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Review

Resuspension of sediment as a method for managing shallow eutrophic lagoons

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The article sets out to demonstrate that resuspension of sediment could be used to counteract the consequences of eutrophication and to manage degraded coastal lagoons subject to frequent periodic dystrophic processes. This is done by a general review of the literature on resuspension of sediment, focusing on its effects in shallow eutrophic lagoons and the results of specific research recently conducted by the author.

Key words: Lagoon, eutrophication, sediment resuspension, lagoon biogeochemistry, lagoon management.

INTRODUCTION

Bottom disturbance causing resuspension of sediment in the water column is usually considered a negative phenomenon. Resuspension of normally steady soft sediment, for example by gales, can have a considerable impact on the water body by raising organic particles and dissolved organic matter towards the surface (Hopkinson, 1985), activating bacterial oxidative mineralization (Fanning et al., 1982) and increasing the remineralisation rate (Wainright, 1987; Wainright, 1990). Resuspension may also activate transport of nutrients in sediment interstitial water and adsorbed on sediment particles. Using a simulation model, Wainright and Hopkinson (1997) established that resuspension causes release of nutrients, an increase in carbonates and increased oxygen consumption in the water column. However, there are contradictory results and different opinions about the effects of resuspension of sediment on the water column. In fact, much depends on the nature of the sediments, the height of the water column, the quality of organic matter present and the environmental conditions under which disturbance occurs (Tengeberg et al., 2003; Arnosti and Holmer, 2003).

Resuspension of sediment may lead to oxidation of iron to ferric oxides, which adsorb orthophosphates, removing them from the water column (Golterman, 1995; 2001). Thus the impact of resuspension may differ considerably from one place to another, in relation, for example, to the amount of iron available in sediments. According to Søndergaard et al. (1992), in Lake Aresø (Denmark), where sediments are low in iron, resuspension is the main factor determining an increase in orthophosphates. On the other hand, in a laboratory study, Sloth et al. (1996) found that resuspension multiplied dissolved oxygen (DO) consumption by ten with respect to control, but caused modest changes in nutrient flow. In laboratory experiments on deep water sediments, Koschinsky et al. (2001) did not find increases in dissolved organic carbon, heavy metals, nutrients or microbiological activity as a result of adsorption by resuspended sediment matter. Tengeberg et al. (2003) found that natural resuspension in a Swedish coastal area in winter reduced carbonates and phosphates in the water column and increased DO, silicates, nitrites and nitrates, while ammonia remained unchanged.

According to these authors, the effects of resuspension can vary in relation to bottom conditions and season. According to Blackburn (1997), a resus-pension event leads to a sudden increase in nitrogen, by mixing interstitial water into the water column, but the same amount would be released in any case by diffusion gradient over a longer period. Tengberg et al. (2003) sustain that more field research is needed to clarify the effects of resuspension in different seasons of the year and its long-term effects.

REPEATED DISTURBANCE AND RESUSPENSION OF SEDIMENT

The effects of occasional resuspension are one case, the effects of which may vary in relation to sediment conditions, accumulation of organic matter, the quality of the latter and water column conditions. The effects of disturbance repeated with a relatively high frequency may be quite different.

In laboratory studies, Stahlberg et al. (2006) showed that frequent resuspension of sediment increased the mineralization rate with respect to undisturbed sediment by a factor between 2 and 5. In an experiment conduced in a limited area of a shallow lagoon (Orbetello lagoon, Italy), Lenzi et al. (2005) found that repeated passages of boats that resuspended soft surface sediment increased the oxidative status of sediments (increase in redox potential - Eh), reducing the organic content, without any significant increase in nutrients or oxygen consumption in the water column.

Lenzi et al. (2010) found substantially the same results in two large areas (20 ha each) of another coastal lagoon (Lake Burano, Italy) when surface sediment was repeatedly disturbed with a specially fitted boat. The trend of dissolved sulphides in this experiment suggested that disturbance interrupted sulphate reduction processes. A possible hypothesis may be that an area subject to frequent turbulence affecting surface sediment, for example every 24-48 h as stated by Stahlberg et al. (2006), may undergo an increase in the mineralization rate, as sustained by these authors, without showing any significant effect on the water column, in line with Lenzi et al. (2005; 2010).

In sediments with oxidative status, orthophosphates bind to ferric oxides-hydroxides (Golterman, 1995; 2001), carbonates and clays (Dodge et al., 1984; De Jonge and Villerius, 1989), becoming increasingly rare in interstitial waters and released less into the water column, in other words, unavailable to algae. As far as nitrogen compounds are concerned, oxidation accelerates nitrification and leads to pre-dominance of nitrates over the reduced forms, nitrite and ammonium (Revsbech et al., 1980). An increase in nitrate concentrations produces an increase in denitrification (Herbert and Nedwell, 1990), which occurs in anoxic microhabitats (in an oxidative milieu) (Fenchel, 1992), with the result that part of the sediment nitrogen is lost as N_2 or N_2O and the eutrophy of the system declines (Novicki et al., 1997). Thus, when a sedimentary substrate undergoes frequent disturbance, oxidation occurs, labile organic matter is reduced, orthophosphates are not released and there is partial loss of nitrogen.

Eutrophication problem in shallow water lagoons

In marine sediments, including those of lagoons and other transition environments, more than 50% of organic matter is degraded by bacterial sulphate-reduction processes (sulphate respiration) (Jørgensen, 1983). Many coastal lagoons and estuaries become eutrophic and produce excessive macroalgal biomass in warm months (Morand and Briand, 1996). These conditions lead to major build up of organic matter in sediments, increasing sulphate-reduction. Breakdown of organic matter by this process produces the acidifying gases CO_2 and H_2S.

Dissolved sulphides are toxic and may have considerable impact (Hijs et al., 2000). This may act on bicarbonate equilibria of interstitial water and water in contact with sediment, producing a white precipitate of $CaCO_3$ (Deelman, 1975). The sediment becomes more acidic and more reduced (very low Eh values), leading to build-up of reduced and reducing components. Low redox potential and pH lead to production of ammonium (Marty et al., 1990) and nitrite by ammonification of organic matter, and this too has a toxic effect on fauna (Torres-Beristain et al., 2006), besides stimulating production of nitrophilic algal species.

Natural baffering

Natural buffering hinders this trend. Production of free sulphide (H_2S, HS^-, S^{2-}) by sulphate-reduction is countered by ferrous and ferric ions: H_2S is oxidized by ferric iron ($H_2S{\uparrow} + 2Fe^{+++} = S{\downarrow} + 2Fe^{++} + 2H^+$) and blocked as sulphide by ferrous iron, as ferrous sulphide ($H_2S{\uparrow} + Fe^{++} = FeS{\downarrow} + 2H^+$) and then as pyrite ($FeS{\downarrow} + S{\downarrow} = FeS_2{\downarrow}$) (Berner, 1984; Luther, 1991; Richard and Luther, 1997; Theberge and Luther, 1997; Rozan et al., 2002). The pool of iron available in sediment may be sufficient to block dystrophic episodes, but if the quantity of organic matter exceeds availability ($H_2S/Fe>1$), then H_2S enters the water column (Giordani et al., 1996), with reducing action (removal of oxygen and anoxia) and toxic effects. Reduction of iron and its blockade by H_2S releases orthophosphates previously bound to ferric oxides-hydroxides (Gunnars and Blomqvist, 1997; Golterman, 2001; Rozan et al., 2002). Thus ortho-phosphates are mobilised into the water column, where they are available to algae.

Macroalgal and microalgal blooms

In coastal lagoons with little water exchange, the anoxia established in sediments due to high nutrient load and accumulation of organic matter leads to increasing degra-dation and continual stress for populations in the warm season, resulting in selection of opportunistic species and in a sudden and drastic change in the phytobenthos (Valiela et al., 1997). This is immediately evident for rooted plants, development of which is curbed by bacterial and chemical conditions in the sediment, by epiphytes development, by phytoplankton that excludes light and by floating macroalgae that can suffocate

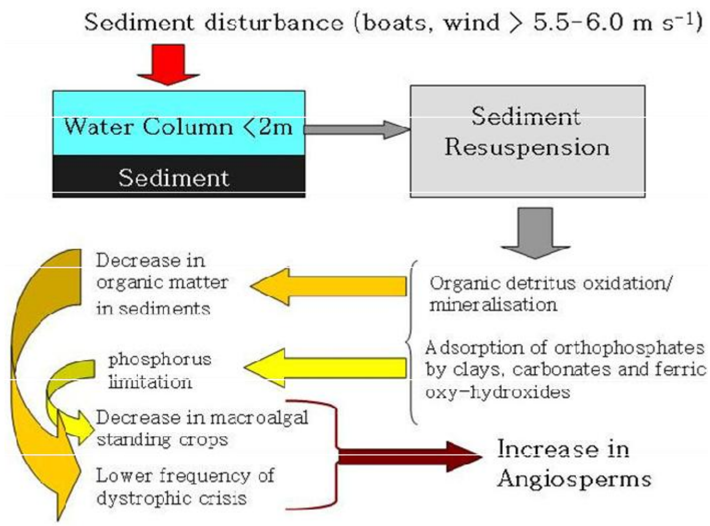

Figure 1. Scheme of biogeochemical events induced by resuspension of sediment in eutrophic lagoon environments.

seagrass meadows (Den, 1994; Raffaelli et al., 1998). High eutrophication favours the change from seagrass to seaweed, and if conditions worsen, to oppor-tunistic microphytes, which have high turnover (Duarte, 1995). Lenzi et al. (2003) observed a macroalgal distribution gradient with phosphorophilic macroalgae near a man-made nutrient source and nitrophilic macro-algae at some distance from it. Finally, anoxia and the bacteria associated with the sulphur cycle may mobilise mineral contaminants, such as mercury in cinnabar as methylmercury (CH_3Hg^+) (Wood and Wang, 1983). These mechanisms are not yet well known and call for further research.

CONCLUSIONS: A POSSIBLE TOOL FOR LAGOON MANAGEMENT

In the framework of such eutrophic environments with little water exchange, frequent disturbance of sediment counters persistence of dystrophic conditions. By virtue of the geo-chemico-physical effects that it produces, disturbance leads to a new selection of bacterial, plant and animal populations, in the opposite direction to the selection produced by eutrophy and dystrophy: oxidative mineralising strains of bacteria increase, fall-out of resuspended matter increases sediment bacterial activity in the vicinity of the disturbed area (Logan and Kirchman, 1991), infauna biodiversity increases (Widdicombe and Austen, 2001), macroalgae suffer phosphorus limitation (Lenzi et al., 2003) and recolonization of the substrate by phanerogams that capture nutrients directly through their roots is promoted. A simplified scheme of the process is shown in Figure 1.

This result was evident during operations carried out to combat severe eutrophication of Orbetello lagoon, which in the first years consisted largely of macroalgal removal by harvesting boats. Though only 3-6% of the estimated maximum macroalgal standing crop was harvested, a radical change in vegetation quality and quantity was obtained in only two years. Chlorophyta decreased sharply, Rhodophyta took their place but developed less, and phanerogams which had been completely eliminated by the environmental crisis, returned (Lenzi et al., 2003). The subsequent experiment with a special boat equipped to raise soft sediment in Lake Burano showed a drastic reduction in macroalgal populations and an increase in phanerogams (with many seedlings establishing directly from seed) in disturbed areas (total, 44 ha) but not in undisturbed areas (total, 40 ha) (Lenzi et al., 2010).

Much has still to be done to establish whether the answer to our initial question is positive, however the results so far are encouraging for eutrophic shallow-water environments. Under these conditions, it has little sense wondering whether sediment disturbance can somehow damage the ecosystem, since it is already severely threatened by frequent dystrophic crises. Fish of commercial interest are often severely impoverished, many microenvironments and typical species are lost and biodiversity is generally reduced in these areas. Of course it is prudent to check sediments for contaminants, as some are best not diffused in the water column (Kim et al., 2006; Kalnejais et al., 2007).

Shallow bottoms make disturbance easy using boats of a suitable size or fitted with motors that mix air and water and direct a jet towards the bottom, suspending the top 3 to 4 cm of sediment. It is more complex, but not impossible, to disturb the bottoms of lagoons and estuaries deeper than 2 m. For example, a trawl for catching flatfish and pectinids, known as “rapido” (Franceschini et al., 2000), could be modified by removing the net and teeth that engage the bottom and adjusting the skids to avoid direct contact with the bottom. Dragged by a boat, this device could be used to disturb and resuspend superficial sediment in relatively deep water.

It would be worth analysing whether this management criterion gives better results than more conventional measures, which are mainly of an engineering nature, such as creation of underwater channels where sediment collects, cement banks, pumping stations to admit sea water and flow accelerators, and environmental emergency works, such as harvesting and disposal of algae, and so forth. Many of these operations have heavy environmental impact, alter ecosystems and are often conducted without studies sufficient to predict their effects. They also involve onerous maintenance that communities do not always manage to carry out correctly and on time. Hence many of these measures very soon become vain and the water body lapses back into a state of degradation.

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