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# BIOLOGICAL FILTER STATIONS: A NEW ARTIFICIAL REEF CONCEPT TO COMBAT THE EFFECTS OF EUTROPHICATION IN COASTAL SEAS

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## *ABSTRACT*

*Shallow coastal waters are the most important marine ecosystems, both ecologically and economically. They are also the most endangered, with eutrophication increasingly being recognized as one of the greatest threats. The present contribution proposes to combat not only the major symptoms of eutrophication - decreased water transparency, excessive algal blooms, mucus production, and oxygen deficiency - but also the causes by utilizing the natural filter-feeding capacity of marine organisms to remove material suspended in the water. The concept involves providing optimal structures on which these organisms can settle and grow. In the North Adriatic Sea, this fauna includes ascidians, bivalves, sponges, and tube worms which function as a natural eutrophication control. This low-tech solution has been developed and tested in the Gulf of Trieste and is patented. It involves inexpensive, miniature "biological filter stations" with many advantages over traditional artificial reef structures. It is the only conceivable strategy that can improve the quality of the marine environment once nutrients and other pollutants have entered the sea. Finally, it also contributes directly to restoring original benthic community structure and function: the overgrown structures are ultimately indistinguishable from the aggregations of sessile organisms that characterize the sublittoral soft bottoms of the North Adriatic Sea.*

**Key words:** artificial reefs, eutrophication, anoxia, phytoplankton blooms, marine snow, benthos, recolonization, North Adriatic Sea

## THE PROBLEM

Shallow coastal waters are the most important marine ecosystems, both ecologically and economically. As opposed to the open ocean, the biomass, diversity, and productivity of the flora and fauna is higher here. The world's main fisheries, including virtually all mariculture efforts, are therefore concentrated in such shallow shelf seas. They are also the most endangered due to coastal and shoreline engineering measures, intense exploitation of mineral (*e.g.*, oil) and biological resources (fisheries, mariculture), unabated input of toxic substances, and rising pressures from tourism. Increasingly, eutrophication - essentially an over-enrichment with nutrients - is being recognized as one of the greatest threats, with the exact role of anthropogenic or "cultural" eutrophication still being debated. The symptoms include reduced water transparency, excessive algal blooms, mucus production ("marine snow"), oxygen deficiency, and mass mortality of benthic organisms. These developments have been registered in many shallow coastal areas, including the North Sea (Rachor, 1985), Baltic Sea (Larson *et al.*, 1985), Scandinavian waters (Rosenberg, 1985), Japan (Imabayashi, 1983), and the U.S.A. (Officer *et al.*, 1984). Eutrophication is also an immediate concern in the Mediterranean Sea (UNESCO, 1988), with a particularly acute situation in the Northern Adriatic Sea (Brambati, 1988).

The primary result of increased nutrient input is the stimulation of plant growth. In the sea this involves seaweed growth and phytoplankton blooms. The former can be a nuisance in certain semi-enclosed systems (*e.g.*, *Ulva* growth in the Venice Lagoon), but cannot be considered to be a chief threat to the ecosystem as a whole. Abnormal phytoplankton blooms and marine snow events, on the other hand, are known to be directly responsible for a wide range of negative impacts. These range from relatively harmless effects such as clogged fishing nets and un-sightly foam deposits on beaches, to major threats to marine life (red tides) and to human health by toxic algal blooms that cause ciguatera,

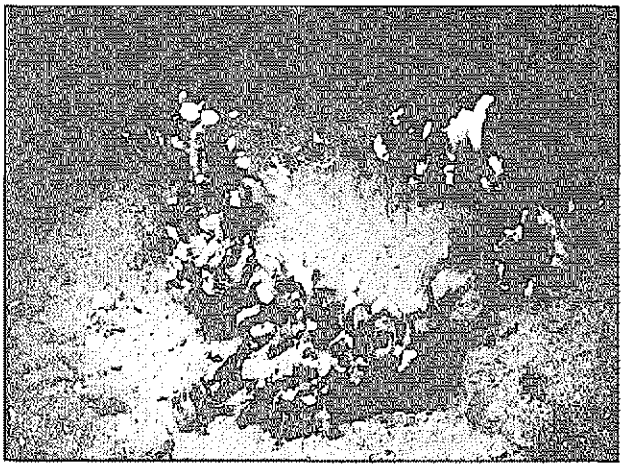

**Fig. 1: Test of *Schizaster canaliferus* with early stage of overgrowth. Note that tube worms (*Pomatoceros triqueter* and *Serpula* sp.) as well as hydrozoan colonies originate from lower surface (from Nebelsick et al., 1997)(25 m depth, Gulf of Trieste). All photos: M. Stachowitsch.**
**Sl. 1: Lupina morskega ježka *Schizaster canaliferus* v zgodnji fazi zaraščenosti. Zanimivo je, da cevkarji (*Pomatoceros triqueter* in *Serpula* sp.) in kolonije trdoživnjakov izvirajo iz spodnje površine lupine (povzeto po Nebelsick et al., 1997) (Tržaški zaliv v globini 25 m). Vse fotografije: M. Stachowitsch.**

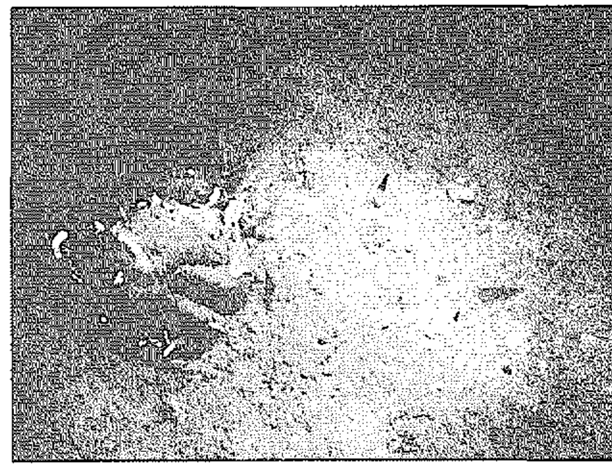

**Fig. 2: Early overgrowth stage on the bivalve *Pecten jacobaeus* consisting largely of dense serpulid tube worms; growth originates from lower surface of shell. Note large, sediment-covered and epigrowth-free top side of valve.**
**Sl. 2: Zgodnja faza zaraščenosti na Jakobovi pokrovači *Pecten jacobaeus*, ki je v veliki meri posledica rasti številnih cevkarskih mnogoščetincev iz spodnje površine školjke. Zanimiva je velika, z usedlinami prekrita gornja stran pokrova školjke brez obrasti.**

amnesic shellfish poisoning (ASP), paralytic shellfish poisoning (PSP), diarrhoeic shellfish poisoning (DSP), and neurotoxic shellfish poisoning (NSP) (for a recent review, see Richardson, 1997). At the same time, however, eutrophication can lead to the destabilization and collapse of entire marine ecosystems. This process typically involves the collapse of plankton populations, which then sink to the sea floor. Here, bacterial decomposition consumes large amounts of oxygen, leading to hypoxia or anoxia in the bottom water layers.

In the Adriatic Sea, for example, the negative impact of settling plankton blooms is compounded by the *"mare sporco"* phenomenon: mucus material in the water column and large-scale mats on the surface. This phenomenon has been known since historic times (Fonda-Umani *et al.*, 1989), but appears to be increasing in frequency and severity. Mucus in the form of less conspicuous *"marine snow"* is common in the Northern Adriatic Sea and, indeed, worldwide. In the Adriatic, marine snow is acknowledged as being produced by diatoms in the pelagic zone, *i.e.*, as being of phytoplankton origin: benthic diatom biomass is insufficiently high to produce the quantities of mucus aggregates observed in 1988 and 1989 (Herndl *et al.*, 1990). Recently, five types or stages of this material have been distinguished:

1. macroflocs,
2. stringers,
3. clouds,
4. creamy surface layers, and
5. gelatinous surface layers.

This typology is based on size, shape, stability, behavior, and effect on benthos (Stachowitsch *et al.*, 1990). Such *"mare sporco"* events pose a serious ecological and economical threat: they accelerate the deterioration of the ecosystem and have a severe negative impact on the fishing and tourism industry.

## TRADITIONAL SOLUTIONS

Mucilage and other effects of eutrophication can only be combated by a multi-pronged strategy. First and foremost is the "beginning-of-the-tube" approach: nutrient inputs into the environment must be reduced. Secondly, "middle-of-the-tube" measures can be implemented. This can involve the restoration of river meanders, of river banks, and of marshlands and estuaries, or the promotion of algal growth in retaining basins before waste water reaches the sea. As opposed to the above long-term approaches, useful, short-term, "end-of-the-tube" measures are more difficult to envision in the sea. Indeed, no technological solution is conceivable that could remove nutrients and/or the resulting phytoplankton blooms once waste waters have entered the sea. In the Adriatic and elsewhere, the applied *in situ* measures have been restricted to cosmetic activities such as installing artificial barriers against floating mucus mats or removing seaweed.

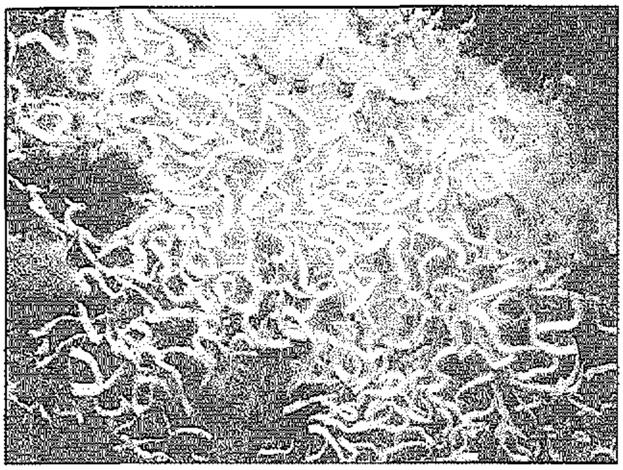

***Fig. 3: Lower surface of horizontally positioned 25 x 25 cm asbestos cement plates in 25 m depth. Overgrowth patterns on artificial substrates confirm those observed on biogenic structures. Dense early-stage epigrowth consists of tube worms, colonial ascidians, bivalves, and hydrozoans. Note sea urchin** Psammechinus microtuberculatus **on lower left and metal rod (bottom middle) holding substrate in place 1m above the bottom. (25 m depth, Gulf of Trieste)***

***Sl. 3: Spodnja površina vodoravno položenih 25 x 25 cm plošč iz azbestnega cementa v globini 25 m. Vzorci zarasti na umetnih podlagah so enaki vzorcem, opazovanim na biogenskih strukturah. Gosta zarast v zgodnji fazi sestoji iz mnogoščetincev, kolonijskih kozolnjakov, školjk in trdoživnjakov. Zanimivo je, kako mali morski ježek** (Psammechinus microtuberculatus) **spodaj levo in kovinska palica (spodaj v sredini) držita podlago skupaj kak meter nad dnom. (Tržaški zaliv v globini 25 m)***

One traditional approach to ameliorating damage to marine ecosystems is to introduce artificial structures into the sea. The great interest in such artificial reefs is reflected in recent bibliographies containing several thousand references (Stanton *et al.*, 1985; Reeff & Mc Gurrin, 1986). Such reefs have been employed in the Adriatic Sea of Italy (Bombace, 1989) and proposals have been made for the Slovene part of the Adriatic as well (Fonda, 1995). The term artificial reef is used to describe benthic structures created accidentally or deliberately by human activities. The more general term, artificial habitat, refers to structures deployed either on or above the sea floor, including floating or midwater fish-aggregating devices (FADs) (Bohnsack *et al.*, 1991). The topic has gained public interest in recent years due to the attempts of the oil industry to abandon or discard their decommissioned oil platform-related structures at sea under the guise of habitat improvement through artificial reefs. The materials used to construct artificial habitats include concrete, iron and steel, reinforced concrete, ceramic, various plastics or plastic concrete, and a wide range of so-called "materials of opportunity" (automobile tires and bodies, derelict ships) (Grove *et al.*, 1991). Overall design also varies widely, with advanced structures having complex modular forms requiring assembly on land or in the water. A recent, global overview of all aspects of artificial habitats is provided in Seaman & Sprague (1991).

The common structural feature of virtually all these artificial reefs is their large size and enormous weight. Similarly, the common biological feature is that most are ultimately deployed to attract fishes. Fishes, however, represent only one of many compartments of the marine ecosystem, and traditional artificial reefs can therefore contribute only little to restoring the original community structure of damaged shallow seas or actually counteracting damaging influences.

## A NEW APPROACH

The present proposal is a low-tech biological strategy that both combats eutrophication-related effects in the sea and promotes the overall recolonization process of the sea floor. It represents a short- to medium-term measure and utilizes the natural filter-feeding capacity of marine organisms to remove excess biomass - bacteria, phytoplankton, marine snow, detritus, *etc.* - from the water.

The macroepibenthos in the Adriatic Sea consists largely of filter- or suspension-feeding organisms and includes sponges, bivalves, ascidians, tube worms, brittle stars, hydrozoans, and bryozoans. This benthic fauna is capable of removing enormous amounts of material from the water column. Depending on water depth, intact benthic communities can potentially filter the entire volume of a basin within days or weeks (3 d, Laholm Bay, 10 m, Loo & Rosenberg, 1989; 4-6 d, Oosterschelde, 5-35 m, Smaal *et al.*, 1986; 20 d, Gulf of Trieste, 25 m, Ott & Fedra, 1977). By regulating the processes in the overlying water, they stabilize the entire system. For example, such communities are considered to control water quality in the Bay of Brest (Hily, 1991) and to stabilize the estuarine ecosystem of the Oosterschelde, Netherlands (Herman & Scholten, 1990). In San Francisco Bay, benthic filter feeders have been termed a "natural eutrophication control" (Officer *et al.*, 1982). In principle, this mechanism involves a conversion of pelagic biomass into benthic biomass, the latter having a lower respiration per unit weight. The benthos functions as a battery in which large, perennial species take up excess pelagic material and store it in the form of body tissue *etc.* (Ott, 1981). This is important for the energetics and oxygen balance of the ecosystem. This feature gains additional significance in eutrophicated waters, where an intact fauna can dampen the effect of large nutrient loading; at the same time, the overall system is very sensitive to fluctuations in the benthic populations themselves (Herman & Scholten, 1990). It is precisely these communities that are, ho-

*Fig. 4: Upper surface of horizontally positioned 25x25 cm asbestos cement plate. Late-stage situation with thick sediment layer on upper surface; epigrowth consisting of tube worms and hydrozoan colonies (overgrown by colonial ascidians) growing from lower side up to edges of substrate.*

*Sl. 4: Gornja površina vodoravno položene 25 x 25 cm plošče iz azbestnega cementa. Stanje iz pozne faze z debelo plastjo usedlin na gornji površini; obrast, ki sestoji iz cevkarjev in kolonij trdoživnjakov (preraslih s kolonijskimi kozolnjaki), raste iz spodnje strani navzgor do robov podlage.*

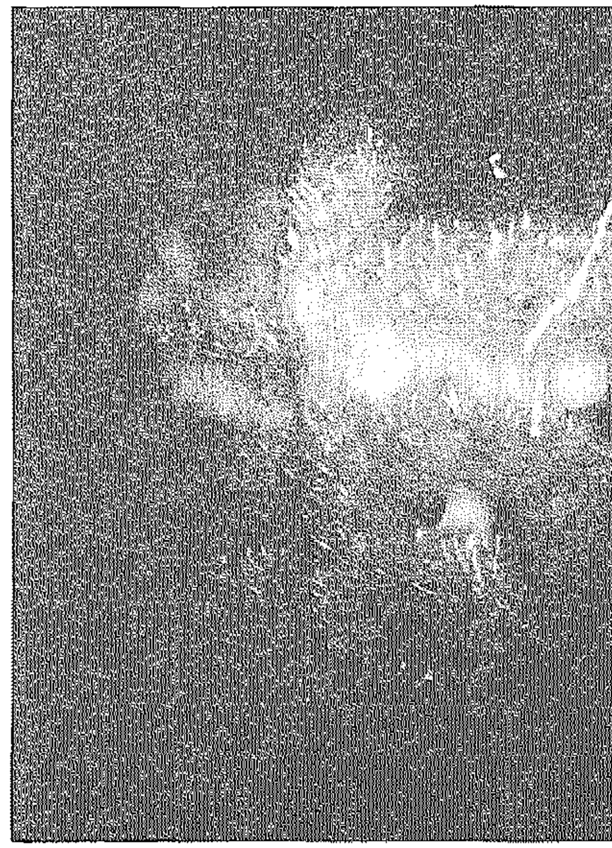

*Fig. 5: Vertically oriented series of asbestos cement panels. Dense epigrowth of tube worms and ascidians on all sides of panels. Higher panels have more growth and also serve as substrate for egg cases of the cephalopod* Loligo vulgaris. *Overall height, ca. 2 m. (25 m depth, Gulf of Trieste)*

*Sl. 5: Navpično postavljene plošče iz azbestnega cementa. Gosta obrast cevkarjev in kolonijskih kozolnjakov na vseh straneh plošč. Višje plošče so bolj zarasle in so hkrati tudi podlaga za jajčeca navadnega lignja* (Loligo vulgaris). *Skupna višina pribl. 2 m. (Tržaški zaliv v globini 25 m)*

wever, most strongly affected by anoxia (Stachowitsch, 1984; 1988). The short-term disturbances in the pelagic subsystem cause long-term disturbances in the benthic subsystem, making the latter the "memory" of ecosystem collapses (Stachowitsch, 1992).

The present proposal involves supporting filter feeders by providing them with optimal structures on which to settle and grow. The larvae of these organisms are naturally present in the water and eventually settle on available hard structures. Such substrates are generally in limited supply on the mud or sand bottoms characterizing shallow coastal seas. In the soft bottoms of the North Adriatic Sea they include a wide range of biogenic structures, mostly dead bivalve shells *(e.g., Chlamys* spp., *Arca noae, Pecten jacobaeus, Acanthocardium* sp., *Laevicardium oblongum)* and gastropod shells *(e.g., Aporrhais pes-pelecani, Murex brandaris, Trunculariopsis trunculus).* Epigrowth on the latter typically takes place during the phase in which they are occupied by hermit crabs (Stachowitsch, 1980). Other structures include the shells of the partially embedded, vertically oriented large bivalves *Pinna* spp. and tests of the irregular sea urchin *Schizaster canaliferus* (Nebelsick *et al.*, 1997), which emerge and die in large numbers during oxygen crises.

Twenty-five years of field research in the Northern Adriatic Sea have yielded valuable information on the conditions necessary for the development of epigrowth on the above secondary hard bottoms. Small, flatter substrates (small bivalves, shell fragments) are suboptimal. Fresh, cleaned bivalve shells and (sealed) gastropod shells, for example, were manipulated, overturned and scattered by hermit crabs, sea stars and holothurians and tended to be rapidly covered by sediment (Stachowitsch, 1979; Fig. 5 in Stachowitsch & Fuchs, 1995). Despite their fragility, the somewhat larger, rounded *Schizaster canaliferus* tests are better suited. After mass mortalities, the white *S. canaliferus* tests are among the most conspicuous and abundant substrates on the sediment surface. Numerous *in situ* observations show that epigrowth typically initiates on the bottom sides of *S. canaliferus*, probably due to the influence of

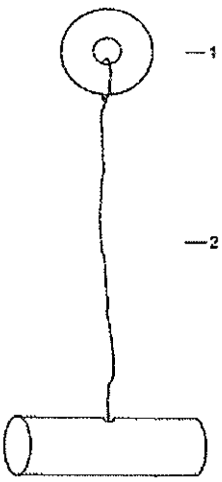


***Fig. 6: Schematic illustration of prototype underwater structure consisting of buoyant element (1), anchoring element (3) and flexible connection (2; not draw to scale). Fist-sized device unfurls automatically when released and lands correctly oriented on the bottom. Overall height ca. 1 m.***
***Sl. 6: Shematski prikaz podvodnega prototipa, ki ga sestavljajo plavajoči element (1), sidro (3) in prožna povezava (2; ni v merilu!). Napravica, velika kot pest, se ob sprožitvi odvije in v pravilnem položaju pristane na morskem dnu. Skupna višina pribl. 1 m.***

sedimentation (*e.g.*, accumulation of sediment in the ambulacral grooves; Fig. 1). This growth pattern was also evident on the larger bivalve *Pecten jacobaeus* (Fig. 2), whose population exploded after a mortality event in 1984. The pattern was further confirmed by artificial substrate experiments: fouling organisms on horizontal asbestos cement plates (25x25 cm) suspended 1m above the bottom (25 m depth) were largely restricted to the undersurface (Fig. 3). The top sides were rapidly covered by a thick layer of sediment (Fig. 4). A reversal of this pattern (*i.e.* no influence of sedimentation, growth on the upper surface) is achieved by hermit crab-occupied gastropod shells (Stachowitsch, 1979, 1980): the crabs' movements keep the shells off the sea floor, free of sediment and predators/grazers, and guarantee a stable orientation. The established organisms on such shells are known to survive after the shell is abandoned by the crab, leading to the aggregations of sessile invertebrates (so-called multi-species clumps) that characterize this benthic community. Larger artificial structures consisting of series of vertically oriented asbestos cement plates were rapidly encrusted on all sides with dense epigrowth (Fig. 5); the higher plates exhibited more growth, which may be related to strong vertical gradients in bottom water oxygen concentrations, with values increasing rapidly further above the sediment surface (Malej & Malačič, 1995).

***Fig. 7: Overview of an overgrown underwater "biological filter station". Such structures accelerate recolonization of the sea floor and help stabilize the entire ecosystem. Note comparatively sparse epigrowth on surrounding sediment bottom (25 m depth, Gulf of Trieste).***
***Sl. 7: Pogled na podvodno "biološko precejevalno postajo". Takšne zarasle strukture pospešujejo ponovno poseljevanje morskega dna in pomagajo pri stabilizaciji celotnega ekosistema. Zanimiva je razmeroma redka obrast na sedimentnem dnu (Tržaški zaliv v globini 25 m).***

These observations enabled the development of an optimal structure for epigrowth by sessile, filter- and suspension-feeding organisms. The configuration, size, overall rigidity, and position in relation to the bottom were among the many factors taken into consideration to prevent burial, reduce predation, and ensure the stability of the device. The structure consists of three elements, 1) a small plastic float, 2) a weight or anchoring element, and 3) a flexible connection (*e.g.*, a line) between the two. The entire, approximately fist-sized device is transported with the line either coiled around the anchoring element or bundled inside a depression in the anchoring element. When dropped into the water, it automatically unfurls and lands correctly oriented on the bottom (Figs. 6-8). The author has been granted a patent for these biological filter stations.

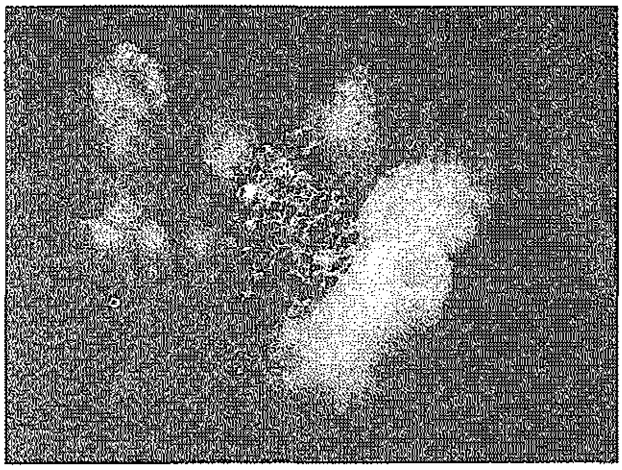

***Fig. 8: Close-up of buoyant element overgrown by 5 ascidians (Phallusia mammillata). Such densely overgrown underwater "biological filter stations" may filter over 1000 liters of water per day.***
***Sl. 8: Bližnji posnetek plavajočega elementa, ki ga je preraslo 5 bradavičastih kozolnjakov (Phallusia mammillata). Tako na gosto poraščene podvodne "biološke precejevalne postaje" lahko precedijo več kot kubik vode na dan.***

The advantages of this system include:
1. not cosmetic (*i.e.*, as in barriers preventing floating mucus from reaching beaches); it helps combat eutrophication and restore community structure
2. very small (not a massive or voluminous artificial reef, *i.e.* modular reef sets, derelict ships, *etc.*)
3. lightweight (no heavy equipment required for assembly or deployment)
4. inexpensive to produce
5. no culturing of organisms necessary (larvae settle naturally; no introduction or attraction of new or "exotic" species)
6. no maintenance, no retrieval
7. non-corroding, non-toxic
8. no hindrance to fisheries or navigation
9. insensitive to storms
10. invisible to tourists

Most suspension- and filter-feeding organisms are known to feed virtually without interruption. The volume of water filtered will vary from group to group. Typical literature values for the pumping rate of large ascidians, for example, vary between 5-17 liters of water per hour, while 2 liters/hour can be assumed for a larger bivalve (Jorgensen, 1952; Fiala-Medioni, 1979). The calculated volume of water pumped by an average structure, based on a growth consisting of one ascidian and four bivalves, would be 400 liters/day (20 l/h x 20 h). Densely overgrown structures (Figs. 8-9) could filter well over 1000 liters/day. Thus, an average structure filters

***Fig. 9: More diverse, late-stage epigrowth on buoyant element consisting of sponges, ascidians, brittle stars, and bivalves: these epigrowth assemblages can sink to the bottom and are then indistinguishable from the aggregations of sessile animals that characterize this benthic community. Note connecting element (bottom center).***
***Sl. 9: Bolj raznolika zgodnja obrast na plavajočem elementu sestoji iz spužev, kozolnjakov, nitastih kačjerepov in školjk: takšni skupki obrasti lahko potonejo na dno, kjer jih potem ni mogoče več razločiti od skupkov sesilnih organizmov, ki so tako značilni za to bentoško skupnost. Spodaj v sredini je povezujoči element.***

the same amount of water that three persons discharge daily into the sewage system.

The attached organisms possess a wide range of filtering mechanisms, resulting in an equally wide range of particle sizes being removed - from bacteria to larger flocculent material, and to a certain extent even dissolved organic matter as well as heavy metals and other pollutants. This principle has already been put to practical use in redeveloping abandoned dockyards in England: nets with cultured blue mussels (*Mytilus*) suspended in the dock basins significantly improved the quality of the water (Wilkinson *et al.*, 1996). This role of filter feeders may have other significant human health-related implications in eutrophicated waters, which are associated with increased toxic algal blooms: in Japan, for example, *Mytilus edulis galloprovincialis* has been shown to rapidly remove the plankton in red tide water masses (Takeda & Kurihara, 1994). Finally, in the North Adriatic, very heavily overgrown buoyant elements of the biological filter stations presented here tend to sink to the bottom, where they are virtually indistinguishable from the aggregations that characterize the intact benthic community. They may thus accelerate the recolonization process of areas damaged by anoxia and other eutrophication-related effects, or help restore benthic communities that have been depopulated by other chronic or acute pollution events.

The actual number of structures that would be employed depends on a number of factors including the size of the basin, the magnitude of the eutrophication-induced symptoms, and the type of filter feeders that can be expected to settle on the buoyant elements. An appropriate number of overgrown structures would process the same volume of water as a waste water treatment plant - at a fraction of the cost. This represents the only conceivable method of removing pelagic material from the system once nutrients or other pollutants have entered the sea. The employment of such artificial substrates is a low-tech solution to a high-tech problem. As such it would have a good potential for success worldwide.

# BIOLOŠKE PRECEJEVALNE POSTAJE: NOVA ZAMISEL O POSTAVITVI UMETNIH MORSKIH GREBENOV KOT SREDSTVA ZA ZMANJŠEVANJE UČINKOV EVTROFIKACIJE V OBALNIH VODAH

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*POVZETEK*

*Plitke obalne vode so najpomembnejši morski ekosistemi tako v ekološkem kot gospodarskem pogledu. Hkrati so ti ekosistemi tudi izredno ogroženi, saj postaja vse očitneje, da je evtrofikacija zanje ena izmed največjih nevarnosti. Avtor pričujočega članka meni, da bi se morali bojevati ne le proti glavnim simptomom evtrofikacije - zmanjšani transparentnosti vode, prekomernemu cvetenju alg, kopičenju sluzi in pomanjkanju kisika - marveč tudi proti njenim vzrokom, in sicer z izkoriščanjem naravne zmožnosti morskih organizmov precejanja vode za odstranjevanje snovi, lebdečih v vodi. Takšni organizmi v severnem Jadranu so kozolnjaki, školjke, spužve in črvi cevkarji, ki delujejo kot naravni zaviralci evtrofikacije. Ta sicer tehnološko zelo nezahtevna zamisel o postavitvi umetnih morskih grebenov je bila razvita in preskušena v Tržaškem zalivu in je tudi že patentirana. Zajema miniaturne "biološke precejevalne postaje", ki imajo ob majhnih stroških mnoge prednosti pred standardnimi strukturami umetnih morskih grebenov. Pravzaprav je edina strategija, ki lahko izboljša kakovost morskega okolja, potem ko se v morju nakopičijo nutrienti in drugi onesnaževalci vode. Nenazadnje pa tudi neposredno prispeva k obnavljanju ustroja in delovanja izvirne bentoške skupnosti, saj zaraslih struktur nazadnje ni mogoče več razločiti od skupkov sesilnih organizmov, ki so tako značilni za obalno morsko dno severnega Jadrana.*

**Ključne besede:** umetni morski grebeni, evtrofikacija, pomanjkanje kisika, cvetenje fitoplanktona, morski sneg, bentos, ponovna poselitev dna, severni Jadran

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