Artificial reefs, environmental offset and the enhancement of marine habitat in Bahrain: a case study.

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Within the Arabian Gulf, an array of anthropogenic impacts have left their mark on the integrity and productivity of marine ecosystems with once complex marine habitats now reduced to rubble. During recent decades, extensive areas of benthic habitat in the Arabian Gulf have been decimated, not only by intense land reclamation and dredging activities, but also as a result of destructive and illegal fishing practices.

The government of Bahrain has long experimented with the use of artificial reefs, not only as a tool to offset environmental damage, but also to enhance those subtidal areas which have the potential for increased productivity. Now, under the umbrella of the Public Commission for the Protection of Marine Resources, Environment and Wildlife (PCPMREW), PH Environment Gulf has been commissioned to design, construct, deploy and monitor ten artificial reefs (2620 artificial reef units in total) strategically located within Bahrain's waters. The key objective is to enhance fish stocks within the selected areas, with a view to expanding the project should this initial phase prove successful.

Artificial reef site selection studies commenced in October 2011 via a GIS-based exclusion mapping exercise; this resulted in the initial selection of ten areas within which more intensive field investigations (e.g. drop-down video, SCUBA diver and fisheries surveys) were undertaken. Three of the ten shortlisted areas were selected as artificial reef sites and a desk-based hydrodynamic assessment of reef unit stability undertaken to confirm their suitability. These selected sites were located off the north, east and north-west coasts of mainland Bahrain.

It was decided at the outset that the US Patented Reef Ball™ system would be the mainstay of the artificial reef unit design although indigenous designs which reflect both Arabian architecture and the natural topography of the seabed have been included. The majority of reef unit types, including all Reef Balls, are constructed in Bahrain at the premises of Reef Arabia using a high strength (50+ MPA) marine-grade concrete mix.

The first artificial reef complex (262 units) was deployed in March 2012 and the target date for deployment of all ten reef complexes is October 2012. Marine environmental monitoring of the reefs will continue for a further year on a quarterly basis; this monitoring will be temporally staggered in accordance with the sequential deployment of the reefs.

1. Introduction

An artificial reef may be defined as "one or more objects of natural or human origin deployed purposefully on the seafloor to influence physical, biological or socio-economic processes related to living marine resources" (Seaman Jr. and Jensen, 2000). Although this definition is limited to *planned* artificial reefs utilising either natural or prefabricated structures, as is the case in the present study, the majority of artificial reef structures are *unplanned*, and include offshore oil and gas structures (e.g. pipelines and rigs), sunken vessels and coastal breakwaters (Feary *et al.*, 2011).

In the Gulf, artificial reefs are most frequently deployed in an attempt to enhance commercial fisheries through the provision of Essential Fish Habitat (EFH). However, the extent to which these reefs actually increase fisheries production, as opposed to merely acting as Fish Aggregation Devices (FADs), is difficult to quantify and requires the implementation of dedicated long-term monitoring programmes. Artificial reef deployment is also a means of benthic habitat enhancement, providing 3-dimensional relief within otherwise featureless 2-dimensional seascapes and promoting the colonisation of the reefs by epibiota (e.g. ascidians, sponges and corals), thereby serving to increase local epibenthic diversity and productivity. This enhancement of benthic habitat also lends itself to the promotion of recreational diving, with artificial reefs possessing considerable tourism potential.

In Bahrain, several factors have contributed to the deterioration and destruction of extensive areas of benthic habitat in recent decades. Anthropogenic causes include widespread land reclamation, most notably along the northern coastline of mainland Bahrain and the island of Muharraq, and associated offshore dredging activities. Destructive fishing practices, particularly demersal trawling, have also contributed to this habitat degradation. In combination with overfishing, this has led to a decline in several commercial fish stocks (FAO, 2011). The coral bleaching events of the late 1990s also led to widespread mortality of living coral on many offshore reefs to the north and east of the main island (Spalding *et al.*, 2001); much of this fragile 3-dimensional reef habitat has now been reduced to rubble.

The main objective of the Bahrain artificial reef project is therefore to offset the past and present environmental impacts of marine construction works, destructive fishing practices and overfishing through the creation and enhancement of benthic habitat, with a view to increasing fisheries productivity.

2. Project background

In September 2011 PH Environment Gulf was commissioned by the Public Commission for the Protection of Marine Resources, Environment and Wildlife (PCPMREW), under the auspices of the Ministry of Municipalities and Urban Affairs (MMUA) Special Projects Unit (SPU), to construct, deploy and monitor a total of 10 artificial reef complexes, each comprising 262 reef units, within Bahrain's territorial waters. The Marine Resources Directorate (MRD) was appointed technical advisor, specifically with regards to the identification of reef sites. URS Bahrain was commissioned to provide auditing/quality control services with regard to the construction, deployment and monitoring phases of the project.

A number of small-scale experimental artificial reef studies using concrete slabs, tyres and large steel pipe sections as base materials have been previously undertaken Bahrain. More recently, a precursor study to this artificial reef project was conducted by WL-Delft Hydraulics and ASR in 2003.

The present project constitutes the first *large-scale* deployment of artificial reefs in Bahrain and a test-bed from which future similar projects may be progressed.

The project Scope of Works (SoW) consists of three phases:

- Phase I – Site selection
- Phase II – Construction and deployment
- Phase III – Monitoring (including acquisition of baseline data)

3. The requirement for artificial reefs

The principle justification for the large-scale deployment of artificial reefs in Bahrain's territorial waters is based upon the need to offset adverse marine environmental impacts generated by ongoing dredging and reclamation activities and the increasing fishing pressures which have resulted in the widespread deterioration of the marine habitats and decline in a number of commercial fisheries. It is also important to note that the *natural* phenomenon of coral bleaching affected many reefs during the 1990s, resulting in the widespread deterioration these habitats throughout Bahrain's waters.

Dredging and land reclamation

Based on PH Environment Gulf's knowledge of past and present dredging activities, a total offshore sea area of at least 226 km² has been exploited for marine aggregate, predominantly for land reclamation. In reality, this figure is likely to be much larger since the first large-scale reclamation of land began in the mid- to late 1960s.

Historically, land reclamation has been concentrated along the north and east coasts of mainland Bahrain (e.g. *Manama* and *Hidd*) and the shores of *Sitra* and *Muharraq* Islands, although it is now spreading southwards. Recent estimates indicate that between 1964 and 2007 a total 88.5 km² (13.4 %) of land has been reclaimed, resulting in the loss (via smothering) of vast areas of productive intertidal and shallow subtidal habitat. During this period, *Muharraq* Island has increased in size by 278.5 %, *Sitra* Island by 59.1 % and mainland Bahrain by 7.47 % (Zainal *et al*., 2009).

Declining fisheries

Over fifty fish and invertebrate taxa currently contribute to Bahrain's capture fishery, with many taxa naturally associated with rocky reef habitats (as juveniles and/or adults). It is these species which will benefit most from creation of artificial reef habitat.

Although it is not possible to account for annual variation in fishing effort, the overriding observation is that of declining catches in recent years (FAO, 2010, 2011).

The Orange-Spotted Grouper *Epinephelus coioides* (*Hamour* in Arabic) is arguably the most important commercial fish in the Arabian Gulf. The fishery for *Epinephelus* sp. (as *E. coioides*) in Bahrain has declined in recent years, with the nominal catch falling from 811 tonnes (t) in 2003 to 176 t in 2009. This follows the global downward trend for *E. coioides*, which is currently classified as 'Near Threatened' on the IUCN Red List (IUCN, 2012).

The Pearl-Spotted Rabbitfish *Siganus canaliculatus* (*Safi*) inhabits coastal waters to 40 m depth. The capture fishery for *Siganus* spp. has fluctuated during the period 1999-2008, with nominal annual catches decreasing more recently (2602 t in 2006 to 1366 t in 2009).

The Sordid Sweetlip *Plectorhincus sordidus* (*Janam*) typically reaches up to 30 cm in length and is commonly found near reefs in either small groups or solitary. The capture fishery for this species has declined overall since 2004 (132 t to 77 t in 2009). During the years 1999-2009, catches for the entire Family Haemulidae (grunts and sweetlips) have also declined, peaking at 354 t in 2004 and decreasing overall to 47 t in 2009.

The Family Nemipteridae (threadfin and dwarf breams) encompasses nine species of the genera *Nemipterus*, *Scolopsis* and *Parascolopsis* in the Arabian Gulf. In Bahrain, annual catches have decreased from 294 t in 1999 to 86 t in 2009. The Family Lutjanidae (snappers and jobfishes) is dominated by Snappers (*Lutjanus* spp.) in Bahrain's waters. Annual nominal catches have declined from 294 t in 1999 to 44 t in 2009.

Coral bleaching

Although Bahrain does not possess any true fringing reefs, offshore reef platform structures, locally known as *fasht*, historically supported healthy coral populations. However, the bleaching events of 1996 and 1998 resulted in the widespread mortality (85-90%) of living corals on these reefs (Spalding *et al.*, 2001), particularly on *Fasht Al Adhm* to the east of Bahrain. During subsequent years, many of the fragile ex-coral structures, particularly those of former branching *Acropora* species, have been reduced to rubble.

4. Exclusion mapping

The artificial reef study commissioned by the Special Projects Department of The Ministry of Works and Housing, and carried out by WL-Delft Hydraulics and ASR (2003), formed the basis of the RFP (Request For Proposal) for the current project. Thus, in accordance with the findings of the site selection procedure presented in this study, the majority of Bahrain's northernmost, west, south-west and south-east territorial waters were excluded from further consideration as artificial reef locations.

For the present study, the remaining sea area was subject to a detailed GIS-based exclusion mapping exercise. The key objective of this was to identify sites which were potentially suitable for the deployment of artificial reefs by eliminating those which were unsuitable. The advantage of undertaking this process was that the scope of further studies (e.g. field investigations), which may be both costly and time consuming, can be reduced in scale. Exclusion mapping therefore highlights those 'priority areas' which require further field or desk-based investigative studies; this facilitated a well-informed assessment to be made of the suitability of reef sites, culminating in the final site selection for ten proposed reef complexes.

The following section briefly describes the exclusion mapping criteria which were applied. **Figure 1** provides an overview of all excluded sea areas and was created by combining the GIS layers for all criteria. Ten potential artificial reef areas were identified for further investigation.

Bathymetry

Bathymetry exclusion mapping was initially carried out based upon a minimum prerequisite water depth of 10 m, as indicated within the project RFP. However, the results indicated that by excluding all water depths less than 10 mBCD, particularly between 6 and 10 m depth, significantly large areas of potentially viable artificial reef habitat would be lost. Following consultation with the Marine Resources Directorate (MRD) it was decided that artificial reefs would be deployed in waters ranging between 6 and 15 mBCD (Below Chart Datum).

Borrow areas

Offshore borrow areas where dredging has been undertaken or is currently underway, as well as those locations which have been earmarked for future dredging, were excluded as potential artificial reef sites. Although the deployment of reefs at former borrow sites is not logistically impossible, it is highly unlikely that such locations will be adequate given the impoverished habitat and unstable bottom substrates (i.e. fine sediments) which remain following dredging operations (D. Edwards, *pers. obs.*).

A 2 km wide buffer zone was also assigned to each borrow area boundary, ensuring that there will be no interaction between the artificial reefs and dredging activities. Of particular concern is the potential for suspended sediment generated by dredging to adversely affect adjacent marine biotopes, particularly with regard to smothering of benthic epibiota by sediment deposition.

Reclamation sites

All known current and future reclamation sites, the latter in accordance with the latest published version of the 2030 National Plan[1], have been excluded from further consideration.

Major shrimping grounds, fashts and fishing areas

The presence of artificial reef complexes within Bahrain's major shrimping grounds would reduce the extent of these grounds (i.e. the area of suitable habitat available for shrimp trawling). Furthermore, the reefs pose a potential threat to demersal trawling, with the risk of entanglement and damage to the trawling gear (e.g. nets, otter boards).

Conversely, the interaction of fishing gear with the reef units may adversely affect the latter, including the physical removal and damage, either sub-lethal or lethal, to epibiota colonising the external surfaces of the reefs (e.g. bivalves, sponges, corals). The process of shrimp trawling would also result in seabed disturbance and sediment resuspension within the water column, reducing the effectiveness of the reefs.

The three major shrimping areas are Bahrain North Area and *Um Al Dud* (581 km²), East Area and Ghumais (256 km²), and Bahrain North Area, *Al Eslah* and *Al Khash* (77 km²). A 1.5 km wide buffer zone was placed around each area as a contingency to ensure that there will be no interaction between the artificial reefs and shrimping activities. The total area excluded due to the presence of shrimping grounds was 1412 km².

A 2 km buffer zone (1735 km²) was added to all areas of *fasht* (619 km²) within Bahrain's waters. These shallow subtidal/intertidal areas, particularly the larger *fashts* of *Fasht Al Jarim* and *Fasht Al Adhm* are intensively fished. The creation of this artificial reef exclusion zone will minimise any negative interactions with ongoing fishing activities or natural Essential Fish Habitat (EFH) currently associated with rock-dominated *fasht* areas. The total sea area excluded due to the presence of *fasht* was 2354 km².

Protected sites

Bahrain is in the process of nominating a number of sites for UNESCO World Heritage Site (WHS) status. Three of the nominated sites are offshore oyster beds (*Hayrs*) in Bahrain's northern territorial waters, namely *Hayr Abu Ath-Thamah* (56 km²), *Hayr Bu am'amah* (48 km²) and *Hayr Shtayyah* (237 km²).

In addition, *Fasht Bu-l-Thamah*, a small shallow-water reef to the north of the *Hayrs*, has been described as "the best and healthiest coral reef area in Bahraini waters (Uwate *et al.*, 1999), with a high fish stock (Abdulqader, 2006), and is surrounded by an oyster bank (Nayar and Al-Rumaidh, 1993)" (GEOMATEC, 2006). This area has been declared a Marine Protected Area

[1] It is important to note that the 2030 National Plan is a 'live' document and as such is subject to review and amendments. PH Environment Gulf have used the latest published version.

(MPA) under Bahrain Ministerial Decree No. 8 of 2007. *Fasht Bu-l-Thamah* is important due to its rich fish resources and rare, vulnerable and biodiverse habitats (GEOMATEC, 2006).

An updated Ministerial Decree is currently being finalised. This decree will declare the 3 aforementioned oyster beds and *Fasht Bu-l-Thamah* (7 km^2), including the extensive buffer zone which encapsulates all 4 sites (948 km^2), protected areas by law. The total area excluded due to the presence of the proposed pearling World Heritage Site (offshore) is 1289 km^2.

Restricted areas and unexploded ordnance

There are several restricted locations which unauthorised vessels are forbidden to approach/enter and these have been excluded. These locations include the sea areas surrounding *Jidah* and *Umm Al Nassan* Islands (north-west Bahrain), the area adjacent to *Mina Salman* port and the US 5^{th} Fleet's naval base (*Manama*), and the approach to Sheikh Isa Air Base (south of *Al Dur* on the east coast). Within the limits of the Port Authority, the 'explosives anchorage' has also been excluded, as well a series of eleven anchorage sites located to the immediate east of this area.

National boundaries, navigational channels and causeways

In order to eliminate potential international conflict arising from artificial reef deployment along Bahrain's territorial waters boundary, a 1 km wide reef exclusion zone was established along this border.

The Bahrain Approach Channel (BAC) constitutes the major shipping lane serving Bahrain's *Sheikh Khalifa Bin Salman* Port and *Mina Salman* Port. Numerous large commercial vessels regularly use the BAC and artificial reefs will not be deployed within the channel or immediately adjacent to it. A 1 km buffer zone was assigned to either side of the Channel to ensure that the reef complexes do not interfere with shipping operations. Other navigational channels (e.g. Saudi Causeway approach channel and dredged channel to the west of *Al Dar* Island) were also excluded.

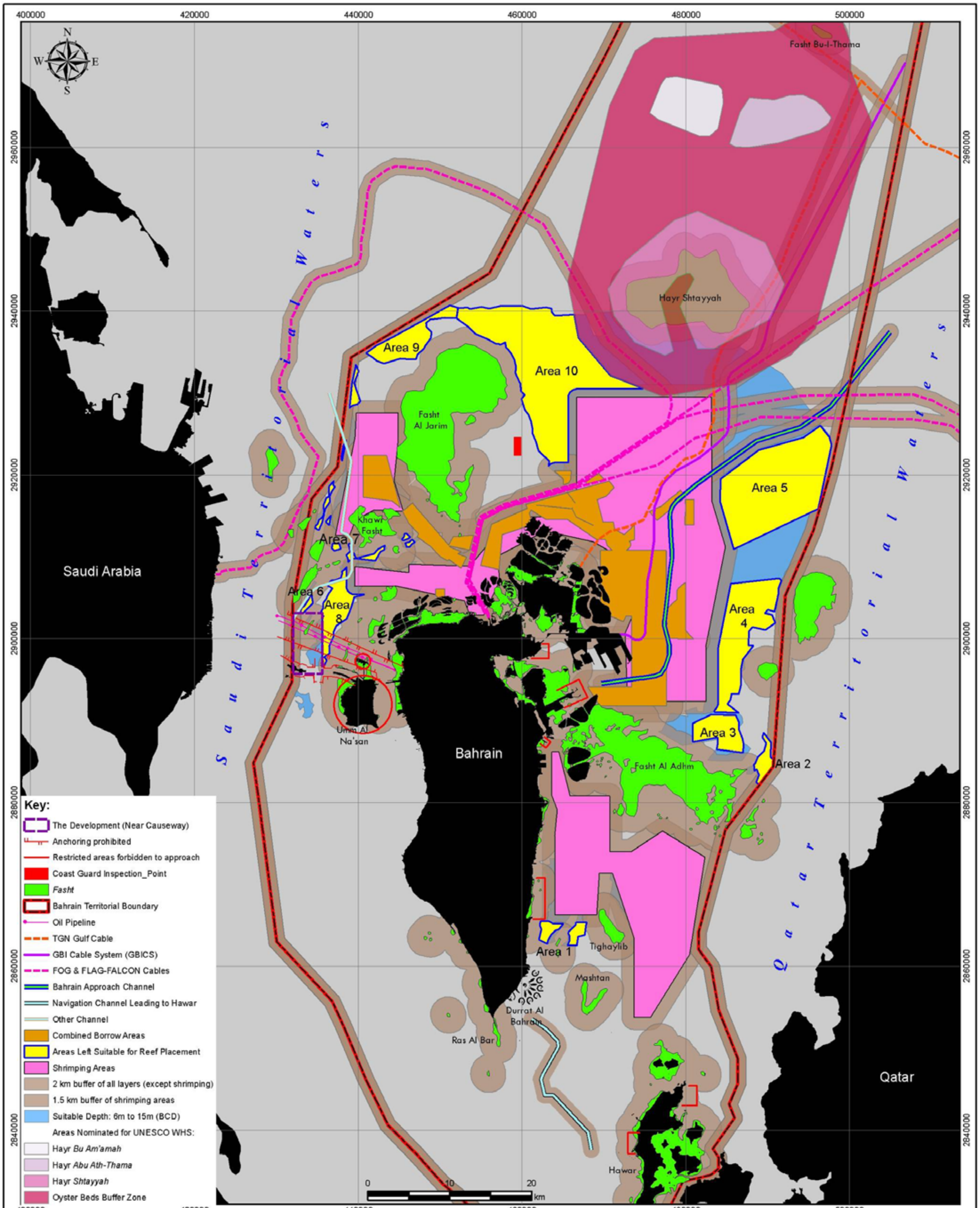
Utilities and services

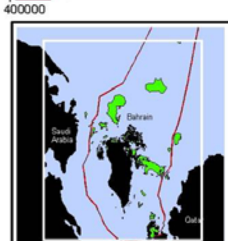
The presence of submarine cables, pipelines and offshore facilities serves to exclude the deployment of artificial reefs at such locations within Bahrain's inshore and offshore environment. There are currently four submarine telecommunications systems with present or planned landing stations along Bahrain's coastline:

- The Fibre Optic Gulf (FOG) communications cable.
- The FLAG-FALCON (FLAG = Fibre Optic Link Around the Globe; FALCON = FLAG Alcatel-Lucent Optical Network).
- The Tata TGN-Gulf (Tata Global Network-Gulf).
- Gulf Bridge International Cable System (GBICS).

All of these cable routes were excluded, including 1 km wide buffer zone areas running either side of the cables.

The Saudi Arabian-Bahrain oil pipeline route, extending from the north-west coast of Bahrain (ca. 1 km north of the Bahrain-Saudi Arabia causeway) to *Al Khobar* on the Saudi Arabian east coast, was also excluded.





Title: **Exclusion Mapping (All Layers) - Remaining Potential Artificial Reef Areas (1-10)**	Client: Public Commission for the Protection of Marine Resources, Environment and Wildlife
Project: Construction, Deployment and Monitoring of Artificial Reefs	Consultant: POSFORD HASKONING ENVIRONMENT GULF W.L.L. a Partner Company of ROYAL HASKONING
Date: January 2012	Figure No.: 1
Datum: WGS 84 - UTM 39 N	Scale: 1: 600,000 (A4)

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5. Field investigations

Following exclusion mapping, ten potential artificial reef areas (A1-A10) were identified (**Figure 1**); these areas required further scrutiny and collection of data via specialist surveys. Initially, a broadscale view of these areas was obtained via remote Drop-Down Video (DDV); more detailed information was recorded by SCUBA divers.

Drop-Down Video survey

This DDV survey facilitated the identification and mapping of seabed habitats and conspicuous epibiota over a wide area without the need for divers, thereby enabling the rapid assessment of key marine ecological features throughout the project area. Although this system allows for remote viewing of the seabed and differentiation between substrate types (e.g. rock, sand, mud), where soft substrates are present the sediment depth cannot be accurately determined.

A summary of the DDV observations for the ten survey areas is presented in **Table 1**. Area 6 was not surveyed and excluded from further consideration due to its proximity to the Bahrain-Saudi approach channel.

Table 1. Summary of DDV survey observations

Area	Water depth range (mBSL)	Total area (km^2)	No. of DDV stations	Observations
A1	6.5 – 11.2	8.0	40	Dominated by soft mud/fine sand sediments with sparse, mixed seagrass coverage
A2	7.9 – 9.3	4.7	12	Rock with Sand Veneer (RSV) habitat, sparse, mixed seagrass at several stations.
A3	7.4 – 11.9	20.4	16	Dominated by coarse, rippled sand substrate with limited RSV habitat.
A4	7.1 – 10.7	70.9	50	Low-relief RSV habitat, sand veneer of variable thickness.
A5	9.2 – 14.9	123.3	50	Low-relief RSV habitat, sand veneer of variable thickness.
A7	6.0 – 12.5	10.3	32	Variable habitat across sub-areas; RSV with good vertical relief dominates around *Khawr Fasht,* mobile sand habitat characterises most northerly sub-area.
A8	6.5 – 11.3	21.3	30	RSV with limited influence of sand veneer and variable topography.
A9	6.2 – 8.5	25.0	17	Mobile sands (strong currents) in central area and limited RSV habitat in the north and east.

Table 1 continued.

Area	Water depth range (mBSL)	Total area (km²)	No. of DDV stations	Observations
A10	7.1 – 14.8	158.0	152	Rippled sand dominant in central and east sections (likely overlying bedrock) with RSV habitat dominant closer to *Fasht Al Jarim* in the west.

Following review of the DDV video footage and additional information on sediment depth obtained from brief 'truthing' SCUBA dives, four of the ten areas, namely Areas 4, 5, 8 and 10, were shortlisted for further investigation. However, following consultation with the Marine Resources Directorate, Area 5 was excluded due to its potential future utilisation as a borrow area. Representative DDV images from Areas 4, 8 and 10 are presented in **Figure 2** below.

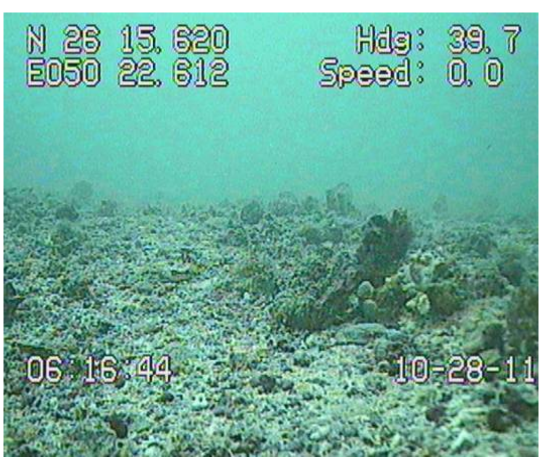
Figure 2. Representative DDV images from Areas 4, 8 and 10

a. Area 4

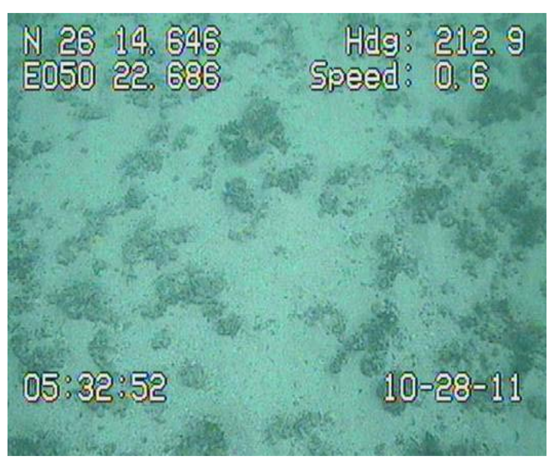
Rock with Sand Veneer (RSV) habitat

Sponges and urchin *Echinometra mathaei*

b. Area 8

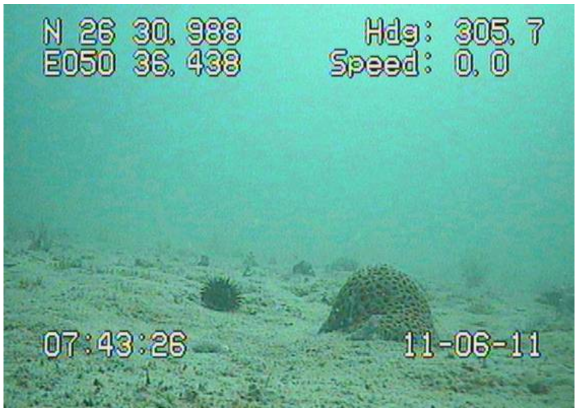


Gravel, cobble and pebble RSV habitat



RSV (coarse sand veneer)

c. Area 10



Low-relief RSV. Faviid coral and *E. mathaei* in foreground

Coarse, rippled sand with scattered rocks

6. Reef unit stability assessment

Actions of water currents and extreme wave action can result in forces at the seabed which have the potential to adversely impact reef units via a number of pathways specifically:

1. Movement of units (i.e. sliding along the seabed).
2. Toppling of units due to strong currents.
3. Undermining of seabed sediments (i.e. scour) which may lead to instability and eventual toppling of units.

In order to determine whether the proposed selected reef locations (Areas 4, 8 and 10) were suitable with regard to the hydrodynamic stability of the reef units, HR Wallingford (HRW, UK) were commissioned to undertake a reef unit stability assessment.

The desk study estimated the potential hydrodynamic forces imposed upon the submerged Reef Balls™ and custom-made units using Morison's equation (Morison *et al.*, 1950; Det Norske Veritas, 2007). Forces on the reef units were calculated using extreme water level and wave conditions from WL-Delft Hydraulics (2007) study together with current information from HRW's own flow model. Corrections for wave-current interaction were also undertaken. The results indicated that all reef units within each of the three shortlisted areas is likely to be stable.

Following the conclusion of exclusion mapping study, analysis of field data and completion of the reef unit stability assessment a total of five reef sites were selected: two sites in Area 4, two sites in Area 10 and one site in Area 8. At each site, two reefs (or 'reef complexes') were deployed, a total ten reef complexes. The layout of the reefs at each site is detailed in **Section 8**.

7. Reef unit design and construction

Reef unit designs

Each artificial reef complex comprises 262 units, the majority from the patented Reef Ball™ range (i.e. Goliath, Ultra, Pallet and Bay Balls) as well as several custom-made units (i.e. wind tower, anti-trawl and *majfara*).

The simplicity and effectiveness of the Reef Ball™ design, which possesses an uncanny resemblance to some of the natural ex-coral/rock 'bommies' in Bahrain's waters, as well as its widespread use and exceptional track record, was instrumental in the selection of this reef unit type as the mainstay of the reefs.

Natural bommies - similar shape and dimensions to Reef Balls™

The indigenous designs, including the low-lying *majfara* (or ridge module) and the high-relief wind tower, were included to introduce both topographic variation and complexity to each reef complex. Natural *majfara* (cracks/fissures within the rocky seabed) provide a preferred habitat for many demersal fish species in Bahrain's waters, including the highly-prized orange spotted grouper *Epinephelus coioides.* The *majfara* modules attempt to mimic this local seabed feature.

Majfara (ridge module)

Goliath Reef Ball™ and wind tower unit

The wind tower units possess dual-purpose functionality; whilst the base of the structure provides habitat for demersal fish, the elevated tower structure is designed to attract pelagic species. The design of the wind tower unit incorporates traditional Arab architecture and may also serve as a curiosity for any visiting recreational divers.

The design of the anti-trawl units is based upon a traditional Arabian fort. As an anti-trawl measure, the protruding concrete hollow core slabs are intended to snag the nets of any shrimp trawlers in the vicinity which threaten the integrity of the reefs.

Reef unit construction

Both Reef Ball™ and *majfara* units are cast within a purpose-built facility operated by the Bahrain-based company Reef Arabia. The facility is staffed by personnel trained and certified by instructors from Reef Ball Australia and Reef Innovations USA. Given the short timescale of the construction and deployment aspect of the project (i.e. 1 year), an efficient production line has been established to enable the mass production of high quality Reef Balls™. When running at full capacity, 27 Reef Ball™ units (of varying sizes) and 6 *majfaras* can be produced per day.

Due to their size and complexity, the manufacture of both the wind tower and anti-trawl units was subcontracted to Delmon Precast. **Table 2** below presents key reef unit specifications and numbers per reef complex.

Table 2. Reef unit specifications and numbers

Reef unit		**Width (m)**	**Height (m)**	**Weight (t)**	**No. of units per reef complex**
Reef-Ball™	*Goliath*	1.83	1.52	Up to 2.7	16
	Ultra	1.68	1.31	Up to 2.0	80
	Pallet	1.22	0.88	Up to 1.0	80
	Bay	0.91	0.61	Up to 0.30	48
Custom-made	*Wind tower*	2.0	3.0	Ca. 6.0	3
	Anti-trawl	2.0	2.0	Ca. 6.0	3
	Majfara	1.2−2.5	Ca. 0.50	Ca. 0.15	32
				Total number of units	**262**

For all reef units a high quality, marine-grade concrete was used with a design strength of 50 MPa (Megapascals). Subsequent cube strength tests revealed a 28-day strength of 87 MPa. This high strength concrete mix eliminates the need for steel reinforcement within the Reef Balls™ and therefore any weakening of the structure as a result of corrosion. The Reef Ball Foundation estimates Reef Ball™ life expectancy to be 500 years or more.

Due to their structural design, wind towers, anti-trawl and *majfara* units require additional internal support or reinforcement. To mitigate against corrosion, fibreglass rebar is incorporated within *majfara* units whereas epoxy coated steel rebar is used within the larger wind tower and anti-trawl units.

In order to counter the high pHs (10−11) often associated with uncured or 'green' concrete, which may inhibit the settlement and growth of many marine species for a period of between 3-12 months (AGSMFC, 2004), a number of key steps were incorporated within the casting process including:

1. Addition of microsilica to the mix – this increases the impermeability of the concrete, minimising the availability of free hydroxide ions (OH^-) which increase the pH of water/surface of the unit once the concrete weathering process is complete.
2. Promoting the surface exposure of aggregate by incorporating sugar water retardants within the casting process. Exposing the aggregate, which accounts for between 50–70% of the unit surface, promotes neutrality of surface pH.
3. Post-curing washing. Each unit is thoroughly washed to remove the effects of retardants (i.e. lose concrete) and to promote the weathering process.
4. All units are stored with full exposure to the elements for a period of at least four weeks prior to deployment to sea.

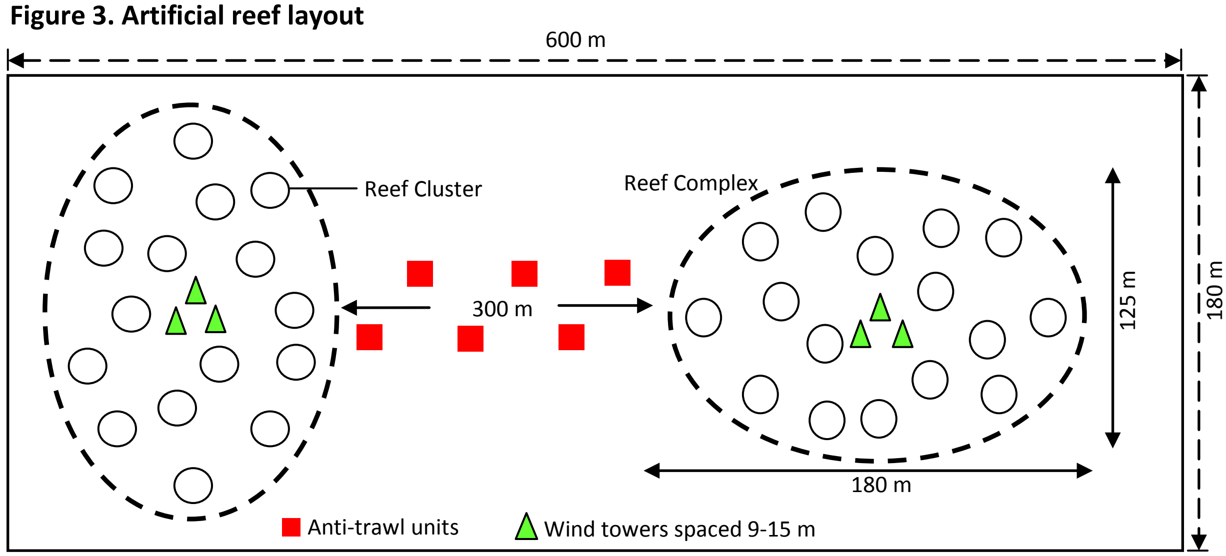
8. Reef complex design

The following terminology describes artificial reef design and layout:

- **Block** – this refers to the area which encompasses a pair of 'reef complexes'. There are two blocks within Areas 4 and 10, and one block in Area 8.
- **Reef complex** - this refers to the 262 reef units deployed in one area. Each reef complex is made up of 16 'clusters' of reef units. The project has a total of ten reef complexes.
- **Cluster** - each cluster is made up of 16 reef units deployed within close proximity to each other. There are 16 clusters within a single reef complex (16 x 16 = 256 reef units) plus 3 wind towers 3 anti-trawl units.

The reef complexes are oval in shape and arranged in pairs, each pair constituting a reef block (**Figure 3**). Each reef block is 600 m x 180 m in size (area = 10.6 ha), with each reef complex measuring 180 m x 125 m at its widest points (area = 1.74 ha). Within each block, the two reef complexes are 300 m apart and linked by six anti-trawl units. This distance provides foraging areas for fish between the reefs whilst the anti-trawl units act as both 'stepping stone' reefs and deterrents to trawling (**Figure 3**).

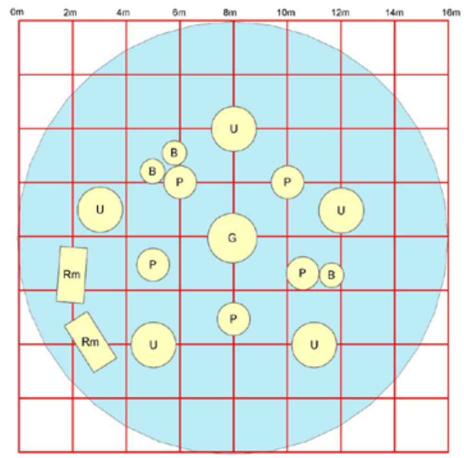
Figure 3. Artificial reef layout



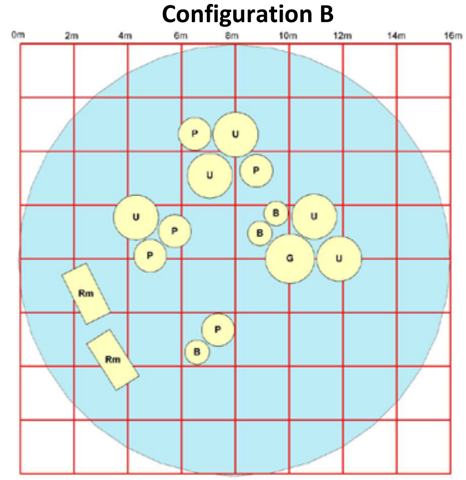
Differences in reef complex orientation may generate variability in the ambient hydrodynamic conditions both surrounding and within the two complexes within each block and for this reason the reef complexes will be deployed as depicted in **Figure 3**. The rationale is that the obstructive nature of the units will generate eddies within the reef complex, thereby promoting the retention of plankton and nutrients within the vicinity of the reefs.

Each cluster comprises 16 reef units: 14 Reef Balls™ of various sizes and 2 *majfara* units. Clusters are circular in shape with an approximate diameter of 16 m. Distances between reef units within a cluster ranges from 0.3 m to 3.0 m with clusters spaced approximately 16 m apart. This configuration aims to increase reef perimeter length, and hence the number of fish that utilise the reef, whilst also providing open spaces for foraging. The layout is also similar to the configuration and density of natural coral bommies in the Gulf (D. Lennon, *pers. comm.*).

Configuration A



Configuration B



G = Goliath, U = Ultra, P = Pallet, B = Bay, Rm = Ridge module (*majfara*)

The layout and orientation of reef units is instrumental in increasing the Reef Effective Area (REA) of the deployed structure(s), maximising the area of protection afforded by the structures as well the potential returns (i.e. fisheries productivity). Observations from neighbouring Qatar suggest a diminishing return for bommies greater than 20 m^3 whereas productivity was maximised for those within the 7-10 m^3 range (D. Lennon, *pers. comm.*). This density is equivalent to that of the five Reef Balls™ which have been arranged in a small group within cluster Configuration 'B' (top right, inset). By incorporating a second configuration, 'A' (bottom right), comparisons of artificial reef-associated fish assemblages between the two configurations can be made.

9. Deployment

The deployment of artificial reef units represents a challenging logistical task, particularly since weather conditions (i.e. wind, sea state) are an influential factor. In order to minimise deployment time, it was decided that an entire reef complex (i.e. 262 units) would deployed by crane from a large barge (750 m^2 deck mounted with a 100 tonne, 45 m boom crawler crane) in one session, with the barge and accompanying tug remaining at sea overnight. Furthermore, by arranging the reef units on the barge into small groups based on their deployment configuration, and coupled with the ability to lift multiple units using a 3 m spreader bar and several slings, the number of crane movements and hence deployment time can be further reduced.

Once on site, a pre-deployment team marks the centre point of each of the reef clusters (typically three clusters at a time) with suitable marker buoys. Care is taken to ensure that the length of the downlines and hence surface drift of the buoys is minimised, as excessive drifting may lead to inaccuracies in the marking of cluster positions. The barge is worked into position using the tug and rendered stationary via the lowering of two aft spud legs. Communication between all parties is via VHF radio. By using quick-release 'wangers' attached to the slings the installation of reef units is achieved without the need of divers. Positioning of units is 'by eye', using marks on the barge as reference points, and following as closely as possible Configurations A and B.

Deployment of Reef Balls™

Reef unit installation is progressed along the long axis of each reef complex such that installed reefs are not damaged during barge spudding operations. Following installation, the repositioning of reef units is both time consuming and costly. Careful planning and communication between all parties aboard the barge, tug and survey vessel is therefore vital during deployment.

10. Monitoring

A key requirement of the project is to conduct marine environmental monitoring at the artificial reef sites to determine the effectiveness of the reef in enhancing fish productivity. Monitoring also provides an opportunity to assess other key parameters including the presence of epibenthic flora and fauna associated with the reefs.

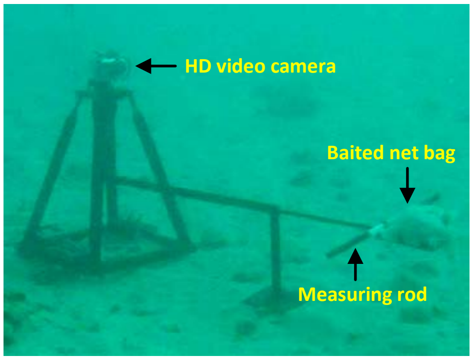
Monitoring will be conducted for one reef complex (inclusive of two control sites) per Area (i.e. 4, 8 and 10) on a quarterly basis over a period of 12 months. Based upon the homogenous nature of marine habitat within each Area, one reef complex per Area is considered representative of all reef complexes within that Area. Two of the four monitoring sessions will be considered are more comprehensive (major) and two less so (minor). The different components of these monitoring sessions are presented in **Table 3** overleaf. Monitoring will be temporally staggered in accordance with the sequential deployment of the reefs.

Table 3. Survey components of major and minor monitoring sessions

Major monitoring session	Minor monitoring session
- Baited Remote Underwater Video System (BRUVS) - Fish capture (*gargoor*) - SCUBA diver fish counts and diversity - SCUBA diver assessment of marine biota - Zooplankton sampling - *In situ* water quality monitoring	- SCUBA diver fish counts and diversity - SCUBA diver assessment of marine biota - Zooplankton sampling - *In situ* water quality monitoring

BRUVS (Baited Remote Underwater Video System)

A BRUVS comprises a digital video camera mounted on a metal frame approximately 40 cm above the seabed. A baited net bag is placed approximately 80−100 cm from the camera and attached to a feeding platform mounted on a metal arm. A 30 cm measuring rod is also attached to the feeding platform to aid in the estimation of fish length (see inset, right).



The BRUVS is lowered from the survey vessel to the seabed and the GPS coordinates recorded. Video footage is obtained for 30 minutes after which the camera is hauled to the surface. Footage is then immediately transferred to laptop computer. The process is repeated the following day.

Fish capture surveys

Whereas the data obtained by the BRUVS deployments will provide a good indication of fish populations at the reef sites, observations will only be for a period of 30 minutes for each monitoring session. Also it does not allow for an understanding of the productivity and commercial value of fisheries in the area; this may be determined by the deployment of *gargoor*, a traditional fishing technique.

Trap openings will be set to target commercial species (e.g. grouper, snapper and bream).

PH Environment Gulf will deploy a total of 12 *gargoor* within each reef study area. Deployed *gargoor* will be left to soak for 4 days after which all individuals within each catch will be identified to species level and their weight and total length recorded.

Other relevant observations will be made (e.g. whether females are egg bearing) and the *gargoor* redeployed for a further 4-day period. All data obtained will be recorded on *proformas* along with representative photographs.

SCUBA surveys

The key objective of this monitoring is to assess any changes in fish populations with reference to control stations. Although the accuracy of quantitative fish counts may be affected by the movement and noise generated by SCUBA divers, the proposed surveys will be conducted using a static visual observation method whereby stationary divers identify and count all fish within a fixed field of view for two minutes. This procedure will be repeated three times during each SCUBA dive. Furthermore, a qualitative assessment of fish present in the vicinity of the reefs will be made during a 10-minute random swim. During this time all species will be identified to species level and key observations noted (e.g. approximate length, presence of juveniles and how the fish are utilising the reefs). All data will be accompanied, where possible, by still photographs.

Dive inspections of the artificial reef sites will also allow for assessing the development of the reef, including the colonisation of the reef units by epibiota. Baseline data will provide data on those species currently present. During dives, an inventory of species present will be made. Other notable observations (e.g. occurrence of sand scour or sedimentation) will be made and supported, where possible, with still photographs.

Zooplankton sampling and identification

Zooplankton sampling and identification will be undertaken in order to provide an indication of the composition of the zooplankton assemblage and relative abundance of different taxa in the vicinity of the reefs. In this respect, the presence of icthyoplankton (fish eggs and larvae) and coral larvae is of particular interest. This monitoring will allow potential pre- and post-deployment differences in zooplankton assemblages to be determined as well as providing an indication of seasonal variation in plankton abundance and diversity.

On each sampling occasion, three replicate zooplankton tows will be undertaken within each reef study area. The plankton net (250 µm mesh size) will be towed just below the sea surface at a speed of 3 knots for 15 minutes. The volume of water passing through the net may be calculated by multiplying the distance towed (according to the number of revolutions of the net counter) by the area of the mouth of the net. This enables quantification of zooplankton abundance during subsequent identification.

Water quality

During all monitoring sessions, *in situ* water quality parameters (e.g. dissolved oxygen, pH, salinity, turbidity) will be measured using a Hydrolab MS5 multi-probe and Secchi disc.

Analysis of monitoring data

Where appropriate, potential differences in biological community composition and water quality parameters between different monitoring stations/sessions at each artificial reef site will be identified using relevant univariate and multivariate statistical analyses.

11. Discussion and conclusions

The Bahrain artificial reef project is a bold step but one which is not without its dangers. The concept that artificial reefs are a panacea for past environmental degradation could not be further from the truth. Without the integration of the project within a wider national fisheries management programme, which incorporates the stringent enforcement of existing laws and development of new legislation, the outcome is likely to be counterproductive. Past history in Bahrain suggests that artificial reefs are unlikely to be protected from overzealous fishermen and there is a real concern that sustained fishing pressure on these reefs, following the aggregation of fish at these sites, may actually accelerate the decline of certain commercial stocks.

As a means of offsetting the destruction of marine habitat, one could easily argue that artificial reefs do not necessarily represent a 'like-for-like' replacement for habitats such as seagrass and algal beds which have been destroyed by both past and present dredging and reclamation activities. Furthermore, there is an argument to be made that remedial efforts should firstly be directed at conserving and protecting those areas of existing productive habitat unaffected by anthropogenic disturbances, as well as attempting to 'naturally' re-establish those habitats which have been lost (e.g. seagrass transplantation).

Nonetheless, the placement of artificial concrete structures in areas of seabed devoid of vertical relief can be beneficial, providing the foundation from which a number of opportunities to enhance the existing habitat and associated macroalgal, invertebrate and fish communities may arise. Of particular relevance to the present study are the following:

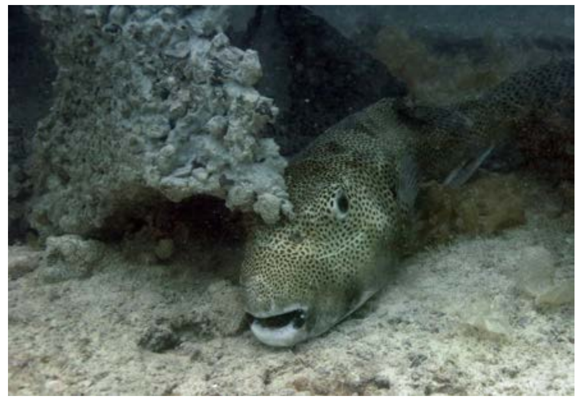
1. The overall transformation of relatively unproductive benthic habitat to one capable of supporting a diverse floral and faunal community. This is accomplished via the provision of a 3-dimensional, stable and hard substrate which may support sessile invertebrates (e.g. oysters, sponges, hydroids, corals) and fish throughout the various stages of their lifecycles.

2. The release of reared fish stock (fingerlings) on artificial reefs in an attempt to increase fisheries productivity, as opposed to the reefs merely acting as a Fish Aggregating Device (FAD). By implementing a fish tagging programme, useful fisheries data may be obtained, including information on the utilisation of the reefs by tagged individuals and the estimation of stock assessment parameters. The results of such studies may also serve as input to a wider stock assessment and fisheries management programme.

3. The provision of suitable substrate for the transplantation and relocation of corals. Areas 4 and 10 host several sparsely distributed coral genera including *Porites*, *Cyphastrea*, *Siderastrea*, *Platygyra*, *Favia* and *Turbinaria*. However, due to the lack of vertical relief, the health of these species is threatened by sedimentation resulting from the settlement of drifting sands. The transport of live coral fragments/corals from compatible source locations and their subsequent propogation on artificial reef structures may give them a

greater chance of survival, as well as increasing local coral biomass and productivity. Cooperation with regional partners (e.g. those based in Saudi Arabia) may also enable those corals now largely absent from Bahrain's waters (e.g. *Acropora* spp.) to be re-established.

4. The creation of artificial reef habitats could also act as a catalyst for the development of new marine conservation legislation, with a view to affording these sites Marine Protected Area (MPA) status.


The stellate puffer *Arothron stellatus* in a Reef Ball™

At this early stage, whilst the artificial reefs are being actively deployed, it is not possible to gauge the success of this project. However, it must be remembered that it is essentially a 'test-bed' upon which future projects may be based. On a positive note, initial images of artificial reef habitation by fish in Area 4, taken a week post-deployment, are encouraging (see inset, right).

Should the Bahrain artificial reef project prove successful, it is hoped that the selected reef areas (4, 8 and 10) will be afforded some kind of protection from destructive dredging works and overfishing; there is considerable potential for the creation of many more artificial reefs within these areas. However, it is equally important to realise that the deployment of artificial reefs is *not* direct compensation for the continued loss of extensive areas of naturally productive marine habitat or the overall deterioration of Bahrain's marine environment.

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