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Review

Environmental impacts of dredging and other sediment disturbances on corals: A review

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ABSTRACT

A review of published literature on the sensitivity of corals to turbidity and sedimentation is presented, with an emphasis on the effects of dredging. The risks and severity of impact from dredging (and other sediment disturbances) on corals are primarily related to the intensity, duration and frequency of exposure to increased turbidity and sedimentation. The sensitivity of a coral reef to dredging impacts and its ability to recover depend on the antecedent ecological conditions of the reef, its resilience and the ambient conditions normally experienced. Effects of sediment stress have so far been investigated in 89 coral species (∼10% of all known reef-building corals). Results of these investigations have provided a generic understanding of tolerance levels, response mechanisms, adaptations and threshold levels of corals to the effects of natural and anthropogenic sediment disturbances. Coral polyps undergo stress from high suspended-sediment concentrations and the subsequent effects on light attenuation which affect their algal symbionts. Minimum light requirements of corals range from <1% to as much as 60% of surface irradiance. Reported tolerance limits of coral reef systems for chronic suspended-sediment concentrations range from <10 mg L^{-1} in pristine offshore reef areas to >100 mg L^{-1} in marginal nearshore reefs. Some individual coral species can tolerate short-term exposure (days) to suspended-sediment concentrations as high as 1000 mg L^{-1} while others show mortality after exposure (weeks) to concentrations as low as 30 mg L^{-1}. The duration that corals can survive high turbidities ranges from several days (sensitive species) to at least 5–6 weeks (tolerant species). Increased sedimentation can cause smothering and burial of coral polyps, shading, tissue necrosis and population explosions of bacteria in coral mucus. Fine sediments tend to have greater effects on corals than coarse sediments. Turbidity and sedimentation also reduce the recruitment, survival and settlement of coral larvae. Maximum sedimentation rates that can be tolerated by different corals range from <10 mg cm^{-2} d^{-1} to >400 mg cm^{-2} d^{-1}. The durations that corals can survive high sedimentation rates range from <24 h for sensitive species to a few weeks (>4 weeks of high sedimentation or >14 days complete burial) for very tolerant species. Hypotheses to explain substantial differences in sensitivity between different coral species include the growth form of coral colonies and the size of the coral polyp or calyx. The validity of these hypotheses was tested on the basis of 77 published studies on the effects of turbidity and sedimentation on 89 coral species. The results of this analysis reveal a significant relationship of coral sensitivity to turbidity and sedimentation with growth form, but not with calyx size. Some of the variation in sensitivities reported in the literature may have been caused by differences in the type and particle size of sediments applied in experiments. The ability of many corals (in varying degrees) to actively reject sediment through polyp inflation, mucus production, ciliary and tentacular action (at considerable energetic cost), as well as intraspecific morphological variation and the mobility of free-living mushroom corals, further contribute to the observed differences. Given the wide range of sensitivity levels among coral species and in baseline water quality conditions among reefs, meaningful criteria to limit the extent and turbidity of dredging plumes and their effects on corals will always require site-specific evaluations, taking into account the species assemblage present at the site and the natural variability of local background turbidity and sedimentation.

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1. Introduction

Coastal construction, land reclamation, beach nourishment and port construction, all of which involve dredging, are increasingly required to meet the growing economic and societal demands in the coastal zone worldwide. In tropical regions, many shorelines are not only home to people but also to coral reefs, one of the most biodiverse ecosystems on earth (Hoeksema, 2007). World-wide, ~3 billion people depend more or less directly on coral reefs for a significant part of their livelihood, obtaining their protein needs or other essential commodities (Bryant et al., 1998). Even if not necessarily sustaining human life in many wealthier regions of the world, the economic value of the realised tourism potential of coral reefs can be enormous. For example, three southern Florida counties (Miami-Dade, Broward and Palm Beach) derive ~6 billion dollars annually from reef-oriented tourism and fisheries (Johns et al., 2001). Clearly, coral reefs are a biologically as well as economically valuable resource worth protecting. Unfortunately, coastal construction and dredging is frequently unavoidable in their immediate vicinity (Salvat, 1987).

The excavation, transportation and disposal of soft-bottom material may lead to various adverse impacts on the marine environment, especially when carried out near sensitive habitats such as coral reefs (PIANC, 2010) or seagrass beds (Erftemeijer and Lewis, 2006). Physical removal of substratum and associated biota from the seabed, and burial due to subsequent deposition of material are the most likely direct effects of dredging and reclamation projects (Newell et al., 1998; Thrush and Dayton, 2002). Dredging activities often disturb sediments reducing visibility and smothering reef organisms (Dodge and Vaisnys, 1977; Bak, 1978; Sheppard, 1980; Fortes, 2001). Coastal engineers and conservation officials need to balance the needs of a healthy economy, of which construction and dredging are often an integral part, with those of a healthy environment. Managing these potentially conflicting priorities can at times be a formidable challenge, particularly where coral reefs are concerned (Smith et al., 2007).

In many cases, dredging operations have contributed to the loss of coral reef habitats, either directly due to the removal or burial of reefs, or indirectly as a consequence of lethal or sublethal stress to corals caused by elevated turbidity and sedimentation. Dredging activities potentially affect not only the site itself, but also surrounding areas, through a large number of impact vectors (e.g. turbid plumes, sedimentation, resuspension, release of contaminants, and bathymetric changes) (Wolanski and Gibbs, 1992). Effects can be immediate or develop over a longer time frame and they may be temporary or permanent in nature. Some coral species appear to be more sensitive than others to increases in turbidity or sedimentation that are commonly associated with dredging operations. Their responses to such increases may depend on typical local conditions and vary between seasons. In general, the impact from dredging on corals and coral reef ecosystems is complex and far from fully understood. Yet there is an extensive body of experience to learn from. This experience lies with dredging contractors, in assessment reports, in monitoring data and in scientific literature derived from field-based and laboratory studies.

In this review we examine the environmental impacts of dredging on corals. We outline the type and level of dredging operations near coral reefs; provide an overview of the general impacts of sediment disturbances on corals; examine the current state of knowledge regarding sensitivity among and within coral species, tolerance limits and critical thresholds; and, finally, discuss mitigating factors and the potential for recovery. Where appropriate, these findings are illustrated with case studies. The focus of this review is limited to the effects of dredging on corals. The nomenclature of the coral species discussed in this review has been updated according to the most recent taxonomic revisions. The effects of dredging on other reef-associated organisms were not considered, except those depending on corals as specific host organisms. A similar analysis for seagrasses can be found in Erftemeijer and Lewis (2006). Information sources for the review included peer-reviewed scientific literature, "grey" literature in the form of environmental impact assessments, consultancy and technical reports, and additional information obtained from members of Working Group 15 of the Environmental Commission of the World Association for Waterborne Transport Infrastructure (PIANC, 2010). While the emphasis of this review is on the impacts of dredging, the findings and implications presented here are equally applicable to other sediment disturbances as sources of elevated turbidity or sedimentation (rivers, natural resuspension, flood plumes, bottom-trawling, etc.).

2. Dredging near coral reefs

An overview of 35 selected case studies of documented dredging operations in, near or around coral reef areas is presented in Table 1, which provides an indication of the scale and type of impact that dredging operations can have on corals and coral reefs. Undoubtedly, there are many more cases of coral damage associated with dredging operations worldwide, some of which are reported in confidential documents or in local languages, to which access is limited. Many of the historical dredging operations and port developments near coral reefs have never been documented and effects on corals were rarely quantified. The actual scale of dredging damage to coral reefs worldwide can therefore be assumed to be much greater than the available literature may suggest. Not all dredging projects near coral reefs lead to mortality of corals and not all observed changes in coral health in the immediate vicinity of dredging sites are necessarily the result of dredging-induced turbidity. Indeed, distinguishing the effects of anthropogenic disturbances from natural dynamics in the marine environment can be a challenge and calls for an appropriate monitoring design (Underwood, 2000; Stoddart et al., 2005). Nevertheless, the cumulative effects of dredging, filling and other coastal construction activities in coral reef environments have collectively resulted in major adverse ecological impacts on many reefs (Maragos, 1993).

Coral reefs are generally recognised as biogenic structures, but it is rarely appreciated that over half of the material in most coral reef complexes is actually made up of sediments (Hubbard et al., 1990; Dudley, 2003). Over 90% of the sediments on most coral reefs consist of carbonate (aragonite, high-magnesium calcite and calcite) produced by the growth and subsequent destruction of reef organisms as well as pre-existing reef rock through physical, chemical and biological erosion processes. Only on nearshore fringing reefs do silicate mineral grains from weathered and eroded igneous or metamorphic rocks (terrigenous sediments) constitute a significant part of the sedimentary material (Dudley, 2003). With time, the skeletons of primary and secondary reef organisms and loose sediments may be changed into a firm sedimentary rock (reef rock) and eventually into a dense solid limestone through consolidation of reef material, binding, cementation and diagenesis (Hubbard et al., 1990; Dudley, 2003). Levels of sedimentation in coral reef environments can vary substantially over spatial and temporal scales, often by several orders of magnitude within kilometres and weeks (Wolanski et al., 2005). Sedimentation is usually highest on inshore reefs and sheltered, wave-protected parts of reef systems, and decreases with distance from shore and with increasing exposure to wave energy (Wolanski et al., 2005).

Due to their geotechnical nature, limestone and coral materials tend to break when dredged and/or transported hydraulically

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