

Viewpoint

The Estuarine Quality Paradox, Environmental Homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas

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Abstract

Estuaries have long been regarded as environmentally naturally stressed areas because of the high degree of variability in their physico-chemical characteristics, for example oxygen, temperature and salinity in the water column and bed sediment dynamics. However, their biota is well-adapted to cope with that stress and so the areas may be regarded as resilient because of that inherent variability; their ability to absorb stress without adverse effects is regarded here as *Environmental Homeostasis*. Hence these areas may only be regarded as stressful for marine or freshwater-adapted organisms and that for estuarine organisms this environmental stress is regarded as a subsidy whereby they successfully capitalise on the stressful conditions. In addition, using examples of the estuarine fauna and flora, this article indicates that the characteristics of natural stress in estuaries are similar to those for anthropogenic stress. An over-reliance on ecosystem structural features, such as diversity, in quality indicators therefore makes the detection of the anthropogenic stress more difficult. This difficulty is termed the *Estuarine Quality Paradox*. Because of these difficulties, the article argues that functional characteristics either as well as or rather than structural ones should be used in detecting environmental perturbations in estuaries.

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Keywords: Estuarine Quality Paradox; Environmental Homeostasis; Estuaries; Stress; Resilience; Benthos; Biodiversity-ecosystem functioning

1. Introduction

As the recent article in this journal by Dauvin (2007) attributed the phrase '*Estuarine Quality Paradox*' to the first author here, this paper attempts to explain the concept and at the same time put it into context of the way in which we derive indicators of change (e.g. see papers in the Marine Pollution Bulletin issue dedicated to the implementation of the Water Framework Directive, vol. 55, 2007). Here we examine the central thesis that estuaries are naturally stressed, highly variable ecosystems and at the same time they are exposed to high degrees of anthropogenic stress. In particular, we describe the similarity between the features of organisms and assemblages in both estuaries and anthropogenically-stressed areas and hence the difficulty of distinguishing natural from human-induced stress

in estuaries – this is what is termed here the *Estuarine Quality Paradox*. The features of coping with stress, whether natural or anthropogenic, relate to both areas.

Most texts automatically consider estuaries as stressed ecosystems because of their highly variable salinities which are also, by definition, usually lower than the adjacent coastal areas (Elliott and McLusky, 2002; McLusky and Elliott, 2007). The other physico-chemical elements such as current speed and direction, temperature, nutrient levels, pH, etc are also more variable than in corresponding coastal and marine sites and so it is assumed that this also contributes to stress on the biota. Although the estuarine fauna and flora has freshwater elements, such as tubificid oligochaetes, which are of course able to tolerate very low salinities but are stressed by any salinity greater than 0.5, most estuarine biota are marine-derivatives in which the assumption is that therefore they will be stressed in salinities below 30. It is assumed that typical estuarine species, i.e. those such as tubificid oligochaetes and certain

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neriid polychaetes which occur mainly in estuaries, will not be stressed by variable salinity.

2. Anthropogenically and naturally stressed areas

Faunal and floral community structure, and especially the analysis of soft sediment infaunal benthic communities, has long been the mainstay of environmental impact assessments in the coastal environment (Elliott, 1994). That background knowledge has provided ideal models against which to measure change. For example, the Pearson–Rosenberg paradigm (Pearson and Rosenberg, 1978; Rhoads and Germano, 1986), a well-reported conceptual model, has long formed the basis of approaches and indices used to detect and explain anthropogenic stress, especially that for various forms of organic enrichment. The latter includes many causes of environmental damage such as pulp and paper mill waste, urban sewage, the later stages of oil pollution and organic dredged sediments.

Using the Pearson–Rosenberg model and others, it is possible to identify the features of anthropogenically-stressed benthic infaunal communities, which are well known (Table 1). They are characterized by small organisms, r-strategists and the replacement of k-strategists, high abundances of few species, low diversity and low individual biomass organisms with the potential to produce high biomasses. In addition, they have a high turnover and biological productivity (as shown by an increase in the produc-

tion to average biomass ratio, P/B) and a dominance by oligochaetes and oligochaetiform polychaetes. Furthermore, given the inputs of organic matter (from sewage, etc.) and/or fine sediment, which also accumulates organic matter, in hydrodynamically low energy areas, there is dominance by detritus and deposit feeding organisms in which food rather than space is the limiting factor. Coupled to this, the community is tolerant of adverse environmental conditions such as low oxygen and low and variable salinity, especially where many inputs have a freshwater component. However, it is particularly notable that these are the expected characteristics of many stressed ecosystems not only pertaining to the marine and estuarine environment (Odum, 1969; 1985) (Table 2).

The estuarine stress response does not just apply to the benthic faunal community but also to the floral community (e.g. Wilkinson et al., 2007) as well as to individual (physiological) stress. Polluted estuarine areas, especially those influenced by organic discharges, sewage run-off and industrial effluent become dominated by opportunistic green algae, occasionally forming mats. Large concentrations of ephemeral green filamentous algae are naturally occurring in transitional waters bodies which naturally have large nutrient inputs and retain these nutrients (Wilkinson et al., 1995). While estuaries naturally show the transition from a highly diverse marine flora, with many red and brown macroalgae as well as green macroalgae in the outer regions to an upper estuarine algal flora dominated by the

Table 1

Conceptual basis and assumptions inherent in macrobenthic impact studies (modified and expanded from McManus and Pauly, 1990; Warwick, 1986)

(A) Natural state

- (1) A natural macrobenthic assemblage either tends towards or is in an equilibrium state
- (2) Under non-impacted conditions, there are well-defined relationships (which therefore may be modelled) between faunal and environmental (abiotic) variables
- (3) In approaching the normal equilibrium state, the biomass becomes dominated by a few species characterised by low abundance but large individual size and weight
- (4) Numerical dominance is of species with moderately small individuals, this produces among the species a more even distribution of abundance than biomass
- (5) The species are predominantly k-selected strategists

(B) Moderate pollution

- (6) With moderate pollution (stress), the larger (biomass) dominants are eliminated, thus producing a greater similarity in evenness in terms of abundance and biomass
- (7) Also with moderate pollution, diversity may increase temporarily through the influx of transition species

(C) Severe pollution

- (8) Under severe pollution or disturbance, communities become numerically dominated by a few species with very small individuals
- (9) Those small individuals are often of opportunist, pollution-tolerant species which have r-selected strategies
- (10) Under severe pollution, any large species that remain will contribute proportionally more to the total biomass relative to their abundance than will the numerical dominants
- (11) Thus under severe pollution, the biomass may be more evenly distributed among species than is abundance
- (12) However, under severe pollution, species with large individuals may be so rare as to be not taken with normal sampling
- (13) The change in assemblage structure with increasing disturbance is predictable, follows the conceptual models and is amenable to modelling and significance testing

(D) Recovery

- (14) Opportunists are inherently poor competitors and may thus be out-competed by transition species and k-strategists if conditions improve

McManus and Pauly (1990) also consider that under normal conditions:

- (1) The biomass-dominants will approach a state of equilibrium with available resources
- (2) The smaller species are out of equilibrium with available resources
- (3) The abundances of the smaller species are subject to more stochastically controlled variation than the larger species

Table 2
Trends expected in stressed ecosystems: the estuarine features as applied to topics summarised by Odum (1985)

Feature	Odum (1985)	Estuarine feature	
Energetics	(1) Community respiration increases	Yes, in general	Higher respiration in larger populations of small organisms and organic rich sediments; possibly with osmoregulatory stress caused by salinity change
	(2) <i>P/R</i> (Production/respiration) becomes unbalanced	Unknown	Possibly due to higher respiration caused by salinity stress
	(3) <i>P/B</i> and <i>R/B</i> (maintenance: biomass structure) increase	Yes, in general	Higher <i>P/B</i> in smaller and shorter lived organisms, e.g. dominance by oligochaetes and small polychaetes; high turnover by organisms
	(4) Importance of auxiliary energy increases	Depends on meaning	Increase in allochthonous energy input as well as relatively high autochthonous production
	(5) Exported or unused primary production increases	Depends on meaning	Export of material to adjacent sea areas but also import from catchment
Nutrient cycling	(6) Nutrient turnover increases	Yes, but	because of physical characteristics – high nutrient inputs and use
	(7) Horizontal transport increases and vertical cycling of nutrients decreases (cycling index decreases)	Partly the case	Both horizontal and vertical cycling is high, depending on flushing characteristics and residence time; importance of material movement from pelagic to benthic system
	(8) Nutrient loss increases	Yes, but	because of the physical characteristics – high nutrient loss through flushing and export through predators
Community structure	(9) Proportion of r-strategists increases	Yes	High abundances of few, short-lived stress-tolerant species
	(10) Size of organisms decreases	Yes	High abundances of small organisms dominant in benthos; low megafaunal populations
	(11) Lifespan of organisms decreases	Yes, in general	On average, benthic and planktonic community composed of short-lived organisms; planktonic organisms adapted to prevent flushing of populations
	(12) Food chains shorten because of reduced energy flow at higher trophic levels and/or greater sensitivity of predators to stress	Not necessarily	Food chains can be very short (macrophytes-herbivorous ducks) but also very long because of the opportunistic nature of many predators; while marine predators (stenohaline marine fishes) may be reduced there are many other fish and bird predators
	(13) Species diversity decreases and dominance increases; if original diversity is low, the reverse may occur; at the ecosystem level, redundancy of parallel processes theoretically declines	Yes (first part); unknown (second part)	Classic estuarine community in all components of few species; exacerbated with distance landward in the estuary; competition between species may be less than competition within species
General system-level trends	(14) Ecosystem becomes more open (i.e. input and output environments become more important as internal cycling is reduced)	Not necessarily so	Internal cycling is important even though nutrients and organic matter are delivered from external sources
	(15) Autogenic successional trends reverse (succession reverts to earlier stages)	Unknown	
	(16) Efficiency of resource use decreases	Not necessarily so	While there may be an excess of organic resources, leading to export, much is used within the system to support high predator populations
	(17) Parasitism and other negative interactions increase, and mutualism and other positive interactions decrease	Not shown	
	(18) Functional properties (e.g. community metabolism) are more robust (homeostatic-resistant to stressors) than are species composition and other structural properties	Yes	Ability of the system to withstand stressor-effects without adverse impacts

Chlorophyceae, under high organic and nutrient loading the features produce macroalgal mats with the latter often displacing seagrass beds (de Jonge and Elliott, 2002).

Not only is such an estuarine stress detected at the community level but also at the physiological level of biological organisation. Methods such as scope-for-growth (SFG) have long been used to good effect as an indication of anthropogenic stress in marine and estuarine areas (e.g. Widdows and Johnson, 1988). However, Navarro (1988) and Guerin and Stickle (1992) both indicate the way in

which salinity stress, through natural freshwater inputs, reduces energetic budgets. Therefore as SFG will detect a reduction in physiological fitness due to salinity stress, there is the difficulty in using the technique for detecting and separating anthropogenic stress from natural stress.

Methods for detecting anthropogenic stress include those centred on the primary community structural variables (abundance, species richness and biomass) and derived community structural variables (such as diversity indices, abundance (A/S) and biomass (B/A) ratios, evenness indices) (see

Quintino et al., 2006; Weisberg et al., 1997; McLusky and Elliott, 2004 for references and details). They also include functional analyses such as those involving feeding guilds (as in the Infaunal Trophic Index, ITI, by Word, 1990) and their responses to elevated organic levels (as in the AZTI Marine Biotic Index, AMBI, by Borja et al., 2000; and the Benthic Quality Index, BQI, by Rosenberg et al., 2004; amongst others). For example, detritus and deposit feeding dominance is reflected in any assessment of trophic status. As indicated in many reviews, there are well-defined numerical methods which aim to detect and reflect stress in benthic communities. For example: Species–Abundance–Biomass curves (Pearson and Rosenberg, 1978), Abundance–Biomass–Comparisons (Warwick, 1986), the AMBI and diversity indices etc. (e.g. Borja et al., 2007; Rosenberg et al., 2004). Given the assessment above, however, the main problem is that these methods detect naturally as well as anthropogenically stressed areas thus decreasing the ability of detecting and maximising the signal (anthropogenic change) to noise (natural change) ratio.

Now let us turn to the natural (non-anthropogenic) characteristics of estuaries, and many other transitional waters – in brief these are characterised of course by freshwater inputs leading to a reduction in salinity, high organic production and organic inputs from the adjoining catchment and wetlands, a low diversity of all components but often high abundances of those species which can tolerate the variable and (assumed to be) environmentally stressful conditions (e.g. McLusky and Elliott, 2004, 2007). As indicated in Tables 1 and 2, the features of anthropogenic stress coincide with those for natural stress. Therefore there is a problem (the ‘*Estuarine Quality Paradox*’) when attempting to determine the effects of human activities in estuaries and other highly variable but organically-enriched transitional waters: the estuarine benthic communities have many of the same characteristics as areas suffering from human-induced stress. This is especially the case in the mid to upper estuarine regions which receive organic matter from natural autochthonous and allochthonous sources and where the Freshwater–Seawater Interface has highly variable and thus naturally stressful conditions.

In having the characteristics described above, it is questioned whether the estuarine community is a climax one or whether it is just held at a sub-climax level. The estuarine fauna and flora do not show recovery to maintain a full k-strategist complement, large individuals (both fauna and flora) are not present, hence there is a naturally lower biomass/abundance ratio and higher abundance/species richness ratio, and the trophic system is dominated by organic/detritus-responsive invertebrates and nutrient-reflecting algae.

3. The Estuarine Quality Paradox

These features, in particular the difficulty of separating natural and anthropogenic stress in estuaries, have given rise to the suggestion of the ‘*Estuarine Quality Paradox*’.

It is suggested here for further exploration and analysis but may be defined as the following feature: *that the dominant estuarine faunal and floral community is adapted to and reflects high spatial and temporal variability in naturally highly stressed areas but that it (the community) has features very similar to those found in anthropogenically-stressed areas thus making it difficult to detect anthropogenically-induced stress in estuaries. Furthermore, as estuaries are naturally organically-rich areas then the biota has similarities to anthropogenically-organic rich areas. Because of this, there is the danger that any indices which are based on those features and used to plan environmental improvements are flawed.*

The Estuarine Quality Paradox has repercussions for the implementation of all environmental management systems which all rely on an ability to detect a change in estuarine flora and fauna from a defined reference condition. These systems include the European Union Water Framework Directive (Borja et al., 2000; 2007; Aritz et al., 2006; Breine et al., 2007; Coates et al., 2007), the National Land and Water Resources Audit in Australia (Heap et al., 2001), the Clean Water Act in the US (USEPA, 2002) and the 1998 Water Act in South Africa (Adams et al., 2002).

If this paradox is accepted, by relying on the presumption that estuaries are stressed areas, then we need ways of breaking out of this circle. This leaves two choices – either to fully quantify and explain the natural variability and stress and subtract this from the anthropogenic stress or alternatively by having an alternate set of methods which can detect anthropogenic stress but against a background of natural stress. This requires us to find methods of determining whether an estuary is still functioning as an estuary and hence the recommendation here is to use functional symptoms as well as structural ones (see also de Jonge et al., 2006; Hooper et al., 2005). This is in agreement with Odum (1985), who suggests that functional properties may be more robust than structural ones (de Jonge et al., 2006). However, this is in contrast to the recommendations in management systems such as the EU Water Framework Directive, which relies heavily on structural features such as taxonomic richness, diversity and abundance, and so it is likely that we will need one set of methods for the open coast and another for the estuaries.

4. Estuarine resilience, Environmental Homeostasis and the Stress-Subsidy Continuum

Margalef (1981), in thinking more about physiological response, considered that stress leads to organisms implementing homeostasis as a mechanism to withstand the stress (see also Costanza et al., 1992). More simply, Odum (1985) regarded stress as a detrimental or disorganising influence and, more recently, in discussing the effects of pollutants, it has been regarded as a reduction in the fitness-for-survival (McLusky and Elliott, 2004). The ability of the level of biological organisation, be it at the individual, population, community or ecosystem, to withstand/

tolerate/adjust/adapt to stressors is homeostasis. Thus homeostasis in this context is the ability of the estuary to achieve a stable state by compensating for changes in the environment; this may also be regarded as robustness in an ecological context. Hence it is suggested here that the response homeostasis can operate at any level of biological organisation so in addition to physiology homeostasis, we can have population homeostasis, community homeostasis and ecosystem homeostasis. It is hypothesised that in the case of estuaries, the high natural variability may confer an ability to withstand stress, both natural and anthropogenic, thus showing a resilience created by Environmental Homeostasis. Following from the initial discussion here, therefore, within a background of high variability (i.e. noise) then there is an increased difficulty of detecting a signal reflecting anthropogenic change.

However, using Odum's (1985) logic regarding naturally-stressed areas, in estuaries salinity decrease is not a stress but a subsidy (Costanza et al., 1992). If an estuary had such a high level of natural stress, let alone anthropogenic stress, then one would expect it to collapse whereas it does not and therefore exists with that stress. Hence instead of considering estuaries as naturally stressed areas, we should consider the definition of a subsidy rather than a stress, as a perturbation with a positive effect on the system (Costanza et al., 1992). The positive effect here is shown by the ability of organisms which can tolerate the adverse and variable environmental conditions in an estuary to capitalise on the lack of inter-specific competition and thus achieve high population densities. In this way, this ensures the estuarine system is maintained but as a benefit for those species adapted to the inherently variable conditions. In essence, those looking for estuarine indicators of change have to question whether natural stress is occurring in estuaries, in particular whether salinity decrease is a stress or, for a brackish community, the stress is in having no salinity decrease. Thus reduced and highly varying salinity may only be a stress for a marine-dominated or marine-derived estuarine community.

The comments here require that estuaries and other transitional waters need further study in order to define and quantify the way in which they respond to human activities. We also need to emphasise that their functioning, such as the ability to support high predator populations of fishes and overwintering birds, does not rely on a high biodiversity *per se*. The biodiversity-ecosystem functioning debate, i.e. that a high diversity is required for successful functioning and vice versa, seems to be well developed and agreed for terrestrial, freshwater and microbial systems (e.g. Loreau et al., 2002; and papers therein) but little considered for transitional waters. Estuaries and other transitional waters are an anomaly in this in that they function successfully precisely because they have a low biodiversity. This means that analyses of ecosystem structure (which may rely on diversity measures of various types) in relation to human impacts are not sufficient and so ecosystem function has to be given more importance. This then has to be

incorporated into the conceptual models, such as by Costanza and Mageau (1999) which aim to assess estuarine ecosystem vigour (based on function) together with organisation (i.e. structure).

In conclusion, the discussion of the Estuarine Quality Paradox relies on two main aspects – our decision of what constitutes stress and our ability to detect stress/show stress. Stress can be regarded as a perturbation with a negative effect on an area and thus a pressure which will reduce the ability to survive (and function) of a level of biological organisation (cell, individual, population, community or ecosystem). That stress can be the result of natural or anthropogenic factors and therefore we need to determine the presence of that stress, determine its cause and separate the various influences. If, however, an area is so inherently variable that it is difficult detecting such a change (i.e. a low signal to noise ratio) then this will reduce our ability to detect anthropogenic change. If, however, we regard natural estuarine stress as a subsidy then we have to separate the manifestation of that subsidy (natural estuarine biological characteristics) from the manifestation of stress *per se* (anthropogenic estuarine biological characteristics).

The above feature is regarded here as an example of what Rapport et al. (1985) consider as the subsidy-stress gradient (or more correctly a continuum). The central point here is that whereas in open marine systems it is easier to detect the location of an anthropogenically affected area along that continuum, in estuaries this is much more difficult. Present methods indicate that such a separation is difficult unless the anthropogenic stressor action is severe, such as adjacent to a sewage outfall, fish cage or oil spill area. Hence we have to question whether we are using methods based on false paradigms and how we can break out of this difficulty. For example, the continued use of ecological structural elements instead of a combination of structure and functioning will probably not allow us fully to determine if an area is anthropogenically affected.

Secondly, as indicated here, we have to re-assess whether we regard transitional waters (including estuaries) as naturally environmentally-stressed areas or whether we acknowledge that natural environmental variability only constitutes stress for those organisms not able to tolerate it. Thirdly, we have to further assess estuaries within the framework of the biodiversity-ecosystem functioning debate and consider that, in such transitional habitats, a high biodiversity is not a prerequisite for successful ecosystem functioning. Finally, we have to find ways to test the hypothesis that environmentally variable areas are more able to withstand the effects of anthropogenic perturbations (Environmental Homeostasis) which again makes more difficult the detection of anthropogenic signals against background environmental noise.

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