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The Application of D(A)PSI(W)R(M) Framework to Coral Reef Conservation

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Abstract: A total of 379,834 people visited Ras Mohammed National Park in 2020/21, most of whom snorkelled or dived to see the coral reefs. Current management frameworks seem to be insufficient to tackle the increasing visitation, underlining the need for a holistic approach for integrated planning. The objective of this article is to analyse the application of the various elements of the most evolved expanded derivative of the DPSIR framework, (D(A)PSI(W)R(M)) (drivers, activities, pressures, state, impacts, welfare, responses, and measures), in relation to reef conservation and to elucidate how the framework might improve reef management in the park. To achieve the abovementioned objective, documentation on Ras Mohammed was reviewed, a selected sample of stakeholders were interviewed, and the park was visited to assess its assets, ecosystems, resources, facilities, regulations, ongoing visitation system, links between social and ecological systems, and the effectiveness of management. The main drivers were analysed and introduced, and a number of actions and responses were recommended depending on the framework analysis. The results of this study can guide the preparation of a management and restoration plan for reef sites and integrated coastal zone management.

Keywords: coral reefs; DPSIR; recreation; protected areas; Ras Mohammed National Park

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1. Introduction

Ras Mohammed was declared a national park in 1983 and covers an area of 460 square kilometres. The well-developed coral reefs, renowned SCUBA diving sites, diversity, clear warm water devoid of pollutants, accessibility in most weather conditions, and central location bridging three continents, Europe, Asia, and Africa, make the park a popular tourist destination [1,2]. Visitors to Ras Mohammed grew from a few hundred in 1988 to 444,653 in the fiscal year 2018/9, of which 400,461 (90%) were international tourists [3]. The number of visitors, along with the heavy recreational use by snorkelers and SCUBA divers, has damaged the reefs [4]. Other threats to coral reefs include coastal development, sedimentation, dredging, pollution, and overfishing [5]. The coral cover has decreased in many sites by 30% [6].

A landscape–seascape perspective for coral reef conservation that links together the causes, effects, and management of change should be adopted. The DPSIR framework is a valuable tool to map and assess multipart environmental issues from a macro perspective [7]. It is an extension of Statistics Canada's Stress–Response (S-R) framework from 1979 [8] and the OECD's Pressure–State–Response (PSR) model from the early 1990s [9]. Elliott and O'Higgins [10] summarised it as *drivers* placing *pressures* on the environmental *state*, which leads to *impacts* that elicit a management *response*. The framework has been applied in numerous environmental contexts, ensuring environmental management that connects ecological and socioeconomic factors and assesses whether specific policy decisions are effective [8]. It can establish connections among the various elements of environmental management, including research, society, and policy [11]. It incorporates both the internal status and the external factors and acts as a comprehensive method for reporting the environment state [12] and monitoring to decide whether management measures are effective [13]. Due to its communicative power, diverse application, and demonstrated utility, DPSIR continues to be used. DPSIR has been the subject of 577 articles, mainly in the fields of environmental science (70%), water resources (15%), and ecology (11%), according to the Web of Science. Eighty-eight articles were published during the period 1999–2010 and four hundred and eighty-nine during the period 2011–2021. Gari et al. [8] listed many studies that appreciated the DPSIR framework and advocated its usefulness as an effective scoping approach for complicated environmental issues and for integrating economic development and conservation functions. After a comprehensive review of two decades of use, Patrício et al. [11] asserted that the framework is needed and can potentially be used to address a variety of environmental challenges. Many international institutions have recommended its application, such as the OECD, EU, EPA, EEA, and UNEP. The framework describes societal and environmental cause-and-effect relationships: the impact of human activities on the state of the ecosystem and the provision of ecosystem services and benefits to human well-being [14]. However, DPSIR mainly addresses the first part, the human impacts on the environment, and pays little attention to the supply and demand of ecosystem services [10]. Moreover, some scholars have argued that the DPSIR framework tends to be rigid, a means of disseminating information and a reporting tool rather an analytical tool [15]. Other scholars have suggested combining it with other techniques to improve it [8,11]. It ought to continue to be developed into a more sophisticated tool for analysing and assessing environmental issues and managing ecosystems and natural resources [8]. Elliott et al. [14] refer to the confusion among DPSIR's components, especially distinctions between drivers and pressures and between state and impacts. DPSIR has evolved to become DPSWR (driver–pressure–state–welfare–response) [16] and then D(A)PSI(W)R(M) [14]. In this new form, the *drivers* necessitate *activities* that result in *pressures* on the *state* of the environment, leading to *impacts* on human *welfare* and requiring *response* as *measures*. This form is the latest attempt to optimise the DPSIR framework for environmental management and comes at the top of the evolutionary tree [11]. In another evolution, DPSIR has been linked to services and benefits through ecosystem-based management (EBM) [17] or structured decision making (SDM) [18–20]. Bradley et al. [18] used SDM to engage different parties in a deliberative environment to underline the impacts of management interventions on coastal ecosystems. They noted that SDM and the associated workshops contributed to a better comprehension of stakeholder values and preferences, as well as decision making options, interconnectedness, and landscapes. Rehr et al. [19] used a decision support framework consisting of two parts, DPSIR analysis and decision landscape analysis, to combine the stressors, processes, and outcomes with the legal, social, and institutional dimensions of decisions. Yee et al. [20] employed DPSIR as a tool in structured decision making to explore the alternatives, recognise the trade-offs, conform to stakeholder values, increase the likelihood of relating scientific results to practical problems, and enhance the management of marine ecosystems. Rehr et al. [21] applied the expected consensus index of new research (ECINR) to reduce stakeholder conflicts, harmonise management actions, and improve environmental decision making for coral reefs.

The challenge for reef-associated activities in Ras Mohammed is to evaluate the effectiveness of certain policies and to agree on measurable targets based on pre-established indicators. It is hypothesised that the identification of these measures depends on the ability to describe the linkages between reef benefits, services, and attributes and the availability of monitoring data. This study sought to contribute to this debate by exploring the current situation of coral reefs in Ras Mohammed, determining the factors that impact the reef areas, investigating their gradual changes and other park attributes, analysing the governance regimes that regulate the use of the park, and assessing the management responses to the issues and challenges facing the park. To this end, D(A)PSI(W)R(M) was used, and the application of its components was analysed in relation to reef management in the park.

2. Materials and Methods

2.1. Study Area

At the northernmost point of the Red Sea, on the southernmost tip of the Sinai Peninsula, is the National Park of Ras Mohammed, which has a view of the confluence of the Gulfs of Suez and Aqaba. It is only 12 km from Sharm El-Sheikh and 446 km from Cairo. Under Decree No. 1068, Ras Mohammed was declared a marine protected area in 1983. The park extends over 56 km of coastline and covers an area of 460 km^2 (133 km^2 of land area and 327 km^2 of sea area) [22]. The coral reefs at Ras Mohammed are well-known worldwide and include some of the top diving sites [23,24]. Day trips from land or sea bring visitors to Ras Mohammed.

2.2. Participants and Data Collection

Using information from documents on Ras Mohammed, it was possible to capture the current status of the park, the reef conditions and characteristics, and important stakeholders. Semi-structured interviews and stakeholder discussion meetings were the primary data collection methods, along with field observation and content analysis. Participants in the interviews represented the major stakeholders in the area (i.e., director of South Sinai Protectorates, manager of Ras Mohammed National Park, Nature Conservation Sector (NCS) and park staff, group of Egyptian Environmental Affairs Agency (EEAA), tour operators, tourism guides, tourists, and local communities). The stakeholders were selected to represent the reef users, management, and businesses. A structural elicitation of beliefs and preferences carried out in these interviews and meetings indicated a relative order of magnitude of many factors impacting the reef ecosystem (Appendix A, Elicitation Form for Ras Mohammed Interviews in the Supplementary Materials). The D(A)PSI(W)R(M) framework for coral reefs in Ras Mohammed was developed by applying an inductive technique to analyse data collected during the stakeholder meetings, semi-structured interviews, and field visits to the park. The framework with its combined tools contributed to simplifying the complexity and dynamics of reef ecosystem aspects and bridging the gap between resource managers and business groups.

2.3. The Framework

The application of D(A)PSI(W)R(M) in Ras Mohammed included archival research and a literature review on the park reef ecosystem and semi-structured interviews and meetings with the relevant stakeholders and decision-makers. The monitoring data can inform the relationships among the framework components. Existing knowledge was defined for each component. These components are as follows:

Drivers: The conventional DPSIR framework used drivers as synonymous with activities. Drivers, here, refer to vital social processes shaping human activity and affecting the coral reefs.

Activities: Satisfying needs leads to activities. Activities induce pressures influencing the state of the reef and generating impacts on human well-being and the ecosystem, which require responses.

Pressures: These are the means of change from activities to the ecosystem (state) and the social system (welfare). They ought to identify each activity's temporal and spatial impacts [10]. Each activity may cause one or more pressures, and every pressure may come from one or more activities.

State: This refers to the ecosystem, while impact refers to the changes to the ecosystem and the social system [11]. Such changes could be described as structural characteristics (e.g., the number of species in a community) or functioning variables (e.g., productivity) [10].

Impacts: These reflect the changes in the natural system (ecosystem physical, chemical, or biological state) and in the social system and human welfare (ecosystem services and benefits).

Responses: Management responses' interventions may target some drivers and activities and enable them to be avoided, mitigate the magnitude of the pressure or impact allowing use to occur within sustainable limits, restore the state of the environment itself, or promote understanding, awareness, and appreciation of the benefits derived from the reef ecosystem.

An understanding of these relationships is needed to justify management responses and promote adaptive management.

3. D(A)PSI(W)R(M) Framework for Coral Reefs in Ras Mohammed

Depicting the causal chain from drivers to responses is a challenging task for the reef ecosystem due to the complexity and dynamics of the ecosystem aspects, the mobile links with adjacent ecosystems (e.g., seagrass beds and mangroves), and the interdependence between the social, economic, and biological systems [2]. In order to comprehend the reef ecosystem's complexity, extended DPSIR (D(A)PSI(W)R(M)) was employed in a holistic way. The framework for reef management was completed by encompassing reef functioning, services, and benefits.

3.1. Drivers

Elliott and O'Higgins [10] stated that drivers refer to basic human needs (e.g., food, shelter, security, and goods) in addition to cognitive needs (e.g., knowledge, education, and research), aesthetic needs (e.g., recreation), and transcendence needs (e.g., non-use values). Many of these needs rely on ecosystem services and benefits and can be achieved through human activities. The aggregate of these needs are the forces that propel economic development.

Most of the literature on coral reefs is mixed between drivers and activities or between drivers and pressures. In addition, some studies use drivers synonymously with economic sectors, and others refer to them as the root causes of issues related to the reef ecosystem. Spurgeon [25] presented some instances of the underlying factors that contribute to coral damage, including population growth, poverty, human greed, insufficient resources, inappropriate policies, insufficient enforcement, poor education, public good nature of most of the reef benefits, user externalities, and market failure, to reflect many impacts on the reef system. Pearce [26] attributed the damage to a lack of information, resources, and commitment. Yee et al. [20] defined drivers as social and economic forces leading to human activities and exemplified the fishing, tourism, and shipping industries as drivers that impact the reef ecosystem. Bradley et al. [18] described them as key economic sectors (e.g., transportation, construction, tourism, and fisheries) that induce pressures on coral reefs. In Rehr et al. [19], drivers are economic activity (industry, agriculture, recreation, and tourism), waste disposal, culture, and housing. Leujak [27] described the anthropogenic reasons for reef deterioration at Ras Mohammed, as visitors might not care or cannot change their behaviour, or they do not know the existing rules. Similarly, Hime [28] attributed the reef damage to accidental and intentional contact with the reef by snorkelers and divers. Recreational users may also have adverse effects on the reef ecosystem through the increasing need for infrastructure, development, and seafood for restaurants. Moberg and Folke [29] noted that the multiple benefits provided by coral reefs made these ecosystems vulnerable to exploitation, from overfishing to coastal zone overdevelopment. The lack of knowledge about their value is a main cause of many threats to coral reefs.

3.2. Activities

Many human activities place pressure on coral reefs and exceed the carrying and assimilative capacities of the reef system. Elliott et al. [14] grouped human activities in the marine environment into 15 sectors and elucidated that these activities do not inevitably cause pressures on the ecosystem if management responses are taken. By adding activities, the D(A)PSI(W)R(M) framework succeeded in separating drivers and pressures and removing the confusion between them.

Human populations and tourist numbers are increasing rapidly in South Sinai, particularly at Sharm El-Sheikh, where the development now extends down the shoreline from

Ras Mohammed's northern edge to Nabq's southern edge. Shipping, transportation, local marina activities, and recreational vessels are also growing rapidly.

Coral reefs are deteriorated by the same economic activities they sustain. The main source of income for Ras Mohammed is tourism, which also poses the greatest damage to its coral reefs. Its expansion can be seen in the park, where the number of visitors increased from 77,550 in 1994/95 to 520,012 in 2009/10, but decreased to 379,834 in 2020/21 due to the spread of COVID-19 [3]. Over the past few decades, the park has seen an upsurge in tourists. Although some incidents, including the 11 September attacks in 2001, the Sharm El-Sheikh attacks on 23 July 2005, the revolution on 25 January 2011, and the Russian aircraft crash in Sinai on 31 October 2015, have had an impact on the number of visitors, recovery has been buoyant (Figure 1). March to April and August to October are peak seasons for the park.

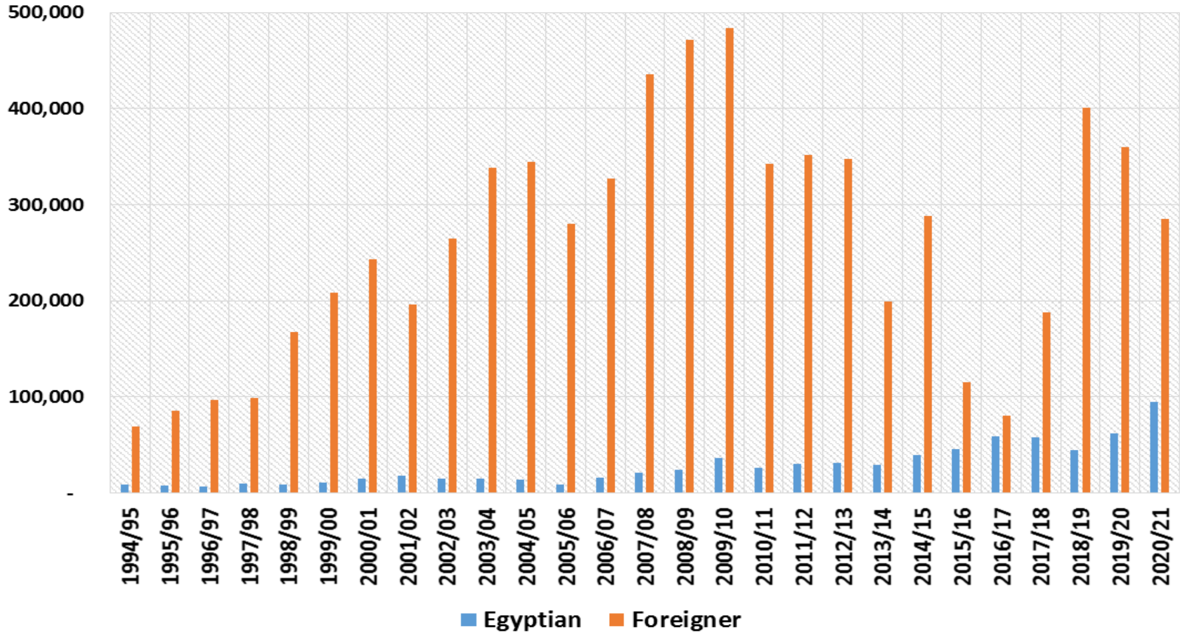

Figure 1. Annual tourists to Ras Mohammed. Source: EEAA [3].

Many reef sites are now showing signs of overfishing [5,30]. Giant clams, octopods, and strombids are among the invertebrates targeted, while groupers, emperors, rabbitfish, parrotfish, and snappers are among the fish targeted. El-Koniesa, an Egyptian company for fishing and exporting ornamental fish, began the exploitation of a 70 × 40 km area in the Gulf of Suez in 1985, not far from the park's southwestern boundary [31]. Many locations in the Red Sea have seen the harvest of sea cucumbers. The General Authority for Fish Resources Development doubled the total fish catches within the last three decades.

The Red Sea is one of the busiest international shipping routes, and the Suez Canal is regarded as the quickest route between the East and the West. This prominence is increasing with the development of maritime trade and transportation. Shipping is the most affordable form of transportation, and the majority of the global trade volume is transported by sea.

3.3. Pressures

Elliott [32] divided the pressures affecting marine ecosystems into exogenic unmanaged pressures (their cause emanates outside the area, e.g., climate change) and endogenic managed pressures (take place inside the management area, e.g., overfishing, coastal development, dredging, and land reclamation).

The damage inflicted by SCUBA divers and snorkelers includes sitting and standing on corals, hitting them with their fins and tank, creating sediment clouds, taking pictures [33], and introducing chemicals into the water [28]. In more heavily dived areas, reef damage was much higher, according to Hawkins and Roberts [34,35]. They noted that between 35,000 and 50,000 dives occur annually at these sites. Another study found that the six most heavily visited sites in Ras Mohammed receive more than 70,000 divers per year [31]. However, the carrying capacity has been estimated as 10,000 divers/year [36]. Medio et al. [37] noted that divers are the primary cause of coral mortality at Ras Mohammed. According to Salm [38,39], underwater photographers may be the most damaging to coral reefs.

South Sinai's population has grown from 54,806 in 1996 to 113,795 in 2022 [40]. Illegal fishing and the rising demand for seafood from Sharm El-Sheikh's residents and restaurants has affected several reef fisheries. The number of hotel rooms has grown from 515 in 1988 to 51,695 (180 hotels) in 2016 in Sharm El-Sheikh, corresponding to 29% of Egypt's overall hotel room capacity [41]. Furthermore, the number of diving vessels in Sharm El-Sheikh has increased from 26 in 1988 to approximately 300 today, resulting in increased reef damage. The number of diving centres has also expanded between 1988 and 2016 from 5 to over 70, with huge differences in standards, services, and quality [3,42]. Being a major international maritime route, the Red Sea is vulnerable to many vessel accidents and ship groundings on reefs due to the increase in recreational boat traffic. Coastal development, dredging, waste, and land reclamation represent additional stressors on coral reefs in the region.

The reefs of the Red Sea are vulnerable to few natural threats. Because the Red Sea is narrow and outside of tropical storm paths, waves are typically small and storms are uncommon [27]. Furthermore, the region is distinguished by an arid climate and a lack of river runoff, which results in relatively clear water. Good water circulation reduces seasonal variations in sea surface temperatures. For example, the Northern Red Sea has not yet experienced elevated sea surface temperatures that would cause widespread coral bleaching occurrences [24,43,44]. Coral reefs are naturally threatened by flooding, disease, and predator outbreaks. However, these events might be due to human influences [45]. Breakage that had occurred in the upper 10 m, where most human disturbance occurs, was the most common type of damage to coral reefs seen in Egypt [46]. Coral breakage was more common at heavily visited sites, according to Medio et al. [37]. Jameson et al. [47] noted that natural hazards caused low frequencies of coral damage, affecting 0–2% of colonies.

3.4. State

The interaction between physical, chemical, and biological variables determines the ecosystem's state. The Red Sea's geological and biogeographical features offer an ideal environment for a wide range of species and habitats [23,48]. In summer, the salinity ranges from 36.5 ppt in the south to 41 ppt in the north, with low freshwater inflows and high evaporation rates [49]. In comparison to the south (approximately 5 m), the water is clearer in the north (40–50 m) [50]. The climate is very hot and arid, with an annual rainfall of less than 5 mm, and the water temperature ranges from 21 °C to 30 °C [35,51]. The Red Sea's clear, warm, and saline water provides an ideal setting for coral recruitment. The Red Sea is rich in biodiversity, with approximately 209 hard coral species [52]. A total of 1000 fish species have been identified, with 17% of them endemic to the Red Sea [53]. The presence of considerable diversity in such a limited space confers great specificity of uniqueness.

Ras Mohammed's coral reef ecosystems are internationally regarded as among the best in the world, varying from shallow slopes with a sandy plateau to steep walls [54]. The most predominant reef type in the park is fringing reefs, which have a reef flat of 5 to 50 m and a reef slope depth of 10 to 85 m [45]. The dropping and submerged mountains of the Sinai Peninsula form the breadth of the reef flats at different sites [27]. Patch reefs are found in the Tiran Strait and the northeast of the park, with a shallow sandy platform from 10 to 140 m and a reef slope from 3 to 200 m [45]. Discontinuous fringing reefs with a shallow reef flat of 200 to 1800 m in width can be seen on Ras Mohammed's western side [45]. It has been estimated that the park has an average hard coral cover of 72% at a 1 m depth, 63% at a 5 m depth, and 54% at a 15 m depth [55]. However, lower percentages have been observed for some reef sites inside Ras Mohammed in other studies [27]. The genera diversity was discovered to peak between 10 and 15 m, where a shallow *Acropora* zone (hard corals) down to 5 m, a *Millepora* zone (hydrocorals) at 5 to 10 m, a *xeniid* zone (soft corals) at 10 to 40 m, and an overlapping *Montipora* zone (hard corals) at 20 to 25 m form the coral community [55,56]. The diversity of coral reefs contributes to Ras Mohammed's prominence as a travel destination, and the presence of endemic species lends it global significance as a biodiversity repository [49].

3.5. Impact

3.5.1. Impact on Reef Ecosystem

Ras Mohammed's slogan is "take nothing with you ... leave nothing behind". Nevertheless, because of their sheer number, park visitors leave a lot of damage behind them. Bryant et al. [57] stated that approximately 61% of Egypt's coral reefs are seriously threatened by anthropogenic threats. Many Red Sea sites have witnessed a 20 to 30% decrease in coral cover [5,47]. Hassan et al. [50] demonstrated that coral cover fell from 37% in 1997 to 13% in 2002 in two locations in the Gulf of Aqaba, and butterfly fish, which are deemed an indicator species for reef health, declined from 9.7/100 m^2 to 5.2/100 m^2, and the number of sweetlips decreased by 69%. El-Haddad et al. [30] elucidated that overfishing in the central and northern regions of the Gulf of Aqaba resulted in reef degradation. Dive sites near Sharm El-Sheikh featured less hard coral cover and more fragmented and partially dead coral colonies [4,34]. Medio et al. [37] reported that 8.2% of corals were shattered at accessed sites, compared to only 0.6% to 1.2% at closed sites. In 2002, a very low tide with a sea level of less than 0.2 m and strong winds pushed water from the reef flat and exposed the upper parts for roughly two hours at Ras Um Sidd in Sharm El-Sheikh. Following this incident, exposed parts blanched [27]. Coral diseases at Ras Mohammed (e.g., black band) have multiplied by ten [50] and have been linked to anthropogenic stressors [58,59]. A moderate crown-of-thorns starfish outbreak took place at the park in 1994, while there was a main outbreak in 1998 [45]. These outbreaks resulted in a 20% to 30% loss of coral cover at strongly afflicted locations [6].

3.5.2. Impact on Human Welfare (Benefits and Services Provided by Coral Reefs)

It is crucial to comprehend how reef services benefit people in order to manage them effectively. The reef services, their features, and how and where they are created, as well as where and how the benefits are realised, should be recognised. There is a need for ecosystem thinking to determine priorities for management interventions. The MA classified ecosystem services into four categories: provisioning services (e.g., food, medicines), supporting services (e.g., photosynthesis and nutrient cycling), regulating services (e.g., regulation of erosion and natural hazards), and cultural services (e.g., recreation and education) [60]. Moberg and Folke [29] identified the ecological goods (i.e., renewable resources and reef mining) and services (i.e., physical structure services, biotic services, biogeochemical services, information services, and social and cultural services) of a coral reef ecosystem.

The coral reefs at Ras Mohammed provide biodiversity and other reef services. The condition of the reef sites determines the quality of the cultural, social, and economic benefits the society and different stakeholders derive from these services. If the reef ecosystem has an appropriate structure and functioning, it is fostering a healthy environment and providing ecosystem services and benefits [61]. The activities in the region place pressures on the state of the reef ecosystem, leading to a range of impacts diminishing the condition of the reef value and affecting the quality of the benefits derived and human welfare, which elicits a management response. Understanding these relationships assists in predicting the potential changes in human well-being due to the changes in ecosystem services.

3.6. Responses (Measures)

Identifying the different components and understanding causal links in the framework are essential to guiding management actions (Figure 2). Reef management relies on governance that includes laws, regulations, and administrative procedures in addition to other tools such as economic instruments, education, research, and technological advancements [14]. These management responses to face the negative impacts of the drivers, activities, and impacts on the state of the ecosystem need to encompass measures, as management needs measurement to be achieved. Barnard and Elliott [62] presented 10 tenets of adaptive management and sustainability as measures in the framework: that our actions should be ecologically sustainable, economically viable, technologically feasible, socially desirable/tolerable, administratively achievable, legally permissible, politically expedient, ethically defensible, culturally inclusive, and effectively communicated. Comte and Pendleton [63] reviewed 767 published articles that address coral reef management and found that they focused mostly on conservation strategies, then mitigation and adaptation strategies and, finally, on restoration strategies.

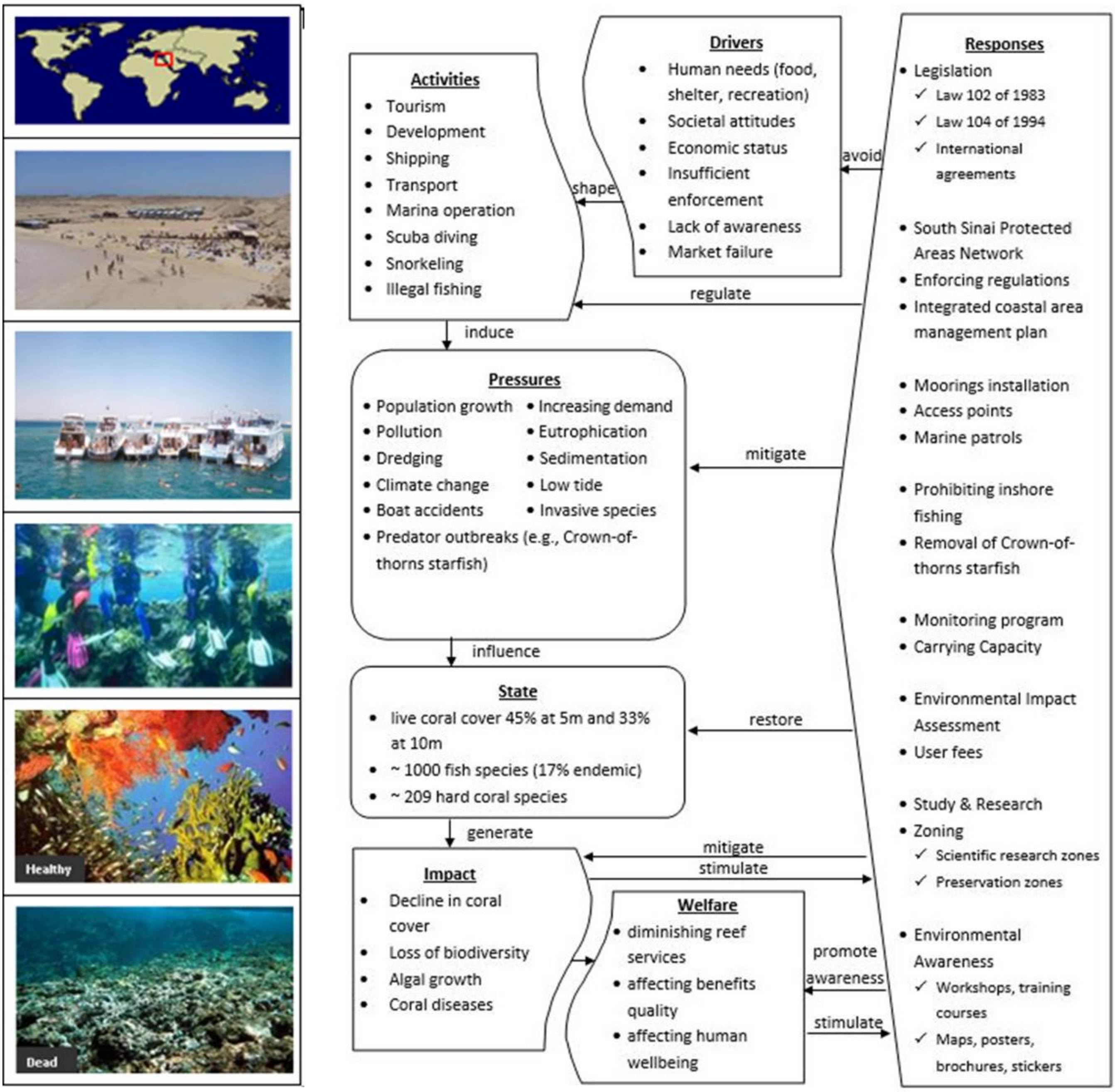

Figure 2. D(A)PSI(W)R(M) framework for coral reefs in Ras Mohammed.

Egypt has identified three future needs for coral reef protection: development challenges, information requirements, and public awareness [45]. The Egyptian government's challenge is to strike a balance between environmental protection and economic development. Consequently, several laws have been enacted to govern this relationship. Article 45 of Egypt's 2014 Constitution dictates that the state commits to conserve its seas, beaches, lakes, waterways, mineral water, and natural reserves. Environmental Law 104 of 1994 is the main law that specialises in matters of environmental protection. Nature Protectorates Law 102 of 1983 prohibits activities that endanger organisms and ecosystems within protected areas. Implementation and enforcement, however, are inadequate, with competing objectives and conflicting policies across different government agencies. Egypt is also a signatory of all the major international agreements and conventions and regional organisations regarding the conservation of biodiversity. Examples include CBD, RAMSAR, WHC, CITES, and PERSGA.

The Nature Conservation Sector (NCS) of the Egyptian Environmental Affairs Agency (EEAA) is responsible for nature conservation and the management of protected areas. A network of protected areas, representing the principal ecosystem types of scientific importance, was established throughout the country to safeguard the environment against damaging development, maintain natural resources, and control traditional extractive uses. Zones for scientific research and preservation are kept closed. Mooring buoys, walkways, and access points have been established to reduce the damage to coral reefs. Environmental impact assessments are requested from developers. Marine species identification using taxonomical methods is employed. However, effective modern tools in marine biodiversity assessment (e.g., DNA barcoding) should be used more widely [64]. A user fee (USD 5 per day) in addition to a reef damage fee system (USD 300 per m^2) was implemented. Starfish removal campaigns were organised. Inshore fishing is prohibited in the park.

Environmental awareness has risen as a result of significant efforts. A number of workshops, seminars, and training courses for the hotel staff, instructors, and dive guides were organised in addition to the distribution of brochures and regulations in multiple languages. According to Medio et al. [37], one environmental awareness briefing decreased the divers' contact with living coral and reef substrates from 0.9 to 0.15 and from 1.4 to 0.4 per diver per 7 min, respectively. Therefore, diver instruction might boost the carrying capacity of coral reefs.

4. Management Implications

We may know the solutions, but the problem is applying them. This section illustrates the connection of the D(A)PSI(W)R(M) organisational scheme to decision making. D(A)PSI(W)R(M) incorporates information into a preliminary decision landscape and provides the information needed to decide between different decision options. It is used to clarify the decision context [20], which is the first step in describing the decision landscape [18]. SDM includes clarifying the decision context, defining objectives and measures, developing alternatives, estimating consequences, evaluating trade-offs, selecting alternatives, implementing, monitoring, and reviewing [65]. The decision landscape is a description of issues that could affect a decision (e.g., scale, current condition, decision-makers, and stakeholders) [19].

Coral reefs at Ras Mohammed face challenges that could jeopardize their future success. The park has seen an upsurge in visitors, and the number has increased five-fold since 1995. While tourism development provides numerous benefits to the region (e.g., economic returns, jobs, and infrastructure), it can also have serious and negative environmental consequences. Tourism, in this regard, is a double-edged sword. The implementation of a protective management system is determined by societal values and the government's commitment to protected areas as opposed to other options. Unfortunately, when conservation and development are at odds, the government and other authorities are more likely to favour the latter, because they will not accept any compromises regarding the influx of tourists and the associated earnings.

4.1. Scales and Stakeholders of Reef Benefits

Stakeholder involvement and capacity building are crucial components of the management plan. Beneficiaries and impactors should be identified at all levels (local, national, and international). This provides a more comprehensive picture of the park's effectiveness. Sites established without the adequate consultation of all relevant stakeholders and without taking into account the associated costs and benefits of conservation are likely to face opposition and fail to achieve the desired results. However, if these sites have the support of local communities and national authorities, they can be quite successful in preserving coral reefs. Productive relationships with the main societal groups are the foundation of successful environmental governance. Government authorities, developers, NGOs, hoteliers, tourists, tour operators, guides, and local communities are examples of the region's stakeholders. The key factors described by stakeholders in the semi-structured interviews and discussion meetings were captured in the D(A)PSI(W)R(M) framework.

The park attempted to foster mutual relationships with local communities by offering jobs and services. Bedouins have been hired at Ras Mohammed to work as skippers or community guards, or to perform other duties. Diving centres and tour operators should impose restrictions on their clients' activities because of the importance of reef health to their businesses. The policies of the administrative institutions in charge of developing the tourism industry occasionally clash with the conservation strategies. To receive the deserved recognition, the management objectives of Ras Mohammed's coral reefs should be visible to the public.

Coral reef services are often a function of the beneficiary's perspective [66]. Beneficiaries have varied perceptions and interests regarding reef services at different spatial scales. The value of reef benefits differs among stakeholders according to socioeconomic factors and the degree of reliance on these benefits. This variation has both spatial and temporal components. Hence, the issues of space and time scales should be taken into account in both economic and ecological system analysis. The interests of many ecosystem service stakeholders are significantly influenced by these scales. The beneficiaries of an ecosystem service are determined by the scale at which it is produced [67]. The Gulf of Aqaba's fish resources, although not very significant at the national scale, are beneficial to Bedouins in South Sinai. The coastal protection function that the reef offers to development is of interest to the municipality, investors, and local authorities. The recreation and biodiversity of Ras Mohammed are of primary interest to both the national and international communities. Local users are more concerned with the direct benefits (e.g., food and raw materials), but global society is more likely to prioritise conservation, indirect benefits, and non-use values. The park management plan should take into account and balance these various interests, and it should be acceptable to different stakeholders.

4.2. Policy Scenarios

Decision alternatives should be explored and policy scenarios derived to achieve the objectives. There is a direct link between ecotourism and the presence of coral reefs and protected areas. The development strategy should consider sustainability, guarantee that the number of visitors will not exceed the ecosystems' carrying capacity, and ensure that environmental standards are followed. Coral reef management should focus on enhancing the ecosystem's health, characteristics, and functions in order to maintain the flow of services and benefits.

Three possible scenarios that may be used in creating tourism development policy are depicted in Figure 3. Promoting mass tourism and cheap 3S (sea, sun, and sand) packaged tourists instead of creating niche markets (i.e., elite tourism seeking out environmental uniqueness) and retaining the region as a centre of excellence, attracting classic divers and elite tourism, is thought to be a short-term strategy that will not ensure the tourism industry's sustainability. Long-term planning and sustainability are only ensured by scenario 3. Development should not conflict conservation. Ecotourism depends on the state and health of the ecosystem; therefore, rather than competing with it, it should promote it.

Tourists choose destinations where they can see healthy reefs and an abundance of fish. Many factors influence the demand for reef locations (*driver*), including reef quality (*state*) (e.g., reef health, coral cover, diversity, richness, abundance, biomass, reef type, structural complexity, aesthetic value, marine life, visibility, conditions at the site, ease of access, and availability of substitutes). Diver/snorkeler numbers (*activity/pressure*) significantly influence reef quality (*impact*). Some management measures (*responses*) can mitigate this impact. Some address quantity (control coastal development, number of visitors, number of dive boats, underwater photography, and night diving) and others quality (promote environmental education for divers and snorkelers through briefings, orientations, reef etiquette, monitoring programs, and awareness campaigns). The park management can use several instruments to achieve these measures, including prescriptive regulations (e.g., access limitations, moorings, walkways, and swimming pontoons) and direct market mechanisms (e.g., licensing system, fines, and entrance fees).

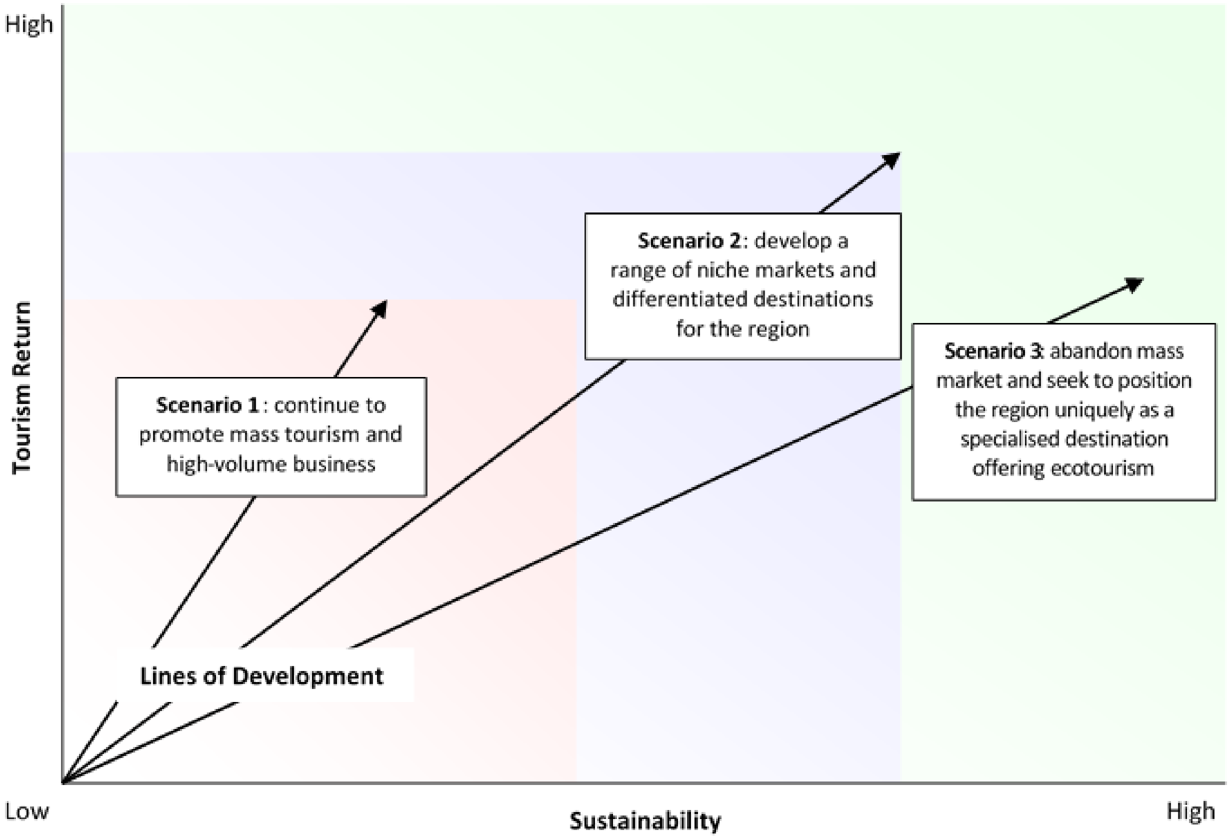

Figure 3. Tourism development scenarios (adapted from Tawfik and Turner [2]).

Tawfik and Turner [2] found that visitors to Ras Mohammed had a preference for less congestion at reef sites in exchange for healthier reefs. The highest WTP value (USD 0.5 for each 1%) was found for improved reef quality, followed by USD 0.4 for more dive sites, and USD 0.2 for fewer people at reef sites. Policy scenarios can be developed based on WTP estimates. Scenario A (the status quo), Scenario B (more sites for the same number of people), and Scenario C (fewer people for the same sites) vary from less (A and B) to more restrictive (C). The results, provided in Table 1, show that the sustainability scenario (C) yields higher net benefits than business-as-usual scenarios (A and B), which justifies the commitment to conserve coral reefs.

Table 1. The costs and benefits of the different scenarios.

	Scenario A	Scenario B	Scenario C
People	Usual number	Usual number	50% Fewer people
Dive Sites	15	25	15
Consumer Surplus		1,897,790	2,361,219
Entrance Fees	2,377,746	2,377,746	1,188,873
WTP	2,377,746	4,275,536	3,550,092
Expenditures	300,000	500,000	300,000
Opportunity Cost	-	1,092,000	-
Net Benefit	2,077,746	2,683,536	3,250,092

Source: Tawfik and Turner [2].

4.3. The Impact of COVID-19 on Tourism and Visitation in Ras Mohammed

Tourism is a major sector in Egypt, with approximately 783 thousand employees in accommodation and food services and USD 12.6 billion (4.2% of GDP) earnings for the economy in 2019 [68]. COVID-19 has had a strong negative effect on tourism in Egypt. Eighty percent of hotel bookings were cancelled with the spread of the virus in March 2020 [69].

The COVID-19 outbreak has had a significant impact on the park's tourism and visitation. The Egyptian Ministry of Environment suspended all visitation, recreation, and tourism activities in protected areas, including Ras Mohammed National Park, as of March 2020 [70]. The park reopened to visitors in June 2020, with strict precautions and measures in place to minimise the potential impact of COVID-19 on park visitors. The total number of visitors to Ras Mohammed decreased by 15% between 2018/19 (444,653) and 2020/21 (379,834) due to the spread of COVID-19 [3]. This drop was in the number of foreign tourists, which decreased by 29%, from 400,461 in 2018/19 to 285,304 in 2020/21, while the number of national tourists increased by 114% from 44,192 in 2018/19 to 94,530 in 2020/21 [3]. The pandemic has had a negative economic impact on park tourism. Entrance and camping fee revenues, which were significant sources of the park's budget, were lost. Millions of dollars in tourism activities were also lost. Furthermore, the pandemic has had a negative impact on local communities. Hundreds of tourism workers (e.g., local tour guides, drivers, boat captains, concierges, technicians, and hotel staff) lost their jobs. Local women who make handcrafts lost their income. From an ecological perspective, the lower number of visitors provides an opportunity for environmental healing for the coral reef ecosystem.

The park management plan should include the social, ecological, and economic trade-offs and guarantee that the number of tourists does not exceed the carrying capacity of the ecosystems and that sufficient management is in place to ensure that environmental standards are followed.

5. Discussion

DPSIR and its derivatives have been employed with increasing frequency and tailored to many different applications. However, the application of the framework in the assessment of marine ecosystems is observed less often. Patrício et al. [11] found that only 26 studies addressed marine habitats covering the Mediterranean region, Portuguese waters, German North Sea, Baltic Sea, Dutch Wadden Sea region, UK waters, North East Atlantic, and Black Sea. They noted that DPSIR has mainly been used in a European context (80%), while other regions (North America, South America, Asia, Africa, and Oceania) represent only 20%. In Egypt, there are only a few studies that have used the DPSIR framework. These are mainly focused on water resources [71] and wetland ecosystems [72]. This suggests a lack of knowledge concerning the DPSIR framework's potential to effectively manage the reef ecosystem in the region, which could lead to the development of regulations that are not effective from a management perspective. This article explored the current situation in Ras Mohammed to understand the drivers, activities, pressures, state, impacts, and responses in relation to reef conservation and provide a discourse on how the D(A)PSI(W)R(M) framework may enhance reef management in the park. To our knowledge, this is the first study that applies DPSIR or its derivatives for the coral reefs in the Red Sea.

The management of the park requires information on the connections between human activities and impacts on the coral reefs and the collation of the related issues to the actual and predicted situations. The D(A)PSI(W)R(M) framework can be useful in visualising the root causes of issues related to the reef ecosystem in Ras Mohammed National Park and conceptualising and translating them to different stakeholders. It can strengthen responses to identify problems and provide a unified platform that considers different components in the reef ecosystem. The framework has been employed in many studies as a pillar in framing environmental problems.

Overdevelopment along the coast, pollution, overfishing, high population growth rate, high dependency rate on coral reefs, mass tourism, increasing demand, overlapping and incompatible regulations, poor enforcement, and ignorance are threats to coral reefs. Environmental awareness, education, legislation, developed institutional capacity, multilayer management systems, research, monitoring, impact assessments, integrated coastal area management plans, adaptive management, and the consent of the community are needed for the sustainability of ecotourism and resilience of the park.

Sustainable tourism is considered the most important commercial use of the park. Ras Mohammed's management should prepare for the growing number of visitors and keep track of their impacts on the reef system in order to maintain its benefits. The expansion of management capacity and facilities within the park in future years will be essential to meet the demands placed on it by increased levels of visitor use. The development of visitor management tools and policies to control activities and diminish impacts on the reef will be measures of the park management's effectiveness and its ability to address the links between environment, development, and tourism and to find a balance between recreation and conservation. In addition to biological concerns, social and economic aspects should be taken into account to maintain both the visitor experience and the reef quality. Failure to do so will have a severe impact on the reef ecosystem and erode Ras Mohammed's reputation as a reputable ecotourism destination.

The DPSIR framework is a valuable tool and an effective scoping approach that has been applied in numerous environmental contexts to connect the causes, effects, and management of change; ecological and socioeconomic factors; internal status and the external factors; research, society, and policy; and economic development and conservation functions. Because of its simplicity and transparency, many international institutions recommended its application. However, some scholars have argued that the framework tends to be a reporting tool rather than an analytical tool. Other scholars suggest combining it with other techniques (e.g., EBM, SDM, and ECINR) to improve it. Bradley et al. [18] used SDM for informing watershed management options in Guánica Bay, Puerto Rico. The application included three workshops with decision-makers, experts, and stakeholders. Rehr et al. [19] applied an integrated DPSIR/decision landscape framework to coral reefs in the Florida Keys. They elicited nine workshop respondents, mainly resource managers, for their preferences and chose water quality for the analysis due to its larger prospects for local and regional management. Yee et al. [20] employed DPSIR as a tool in SDM to support decisions for sustainable reef ecosystem services applied to the development of water quality criteria in the US Virgin Islands and Puerto Rico and to watershed management to protect coastal resources in Guánica, Puerto Rico. Rehr et al. [21] applied ECINR to improve environmental decision making for coral reefs in the Guánica Bay Watershed, Puerto Rico. ECINR incorporates aspects of multiple criteria analysis (MCA), Bayesian belief networks (BBNs), value of information (VOI) analysis, and the DPSIR/decision landscape, and they relied on a study group of seven participants representing resource managers and scientists. This study attempted to analyse the application of the various elements of the most evolved expanded derivative of the DPSIR framework (D(A)PSI(W)R(M)) in relation to reef conservation and to elucidate how the framework might improve reef management in the park. The application included archival research and semi-structured interviews with the relevant stakeholders representing the reef users, management, and businesses and focused more on tourism and recreation, which were thought to be the most important to the different stakeholders. Recreation is frequently considered the most important reef benefit and can be used as a lower bound of the reefs' value. The limitations of the study were reflected in its inability to build a comprehensive numerical model that correlates the pressures, state, and impacts due to the stakeholder sample size. In future research, a larger and more diverse sample group would help to quantitatively elucidate these relationships. Moreover, the linkages between socioeconomic benefits, the ecosystem services that created them, and the reef attributes that provide them should be elucidated to identify potential measures. The absence of scientific information and monitoring data on these linkages makes it difficult to develop decision alternatives and policy scenarios for some factors. A broad management strategy that includes many more drivers than recreational activities is needed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15119133/s1, Elicitation Form for Ras Mohammed Interviews.

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Appendix A. Participant Elicitation and Data Collection

Application of D(A)PSI(W)R(M) in Ras Mohammed included archival research and literature review on the park reef ecosystem and semi-structured interviews and meetings with the relevant stakeholders and decision-makers. The existing scientific research on Ras Mohammed coral reefs was organised into the framework. Participants represented the major stakeholders in the area, including resource managers (the director of South Sinai Protectorates, the manager of Ras Mohammed National Park, Nature Conservation Sector (NCS) and park staff, and a group of the Egyptian Environmental Affairs Agency (EEAA)), businesses (tour operators d tourism guides), and resource users (tourists and local communities). Participants were asked to identify the key factors through constructing their own D(A)PSI(W)R(M) and order or weigh the relative importance of the different factors impacting the reef ecosystem for each component in the framework. The average of the participant responses was used to order these factors and keep only the first six, compiling the remaining factors in 'other'. The reef management preferences gave high weight to the scientific issues and the coral reef health, whereas the business groups and reef users placed more value on economic and social factors.

Table A1. Drivers of coral reef degradation.

Literature and Archival Research					
Source	**Drivers**				
Spurgeon [25]	Human greed, poverty, insufficient resources, inappropriate policies, poor education, public goods, externalities, market failure				
Pearce [26]	Lack of information, lack of resources, lack of commitment				
Yee et al. [20]	Fishing, tourism, shipping industries				
Bradley et al. [18]	Transportation, construction, tourism, fisheries				
Rehr et al. [19]	Industry, agriculture, recreation, tourism, culture, housing				
Leujak [27]	Visitors might not care or cannot change their behaviour, or do not know				
Moberg and Folke [28]	Reef goods and services, lack of knowledge about their value				
Semi-structured interviews and stakeholder discussions					
Driver	Park, EEAA Staff	Tour operators	Tourists	Local communities	Overall rank
• Recreation	☆☆☆	☆☆☆	☆☆☆	☆☆	1
• Coastal protection	☆☆	☆☆☆	☆☆	☆☆☆	2
• Seafood	☆	☆☆	☆☆☆	☆☆☆	3
• Raw materials	☆	☆	☆☆	☆☆☆	4
• Societal attitudes	☆☆☆	☆	☆	☆	5
• Market failure	☆☆	☆	☆	☆	6
• Other	☆	☆	☆	☆	7

☆☆☆: very important, ☆☆: important, ☆: somewhat important.

Table A2. Activities inducing pressures on coral reefs.

Literature and Archival Research					
Source	**Activities**				
Hawkins and Roberts [29,30], PERSGA [31], Abou Zaid [32], Hime [33], Medio et al. [35]	Tourism, scuba diving, snorkeling, swimming, safari, camping, boats and yachts, sailing				
Salm [36,37]	Underwater photographers				
El-Haddad et al. [38]	Fishing				
Tawfik and Turner [2]	Shipping				
Semi-structured interviews and stakeholder discussions					
Activity	Park, EEAA Staff	Tour operators	Tourists	Local communities	Overall rank
• Tourism	☆☆☆	☆☆☆	☆☆☆	☆☆☆	1
• Diving and snorkeling	☆☆☆	☆☆☆	☆☆☆	☆☆	2
• Illegal fishing	☆☆	☆☆	☆☆	☆☆☆	3
• Development	☆☆☆	☆☆	☆	☆☆	4
• Marina operation	☆☆	☆☆	☆	☆☆	5
• Shipping and transport	☆☆	☆☆	☆	☆☆	5
• Other	☆	☆	☆☆	☆	6

☆☆☆: very important, ☆☆: important, ☆: somewhat important.

Table A3. Pressures on coral reefs.

Literature and Archival Research					
Source	**Pressures**				
CAPMAS [40]	South Sinai's population growth				
Abdelmawgoud [41]	The number of hotel rooms in Sharm El-Sheikh				
SSRDP [42]; EEAA [3]	The number of diving vessels and diving centres				
Hime [33]	The increased demand for infrastructure, development, and fish				
Leujak [27]	Natural threats				
Wilkinson [43]; Gajdzik et al. [44]	Climate change				
PERSGA [45], Jameson et al. [47]	Flooding, disease, predator outbreaks				
Pilcher and Abu Zaid [6]	Crown-of-thorns starfish outbreaks in 1994 and 1998				
Semi-structured interviews and stakeholder discussions					
Pressure	Park, EEAA Staff	Tour operators	Tourists	Local communities	Overall rank
• Population growth	☆☆☆	☆☆☆	☆☆☆	☆	1
• Increasing demand	☆☆☆	☆☆	☆☆	☆☆	2
• Pollution	☆☆	☆☆	☆☆	☆☆	3
• Climate change	☆	☆☆	☆☆☆	☆	4
• Boat accidents	☆☆	☆	☆	☆☆☆	4
• Predator outbreaks	☆☆	☆	☆	☆	5
• Other	☆	☆	☆	☆☆	5

☆☆☆: very important, ☆☆: important, ☆: somewhat important.

Table A4. State of coral reefs.

Literature and Archival Research					
Source	**State**				
PERSGA [45]	Reef type in the park (e.g., fringing reef, patch reefs)				
Kotb et al. [55]	Coral cover percentage at different depths in the park				
Veron [52]	Biodiversity, coral species				
Ashworth [53]	Fish species, endemism				
Kotb et al. [49]	Salinity, temperature				
Hassan et al. [50]	Visibility				
Semi-structured interviews and stakeholder discussions					
State	Park, EEAA Staff	Tour operators	Tourists	Local communities	Overall rank
• Coral cover	☆☆☆	☆☆☆	☆☆☆	☆☆	1
• Diversity/richness	☆☆☆	☆☆☆	☆☆☆	☆☆	1
• Abundance/biomass	☆☆☆	☆☆	☆☆☆	☆☆☆	1
• Visibility	☆☆	☆☆☆	☆☆☆	☆☆	2
• Reef type	☆☆☆	☆☆	☆☆	☆	3
• Structural complexity	☆☆☆	☆	☆	☆	4
• Other	☆☆	☆	☆	☆	5

☆☆☆: very important, ☆☆: important, ☆: somewhat important.

Table A5. Impacts on coral reefs and ecosystem services.

Literature and Archival Research					
Source	**Impacts**				
Jameson et al. [47];	Decrease in coral cover				
Hassan et al. [50]	Number of butterfly fish and sweetlips				
Branchini et al. [4]; Medio et al. [35]	Corals breakage				
Hassan et al. [50]; Ammar et al. [60]	Coral diseases (e.g black band)				
Tawfik and Turner [2]; Al-Hammady et al. [61]	The quality of the benefits derived and the human welfare				
Semi-structured interviews and stakeholder discussions					
Impact	Park, EEAA Staff	Tour operators	Tourists	Local communities	Overall rank
• Decline in coral cover	☆☆☆	☆☆☆	☆☆	☆☆	1
• Loss of biodiversity	☆☆☆	☆☆☆	☆☆	☆☆	1
• Diminishing reef services	☆☆	☆☆☆	☆☆☆	☆☆	1
• Affect human wellbeing	☆☆	☆☆	☆☆☆	☆☆☆	1
• Coral diseases	☆☆☆	☆☆	☆☆	☆	2
• Algal growth	☆☆☆	☆☆	☆	☆	3
• Other	☆☆	☆	☆	☆	4

☆☆☆: very important, ☆☆: important, ☆: somewhat important.

Table A6. Management responses.

Literature and Archival Research					
Source	**Responses**				
PERSGA [31]	Legislation, international agreements, and regional organisations				
EEAA [3]	PAs network, zones for scientific research and preservation, mooring buoys, walkways and access points, EIA, user fees, fines				
Trivedi et al. [64]	DNA barcoding				
Tawfik and Turner [2]	Environmental awareness, workshops, seminars, and training courses				
Semi-structured interviews and stakeholder discussions					
Response	Park, EEAA Staff	Tour operators	Tourists	Local communities	Overall rank
• Environmental awareness	☆☆☆	☆☆☆	☆☆☆	☆☆	1
• Legislation	☆☆☆	☆☆☆	☆☆	☆☆	2
• Research and technology	☆☆☆	☆☆☆	☆☆	☆	3
• Administrative procedures	☆☆☆	☆☆	☆☆	☆	4
• Monitoring	☆☆☆	☆☆	☆	☆	5
• Economic instruments	☆☆	☆☆	☆	☆	6
• Other	☆	☆	☆	☆	7

☆☆☆: very important, ☆☆: important, ☆: somewhat important.

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