

2020-09

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<http://hdl.handle.net/10026.1/15712>

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10.1016/j.marpol.2020.104051

Marine Policy

Elsevier

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

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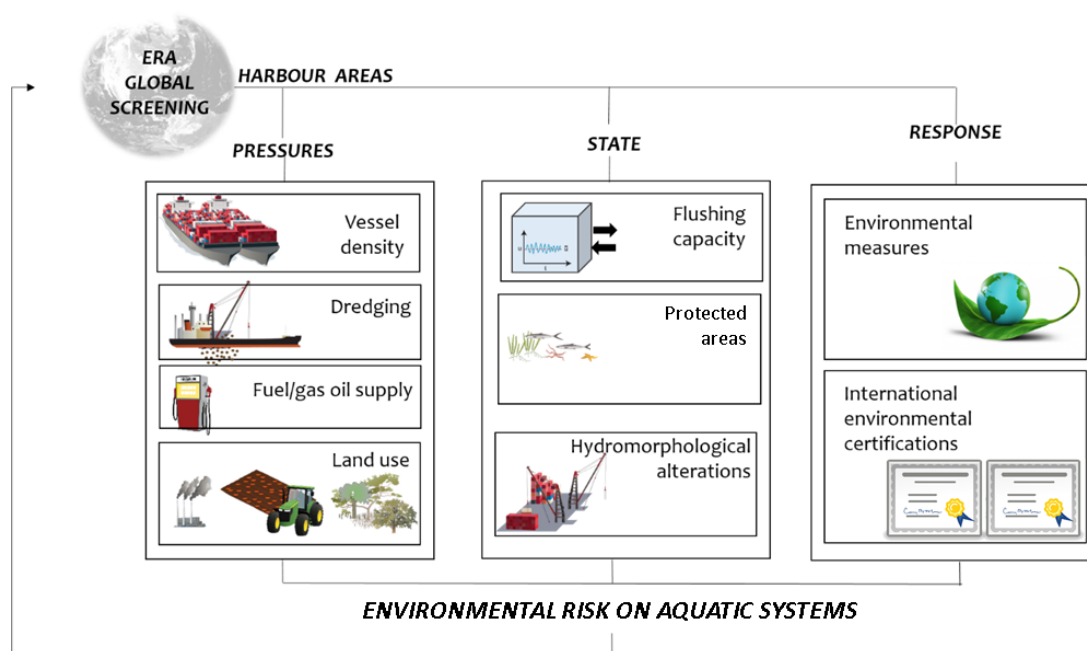
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# A global approach to mapping the environmental risk of harbours on aquatic systems

## 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

19 environmental risk atlas of harbours that should guide the harbour sector to develop a  
20 more globally informed strategy of sustainable development.  
21 **Keywords:** environmental risk assessment; global atlas; pressure-state-response model;  
22 harbour aquatic systems; harbour management; sustainable development.

## 24 1. INTRODUCTION

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

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

47 Infrastructure (PIANC), provide expert guidance (PIANC, 2019), recommendations (PIANC,  
48 2011) and technical advice (PIANC, 2020) on environmental issues related to both  
49 recreational and commercial navigation activity (Brolsma, 2010). The maintenance of high-  
50 quality aquatic systems (e.g. by preventing marine pollution) is a permanent and universal  
51 goal of these conventions, guidelines and the research developed by these international  
52 organisations. Consequently, water quality has been one of the top 10 environmental  
53 priorities of the harbour sector over last years (2003-2009) (ESPO-ECOPORTS, 2019).

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55 Scientific research that provides an evidence-based for decision-making related to  
56 environmental risk on harbour aquatic systems is conducted by projects like the World  
57 Harbour Project (WHP) ([www.worldharbourproject.org](http://www.worldharbourproject.org), Steinberg et al., 2016). This project  
58 enhances research and management across major urban harbours. To develop resilient  
59 urban harbours, a global network of collaborating scientists works on different topics such  
60 as ecological engineering (Strain et al., 2019), environmental management (Valdor et al.,  
61 2019), accessible syntheses and summaries of current knowledge (e.g. Juanes et al.,  
62 2020). Thus, research programs should be responsible in developing science and  
63 communicating findings in an accessible way to a wide range of users to facilitate the  
64 design of global strategies. We suggest that global strategies are needed to ensure that  
65 harbour managers worldwide are able to assess the environmental risk on aquatic  
66 systems using an easy-to-apply and versatile method. In this context, one of the main  
67 objectives of global strategies is to provide standardised methods to analyse risk. In this  
68 way, data among different harbours are comparable, and their management can be  
69 adjusted to the best available practices regarding limiting environmental risk.

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71 However, when global strategies are designed, the harbours' histories, the  
72 geomorphological and environmental contexts and the socio-economic settings are very  
73 different across the world (Steinberg et al., 2016) and thus may affect approaches to  
74 environmental management. In that context, the Environmental Risk Assessment (ERA)

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180 75 arises as a general management tool that is used worldwide to assess potential effects on  
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182 76 the environment due to the exposure to disturbing agents derived from different human  
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184 77 activities (e.g. fishery, industry, urban, agricultural or harbour activities, among others)  
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186 78 (AENOR, 2008; Hope, 2006; Smith et al., 2007; Samhouri and Levin, 2012; Valdor et al.,  
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188 79 2016). Using the ERA approach, the potential effects of environmental hazards on the  
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190 80 quality of aquatic systems in harbour areas have been widely studied (e.g. Ronza et al.,  
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192 81 2006; Grifoll et al., 2010; Gómez et al., 2015; Ondiviela et al., 2012; Parra et al., 2018), and  
193  
194 82 methods to assess the environmental risks of harbour activities have been proposed (e.g.  
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196 83 Gómez et al., 2015; Juanes et al., 2013; Ondiviela et al., 2012; Puig et al., 2015; Valdor et  
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198 84 al., 2016). However, worldwide studies to assess the environmental risk of harbour activities  
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200 85 on aquatic systems to support global strategies, such as Global Sustainable Development  
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202 86 Goals (United Nations, 2015), have not been conducted.

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204 87 Harbours around the world implement different environmental management methods that  
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206 88 make use of different approaches to the characterisation of systems, use different analytical  
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208 89 tools and databases, thus making it challenging to obtain standardised quantitative data  
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210 90 globally (PIANC, 2019). For this reason, qualitative and semi-quantitative data analyses are  
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212 91 more suitable alternatives when conducting an ERA study at a global scale (Gómez et al.,  
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214 92 2019). Moreover, parameters, indicators, and assessment criteria should be carefully  
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216 93 selected to integrate the singularities of each specific harbour (Darbra et al., 2005; Gupta et  
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218 94 al., 2005). We suggest that, at the same time, the simplicity and low computing cost of the  
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220 95 method should allow for wider applicability to harbours of different sizes, hydrodynamic  
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222 96 characteristics, harbour uses and pressures or resources to assess environmental  
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224 97 challenges.

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227 99 The goal of this paper is to propose a method for mapping the assessment of the  
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229 100 environmental risk of harbours on aquatic systems. This method will be: i) flexible enough  
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231 101 to be applied to any harbour worldwide; ii) open-data dependent; and iii) implemented to lay  
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233 102 the foundation to create a global atlas of environmental risk on aquatic systems of harbours.  
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103 The proposed method is tested by applying it to 15 harbours spread across five continents  
104 worldwide. The main contributions of this study are: (i) the development of a standard and  
105 unified ERA method to assess environmental risk of harbour activities worldwide on aquatic  
106 systems (Section 2); (ii) the implementation of the ERA method in 15 harbours around the  
107 world (Section 3); and (iii) the discussion of the proposed method and the results obtained  
108 in the implementation (Section 4).

## 109 **2. MATERIALS AND METHODS**

110 The semi-quantitative method providing an assessment of environmental risk on aquatic  
111 systems is based on the Pressure-State-Response (PSR) model defined by Gómez et al.  
112 (2019) for marinas. The method comprises the following three steps: i) identification of  
113 harbours and data collection; ii) estimation of the risk factors (environmental pressures of  
114 harbour activities on the aquatic system, environmental conditions and management  
115 responses); and iii) assessment of environmental risk.

### 116 **2.1 Identification of harbours**

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

125 For this study, general data, hydro-morphological characteristics and environmental  
126 management information was gathered globally at all 15 harbours through a standardised  
127 form (Supplementary Data. Appendix A) and through other sources of information (e.g.,  
128 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:

$$R_i = P_{ti} \times S_{ti} + R_{si} \quad (\text{Eq. 1})$$

$$R_i = (NV_i + HS_i + HO_i + CD_i) \times (SU_i + EV_i + NA_i) + (AM_i + AI_i) \quad (\text{Eq. 2})$$

Where  $R$  is the environmental risk,  $P_t$  is the Pressure,  $S_t$  is the State and  $R_s$  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
<b>Pressures</b>	<b>Navigation Activity (NV)</b>	<b>Density of trade vessels</b> (vessels per year/m <sup>2</sup> ) by dividing vessels per year by the surface water area where the harbour activities take place.	$NV_i/NV_{\max}$ [0-1]



	<b>Harbour Services (HS)</b>	<b>Harbour services:</b> 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 <sub>i</sub> /HS <sub>max</sub> [0-1]	
	<b>Harbour Operation (HO)</b>	<b>Dredging probability,</b> frequency of dredging operations.	Continual Periodic None	1.0 0.5 0.0
	<b>Coastal Development (CD)</b>	<b>Land uses</b> developed in a 1-km buffer distance around the harbour (worst case scenario) (Gómez et al., 2019).	Artificial Agricultural Natural - Other uses	1.0 0.5 0.0
<b>State</b>	<b>Susceptibility (SU)</b>	<b>Flushing capacity</b> 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 <sub>i</sub> */CTRI <sub>max</sub> * [0-1]	
	<b>Ecological Value (EV)</b>	Number of <b>Protected areas</b> (#) in a 1-km buffer distance around the surface water area where the harbour activities take place (Gómez et al., 2019).	EV <sub>i</sub> /EV <sub>max</sub> [0-1]	
	<b>Naturalness (NA)</b>	<b>Alteration by hydro-morphological pressures</b> in a harbour's environment (harbour's typology) (US National Geospatial-Intelligence Agency, 2015)	Open Roadstead Natural (Coastal or River) Coastal Breakwater/River Basin Tide Gates (Coastal or River)/Canal or Lake	1.0 0.75 0.5 0.0
<b>Response</b>	<b>Adopted Measures (AM)</b>	Number of <b>adopted measures</b> (#) to reduce the pressure of human activities on the environment (garbage disposal, dirty ballast management, etc.) (Gómez et al., 2019).	AM <sub>i</sub> /AM <sub>max</sub> [0-1]	
	<b>Adopted Instruments (AI)</b>	Number of <b>adopted standards</b> (#) to improve the environmental performance (ISO 14001, EMAS, PERS, others.) (Gómez et al., 2019).	AI <sub>i</sub> /AI <sub>max</sub> [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 (m<sup>2</sup>), 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 to 1) by dividing the observed value by the maximum value, after discarding outliers for each parameter with values greater than  $\bar{x} \pm 3 \cdot SD$  (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 ( $R_{si}$ ) 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
<b>Pressures (Pr)</b>	VL (1)	$Pr_i \leq P_{25}$	$Pr_i \leq 2.11$
	L (2)	$P_{25} < Pr_i \leq P_{50}$	$2.11 < Pr_i \leq 2.51$
	M (3)	$P_{50} < Pr_i \leq P_{75}$	$2.51 < Pr_i \leq 2.58$
	H (4)	$Pr_i > P_{75}$	$Pr_i > 2.58$
<b>State (St)</b>	VL (1)	$St_i \leq P_{25}$	$St_i \leq 0.95$
	L (2)	$P_{25} < St_i \leq P_{50}$	$0.95 < St_i \leq 1.10$
	M (3)	$P_{50} < St_i \leq P_{75}$	$1.10 < St_i \leq 1.37$
	H (4)	$St_i > P_{75}$	$St_i > 1.37$
<b>Response (Rs)</b>	Optimal (0)	$R_{si} \geq P_{50}$	$R_{si} \geq 0.75$
	Insufficient (4)	$R_{si} < P_{50}$	$R_{si} < 0.75$

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 ( $R_i \geq 12$ ), (ii) moderate-risk harbour ( $6 \leq R_i < 12$ ), (iii) low-risk harbour ( $1 \leq R_i < 6$ ).

### 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).

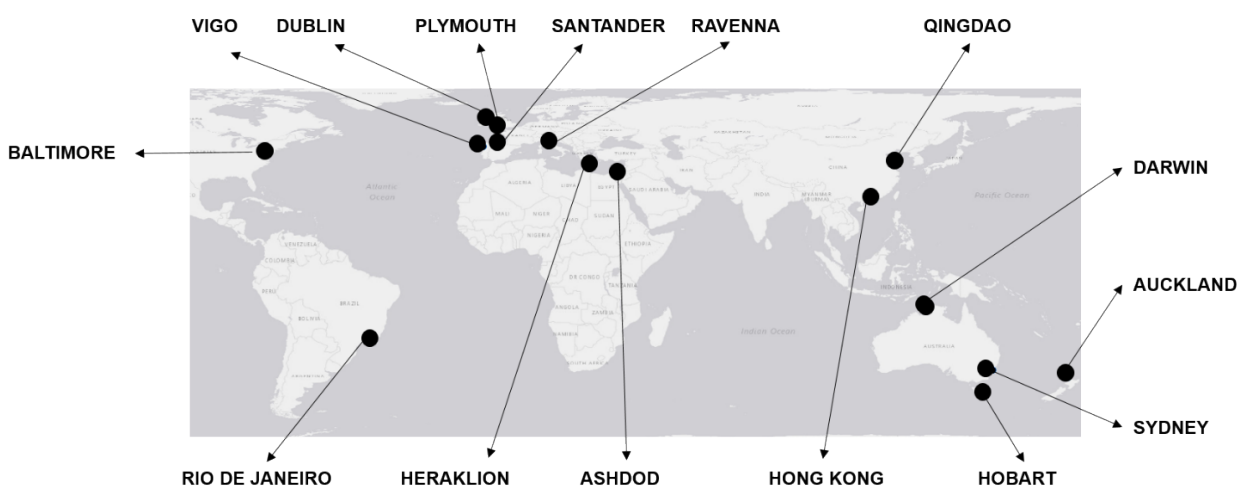


Figure 1. Harbours assessed using the ERA method.

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

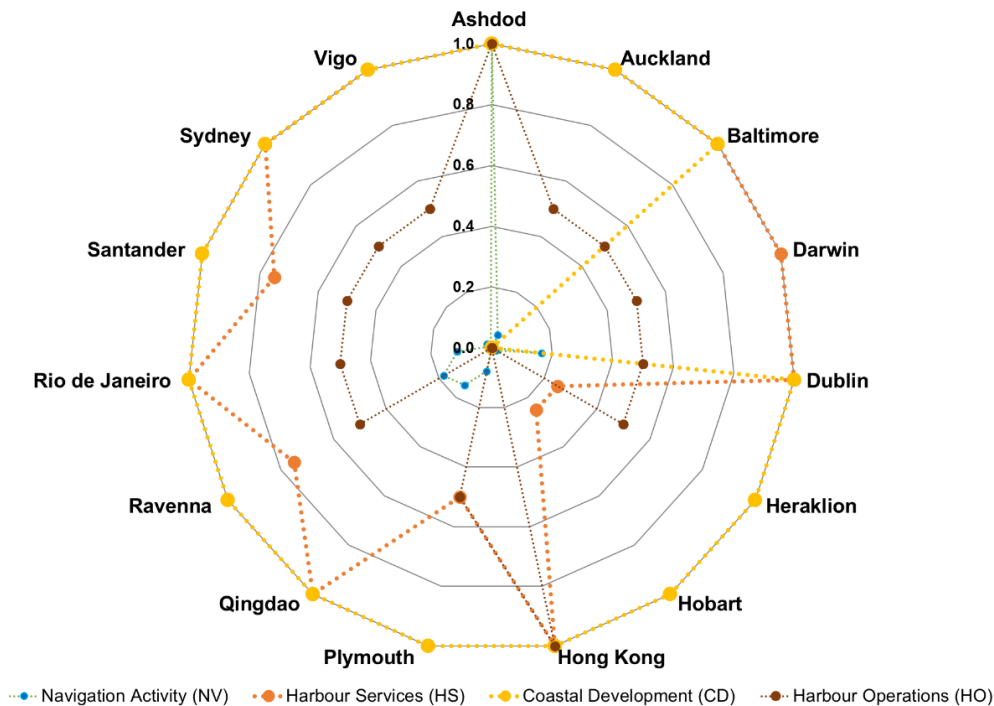
201 **3.2. Estimation of environmental risk**

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

214 *Pressures:* Normalised values of navigation activity (NV) were extremely variable among the  
215 studied harbours. Ashdod had the highest density of trade vessels (1), followed by Ravenna  
216 (0.18), Dublin (0.16), Qingdao (0.15) and Rio de Janeiro (0.11), while the other harbours  
217 showed normalised values lower than 0.07 (Figure 2, NV). Most harbour areas showed the  
218 maximum value of Harbour Services (HS), since 10 of the 15 study sites develop fuel oil and  
219 diesel oil supplies, major repair services and dangerous or hazardous goods handling  
220 activities (Figure 2, HS). Exceptions to this were Hobart and Plymouth, where fuel oil supply

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221 and major repairs are not developed, and Heraklion and Ravenna, where dangerous or  
222 hazardous goods handling is not carried out. Harbour Operation (HO) was estimated  
223 through dredging activities, which is are periodic operation in most of the harbours (0.5)  
224 apart from Ashdod and Hong Kong, where continual dredging operations are undertaken  
225 (1), and Hobart and Qingdao, where dredging operations are not carried out (Figure 2, HO).  
226 Normalised Coastal development scored 1 in nearly all the harbours, since the land use  
227 around the harbours was mainly artificial (urban, mining or industrial). Only one harbour  
228 (Darwin) presented natural land uses in its surroundings (Figure 2, CD).

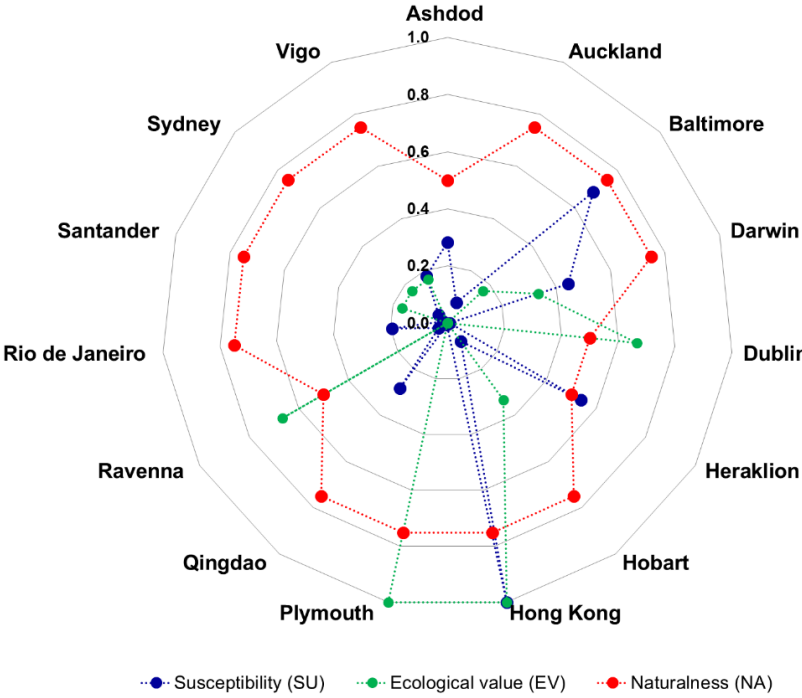


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230 Figure 2. Representation of normalised values of the parameters applied for the estimation of the  
231 environmental pressures (Pressures) at each of the 15 studied harbours  
232

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

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



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247 Figure 3. Representation of normalised values of the parameters applied for the estimation of  
248 environmental conditions (State) at each of the 15 studied harbours.  
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250 Response: All studied harbours implemented a minimum of 3 Adopted Measures (AM) to  
251 reduce the pressures of human activities on the environment (AM normalised value  $\leq 0.5$ ),  
252 with 8 being the maximum number of measures applied in Qingdao and Baltimore (1 AM  
253 normalised value) (Figure 4, AM). A higher variability was registered in the number of  
254 Adopted Instruments (AI), with eight harbours where no instruments to achieve international

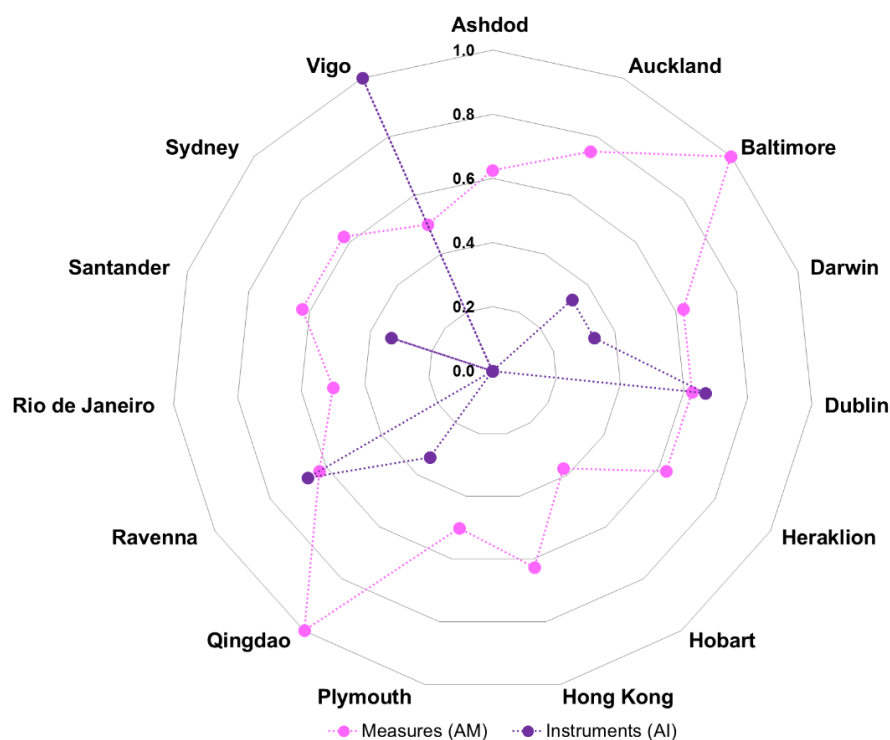


Figure 4. Representation of normalised values of the parameters applied for the estimation of level of response (Response), at each of the 15 studied harbours.

### 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).

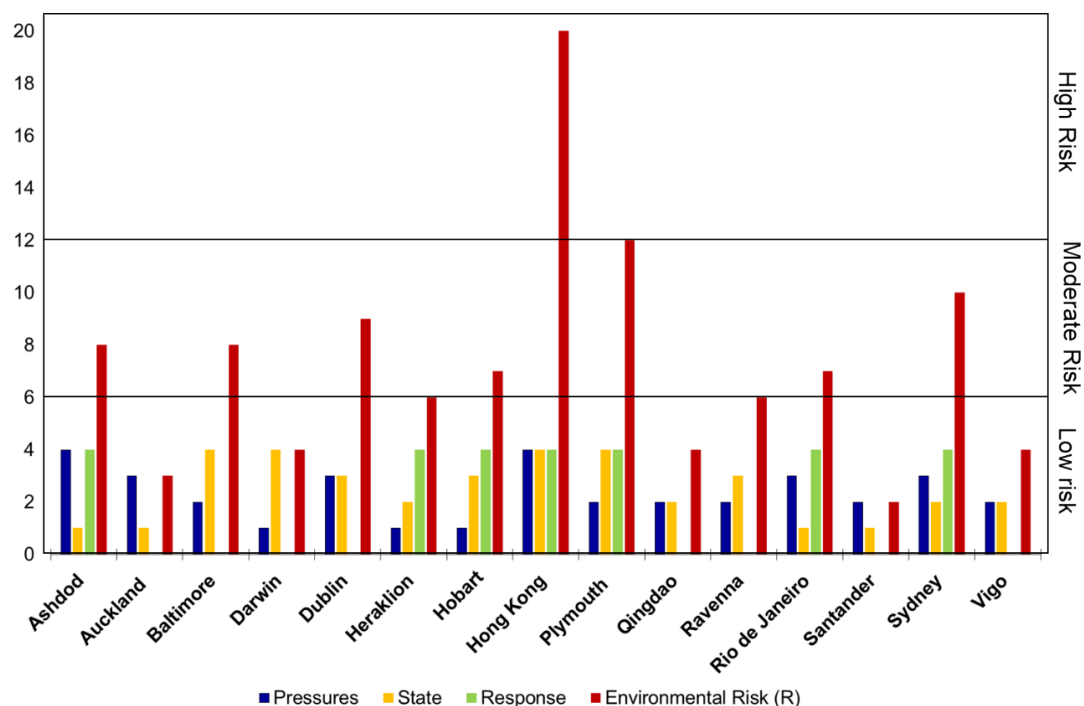


Figure 5. Graphical representation of categorised risk factors (Pressures, State and Response) and categorised environmental risk to aquatic systems at each of the 15 studied harbours.

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).



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

297

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

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316 Indirect or direct pressures are identified by each driving force (Gómez et al., 2019). The  
317 identified pressures produce impacts altering the state of the environment (Ondiviela et al.,  
318 2013; Petrosillo et al., 2010). State factor of risk considers three important aspects of the  
319 harbour's environment: susceptibility, ecological value and naturalness. From the eight  
320 pressure indicators proposed in the conceptual model (Figure 6), there are three related to  
321 quality of the aquatic system (chemical quality, physico-chemical quality and biological  
322 quality) that require periodic monitoring and systematic evaluation. Since each country  
323 applies different monitoring and evaluation systems (in terms of thresholds, frequency, etc.),  
324 the susceptibility to water and sediment contamination was considered as a standard  
325 representative indicator of the quality of the aquatic system of harbours worldwide, assuming  
326 a significant relationship between flushing capacity and water quality in littoral areas  
327 (Ferreira et al., 2005; Fortes and Silva., 2006; Gómez et al, 2014; Yin et al., 2000). This  
328 assumption was previously used for ERA in marinas (Gómez et al., 2017) and harbours  
329 (Gómez et al., 2015). The harbour's ecological value considered that the greater the  
330 protected area in the vicinity of the harbours is, the greater the biodiversity and ecological  
331 processes that maintain that system (Gómez et al., 2015; Langanke et al., 2005; Margulles  
332 and Usger, 1981). Finally, their 'naturalness' (Machado, 2004) was estimated using the  
333 harbour typology (US National Geospatial-Intelligence Agency, 2015) as a surrogate of  
334 number and dimensions of hydro-morphological pressures at the marina level typology  
335 (Gamito, 2008; Gómez et al., 2019).

336

337 The response factor to environmental risk was used to integrate the actions and reactions,  
338 intended to mitigate, adapt to or prevent human-induced negative effects on the environment  
339 that could be applied to minimize the impacts of driving forces and improve the state of  
340 aquatic ecosystems (OECD, 2003). Responses may arise from different sectors, such as  
341 those in social, technical or institutional (i.e. local, national or international administrations)  
342 realms (Figure 6). Among all of them, institutional responses are the option that integrates  
343 a greater number of fields involving social responses (awareness campaigns), institutional

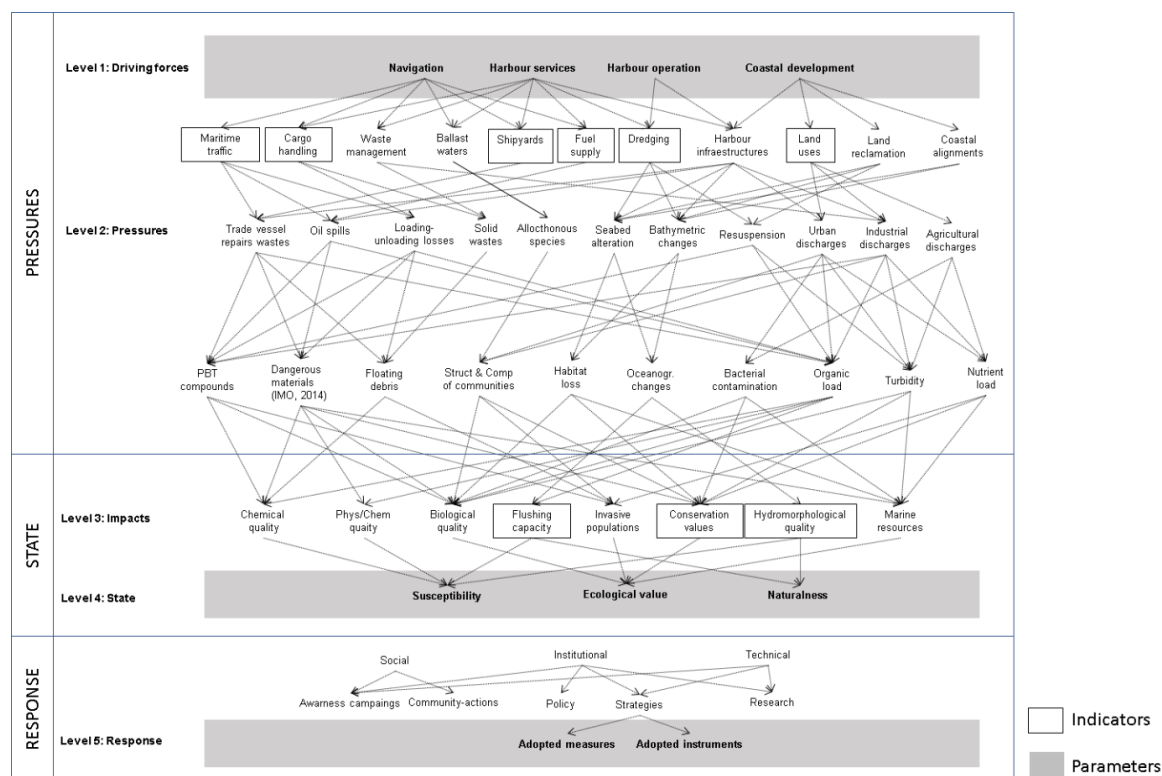


Figure 6. Conceptualisation of the causal links between main driving forces, pressures, impacts, state and response of aquatic systems in harbours.

## 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

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361 category of risk. For instance, Hobart showed a moderate environmental risk on the aquatic  
362 system due to a combination of high vulnerability (high naturalness but a moderate  
363 ecological value of the surroundings) with a high score of environmental management (due  
364 to the low number of adopted measures and none of the international standards  
365 implemented). Heraklion showed a moderate risk on the aquatic system even though they  
366 were adopting a good number of environmental measures (above the average) to reduce  
367 the pressure of human activities on the environment because no international environmental  
368 management instruments were applied. In other cases, the higher susceptibility (Baltimore)  
369 or the higher ecological value (Ravenna), were the parameters of risk that penalised the  
370 result for these harbours. Identification of such risk parameters allows for the targeted  
371 application of more preventive and corrective management actions to help reduce  
372 environmental risk to aquatic systems for those specific harbours.

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

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

385 Once applied, the method can be used to detect which harbours should apply environmental  
386 measures or/and international standards to improve their management of aquatic systems,  
387 based on the highest standards of environmental quality applied around the world. An  
388 example of this is shown in Figure 7, which represents the hypothetical case in which the 15

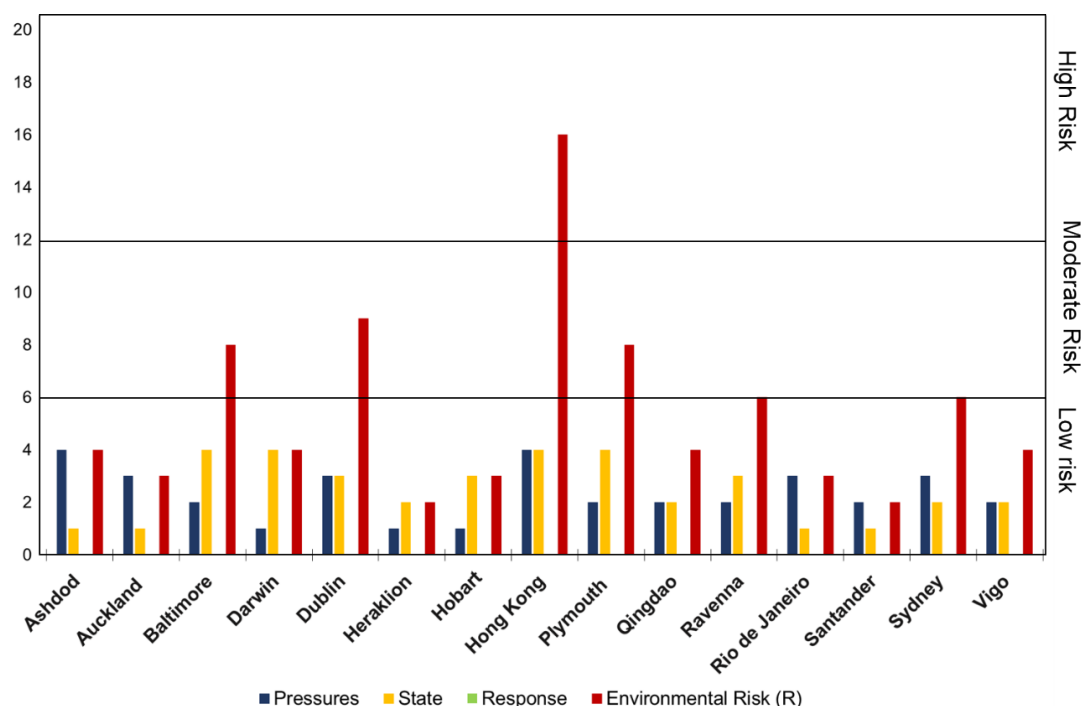


Figure 7. Graphical representation of a hypothetical situation at each of the 15 studied harbours with reduced categorised risk factors (pressures, state and responses) by the application of at least 4 environmental measures and 1 international standard and categorised environmental risk to aquatic systems.

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

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406 environmental risk factors that are penalizing the final value of environmental risk. This is  
407 the case in Hong Kong, which has high pressures due to the presence of intense navigation  
408 activity (NV), the harbour services (HS) provided in the harbour, the continual dredging  
409 activity (DG) in the harbour area and the Coastal development (CD) in their surroundings.  
410 Baltimore is also highly susceptible probably due to the morphological characteristics of the  
411 harbour area, which is very difficult to change from an environmental management  
412 standpoint. In these cases, socio-economic issues should also be incorporated into a long-  
413 term sustainability or management plan, which must assess the disadvantages and benefits  
414 that may result from modifying factors that penalized the final value of the environmental  
415 risk.

416

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

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426 The global atlas developed by using the method presented herein would introduce valuable  
427 ~~bring the~~ elements of judgment to guide managers involved in decision-making (AENOR,  
428 2008) towards the sustainability of aquatic systems in harbour areas, as well as to design  
429 the first global strategy for sustainability related to the water quality at a global level.  
430 Sustainable development goal (SDG) 14 in the UN 2030 Agenda requires to “conserve and  
431 sustainably use the oceans, seas and marine resources for sustainable development”  
432 (United Nations, 2015). Global Sustainable development goals require global analysis of the  
433 problems presented and definition of global strategies to resolve them. Many critical

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434 management and conservation challenges of aquatic systems in harbour areas are  
435 inherently spatial issues (Valdor et al., 2016). As new spatial data are collected on the  
436 distribution and intensity of harbour activities, this will allow for more flexible and adaptive  
437 environmental management processes to identify global environmental problems and  
438 possible sustainable solutions through an environmental risk assessment approach.

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

## 447 **5. CONCLUSIONS**

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

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## 461   **Acknowledgments**

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

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

## 468   **Supplementary data**

### 469   **Appendix A.**

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

### 471   **Appendix B.**

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

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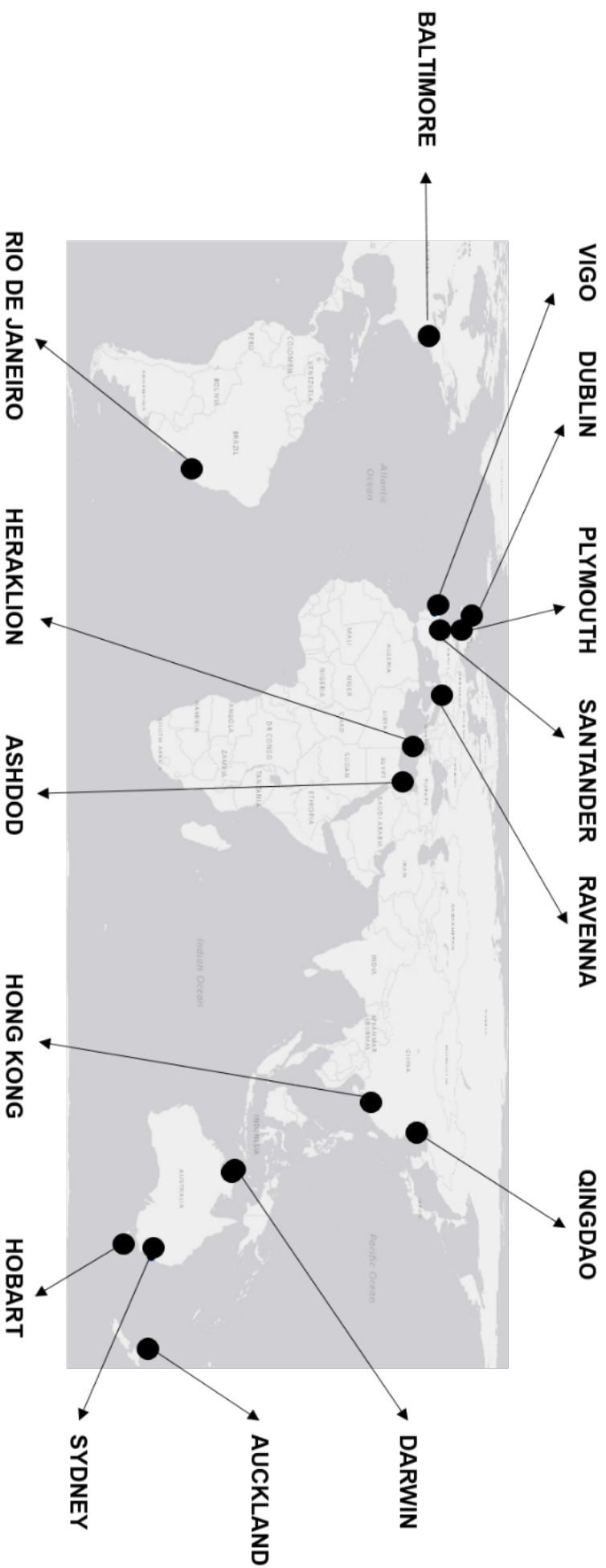
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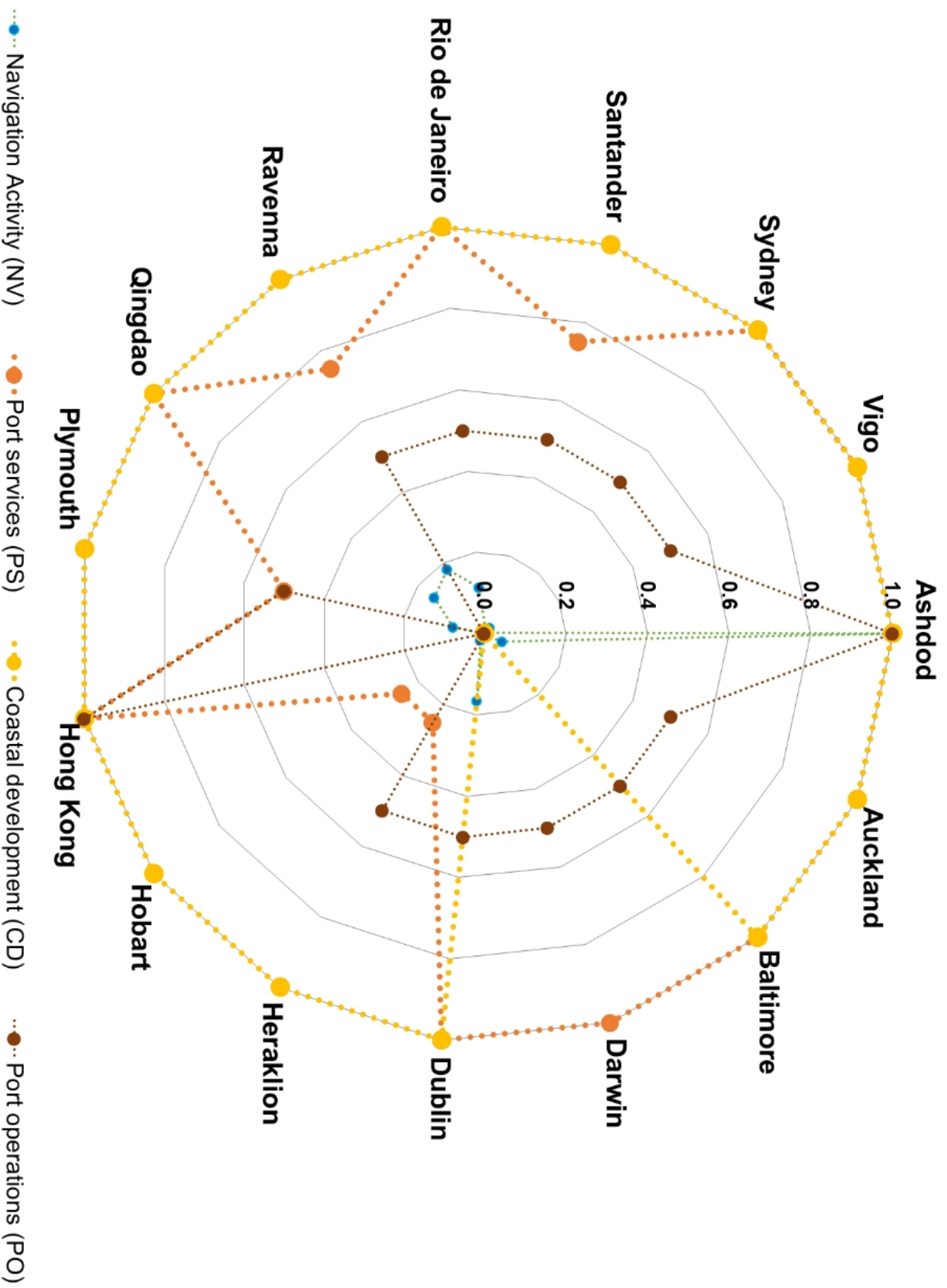
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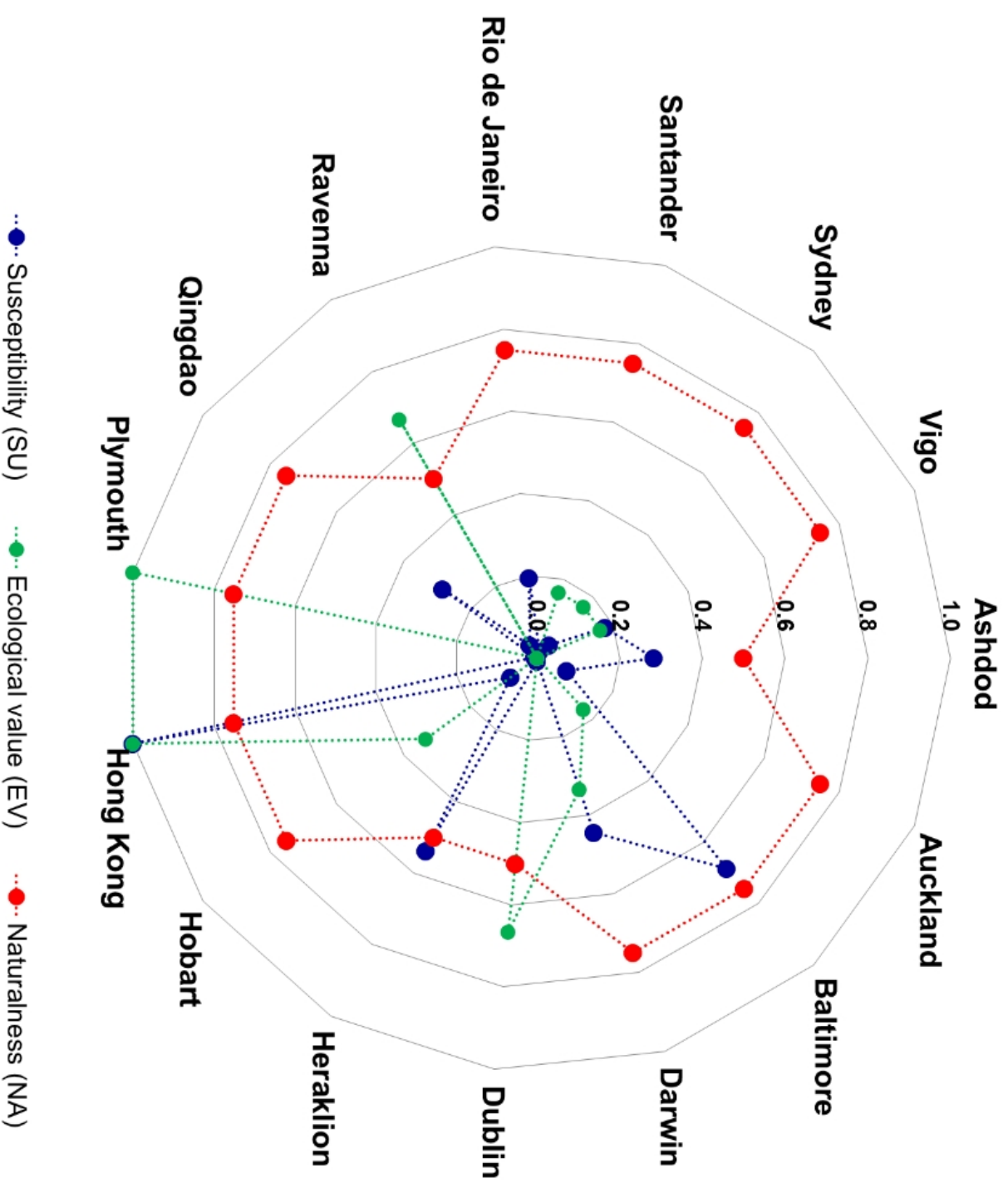
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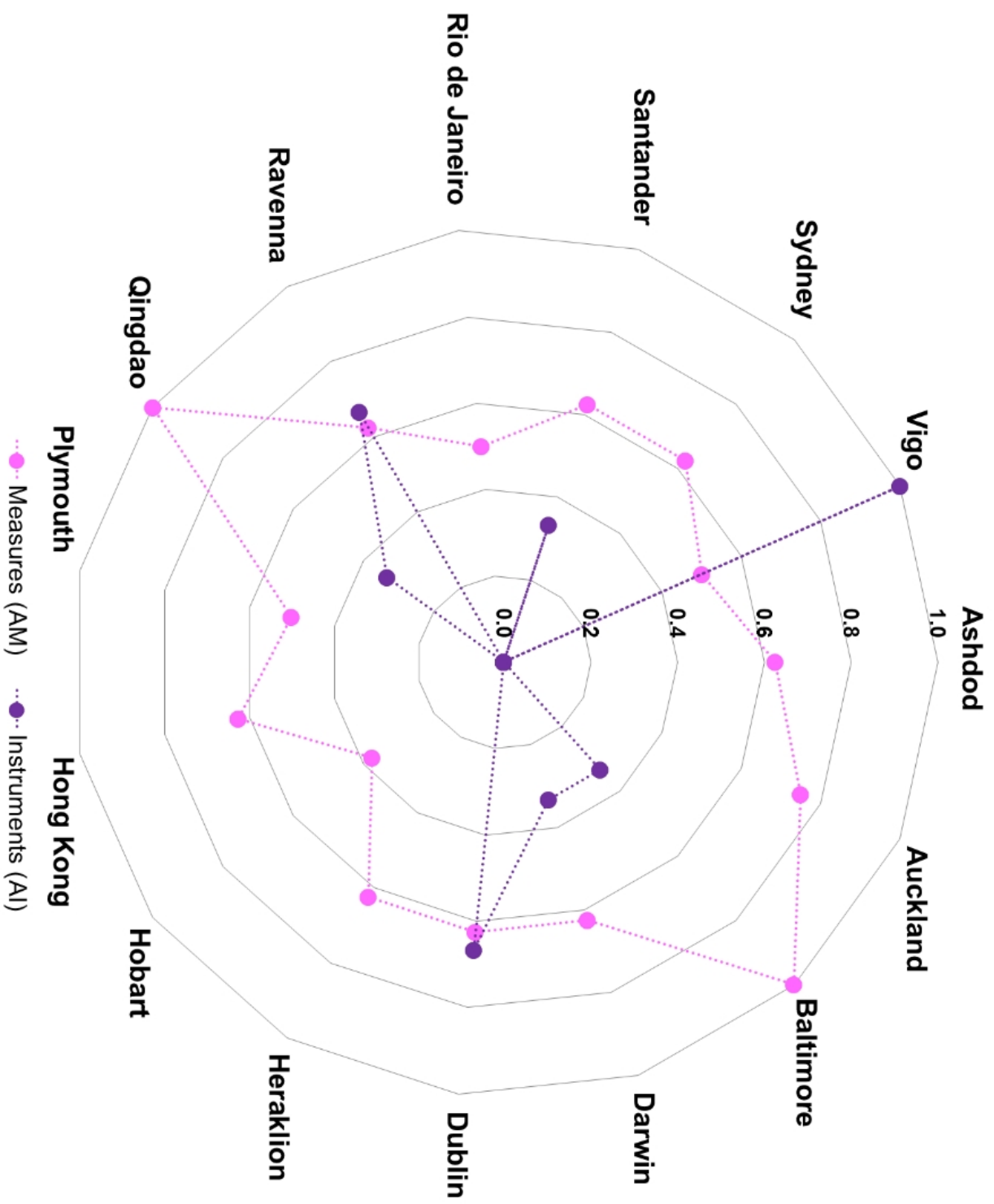
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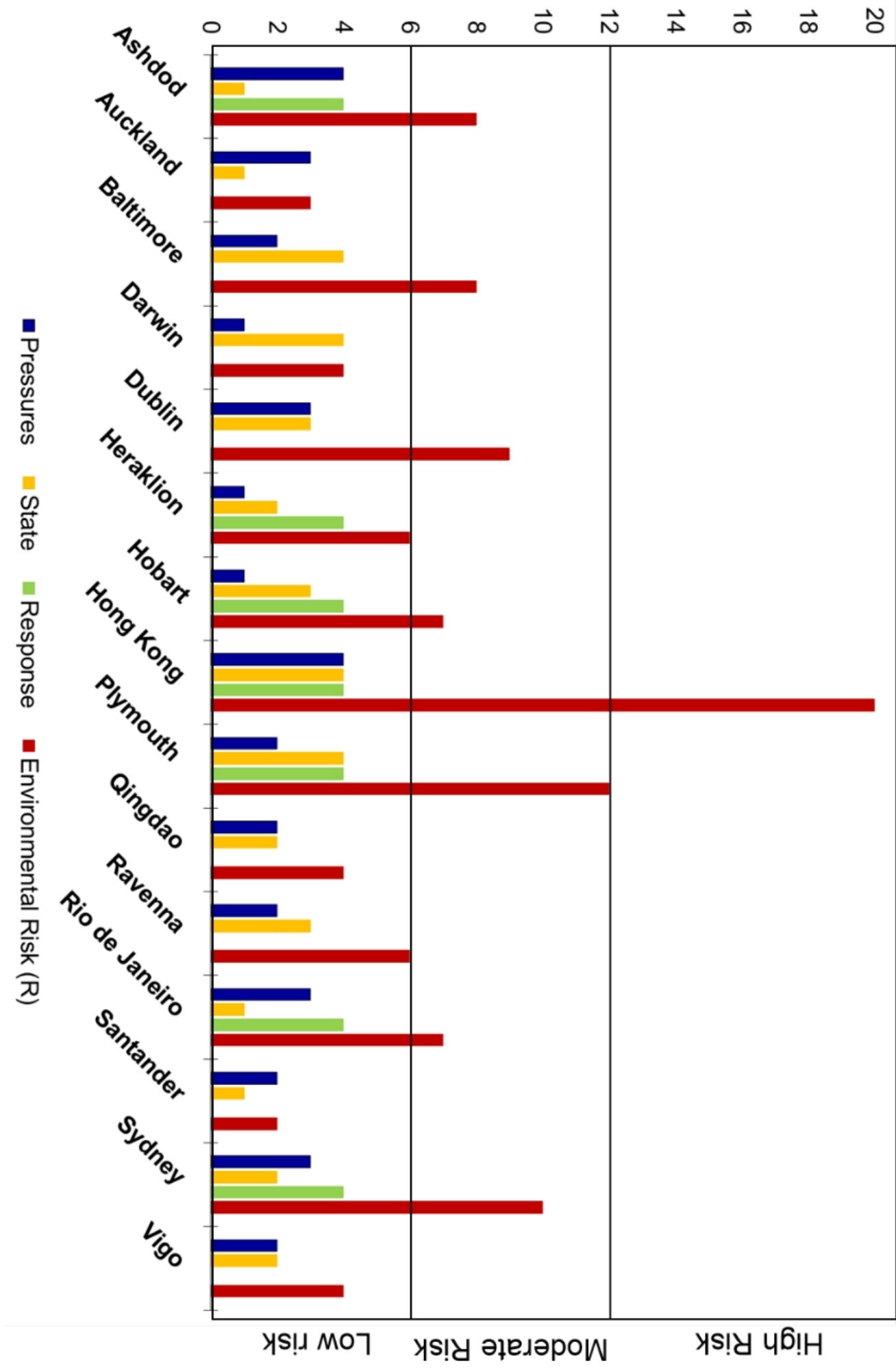


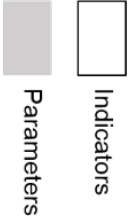
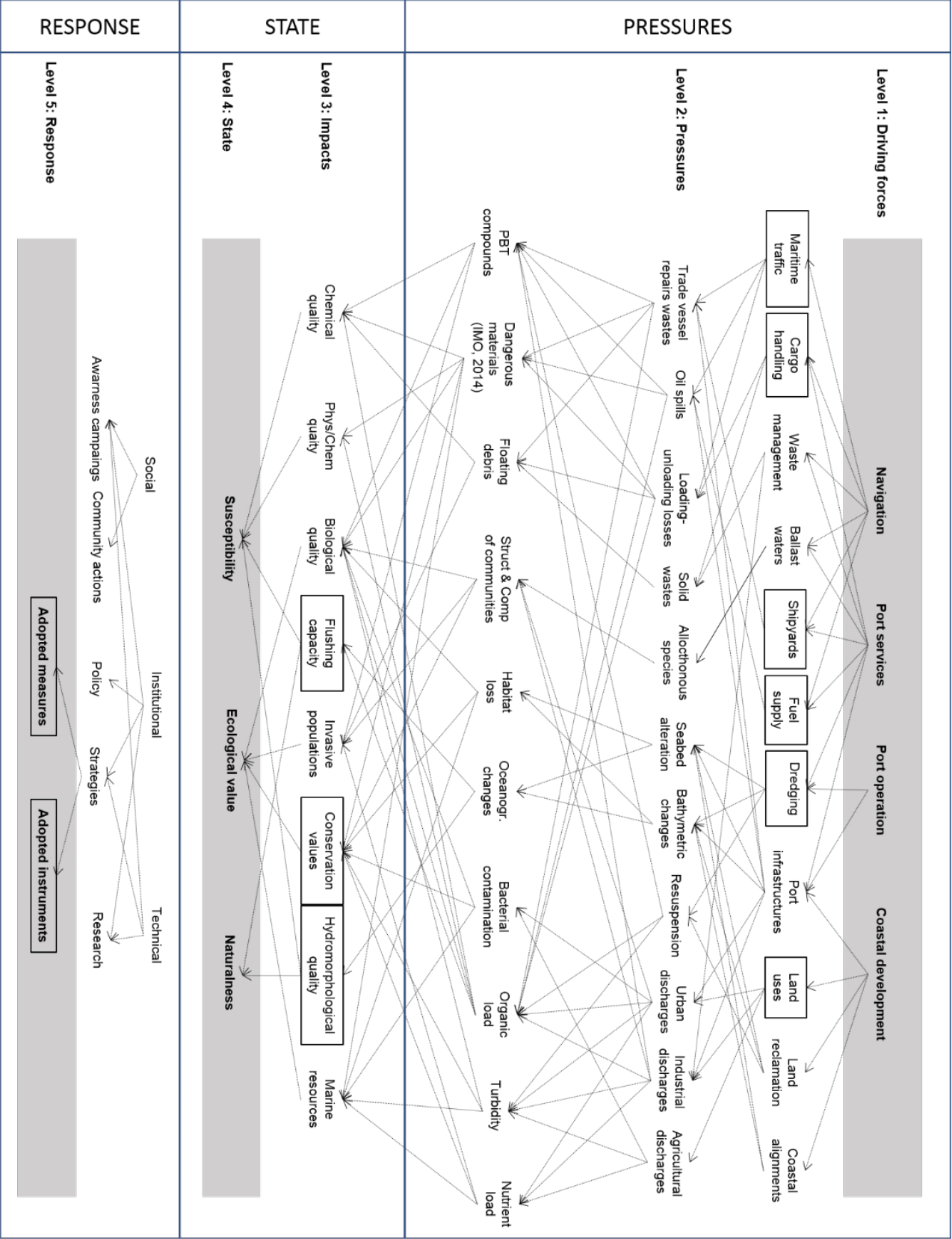


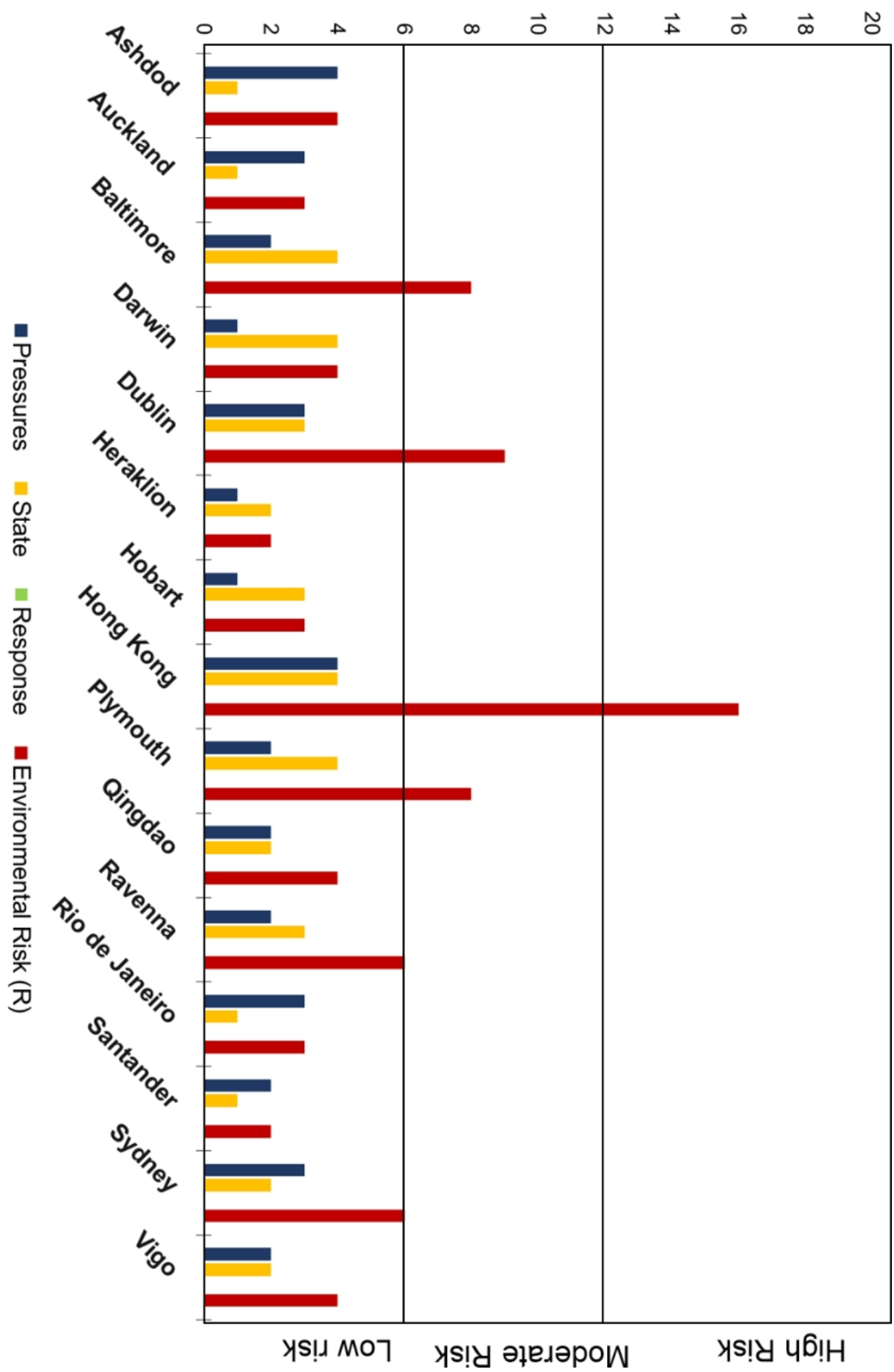












<b>General data</b>
Harbour's name: Postal address: Code: City: Country: web: phone: e-mail address:
<b>Hydromorphological characteristics:</b>
Entrance length (in meters): Average tidal range (in meters): Average depth (in meters): Depth at harbour entrance (in meters):
<b>Human pressures</b>
Number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

<b>Application scope</b>
<ol style="list-style-type: none"> <li>1. Access to GoogleEarth: <a href="https://www.google.es/intl/es/earth/">https://www.google.es/intl/es/earth/</a></li> <li>2. Introduce the name of the harbour in the seeker.</li> <li>3. Using Add -&gt; Add a polygon: draw the water surface where port activity takes place.</li> <li>4. Save the polygon as a .kmz and send it with this questionnaire filled out to: <a href="mailto:xxxxx.xxxx@unican.es">xxxxx.xxxx@unican.es</a></li> </ol>

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