Marine Pollution Bulletin 66 (2013) 105–116

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Novel observations of benthic enrichment in contrasting flow regimes with implications for marine farm monitoring and management

Nigel B. Keeley [a,b,*], Barrie M. Forrest [a], Catriona K. Macleod [b]

[a] *Cawthron Institute, Nelson 7010, New Zealand*
[b] *Tasmanian Aquaculture and Fisheries Institute, University of Tasmania, Taroona, Tasmania, Australia*

ARTICLE INFO

Keywords:
Salmon
Aquaculture
Environmental impact
Macrofauna
Sulfide
Pearson–Rosenberg model

ABSTRACT

We examine macrofaunal and physico-chemical responses to organic enrichment beneath salmon farms in contrasting flow environments, and reveal pronounced flow-related differences in the magnitude and spatial extent of effects. Total macrofaunal abundances at high flow sites were nearly an order of magnitude greater than at comparable low flow sites, representing a significant benthic biomass. These very high abundances occurred in conjunction with moderate-to-high species richness, and were evident in the absence of appreciable organic matter accumulation. Biological responses to increasing sulfide were variable; however a significant biological threshold was evident at 1500 μM. Macrofaunal responses at high flow sites differed substantially from the Pearson–Rosenberg model. The atypical ecological conditions were attributed to (i) limited accumulation of fine sediments, (ii) maintenance of aerobic conditions in near-surface sediments, and (iii) an abundant food supply. Thus, enhanced resilience to organic waste at well-flushed sites appears related to both biological and physical processes.

1. Introduction

Numerous studies have used environmental indicators to characterise benthic soft-sediment enrichment and disturbance gradients associated with marine point source discharges, such as ocean outfalls (e.g., Cardell et al., 1999), terrestrial inputs via rivers (e.g., Hermand et al., 2008; Labrune et al., 2012), oil fields (e.g., Olsgard et al., 1997) and aquaculture (e.g., Kalantzi and Karakassis, 2006). An understanding of how environmental indicators relate to each other, change in response to increasing enrichment, and compare in different soft-sediment habitats is critical to interpreting these assessments (Keeley et al., 2012a). Biotic indices, in-particular, are increasingly used to guide assessments of environmental quality status (Borja et al., 2009b; Dauvin et al., 2012; Llanso and Dauer, 2002; Ranasinghe et al., 2007); but the performance of such indices assumes comparable biological responses across different environments.

Pearson and Rosenberg (1978) provided a comprehensive assessment of benthic enrichment responses for soft-sediment macrofauna, which has become the foundation for many biotic indices, and the paradigm against which subsequent studies have been compared. An important contribution of the Pearson and Rosenberg study was the definition of species/abundance/biomass (hereafter referred to as 'SNB') curves characterising macrofaunal responses to organic inputs (often termed the Pearson–Rosenberg model, or 'PRM'). Although the PRM has been shown to be widely applicable (Heip, 1995), significant deviations have been identified under certain conditions. For example, Maurer et al. (1993) identified major departures from the model in terms of how SNB curves responded in high energy/erosional habitats. In that instance, unusually sharp declines in SNB were observed toward azoic conditions and a proliferation of opportunistic species did not necessarily preclude rare species. Deviations from the model were also identified by Brooks et al. (2004), who described a site that appeared to lack the typical proliferation of opportunists under highly enriched conditions.

Sea-cage fish farms provide excellent case study systems for further evaluating enrichment effects and the general applicability of the PRM, as deposition of particulate organic matter in the form of faeces and waste feed can lead to pronounced gradients in benthic responses across small spatial scales. Typically, near-azoic conditions beneath fish farms progressively decrease in impact with distance from the cages, and natural conditions are usually achieved within 100–200 m (Brooks et al., 2002; Forrest et al., 2007; Giles, 2008). The severity and spatial extent of effects is thought to be strongly influenced by current speed, whereby stronger currents aid dispersal, limit settlement of organic rich biodeposits (Cromey et al., 2002a; Giles et al., 2009) and promote oxygen flux to the sediments (Findlay and Watling, 1997). Current speed also strongly influences abiotic properties, such as sediment grain size and compaction, which in turn, can also influence benthic biodiversity (McArthur et al., 2010).

* Corresponding author at: Cawthron Institute, Nelson 7010, New Zealand. Tel.: +64 3 5393257; fax: +64 3 5469464.
E-mail address: nigel.keeley@cawthron.org.nz (N.B. Keeley).

0025-326X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2012.10.024

Deep sites with strong water current flows are generally perceived to be relatively resilient to organic discharges (Borja et al., 2009a; Frid and Mercer, 1989; Hartstein and Rowden, 2004), although given sufficient organic inputs, the macrofauna beneath fish cages in high flow environments can nonetheless become highly modified (e.g., Keeley et al., 2012a; Macleod et al., 2007). However, in some instances effects on the macrofauna at high flow sites may be poorly reflected by commonly used physico-chemical indicators, such as total organic matter (Aguado-Gimenez and Garcia-Garcia, 2004; Aguado-Gimenez et al., 2007; Keeley et al., 2012a). Hence, water flow may not only influence macrofaunal SNB responses, but also the relative enrichment responses of macrofaunal versus physico-chemical indicators. Such possibilities have important ramifications for the application of established environmental indicators and biotic indices, and the extent to which they can be used to make inferences regarding ecological quality status (Aguado-Gimenez et al., 2007; Keeley et al., 2012a). For example, some biogeochemical parameters (total free sulfides and redox) are increasingly being promoted as key indicators to classify benthic enrichment gradients associated with finfish farms; most recently as a component of the World Wildlife Fund's global aquaculture standards (WWF, 2012). While such approaches are relatively inexpensive and have appeal for their simplicity, it is important that these and other physico-chemical indicators accurately reflect biological responses. Unfortunately, this is difficult to gauge from the existing literature, as very few studies have compared the responses of a common suite of indicators across different flow regimes.

In this paper we extend the work of Keeley et al. (2012a), which identified some flow-specific and regional inconsistencies with a range of benthic environmental indicators, by more closely examining macrofaunal responses to enrichment. In particular, we examine the relationships among and between biological and physico-chemical indicators (e.g. total free sulfide), and compare SNB trends under different flow regimes against the classical responses that characterise the PRM. We then review these findings and their relevance to our current understanding of successional responses along enrichment gradients in different flow environments, identifying the strengths and limitations of different environmental indicators for monitoring. Finally, we consider the implications of our findings for site selection in the context of sea-cage fish farming, and for subsequent assessment and monitoring of benthic effects.

2. Methods

2.1. The study sites and dataset

The data used in this assessment were extracted from a 14 year annual monitoring data set from six study sites, comprising salmon farms aged between 1 and 26 years (Farms A–F, Table 1), located within the Marlborough Sounds, New Zealand (Fig. 1). All of the farms were fixed in position (with only minor adjustments) and operated relatively consistently throughout, with the exception of Farm-D, which was retired in 2001 and reinstated to full capacity in late 2008. The farms were situated in water depths of 27–40 m, and grouped according to their hydrodynamic properties; two of the farms (Farms E and F) had considerably greater current velocities (>15 cm s^{-1}, average at ~20 m depth) than the other four (<9 cm s^{-1}), and were designated as "high flow" and "low flow" groups, respectively. This *a priori* grouping is based on the critical resuspension velocity threshold for farm-derived organic particulates of 9.5 cm s^{-1} recommended by Cromey et al. (2002b) for use in depositional models. This threshold might therefore be expected to have an important bearing on the severity and spatial scale of benthic enrichment effects. The water current data defining the high and low flow regimes were obtained from 28 to 40 day current meter deployments at each site (SonTek™ 1 MHz Acoustic Doppler Profiler), which recorded current speeds averaged over 3 min at intervals of 15, 30 or 45 min. Stations for sampling sediment macrofauna and physico-chemical properties at each site included two beneath cage stations, two or three stations at increasing distances away from the cages (out to 250 m) and a reference station (>1 km away, Table 1). All of the sampling stations were situated over unconsolidated sediments, with low flow sites tending to sandy-mud, and high flow sites tending to muddy-sand according to the standard sediment textural classifications of Folk (1954) (Table 1).

Analyses were conducted on three subsets of the data, as not all parameters were measured consistently throughout the entire sampling period. The first dataset (Dataset 1) combined the information from all the sites over 17 different surveys spanning 9 years (2001–2009). Dataset 1 included feed usage (Feed, total metric tonnes for 6 months prior to sampling) and covered a range of feed input levels (1640–4120 tonnes yr^{-1}) to represent potential extremes in enrichment levels. The farm information also included farm age at sampling (Age, years), and average current speed at ~20 m water depth (Current, cm s^{-1}). The information specific to each sample station included: water depth (Depth, m), site distance from farm (Distance, m), sediment grain size distribution (presented as %Mud), percent organic matter (%OM, measured as % ash free dry weight w/w; Luczak et al., 1997), and a detailed breakdown of the infaunal community structure. All sediment sampling was conducted using a boat-operated Van-Veen grab, with macrofauna collected by sub-sampling with a 13 cm diameter core (sample size: 0.0132 m^2, by 10 cm deep) and sieving to 0.5 mm. Macrofauna were sorted and enumerated to the lowest practicable level and their abundances (hereafter denoted *N*) recorded. We use 'N^*' in places to denote total abundance exclusive of opportunistic taxa; defined in this instance as those species previously classified as first-order opportunists (i.e. Eco-Group V) according to Borja et al. (2000). Sediment grain size and %OM measures were based on sub-samples taken from the grab with a 5.5 cm diameter Perspex core, from which the surface 30 mm was retained for later analysis. Qualitative information was also obtained in the field at each sampling site of sediment odour (H_2S, Odour), bacteria mat coverage (*Beggiatoa*) and sediment out-gassing using pre-specified categories (Keeley et al., 2012b). Results from Dataset 1 were analysed using average values from duplicate or triplicate samples.

The second data set (Dataset 2) comprised environmental information from the same sites over the years 2009–2011 and included the same variables as in Dataset 1, with the addition of total free sulfide (TFS, μM) and redox potential (Eh_{NEH}, mV) (Table 1), and was analysed at the replicate level. Redox was measured directly from the grab (at 1 cm depth) using a Thermo Scientific combination Redox/ORP electrode. TFS was sampled with a cut-off 5-cc plastic syringe driven vertically into the surface sediments (0–4.5 cm depth interval), and the TFS contents were extracted and quantified following the methods of Wildish et al. (1999). The third dataset comprised a detailed gravimetric analysis of macrofauna collected in May and November 2011 from all sample sites (cage through to reference) at each of the six farms (Table 1). In this instance, after taxonomic analysis, the dry weight of the whole macrofaunal sample from each site was obtained by drying the samples on pre-weighed GFC filters (60 °C for 24 h), and then re-weighing on a digital balance (to 4 d.p.). For samples that had exceptionally high densities of nematode and capitellid worms, total dry weight estimates were made from sub-samples. Individual nematodes and capitellids were also separated, counted and weighed from a cross-section of samples, to obtain estimates of their average biomasses.