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Action Plan for Monitoring, Mitigation and Management of Harmful Algal Blooms in the Coastal Waters of Oman

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خطة عمل لمراقبة وإدارة ظاهرة المد الأحمر في مياه الشواطئ العمانية والتقليل من أضرارها

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خلاصة: خليج عمان نظام بيئي واقتصادي ثري يتأثر باستمرار بحدوث ظاهرة المد الأحمر ونمو الطحالب الضارة، وأظهرت الدراسات التي أجريت أخيرا زيادة في عدد أنواع الطحالب التي تتسبب في الآثار الضارة، وفي هذا البحث يتم تقصي أنواع ثلاثة من الطحالب التي تسبب تكوين هذه الآثار الضارة، ويقدم الباحثون مراقبة للأبحاث العلمية عن ظاهرة المد الأحمر متضمنة خطة عمل تحوي نظام مراقبة بيئي فاعل لنمو الطحالب الضارة واحتواء آثارها.

ABSTRACT : The Gulf of Oman, an ecologically and economically rich ecosystem, is frequently impacted by occurrences of harmful algal blooms. Recent studies indicate an increase in the number of causative species and harmful impacts. Many red tide incidents in Oman have been found leading to hypoxia. The frequent bloom forming species here are *Karenia selliformis*, *Nitzschia pungens*, *Prorocentrum arabianum* and *Trichodesmium erythraeum*. We review work carried out in this area, and we propose here a Management Action Plan for not only an effective monitoring system for harmful algal blooms (HABs), but also mitigation of their adverse impacts and rapid response system.

KEYWORDS: Harmful algae, HAB management, mariculture.

1. Introduction

The Oman coast has been witnessing occurrences of harmful blooms (HAB) since 1978 (Mathews *et al.*, 2001; Morton *et al.*, 2002; Al-Busaidi *et al.*, 2007). The coastal waters are since then regularly monitored. In general, the deleterious effects associated with HABs are on human health, marine resources and tourism industry.

Physiological mechanisms, singly or in combination, leading to fish mortality, include physical damage or irritation of gill tissue leading to mucus production, blood hypoxia and possibly bacterial infection (Speare *et al.*, 1989), toxigenic reactions to ichthyotoxic agents (Tanaka *et al.*, 1994, Mallet *et al.*, 1985), blood hypoxia from environmental oxygen depletion (Rensel, 1993), and gas bubble trauma from oxygen super saturation (Kills 1979). Although much is known about the mechanisms responsible for fish death from HABs, there is still lack of information on several important species and groups of fish killing HABs.

The problems arising from HABs are very diverse and the causes are many, therefore effective management is required to mitigate the threat posed by HABs to the economic development of coastal areas and human health. Strategies are needed to efficiently manage marine resources, protect public and ecosystem health, encourage and support aquaculture development, and contribute to policy decision about coastal zone issues.

1.1 Policies for management and mitigation of HABs

These can be broadly classified into PREVENTION, RESTORATION, AMELIORATION and NO ACTION AT ALL (Turner *et al.*, 2000).

1.1.1 Prevention policies

These can cover strategies that aim at minimization of the probability of formation of HABs in the marine ecosystem. Such strategies may be directed for example, at preventing the accidental introduction of exotic harmful algae (resulting from shipping activities). Sophisticated monitoring and surveillance of a wide and complex variety of factors, conditions, and mechanisms present in the marine waters are needed to identify the presence of harmful aquatic organisms in time.

1.1.2 Restoration policy program

Restoration is implemented once HABs has occurred and can be achieved by use of trained crews and special equipment to keep the bloom formation from spreading.

1.1.3 Amelioration policies

This strategy is characterized by individual programs. Amelioration policies comprise of various mitigation measures that can be adopted to reduce impact on marine living resources, human health and recreation. These programs do not focus on attaining the environmental conditions preceding the bloom formation. Amelioration programs can for instance focus on (partial) cleaning activities often translated in actions such as the removing of algal foams from the beach for example by using naturally occurring clay (Chim, 1998; Choi *et al.*, 1998).

2. Objectives of designing a monitoring program

A well-defined objective is essential in designing a HAB environmental monitoring program. A design that is too superficial may produce data inadequate for the intended use; a design that is too complicated may be labour intensive and costly. We should consider the procedure that must match our own specific objectives and site- specific conditions.
Monitoring is to:

- prevent algal toxins from reaching human consumers
- prevent algal toxins from reaching consumers of drinking water (from desalination plants)
- minimize damage to living resources such as fish
- minimize economic loss to fishermen, aquaculturists, tourists, industry etc.
- establish basic knowledge about form and function of the ecosystem investigated and the extent to which it is influenced by anthropogenic factors.

- establish detailed knowledge about selected ecosystem processes to make it possible to understand and predict ecosystem response to eutrophication or exceptional physical and biological events
- establish patterns and trends for algal populations

The ultimate goal is to determine the principal causes of red tide, in order to achieve better skill for forecasting their occurrence and predicting the consequences of phytoplankton on environmental changes in coastal waters.

3. Action plans and mitigation measures

HAB monitoring programs must be dynamic and operable in difficult conditions. The following monitoring modes have been suggested (Andersen *et al.*, 2003):

- Normal / Routine Mode: To operate in non HAB situation.
- Watch Mode: To operate when a HAB is observed, in rather low concentrations or when low levels of algal toxin are detected in fish / shellfish.
- Alert Mode: To operate when a HAB is observed in critical concentrations, when algal toxins are observed in concentrations close to or exceeding regulatory limits or where HAB effects on fish are observed.

The change of a HAB monitoring program from one mode to another must be triggered by specific observations or combinations of observations such as the changes in water temperature, chlorophyll content and fish behavior.

3.1 Common design elements of amount program

According to Andersen *et al.* (2003) the basic elements of a HAB monitoring program include:

1. Sampling of plankton, fish and water.
2. Analysis of the samples (identification of harmful algae, quantification of harmful algae measuring toxicity in water, fish).
3. Environmental observation such as discolouration of the water, fish kills and other animal behavior.
4. Evaluation of results.
5. Dissemination of information and implementation of regulatory action.
6. Action plans / mitigation measures.

It is essential to make reliable measurements of the monitored variables. Site and organism specific features influence the monitoring design. Where upwelling is a factor, oceanography must be assessed. At sites where flushing is important to HAB events, this physical feature must be evaluated; where nutrient loading increases, nutrient chemistry should be measured. The monitoring program, therefore, must be designed in accordance with the major ecological and behavioral features represented by the HAB taxa, their planktonic life mode and the habitat factors regulating their occurrence and growth.

3.2 Sampling design considerations

It is important that all routines for sampling, sample analysis, data analysis and storage be clearly defined. Pre-printed forms should be available to be filled in with the monitoring data. Raw data from the monitoring program should be kept in files, paper or electronic form for later reference and investigation. Data should be stored in a computer database to facilitate data handling, quality assurance and analysis.

3.3 Frequency and distribution of sampling

HAB events are often fast moving, and subject to meteorologically induced disruptions or accumulations. The basic monitoring strategy therefore should be one of high sampling frequency, particularly when the objective is to determine environmental control mechanisms. Ideally, samples should be collected daily but certainly not less than twice a week during longer lasting blooms. The logistics of the sampling requirement obviously are more easily met in coastal regions from which land based monitoring operations can be launched. Diel sampling may sometimes be needed to unravel the basic features and phytotactic migratory behavior of HAB flagellates as a factor in the bloom episode. Some species exhibit a night rise/day descent, others the opposite diel pattern (Kamykowski, 1976; Kamykowski, 1981). Therefore diel abundance at a given depth in the water column and among species can vary significantly because of different motility speeds and diel response patterns.

3.4 Physical habitat measurements

Among physical factors, temperature and salinity should be measured at multiple depths along a spatial gradient. Vertical density profile, if not directly measured, can be calculated from vertical temperature and salinity profiles to evaluate the degree of water column mixing. This is particularly important in upwelling HAB outbreaks that often develop after intense sunlight (Smayda, 2003).

3.5 Chemical habitat measurements

The chemical environment is a complex mixture of macronutrients including nitrogen and phosphorous, micronutrients, iron and other trace metals, organic nutrients, water quality factors and secretions by plankton. It is essential to measure macronutrients in a qualitative and predictive monitoring program. Long-term measurements of NH_4, NO_3, PO_4 will reveal trends of nutrient enrichment of water. Increasing evidence suggests that HAB events in near shore and more open habitats tend to occur with greater frequency and magnitude when nutrient enriched and may increase progressively with nutrification (Smayda, 1989; Hickel *et al.*, 1989; Honjo, 1993). Inorganic nitrogen, phosphorous and oxygen are the minimal chemical measurements that should be made particularly where anthropogenic nutrients modification is occurring. Growing evidence suggests that dissolved inorganic nitrogen (DON) may be of greater nutritional value to some HAB organisms than expected (Berg *et al.*, 1997). Micronutrients also influence HAB taxa, with evidence strongest for iron regulation and cupric ion selectivity (Takahashi and Fukazawa, 1982; Anderson and Morel, 1978).

3.6 Oxygen monitoring

Routine monitoring of seasonal water column oxygen levels with emphasis on bottom water concentrations, is essential in shallower, poorly flushed coastal waters, at aquacultural sites and in regions exhibiting environmental degradation. A progressive decrease in bottom water oxygen levels can induce die offs in poorly flushed regions subjected to increased nutrient loading and phytoplankton abundance. Increased phytoplankton biomass during poorly grazed bloom events such as *Ceratium* blooms (Hickel *et al.*, 1989) become nutrient limited, link to the bottom waters and decomposed leading to hypoxia or anoxia.

3.7 Remote sensing

Monitoring large-scale physically driven events is considerably more difficult than standard monitoring programs. It requires a large interdisciplinary research team, access to a wide variety of physical oceanographic instrumentation of ships and is costly. Satellites and other remote sensing detectors to establish the local incursions, frontal structure and regional movements of water masses based on temperature and chlorophyll signatures have been successfully used in open coastal waters (Kahru *et al.*, 1994; Keafer and Anderson, 1993). Flow-through systems which are deployed on ferries have also been used to monitor HAB populations and accompanying physical and chemical condition (Harashima *et al.*, 1997).

From a practical viewpoint, the taxonomic diversity of HAB species complicates monitoring operation, which requires a high degree of specialized expertise. The automated detection of harmful species e.g., with specific molecular probes (Scholin and Anderson, 1998), seems an attractive approach that would increase monitoring efficiency. Targeted studies and technological innovations are also essential to improve our understanding of HABs.

The behavior variability of bloom species and regulation challenge the design of HAB monitoring programs. HAB bloom events often appear to be stochastic–the result of the bloom species being at the right place at the right time (Smayda and Reynolds, 2001), i.e., being seeded at a time and place when their ecophysiological requirements are accommodated by the bloom habitat. This unpredictability challenges the design of monitoring programs. Within a given HAB event, several species may exhibit concurrent blooms, with their bloom stages in or out of phase with each other. Termination of one HAB event may be followed by another, resulting in a series of HAB outbreaks during a given year (Wong and Wu, 1987). Effective monitoring programs must deal with such situations.

4. HAB management in mariculture

Economic looses from HAB impacts on mariculture can be devastating to local or regional economies but truly large scale fish killing blooms do not occur frequently in mariculture in Oman. Mariculture fish may be less affected by blooms for a variety of reasons, such as remote geographical location, lower density of bloom organisms, smaller extent of bloom and success of management or mitigation efforts. Beside the economic losses, fish mariculture functions as a valuable indicator of the health of our coastal seas. Fish reared in mariculture cages may be affected more than wild fish that have the freedom to move and escape from the harmful blooms. Improperly located mariculture has the capability of actually stimulating algal blooms, but there are effective strategies for dealing with nutrient and other wastes from net pens that have been or are being adopted in different parts of the world (Rensel, 2001).

The occurrence of HABs sometimes are unpredictable, but the effects may be successfully avoided or managed by a variety of means. In practice, fish farmers in areas not subject to recurring HAB events are often ill prepared to deal with fish kills subsequent to major fish losses. Therefore, while preparing plans to manage HABs the local conditions, resources and abilities should be taken into consideration. Conceptual / mathematical models can be developed through hindcasting of empirical data and other means that may give indication of periods of increased HAB risk (Anderson *et al.*, 2001). Remote sensing from buoys, aircrafts, satellites and biosensors that provide sea surface temperature, current data, salinity, chlorophyll and characterization of the species, can help track bloom advection into or through coastal areas with aquaculture facilities. Fish losses may occur very rapidly, so advance preparation of a management plan is recommended and systems must be ready for immediate action.

4.1 Environmental factors related to site selection

Site selection is one of the most important criteria for successful mariculture, both in terms of success of a project and for environmental protection.

4.1.1 Basic hydrographic monitoring

This should be conducted in the general vicinity of proposed fish mariculture in order to evaluate site suitability for the fish species to be reared, minimize benthic and water column impacts, and establish HAB risks. Vertical monitoring of water temperature, salinity, dissolved oxygen, water transparency and chlorophyll during high risk periods can be strong indicators of the potential for certain types of bloom. In temperate waters, large scale mariculture should be located in moderate to deep water areas where currents disperse solids and wastes adequately. Highest consideration should be given to areas already replete with dissolved macronutrients where other factors such as light and vertical mixing limit primary productivity. Adverse effects of HABs may be reduced or avoided by selecting marine aquaculture sites with moderate or greater vertical mixing and tidal current velocity. Microflagellates and dinoflagellates blooms tend to dissipate in turbulent areas and cell growth is reduced (Whyte, 1997).

4.1.2 Nutrient enrichment

Nutrient enrichment from fish farm waste has been associated with increased phytoplankton growth and occurrence of the algal blooms, mainly for farms located in shallow, poorly flushed sites that are sensitive to nutrient addition. Increasingly this type of mariculture location is rarely sanctioned for new sites in both developing and developed economies (Folke *et al.*, 1994).

5. Monitoring practices at mariculture

The occurrence of HABs is sometimes unpredictable, but the effects on fish farms may be successfully avoided or managed by a variety of means. In practice fish farmers in areas not subject to recurring HABs are often ill prepared to deal with fish kills. Plans should be prepared to manage HABs, while considering local conditions, resources and abilities. Monitoring can vary from occasional, simple, qualitative, microscopic examination of plankton net tow contents to detailed, daily species count from water bottles or composite depth samples and remote sensing of chlorophyll by automatic profiling probes and aerial surveys.

It may also be possible to detect the onset of a HAB by monitoring fish behavior. In some cases fish will reduce or stop feeding, seem lethargic, fall back in water currents, or may orient themselves unusually in the water, often swimming close to the surface and losing their self righting ability. Different sized fish or species of fish may react with different behavior patterns and physiological responses and some related fish species are found to be more susceptible to HABs than others. Atlantic salmon, *Salmo salar,* are generally more susceptible to the effects of *Heterosigma akashiwo* than the Pacific salmon *Oncorhynchus kisuthch*, or *O. tshawytscha*, with lethal effects more prevalent in the larger size classes (Black *et al.*, 1991).

6. Mitigation strategies at mariculture

Action plans for aquaculture operations include a range of mitigation measures such as:

- Stop feeding the fish (Wong and Wu, 1987)
- Preparing for and/or conducting pre-emptive harvest (Wong and Wu, 1987)
- Moving culture pens into waters with less risk of HAB (Rensel and Whyte, 2003)
- Applying perimeter skirts to culture pens (Rensel, 2001)
- Aeration (Colt *et al.*, 1991, Boyd and Watten, 1989)
- Potentially suppressing the HAB by adding materials to disperse or suppress the algal bloom (e.g. clays etc., Sengco *et al.*, 2001, Maruyama *et al.*, 1987).

6.1 Oxygenation and aeration

Several aeration technologies are available to prevent fish mortality from environmental hypoxia including aeration from coarse bubble air stones, venturi, aspiration nozzles etc. However, coarse bubble does little to flush microalgal cells from skirted pens (Kills, 1979). The method has not been used on a commercial scale but can be used in net pens equipped with perimeter skirts to retain the oxygenated water. Moderate levels of oxygen supersaturation (< 300% of air concentration with oxygen; Boyd and Watten, 1989) may be beneficial to salmonid and yellow tail subjected to compromised water quality (Boyd and Watten, 1989; Okaichi, 1989). Supersaturated oxygen in fish culture has been used with some success in freshwater fish hatcheries and is often referred to as “oxygen supplementation”. Although oxygen supersaturation has proved effective in the laboratory in reducing fish losses due to at least one harmful alga (*C. concavicornis*), the economics of supplying the entire net pen with large volumes of oxygen are not favorable (Rensel, 1992). Oxygenation of fish culture water by aeration is not recommended to sustain marine fish exposed to HABs because it is marginally effective in increasing the ambient concentration of dissolved oxygen during the blooms. This is because the transfer rate of dissolved oxygen to water is proportional to the difference between ambient and desired concentrations (Rensel and Whyte, 2003). The exception would be during the senescent phase of very high density blooms that in some cases may result in environmental hypoxia at night due to algal respiration and cell decay (Rensel and Whyte, 2003).

6.2 Moving net pens

Towing net pens from an area affected by the HABs to a known refuge area is one of the most effective mitigation measures and is a preferred method in some regions. It does however present considerable risk and expense, particularly for larger systems. Towing of net pens has been used for preventing salmon losses due to *H. akashiwo* in Puget, Sound, Washington State and British Columbia (Horner *et al.*, 1997; Whyte 1997).

6.3 Alternative culture systems

A number of alternative fish mariculture technologies have been proposed or tested in the past. Most do not appear to be economically or technically feasible at present due in part to the globalization of the fish markets that cause intense competition among producers. Some new cage designs are practical and economical, but offer no inherent advantages for dealing with HABs.

6.4 Feeding and handling practices

During minor HABs episodes, a useful management practice is to immediately withhold feed at the onset and during the event. This reduces fish digestive demand for oxygen, which is required for other essential metabolic functions. Increasing the amount of oxygen rich carbohydrate in the diet and reducing the oxygen poor fat content could reduce the metabolic demand for oxygen by the fish (Rensel and Whyte, 2003).

6.5 Water treatment

There has been growing interest in recent years in various means of elimination of harmful algal bloom by different types of water treatment. One of the most promising methods appears to be the use of clay to flocculate cells from the water column. Certain types of naturally occurring blooms destroy or precipitate HABs in and near fish rearing farms in the Republics of Korea and Japan. Several HAB genera have been treated like *Cochlodinium*, *Chatonella* and *Heterosigma* (Maruyama *et al.*, 1987; Shirota, 1989; Kim 1998, Choi *et al.*, 1998). Excessive use of clay treatment at fish farms has the potential to adversely affect benthic and epibenthic fauna, primarily by sedimentation (Maruyama *et al.*, 1987). Additional research is needed to understand aspects of clay flocculation.

Many chemicals are capable of killing HAB organisms but most lack specificity toward target organisms. For example, copper sulphate has been widely used in the past for limiting freshwater blooms of algae, but it is not currently considered a viable option for freshwater HABs or near mariculture because of negative impacts on non-target organisms, contamination of sediments, temporary effects and high costs (Cooke *et al.*, 1993). One large scale treatment is the proposed use of a submerged electrode set at a potential to neutralize harmful oxygen radical produced by *Chatonella antiqua* (Tanaka *et al.*, 1994). Also treatment with sodium per (oxo) carbonate in a concentration of 50 mgl^{-1} eliminated 90% of the *Chatonella* cells, after only 2 hours both in the inshore tanks and in the shallow surface layer of Shido Bay, Japan, in 1987 (Okaichi *et al.*, 1990). The concentration of sodium per (oxo) carbonate did not significantly alter the ambient pH.

6.6 Therapeutics

At present there are no readily available internationally approved therapeutic drugs designed specifically to treat fish that have been affected by HABs. One of the major killers of farmed fish is considered to be the formation of superoxide anion radical (O^{-2}) by *Chatonella antiqua* and *Heterosigma akashiwo* (Tanaka *et al.*, 1994; Oda *et al.*, 1997), and *Cochlodinium polykrikoides* (Kim *et al.*, 1999). The mechanism of death is considered by some to be mucus stripping from the gills of the fish, which leads to osmoregulatory dysfunction and ultimately to death. Reduction of the oxygen radical to the more harmful hydroxy radical is effected in the seawater. Treating the radicals with enzymes superoxide dismutase, catalase, and glutathione peroxidase has been demonstrated to protect fish in laboratory studies (Yang *et al.*, 1995) and could also alleviate the problem in affected water (Colt *et al.*, 1991).

Consequences of physical damage include hypersecretion of mucus and blood hypoxia. Chemicals that can reduce mucus production could potentially provide mitigative action. Mucolytic agents fed to fish as L cysteine ethyl ester, have reportedly reduced gill mucus production and sustained fish during exposure to harmful *Chaetoceros* in the laboratory (Yang and Albright, 1994). This appears to be a useful approach to dealing with acute exposures, but extended exposures over months, may not be effective. Other drugs such as adrenaline and acetylcholine that are vasoactive agents, regulating the distribution of blood to the gill secondary lamellae (Part *et al.*, 1982) could possibly be of some use in treating HAB affected fish. The need to administer these drugs orally and the potentially high cost, however, limits their usefulness.

Other possible mitigation practices for HAB causing fish kill include acclimation of fish to decreased oxygen conditions (Shepard, 1995) which elevates the number of erythrocytes in blood.

7. Sampling procedures

Fish kills in aquaculture may have a wide variety of causes, including toxic chemical discharges, disease, environmental hypoxia or anoxia, due to algal bloom decay, discharge of oxygen demanding wastes by other industries, etc. In some cases it may be difficult to ascertain the cause of a specific fish kill, as a number of HAB species may be present in water-column samples.

7.1 Hydrographic and phytoplankton sampling

Immediate phytoplankton sampling is perhaps the most important diagnostic tool if a HAB is suspected. It is typically more important than normal techniques of fish-tissue analysis. Many lesions and abnormalities including those of gill may represent more than one cause (Anderson *et al.*, 2003). If sampling is delayed too long and major weather changes occur, the causative HAB species may not be detected. Dissolved oxygen sampling should be conducted through out the day especially just before sunrise if microalgal bloom respiration or upwelling of low-oxygen water is suspected as a cause of fish mortality (Andersen *et al.*, 2003).

7.2 Gross morphology of affected fish

External appearance of the fish should be carefully noted, including the presence of excessive mucus on the gills or flowing from the opercular cavity, the colour and shape of gills, condition of scales and fins, presence of lesions and other abnormalities. Scraping of the gill surface to prepare a microscope slide as a wet mount can be simple and effective method to see if certain HAB species are present (Rensel and Whyte, 2003)

7.3 Tissue for histopathology and bacteriology

Sampling of moribund fish and apparently unaffected fish, rather than dead fish, is highly recommended. Fish that have been dead for more than a few minutes may be useless to determine the cause of death using histopathology because tissues are rapidly affected by post-mortem changes (Speare and Ferguson, 1989).

8. Conclusion

The challenge is to understand the critical features and mechanisms underlying the population dynamics of HAB species. This understanding will serve as a basis for improved monitoring and to build models that predict the occurrence, movement, toxicity and environmental effects of HABs.

In summary, the Sultanate of Oman has the largest coastline in the Arab world. At present, the fishing industry is prosperous, but there are many environmental hazards such as industry and biological factors that can kill a large population of fish. It is significant to point out there is a need for more experts to monitor the marine environment, collection and analyzing data more frequently to be aware of the changes in the environmental conditions. Consequently, increasing the scientific personnel is the key factor in setting up a conservation strategy to protect the marine environment.

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