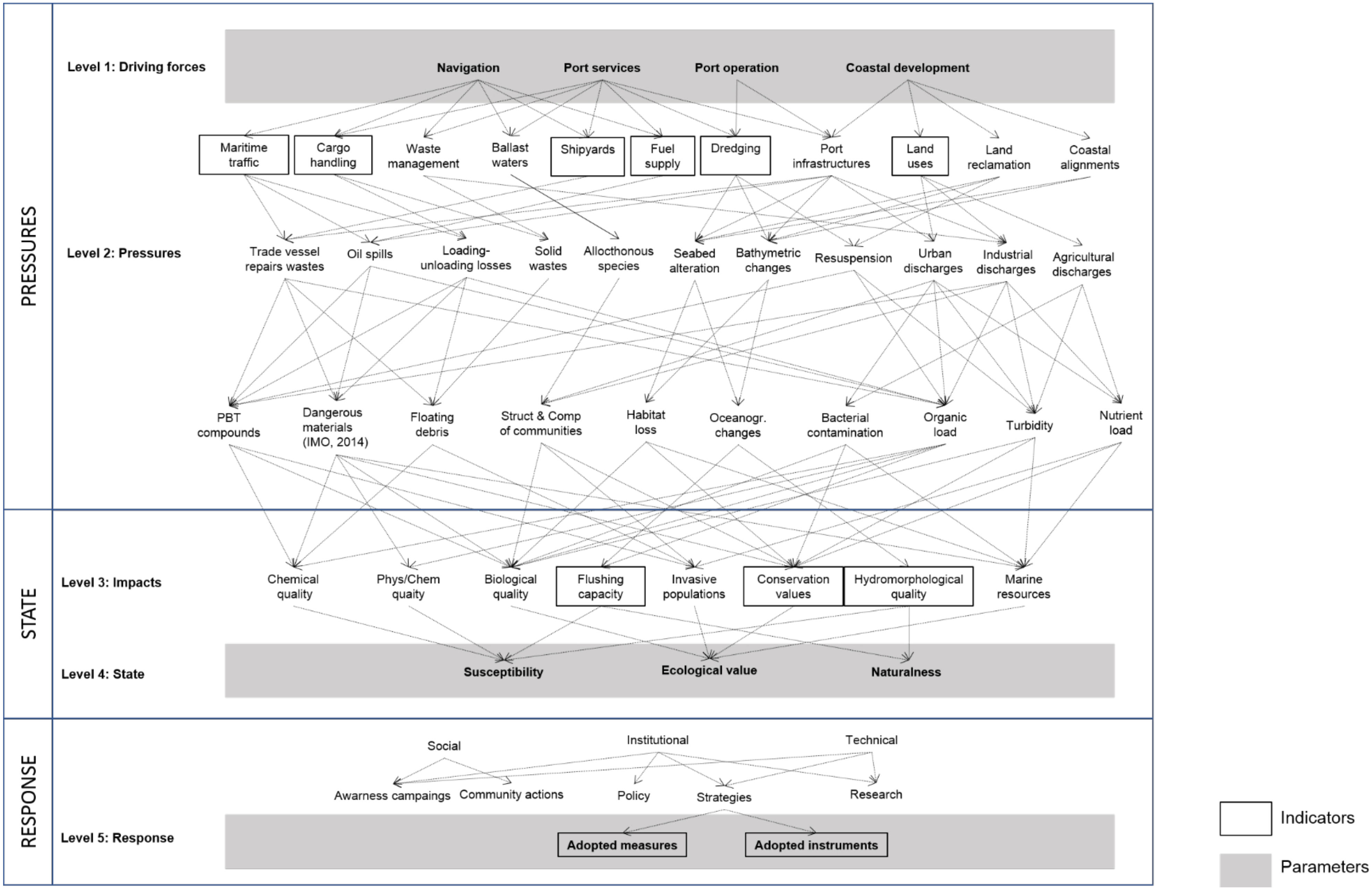
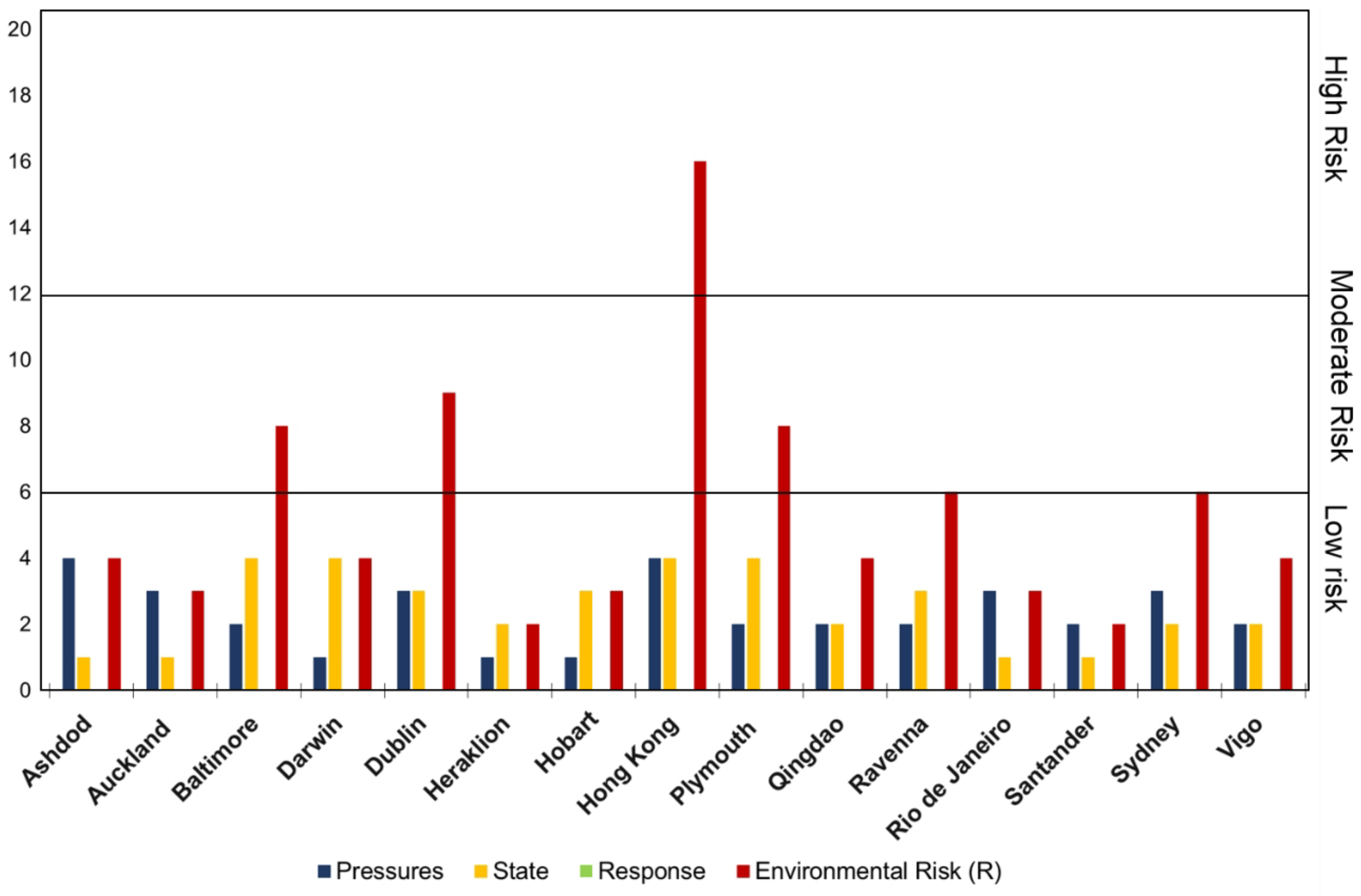

PRESSURES
STATE
RESPONSE
Level 1: Driving forces
Navigation
Port services
Port operation
Coastal development
Maritime traffic
Cargo handling
Waste management
Ballast waters
Shipyards
Fuel supply
Dredging
Port infrastructures
Land uses
Land reclamation
Coastal alignments
Level 2: Pressures
Trade vessel repairs wastes
Oil spills
Loading-unloading losses
Solid wastes
Allocthonous species
Seabed alteration
Bathymetric changes
Resuspension
Urban discharges
Industrial discharges
Agricultural discharges
PBT compounds
Dangerous materials (IMO, 2014)
Floating debris
Struct & Comp of communities
Habitat loss
Oceanogr. changes
Bacterial contamination
Organic load
Turbidity
Nutrient load
Level 3: Impacts
Chemical quality
Phys/Chem quaity
Biological quality
Flushing capacity
Invasive populations
Conservation values
Hydromorphological quality
Marine resources
Level 4: State
Susceptibility
Ecological value
Naturalness
Social
Institutional
Technical
Awarness campaings
Community actions
Policy
Strategies
Research
Level 5: Response
Adopted measures
Adopted instruments
Indicators
Parameters



20
18
16
14
12
10
8
6
4
2
0
High Risk
Moderate Risk
Low risk
Ashdod
Auckland
Baltimore
Darwin
Dublin
Heraklion
Hobart
Hong Kong
Plymouth
Qingdao
Ravenna
Rio de Janeiro
Santander
Sydney
Vigo
Pressures
State
Response
Environmental Risk (R)

| ***General data*** |
|---|
| Harbour's name:<br>Postal address:<br>Code:<br>City:<br>Country:<br>web:<br>phone:<br>e-mail address: |
| ***Hydromorphological characteristics:*** |
| Entrance length (in meters):<br>Average tidal range (in meters):<br>Average depth (in meters):<br>Depth at harbour entrance (in meters): |
| ***Human pressures*** |
| Number of trade vessels visits per year:<br>Select which activities are developed in the harbour:<br> Fuel oil and diesel oil supplies<br> Major repair services<br> Dangerous/hazardous goods handling<br>Frequency of dredging operations:<br> Continual<br> Periodic<br> No dredging |
| ***Environmental management*** |
| Number of Environmental Standard:<br>Please, specify what kind of environmental standards (international certifications) are implemented in the marina:<br>Select which environmental measures are implemented in the harbour:<br>Measures:<br> Garbage disposal<br> Dirty ballast management<br> Waste management<br> Bilge management, Sewer Pump-Out<br> Oil management<br>Specify any other environmental measure or instrument implemented in the harbour: |

| ***Application scope*** |
|---|
| 1. Access to GoogleEarth: https://www.google.es/intl/es/earth/<br>2. Introduce the name of the harbour in the seeker.<br>3. Using Add -> Add a polygon: draw the water surface where port activity takes place.<br>4. Save the polygon as a .kmz and send it with this questionnaire filled out to: xxxxx.xxxx@unican.es |

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