Environmental status of Yemen's Gulf of Aden coast determined from rapid field assessment and satellite imagery

G. Wilson,[1] A. R. G. Price,[1*] T. Huntington,[2] and S. C. Wilson[1,3]

QUERY SHEET

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G. Wilson,[1] A. R. G. Price,[1*] T. Huntington,[2] and S. C. Wilson[1,3]
[1]Department of Biological Sciences, University of Warwick, Coventry, UK
[2]MacAlister Elliott and Partners Ltd, Lymington, Hampshire, UK
[3]Seeb, Oman
*Corresponding author: Department of Biological Sciences, University of Warwick, Coventry, CV4 7AL, UK;
E-mail: APrice@bio.warwick.ac.uk

Ninety-one sites covering 1400 km of the Gulf of Aden coast of Yemen were examined by rapid field assessment, yielding ordinal data on the extent of habitats, abundance of species groups and magnitude of human uses/environmental impacts. Satellite imagery was used to determine sea surface chlorophyll concentrations. Mangroves and seagrasses were largely absent, due to the high-energy conditions and unstable substrata. Coral development was also limited, principally because of cold upwelling sea temperatures. Macroalgal prevalence and abundance were greater on account of high nutrient levels. Nesting sites of three turtle species (Green, Hawksbill, and Loggerhead) were all impacted at low levels. Coastal construction was small-scale and located near larger towns (Al Mukalla, Foua and Shehir), while water- and land-based pollution and fishing were widespread but minimal. Fish abundance showed significant positive correlation with chlorophyll concentration. These and other associations observed probably involve causal links, although habitat effects and other factors may also be important. Classification of sites by cluster analysis using biological data and use/impact data separately revealed considerable environmental heterogeneity. The lack of clear geographical patterns contrasts with results from the Red Sea, where latitudinal related groupings using comparable biological data are evident.

Keywords: coastal ecosystems, cluster analysis, resource-use conflicts

Introduction

Several ecological studies have been undertaken along or included the Red Sea coast of Yemen (Price et al., 1988; Sheppard, 2000; Medio et al., 2000). Along the Gulf of Aden coast of Yemen studies have included oceanographic research (Wilson and Klaus, 2000), fishery investigations (Sanders, 1981a, 1981b; Sanders and Morgan, 1989; MEP, 1998) and various biological assessments (Sheppard et al., 2000; Wilson and Klaus, 2000). The only comprehensive assessment of environmental pressures and coastal management requirements to date appears to be an extensive rapid habitat/environmental appraisal (Huntington and Wilson, 1995). This was followed by a more detailed assessment at selected sites (Watt, 1996). Wilson and Klaus (2000) provide a review of environmental work undertaken in the region.

Environmental assessments can be undertaken at a range of intensities and scales (Price, 1990). These range from use of high resolution quantitative data, usually of limited spatial coverage, to those derived from lower resolution data (e.g. ranked/ordinal or binary) generally collected over larger areas (e.g. Price et al. 1998). This study is a broadscale assessment of Yemen's southern (Gulf of Aden) coastline based on analysis of ranked/ordinal environmental data collected by Huntington and Wilson (1995). The principal

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aims of our study are to: 1) provide a statistical analysis and synopsis of environmental conditions in the region, augmenting the earlier, preliminary appraisal (Huntington and Wilson, 1995); and 2) demonstrate the utility of combining satellite imagery and rapid assessment data to improve the environmental knowledge of a poorly known region.

Environmental setting and study area

The Gulf of Aden forms a part of the Red Sea Large Marine Ecosystem (Sherman, 1994) and is influenced by three significant water current regimes; 1) wind/tide/salinity-driven water exchange with the Red Sea; 2) the Somali upwelling; and 3) the southeast Arabian upwelling. The Arabian upwelling is one of the world's five major upwelling systems (Ormond and Banaimoon, 1994). It occurs during the southwest monsoon (April–September) when warm surface water is blown offshore and replaced by colder nutrient-rich oceanic water.

The Yemen coastline along the Gulf of Aden consists of rocky cliffs which alternate with long stretches of littoral and sub-littoral sand dunes (Sheppard et al. 1992; Huntington and Wilson, 1995). Although shallow waters are extensive, mangroves and seagrasses are not well developed because of the predominantly high-energy environment and unstable substrates (Sheppard et al., 1992; Zahran and Al-Kaf, 1996). Macroalgal growth is relatively high because of high nutrient levels and hard substrate. Reefs are limited, with coral assemblages interspersed among macroalgae (Sheppard et al.1992).

Megafauna of conservation importance include three turtle species: the Green (*Chelonia mydas*), Hawksbill (*Eretmochelys imbricata*) and Loggerhead (*Caretta caretta*), as well as mammals such as the very rare Indo-Pacific Beaked Whale (*Indopacetus pacificus*) (IUCN/UNEP, 1985; Barrett et al. 1987; WCMC, 1994; Huntington and Wilson, 1995; Wilson and Klaus, 2000). Yemen also has a rich avifauna due to the diversity of habitats and its position at the centre of a major flyway between Eurasia and Africa (Huntington and Wilson 1995; Wilson and Klaus, 2000).

The survey area covered the entire (1,365 km) southern coastline of Yemen, from the former North/South Yemen border at Bab al Mendab to the eastern border with Oman (Figure 1). Observations were undertaken at 91 mainland sites between October and December 1995.

Methodology

Origin of data

This study utilises a dataset on biological resources (habitats and major species groups) and human uses/impacts originating from a preliminary unpublished rapid environmental assessment of the Yemen coastline of Gulf of Aden (Huntington and Wilson, 1995), as well as satellite imagery. Survey sites (Figure 1) were established every 15 km along the shoreline, from west to east, and positions determined using a Garmin 45 Global Positioning System (details in Huntington and Wilson, 1995). In this paper, the original dataset is analysed more comprehensively, following transformation of part of it as outlined below.

Rapid assessment methodology

The methodology used for data collection by Huntington and Wilson (1995) is based on that developed for the Red Sea (Price et al., 1988, 1998) and also used in the Arabian Gulf (Price, 1990; Price et al., 1993), the Chagos Archipelago (Price, 1999) and Cameroon (Price et al., 2000). Observations were made within geographically discrete 'site inspection quadrats' c. 500 m × 500 m bisecting the beach, extending 250 m up the shore and 250 m down into the subtidal zone. The latter was examined while snorkelling. Within each quadrat the extent of habitats, abundance of species groups, and magnitude of uses and impacts (Table 1), were estimated and recorded (see below). Species richness, or other biodiversity measures within each species group, is not determined.

A scale of 0–6 was used for estimates of the relative extent of each habitat and abundance of each major species group. In the case of flora (and reefs), scores represent estimates of areal extent (m^2), while

Table 1. Attributes assessed in the rapid assessment survey in Yemen.

Habitats/Species		
Flora	Fauna	Human Uses/Impacts
Mangroves	Reefs and corals	Construction
Seagrass	Fish	Fishing/collecting
Halophytes	Invertebrates	Water-borne pollution
Algae	Turtles	Land-based pollution
Freshwater vegetation	Birds	
	Mammals	

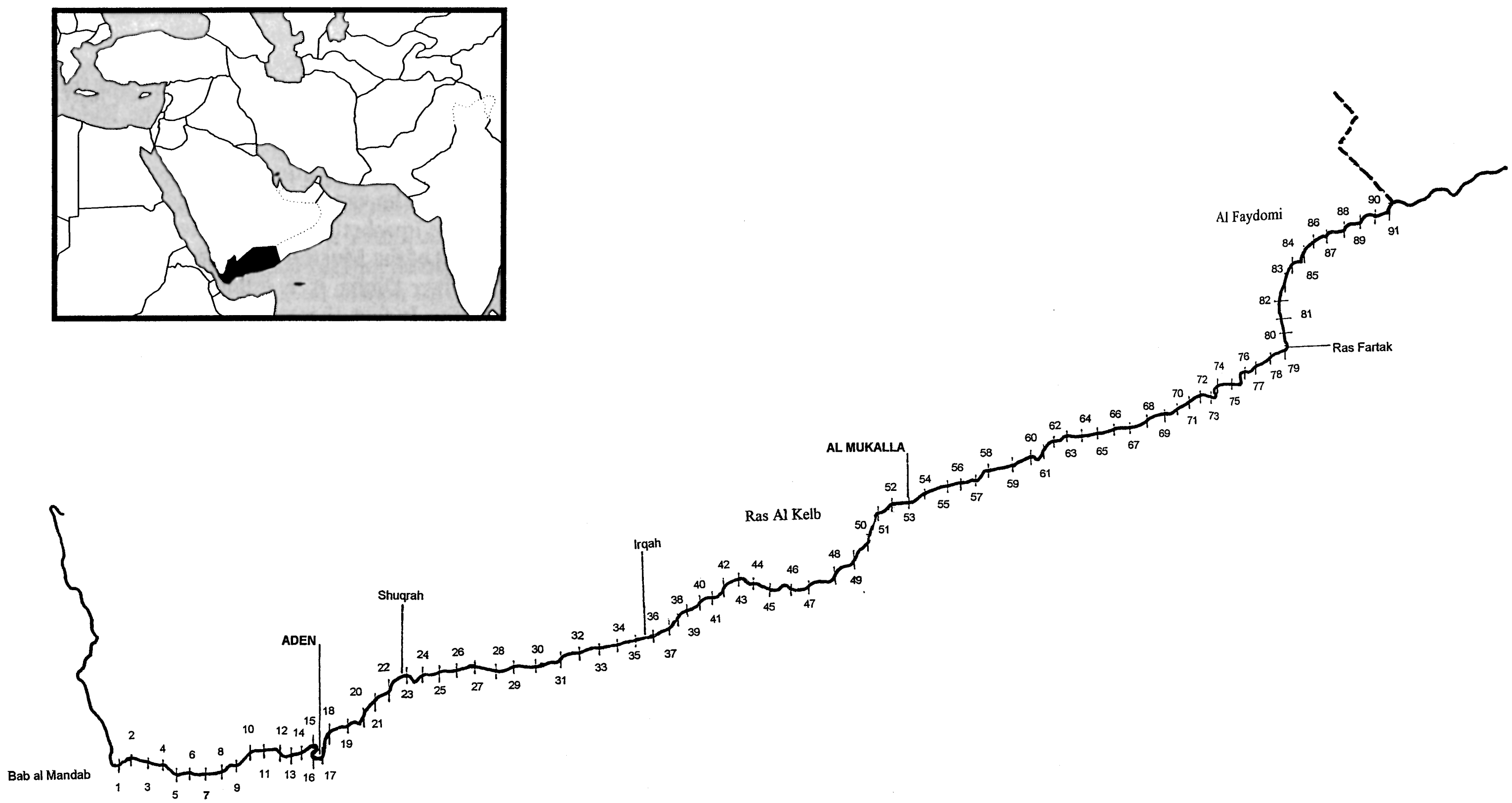

Figure 1. Map of the Gulf of Aden region (insert) showing coastal survey area between Yemen-Saudi Arabia border and Yemen-Oman border (between the two arrows), and locations of the study sites in Yemen, numbered 1 to 91 (main map).

Table 2. Ranked abundance scale used for extent/cover of coastal habitats (flora and reefs; areal extent) and abundance of major species groups (fauna; no. of individuals).

Description	Ranked Abundance Score	Flora: Areal Extent (m^2) Fauna: No. of Individuals (Equivalent Arithmetic Range)[1]
No record	NR	No record
Absent	0	0
Present	+	present
Few	1	1–9
Some	2	10–99
Common	3	100–999
Very common	4	1,000–9,999
Abundant	5	10,000–99,000
Super abundant	6	100,000+

[1] Log scale as used in earlier surveys (e.g. Price, 1999) and used as the basis for this study. However, fish and invertebrates abundances were scaled relative to the whole coast by Huntington and Wilson (1995) because of the high values (6) that would have been attained at all sites. (See also Methodology).

for fauna they represent the estimated number of individuals, both within 250,000 m^2 (500 m × 500 m). However, both use the same ordinal scale (Table 2). Hence, a mangrove stand estimated to be 5,000 m^2 in extent is given a score of ‘4,’ is a bird population estimated to be 5,000 individuals. In the original survey of Huntington and Wilson (1995) habitats and species groups were assessed in this way, except invertebrates, fish. Abundances of these groups were scaled relative to the whole coast, because of the high values (‘6’) that would have been attained at all sites. The ordinal scale for these attributes are therefore not strictly comparable with that adopted for other attributes. Implications of this are considered below (Discussion).

The same ordinal scale was used for assessing the magnitude of human uses and impacts. Recorded scores simply represent the estimated relative magnitude of each use/impact (where 0 indicates no impact and 6 the greatest impact). During the field survey assessment was made using a scale of finer (0–10) resolution. Following the approach of Price et al. (1998) use/impact values were converted subsequently to a 0–6 scale by multiplying the original values by 0.6 and rounding to the nearest integer. Although these (and the biological) assessments are only semi-quantitative, the approach has been validated in earlier papers (Price, 1999; Price et al., 1993).

In instances where attributes were not, or could not be, quantified, a scale of either ‘0’ (absent) or ‘+’ (present) was used in the survey. A number of these qualitative records were transformed into numerical data using the ordinal (0–6) scale. For example, instances of qualitative records of ‘some present’ for some species groups, (e.g. halophytes) were changed to a value of ‘1.’ Similarly, some qualitative records of construction and development could be converted into the 0–6 scale (see Price et al., 1998). Overall, 15% of the total data (202 of the 1316 values) were transformed in this way. Further details and the justification for such transformations are given elsewhere (Jobbins, 1996; Price et al., 1998; Wilson, 1999). In particular, these transformations created a more extensive quantitative dataset available for statistical analysis, particularly cluster analysis (Price et al., 1998).

Physical attributes recorded included details of the shore profile, substratum type, surface temperature and salinity, the latter using a hand-held refractometer. In addition, qualitative notes on the environment were made.

Remotely sensed image data

A remotely sensed image, from the Coastal Zone Colour Scanner (CZCS) of September upwelling values (1978–1985), was used to estimate chlorophyll concentration in surface waters at each of the 91 sites along the Yemen coastline (Figure 2). The image was adapted from the UNESCO TredMar remote sensing lesson series (Sheppard and Dixon, 1998). Chlorophyll concentrations (C mg m^{-3}) were determined from the linear colour bar shown below the satellite image (image and

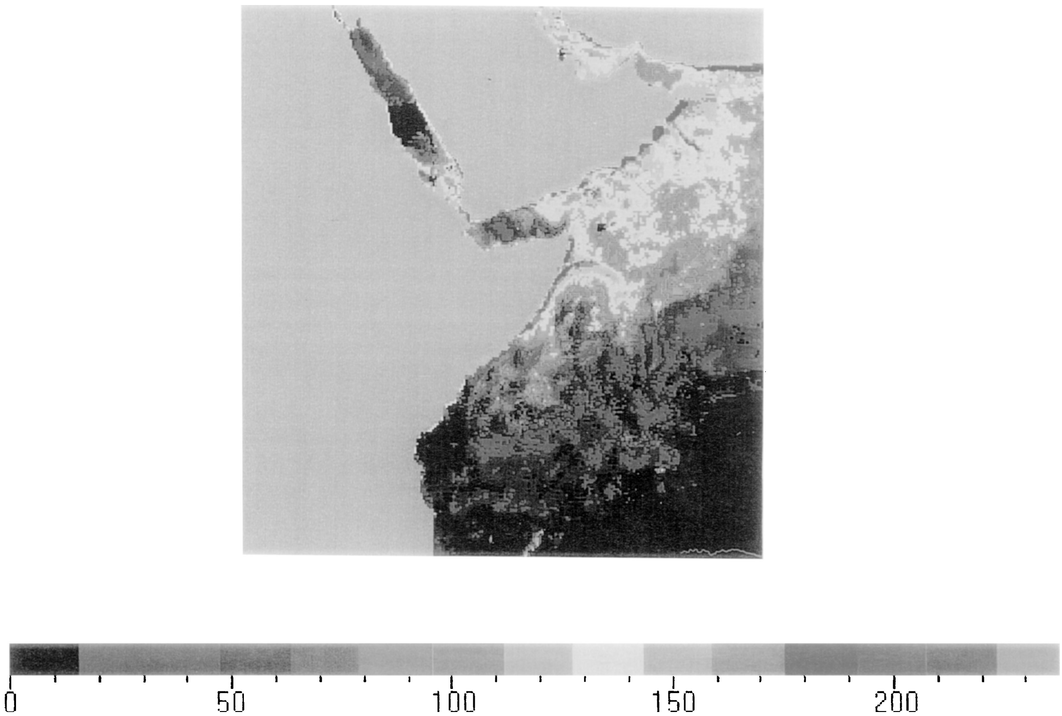

Figure 2. Satellite data showing concentration of chlorophyll in surface waters of Arabian region, including Gulf of Aden, during September upwelling period from 1978–85 (Coastal Zone Colour Scanner—CZCS). Colour bar represents Digital Number (DN) values for calculation of chlorophyll concentrations (Satellite image and colour bar reproduced here in black and white; see also Methods).

colour bar reproduced in black and white in Figure 2), using a standard image processing algorithm (NASA, 2001): $C = 10^{(N-117)/84}$. Each colour of the colour bar represents one of sixteen Digital Number (DN) values from 0–255, from which the mid-value for the colour was used for the above equation.

Database and data analysis

The non-parametric dataset was compiled onto Excel. Average abundances of habitats and species, and average magnitude of uses and impacts were determined by medians (rather than means). Spearman's rank correlation coefficient (R_s), corrected for ties, was used to measure correlations, and significance determined using a one-tailed test because of the assumed directionality of the particular correlations.

Cluster analysis was performed on biological and impact/use data, using the software of Sheppard (1993), to classify sites in terms of species, habitat or impact patterns. The Bray Curtis similarity coefficient was used, and a dendrogram produced using the weighted group average method. The value taken for cut-off is not fixed, but arbitrary (Sheppard and Sheppard, 1985). In this study the value was taken as 0.4. Higher values of the similarity coefficient result in greater separation. In previous studies in the Red Sea, it has been drawn at 0.33 (Loya, 1972; Sheppard and Sheppard, 1985) and 0.43 (Price et al., 1988, 1998).

Results

Overall state of the environment and comparison with the Red Sea

Environmental data for the Gulf of Aden are summarised in Table 3. No mangrove stands were observed and seagrasses were scarce. Halophytes and corals/reefs were scattered along the coast, but seldom abundant. Fish, invertebrates and birds were prevalent and relatively abundant, and fishing activity was evident at most sites. Turtles and marine mammals were observed at 19% and 16% of the sites respectively but were not abundant. Construction along the coastline was small-scale and near to larger towns (Al Mukalla, Foua and Shehir). Impacts from water- and land-based pollution and fishing were widespread but recorded only at low levels.

Table 3. Summary data for habitats, species groups, uses and impacts along the Gulf of Aden coast of Yemen. The values shown are frequency of each abundance score for habitats and species, and frequency of each magnitude score for uses and impact, using an ordinal scale of 0–6 (+– presence only recorded; see also Methods). Data from eastern Red Sea coast (Price et al., 1999) also shown for comparison, and summary chlorophyll data from satellite imagery also presented.

Attribute	Gulf of Aden Abundance/Magnitude								Preval. 1. (%)	Mn	Range e	Red Sea Preval. (%)	Mn	Range
Habitats and species groups	0	+	1	2	3	4	5	6						
Mangroves	91	0	0	0	0	0	0	0	0	0	0	29	0	0–6
Seagrasses	89	1	0	0	0	1	0	0	2	0	0–4	52	3	0–6
Halophytes	74	4	3	3	5	1	0	0	19	0	0–4	73	3	0–6
Algae	59	8	9	10	1	4	0	0	35	0	0–4	75	3	0–6
Sea surface chlorophyll (C mg m^{-3})										4.05	(0.12–9.73)			
Freshwater vegetation	82	4	1	1	2	1	0	0	10	0	0–4	11	0	0–6
Reefs/corals	72	3	2	1	7	3	1	0	19	0	0–5	53	2	0–6
Fish	13	15	12	13	13	7	0	0	82	2	0–4	84	1	0–6
Invertebrates	0	4	1	13	38	32	2	1	100	3	0.1–6	85	5	0–6
Turtles	86	0	13	3	0	0	0	0	19	0	0–2	7	0	0–2
Birds	15	1	32	20	18	4	0	1	84	1	0–6	49	0	0–5
Mammals	74	2	11	1	0	0	0	0	16	0	0–2	3	0	0–2
Uses/Impacts													0	
Construction	49	1	26	9	3	0	2	1	46	0	0–6	23	0	0–6
Fishing/collecting	16	2	36	28	6	2	0	0	82	1	0–4	39	0	0–6
Water–based pollution	18	1	55	15	0	2	0	0	80	1	0–4	45	0	0–5
Land-based pollution	60	2	15	8	1	3	0	0	33	0	0–4	65	1	0–5
Other impacts	43	3	24	14	1	0	0	0	50	0	0–3			

Environmental conditions in the Red Sea, assessed using the same overall methodology, are also shown in Table 3 for comparison. The Gulf of Aden has lower prevalence and abundance of coastal flora and corals than the Red Sea, but greater prevalence of invertebrates, birds, turtles and mammals. Additionally construction, principally as small settlements, was more prevalent and fishing activity greater than on the Red Sea coast.

Correlations between environmental variables

Chlorophyll concentration and fish abundance showed significant positive correlation ($N = 58$, $R_s = 0.26$, $P \leq 0.05$), as did fish and bird abundance ($N = 57$, $R_s = 0.259$, $P \leq 0.05$). An even stronger correlation was observed between coral and fish abundance ($N = 55$, $R_s = 0.404$, $P \leq 0.01$). Associations involving human uses included a highly significant positive correlation between fish abundance and fishing activity ($N = 56$, $R_s = 0.475$, $P \leq 0.01$), perhaps suggesting that harvesting was at sustainable levels. The magnitude of construction and land-based pollution was also positively correlated ($N = 86$, $R_s = 0.405$, $P \leq 0.01$).

Classification of sites by cluster analysis

Figure 3 is a dendrogram from cluster analysis classifying the sites according to the biological data. At a similarity coefficient of 0.4 five groups are apparent,

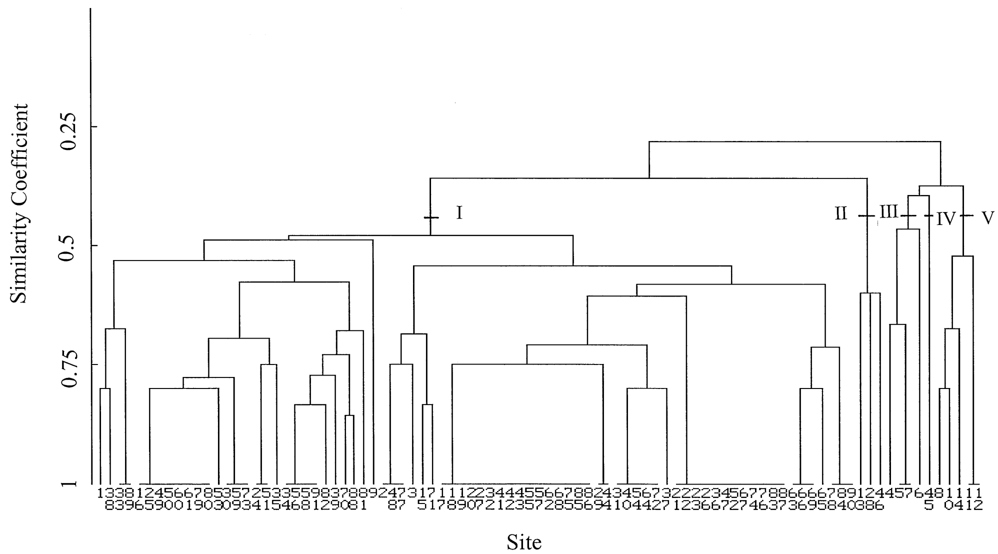

Figure 3. Dendrogram showing classification of sites along Gulf of Aden coast of Yemen resulting from cluster analysis using biological data. At a similarity coefficient of 0.4, five groupings (I–V) are recognised.

whose characteristics are shown in Table 4. Group I contains the majority (78) of the 91 sites. In comparison with the other groups, birds were moderately abundant, and fishing/collecting and water-based pollution occurred at low levels. The four remaining groups contained fewer sites and are more distinctive.

Figure 4 is also a dendrogram, but separates the sites according to the use/impact data. At a similarity coefficient of 0.4 five groups are apparent, whose diagnostics are shown in Table 5. Group I sites have wide-ranging uses and impacts, as might be expected from a large group of 73 sites, but at low levels. Group II sites (4) are impacted only by fishing while Group III sites, which extend from Al Mukalla to the west of Aden, are impacted only by water pollution. Group IV (3 sites) are heavily impacted in terms of water-based and land-based pollution as well other impacts. Group V consists of only two sites (13 and 14) located around

Table 4. Environmental diagnostics of groupings of sites derived from cluster analysis of biological data. (Median values for seagrasses, algae, turtles and mammals were all 0, and therefore are not shown).

Variables	Median (Mn) Values for Sites				
	Group I	Group II	Group III	Group IV[1]	Group V
Habitats & species (factors used in cluster analysis)					
Halophytes	0	0	3	0	0.1
Freshwater vegetation	0	0	0	0	2
Reefs	0	3	0	0	0
Fish	1	2	0	0	0
Invertebrates	3	4	3	2	3
Birds	2	0	0	0	0
Uses/impacts (factors not used in cluster analysis)					
Construction	0	1	0.5	0	0
Fishing/collecting	1	1	0	2	0
Water based pollution	1	0	0.5	2	1
Land based pollution	0	0	0	0	1
Other impacts	0	0	0	0	2

[1] Single site.

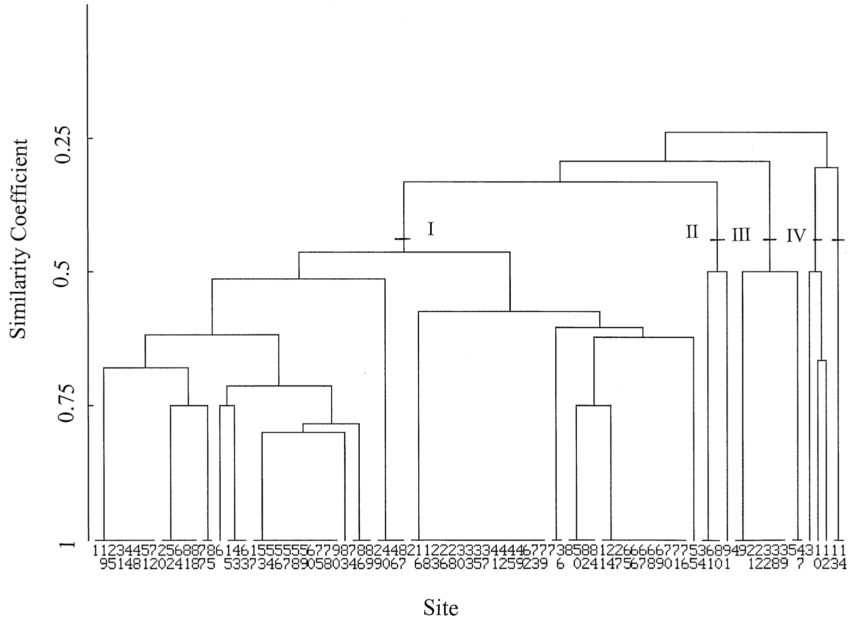

Figure 4. Dendrogram showing classification of sites along Gulf of Aden coast of Yemen resulting from cluster analysis using use/impact data. At a similarity coefficient of 0.4, five groupings (I–V) are recognised.

Little Aden, which were affected by land-based pollution and construction.

Resource use conflicts

Sites associated with conflicts (resources overlapping with uses/pressures) and compatibilities (non-overlapping areas) can be identified by interrogation of the database (see Price et al., 1998). Examples are shown in Table 6, which lists study sites associated with combinations of particular abundance/magnitude values for resources and use/impacts. This can be valuable for identifying actual or potential conflict areas or environmental 'pressure points,' and hence where management might be desirable. Similarly, identification of sites associated with resource-use compatibility gives insights into possible openings for further resource use and coastal development.

Discussion

The value of semi-quantitative data collected in rapid coastal assessments has been reviewed extensively (Price, 1990, 1999; Price et al., 1998). The methodology is low cost compared to more quantitative surveys and yields useful baseline or preliminary coastal environmental data. The data can be analysed to identify resource use conflicts, candidate sites for a protected areas system, and the methodology has other applications in coastal management (1990) and ecology (Price et al., 1988).

Limitations of the approach and the possibility of confounding factors must also be acknowledged. This mainly reflects the lower precision and accuracy compared with strictly quantitative studies (Price, 1990; Price et al., 1998). In the present study, the following points are particularly significant. *First*, the

Table 5. Analysis of dendrogram resulting from cluster analysis on use/impact data.

Variables (Impacts)	Group I	Group II	Group III	Group IV	Group V
Construction	0.1	0	0	0	1.5
Fishing/collecting	1	1.5	0	0	0
Water based pollution	1	0	1	1	0
Land based pollution	0	0	0	1	1.5
Other impacts	1	0	0	2	0

Table 6. Illustration of database for identifying sites associated with actual or potential resource-use conflicts along Gulf of Aden coast of Yemen.

Resource (Abundance)	Use/Impact (Magnitude)	Sites of Resource/ Use Conflicts
Turtles >0	Fishing >3	31, 34, 40, 58, 64
Turtles >0	Any impact/ use >2	31, 34, 39, 40, 58, 64, 65, 84, 90
Seagrasses >0	Any impact ≥ 2	81
Reefs/corals >0	Fishing ≥ 2 and Water-based pollution ≥2	16, 24, 29, 49, 50, 51, 79, 80
Halophytes >3	Water-based pollution >2	2

faunal abundance scale for invertebrates and fish used during the survey was not directly comparable to that used in earlier rapid assessments (e.g. Price et al., 1998). Huntington and Wilson (1995) scaled values of these two attributes, to prevent the occurrence of high scores (‘6’) at every site. This has implications for the cluster analysis, regional comparisons and correlations (below). *Second*, use/impact assessments are more qualitative and less precise than those adopted in recent surveys using the same overall methodology (e.g. Price, 1999). However, conversion from a scale of high resolution (0–10) used in the field to the same scale used for all other attributes (0–6) follows earlier practice (Price et al., 1998). *Third*, a relatively small proportion (15%) of qualitative records were transformed to semi-quantitative data on the ordinal (0–6) scale. Although this also follows earlier practice, which is considered justifiable (Price et al., 1998), there is inevitably some uncertainty associated with this (small) proportion of the data. In summary, good survey design and statistical rigour is always desirable. Yet there must often be a trade-off between high resolution data collected at relative few (perhaps unrepresentative) sites, or for relatively few attributes and lower resolution data gathered at a greater number of sites or for a greater number of attributes.

With regard to the satellite imagery, chlorophyll concentrations were calculated from a hardcopy output of a remotely sensed (CZCS) image. This relates to an earlier part of the season (September) than the field assessment (October–December). Nevertheless, chlorophyll concentrations and fish abundance, determined from the survey, showed significant positive correlation. Using data from earlier studies (Barratt et al., 1986; Smith, 1995), it is possible that the observed pattern at least partly reflects time lags during ecological transfer of energy up the food chain. However, at present this is speculative, and it would be desirable to have had closer correspondence between the timing of the satellite image/observation and field survey. A further point is that no correlation with chlorophyll would have been evident had all fish abundance values remained at ‘6,’ i.e. un-scaled (see Methods). For these various reasons, the main value of satellite imagery in this study to illustrate the potential for combining different assessment methodologies and technologies.

Khor Umairah Lagoon contains the only sites with high abundances of halophytes and seagrasses, because of the sheltered condition, relatively stable sediments and low slope angle of the super-littoral. Compared with the Red Sea, the Gulf of Aden coast of Yemen has a less prevalent and abundant coastal terrestrial flora (halophytes), possibly because of the latter’s high-energy environment and groundwater differences. The prevalence and abundance of coral communities was also lower in the Gulf of Aden compared with the Red Sea, principally because of lack of suitable substrates and the effects of cold, nutrient-rich upwelling. However, conditions in the southern Red Sea are also far from optimal for reef development because of the influence of Gulf of Aden water in winter and the sedimentary conditions (Sheppard et al., 1992; Price et al., 1998). Where coral communities do occur in the Gulf of Aden, they are well developed and in places form incipient reefs (e.g. Belhaf, Bir Ali and Shuqrah) (Sheppard et al., 2000).

Although significant correlation was found between chlorophyll concentration and fish abundance, this does not imply a simple causality. Observed fish abundance also depends on the (spatio-temporal) extent of upwelling, as well as the surrounding habitat, environmental impacts, predator level (e.g. birds), their proximity to the shore and other factors. The significant positive correlation observed between birds and fish might be expected, given that many species of birds (dominated by gulls and terns) recorded are piscivorous (Huntington and Wilson, 1995). Invertebrates are also major food sources for coastal birds, but their abundances were not significantly correlated.

Cluster analysis based on biological data indicated little geographical separation. This contrasts with results from the Red Sea (Price et al., 1998), where the relationship between the geographcial location and the clustering of sites based on biological data is much more marked because the coast runs along biologically important latititudinal gradients. Cluster analysis based on use/impact data also revealed few broadscale geographical patterns, very limited geographical separation of sites. The least impacted sites lie in the vicinity of Khor Umairah lagoon. Sites close to the Little Aden oil refinery and local housing were the most heavily impacted by water- and land-based pollution.

Coastal villages and other forms of construction were more common on the Gulf of Aden coast than on the Red Sea coast, reflecting the greater dependence on fishing as a source of employment and protein (Sheppard et al., 1992). Water-based pollution (e.g. tar balls, sewage) is limited but greater in the Gulf of Aden than along the Red Sea coast. Beach tar is mainly attributable to shipping that passes through the Gulf of Aden *en route* to the Mediterranean and the Red Sea. Significant threats to turtle populations on southern Yemen include uncontrolled tourism at nesting beaches, incidental by-catch in coastal gillnets and other disturbances.

The present study fills a gap in a poorly known but strategic and environmentally important part of the Arabian region and the world. Over the past 15 years, almost the entire coast of the Arabian Peninsula has been assessed using this standardised rapid assessment protocol. As a result it has generated a valuable dataset that can be used for coastal management at a national, regional or Large Marine Ecosystem (LME) level.

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