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Development of a biologically based environmental quality standard from a long-term benthic monitoring programme in the North Sea

Long-term
Monitoring
Benthos
Effluent
EQS

Long terme
Surveillance
Benthos
Effluent
Critère de qualité

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ABSTRACT

The paper describes the derivation and effectiveness of a benthic macrofauna environmental quality standard (EQS). The EQS is derived from a continuing, long-term (24 years) monitoring programme, designed to determine the effect of mining effluent discharged into coastal waters off the NE coast of England.

The area under study is at the Cleveland Potash mine at Boulby. Benthic monitoring began there in 1970 and five years of baseline data were gathered before discharge commenced in 1974. During the course of the monitoring programme (1970-1993) annual surveys have been completed at the discharge point and at more distant reference sites. The complete data set includes results from over 1000 benthic grab samples.

The effect of the discharge is clearly demonstrated by the local benthic community and is primarily a response to the physical smothering of the sea bed by a dense, saline effluent. The long-term monitoring programme has aided the regulation of the Boulby discharge. In 1990 the data was used to derive an EQS based on the benthic community structure in the survey area, as defined by the multi-variate statistical technique MDS. Since the introduction of the EQS, breaches have coincided with increases in insoluble material discharged from the mine. The technique is now established as part of the mechanism by which the UK National Rivers Authority (NRA) regulate this discharge.

RÉSUMÉ

Programme de surveillance à long terme du benthos de la mer du Nord et critère biologique de qualité de l'environnement.

Un critère de qualité de l'environnement de la macrofaune benthique est décrit dans ce travail ; il résulte de la surveillance à long terme (24 ans) des effets d'effluents miniers déversés dans les eaux côtières, au large des côtes NE de l'Angleterre.

La région étudiée est la mine de la potasse Cleveland à Boulby. La surveillance du benthos y a commencé en 1970, cinq ans avant le début des rejets. Le programme de surveillance (1970-1993) a consisté en campagnes annuelles effectuées au point de décharge et sur des sites de référence plus éloignés. Les données portent sur plus de 1000 échantillons de dragages benthiques.

Il apparaît clairement que les rejets dans la communauté benthique locale provoquent d'abord une réaction à l'étouffement physique du lit marin par un effluent dense et salin. Le programme de surveillance à long terme a contribué à réguler les rejets de Boulby ; en 1990 une norme de qualité a été définie par la technique d'analyse statistique multi-variable, à partir des données caractérisant la structure de la faune benthique dans la région étudiée.

Depuis l'introduction de cette norme, les infractions à la règlementation ont coïncidé avec des déversements accrus de matières insolubles en provenance de la mine.
La norme fait partie maintenant de l'approche par laquelle le *National Rivers Authority* (NRA) du Royaume Uni réglemente les rejets.

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INTRODUCTION

Long-term benthic ecological monitoring has been advocated by many to be an efficient and accurate means of determining the effect of pollution on the marine environment (Gray and Christie, 1983; Pearson and Duncan, 1986; Rees *et al.*, 1991). Only after a "long", sustained period of investigation of the receiving environment, can anthropogenic/pollution induced change be differentiated from natural variation (Shillabeer and Tapp, 1990). When this high level of understanding is achieved it should also be possible to accurately predict environmental responses to varying pollution loads and even set "environmentally acceptable" discharge limits. During the setting of these limits there may be a trade off between environmental and industrial and commercial interests.

The release of waste material into the environment may be harmful and it is generally accepted that there will be a "mixing zone" around any release point in which damage may occur (Edwards, 1992). The final decision about how much material may be discharged and therefore the size of the mixing zone rests with the regulator. However, this decision may be facilitated by accurate, predictive information which can be supplied by long-term ecological monitoring programmes.

From 1976 Environmental Quality Standards (EQSs) were introduced throughout the EC for the levels of specific chemical determinands in water (EC Directive 76/464, 1976). These standards were based on toxicological measurements but a better approach may be to use information from ecological monitoring programmes (van de Meent *et al.*, 1990).

The concept of an ecologically based EQS has been the subject of some recent papers (Rees and Pearson, 1992; Cotter and Rees, 1993). This work has involved setting empirical standards for change between "Treatment" and "Reference" sites, based on univariate measures of benthic community structure. However there is evidence to suggest that in certain circumstances, suitable reference stations may not be available and pollution induced change at the treatment site cannot be discerned from the natural background variation (Rees, pers. comm.; Shillabeer, in press). The aim of this paper is to describe how the detailed results of a long term ecological monitoring programme can be used to elucidate the effects of a specific marine discharge and then enable the derivation of an appropriate, ecologically based EQS, using the multi-variate statistical technique Multi Dimensional Scaling or MDS (Field *et al.*, 1982).

The area of study is a 2 km^2 sand patch bounded by rocky outcrops, lying approximately 1 km offshore from a potash mine at Boulby, on the North East coast of England (Fig. 1). The Boulby sand patch annually receives 120,000-170,000 tonnes of insoluble effluent from the mine. The effluent is a dense mixture of saline water and suspended clays (Table 1) and is discharged via a 1.25 km long sea outfall. Despite the alternate use of two specially designed diffusers approximately 150 m apart, the high density and insoluble nature of the effluent leads to a physical smothering of the local sediments by silt clay. The encroachment of insoluble mining waste on the sand patch may be perceived by following the distribution of sediment with high percentages of silt clay, typically <20 %. Another tracer is boron concentration, which is elevated in the particulate mining waste compared to background levels (Table 1). The impact of the Boulby discharge is limited to the Boulby sand patch, beyond which particulate deposition is probably compensated by resuspension and dispersion by tidal currents which have a south east residual drift (Lee and Ramster, 1977).

Table 1

Physico-chemical composition of the Cleveland Potash effluent.

Determinand		Concentration (%)
Brine	NaCl	15-20
	Kcl	2-2.5
Insolubles	Gypsum ($CaSO_4$)	20-35
	Clay and Dolomite ($CaMg(CO_3)_2$	50-70
Boron		× 200 background conc.
pH		6
Density		1.5 kg l^{-1}

The impact of the disposal of similar fine particulate waste, in the form of pulverised fly ash from coal fired power stations along the North East coast, has been demonstrated (Bamber, 1980). The deposition of fine particulate material inevitably alters the natural sedimentary regime. Sediment particle size has been shown to be a limiting factor controlling the nature of sediment fauna communities (Rhoads, 1974), therefore a monitoring programme has been designed to assess the effects of the Boulby discharge on the local sediments and the resident benthic community. The results of this continuing programme span 24 years from 1970 to 1993 and effectively include five years predischarge data.

MATERIALS AND METHODS

A pilot survey was completed at Boulby in 1969 in order to determine a sampling regime for the benthic monitoring programme. Three reference survey areas (R1-3) were also established at this time. Biannual (spring and autumn) monitoring began in 1970 and effluent discharge commenced in 1974. Sampling frequency was reduced in 1990 and since then surveys have been completed annually in the autumn.

The long-term data set and its use in determining the effect of the discharge has already been documented (Craig *et al.*, 1993). Between 1975-1989 there was a general increase in the total annual discharge of insoluble material to the Boulby sand patch (Fig. 2). This caused an increase in the percentage of fine sediment as silt clay, which was accompanied by a reduction in species diversity and abundance and the emergence of an impacted and intermediately impacted benthic fauna zone surrounding the outfalls (Fig. 1).

A total of 17 fauna stations and 93 sediment stations have been regularly sampled at Boulby (Fig. 1). Triplicate fauna/sediment samples were also obtained at each of the three reference areas. The benthic fauna were sampled using a 0.1 m^2 Day grab (Warwick and Davies, 1977). A 21 mm diameter corer was used to subsample the sediment within each grab for particle size analysis by a Malvern 3600E laser particle sizer. The remaining sediment was then washed through a 1 mm mesh sieve and the retained fauna were preserved in a mixture of 4 % formalin in seawater, together with the dye Rose Bengal. The fauna in each sample were described in terms of number of taxa and total number of individuals.

The data analysis described in this paper is complementary to the 1970-1989 data analysis for Boulby (Craig *et al.*, 1993). The abundandance/taxa data for the four annual surveys from 1990-1993 were analysed using the MDS# technique (Field *et al.*, 1982). The data were not truncated to remove rare species nor statistically transformed. The data for 1990 demonstrated a maximum impact associated with a peak discharge and was therefore considered to represent a point of reference with which subsequent annual data sets could be compared.

#MDS adapts the Bray Curtis similarity matrix of the data (Bray and Curtis, 1957) and represents it as a two dimensional plot. Individual stations are marked by a single point on the plot. Small interpoint distances indicate close similarity in fauna type and abundance between stations, whereas stations with dissimilar fauna are placed further apart. Each MDS plot can therefore be used to identify

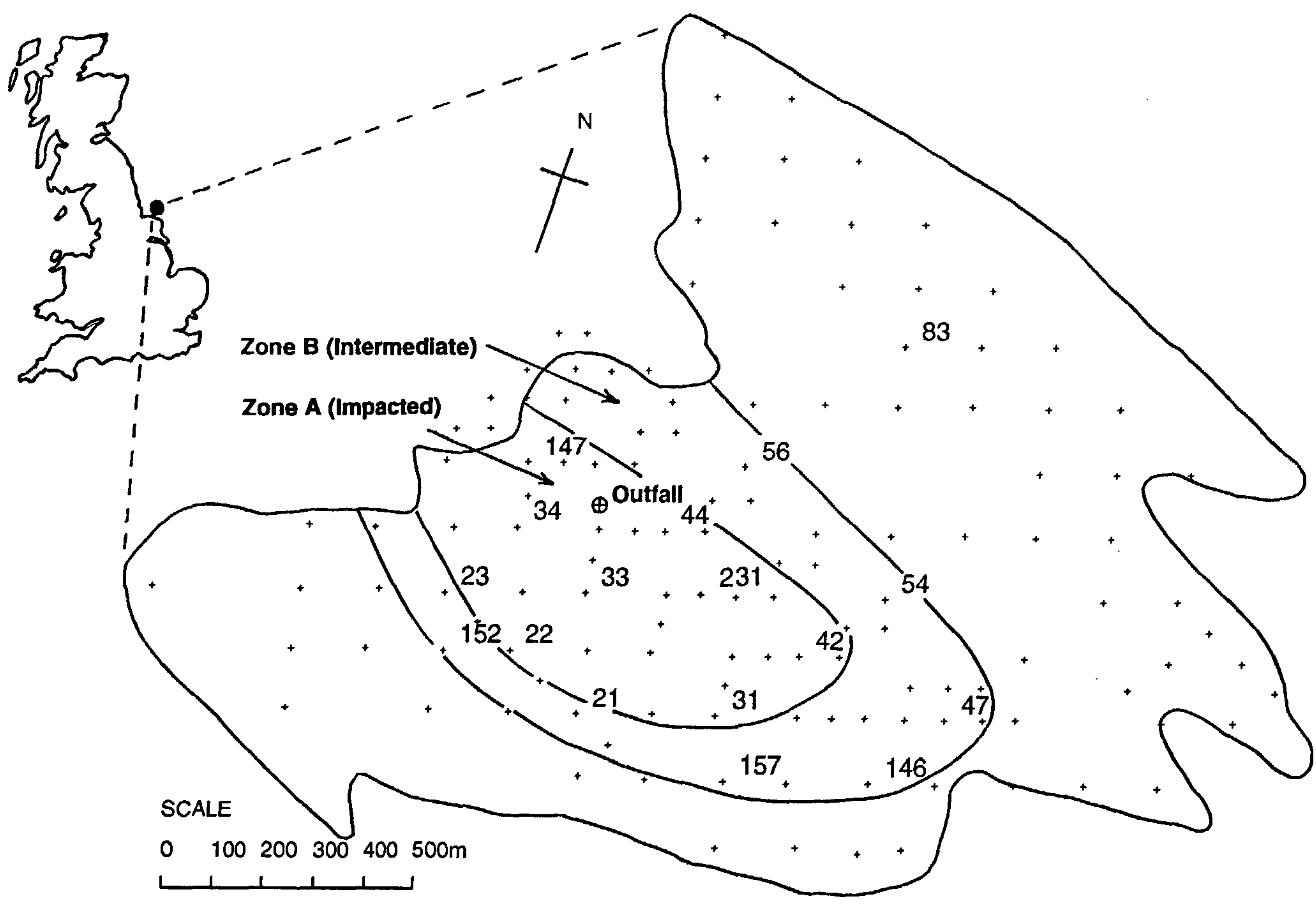

Figure 1

Boulby sand patch sampling stations (fauna stations are numbered, sediment stations are blank).

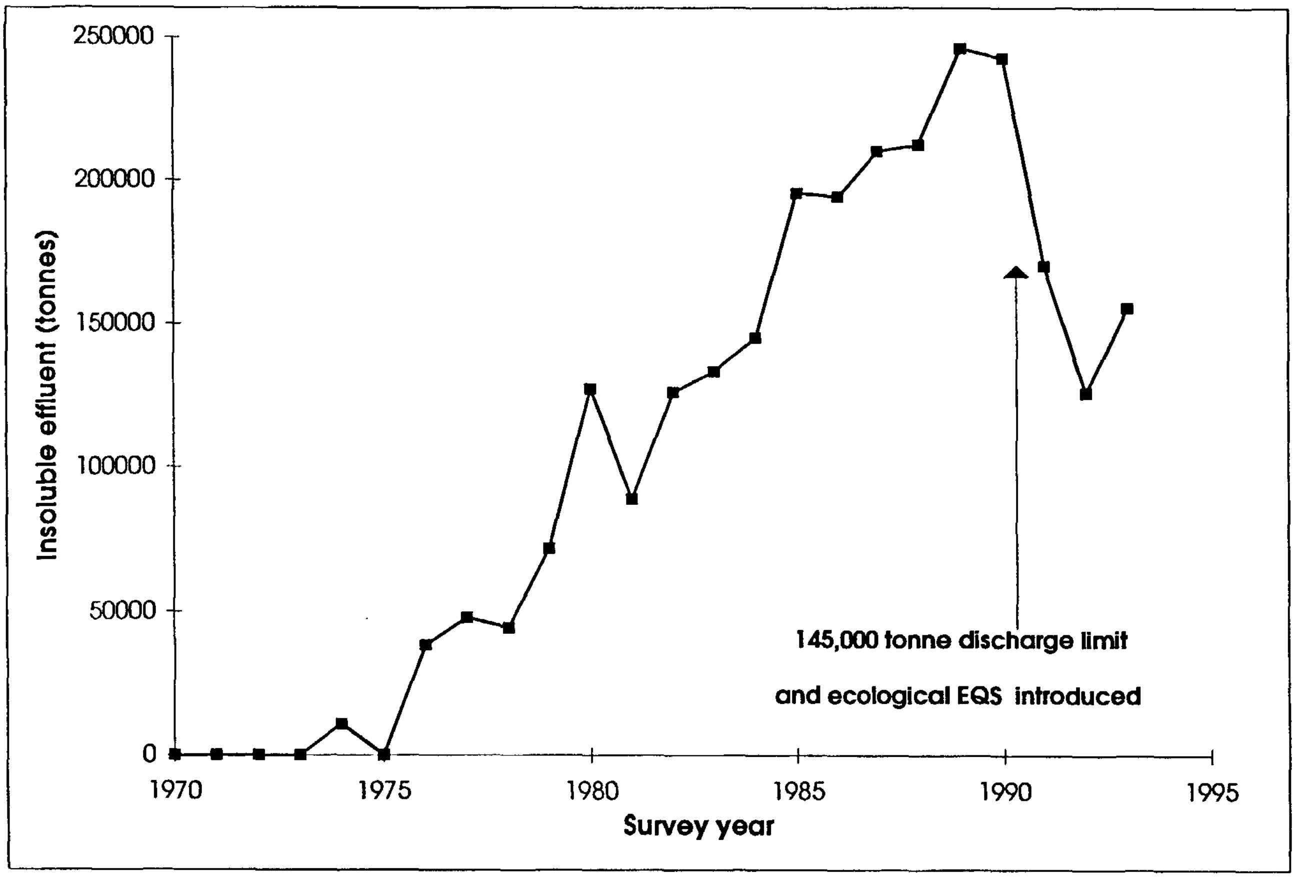

Figure 2

Variation in total insoluble effluent discharged annually between 1970-1993.

distinct fauna zones or groups of stations having similar fauna.

RESULTS

The long-term monitoring of the Boulby discharge 1970-1993 may be divided into three distinct periods. The first period from 1970-1974 represents the baseline situation prior to discharge, when the survey area constituted an undisturbed sand patch with a stable benthic fauna community. The next period 1975-1989 is one in which there was an increase in the annual discharge of insoluble material to the Boulby sand patch from zero to 246,000 tonnes (Fig. 2) [The annual tonnages quoted in this paper are the instantaneous amounts of "insoluble material" upon discharge, as opposed to post discharge values which may be lower by a factor of 0.5-0.6, due to the dissolution of a slowly soluble fraction of the effluent, at the sea bed]. This lead to the smothering of the sediments by silt clay and a reduction in species diversity and abundance in the vicinity of the outfalls themselves (Fig. 3). Between 1990-1993 a change in mining conditions lead to a reduction in the annual discharge to an environmentally acceptable level, as defined by statistical analysis of the long-term ecological data set.

The peak discharges of insoluble material in 1989 and 1990, coupled with an increase in the number of impacted stations surrounding the Boulby outfalls, prompted the National Rivers Authority (NRA) to set an annual discharge limit of 145,000 tonnes of insoluble material. The objective of setting this limit was to permit a recovery of the Boulby ecosystem from a severely impacted condition in 1989-1990. Such an objective is termed the Environmental Quality Objective (EQO) and is achieved by setting an Environmental Quality Standard (EQS). The EQS for the Boulby sand patch (Table 2) was based on the MDS-

Table 2

An ecologically based EQS for the Boulby sand patch.

Part 1) The grouping of any three stations in zone A (impacted) with the grossly affected stations 33 and 147 in two consecutive years is classed as a significant disturbance requiring further action.
Part 2) The grouping of any three stations in the adjacent zone B (intermediately impacted) with zone A stations 23, 31, 42 and 44 in two consecutive years, of the grouping of any other stations with stations 33 and 147 on any other occasion is classed as a significant disturbance requiring further action.

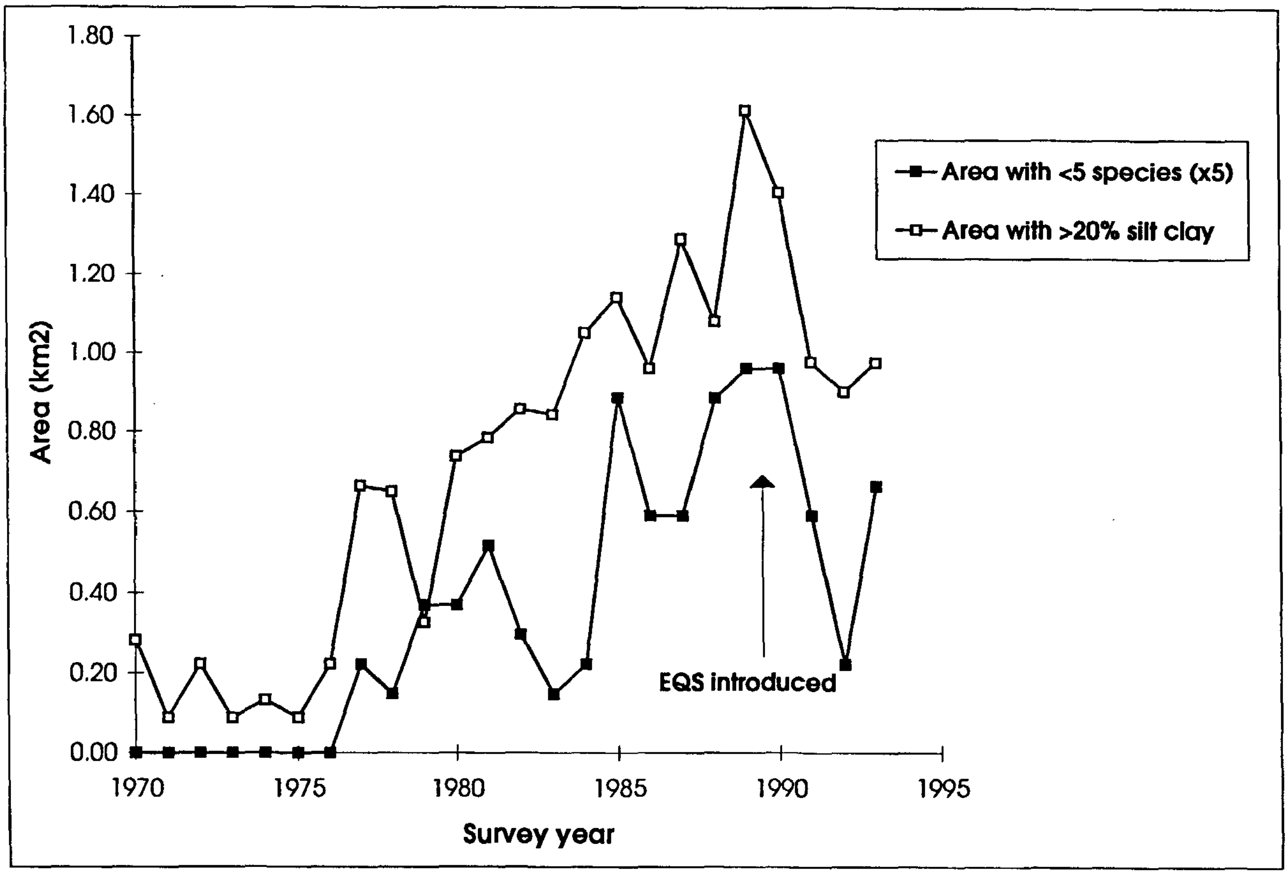

Figure 3

Variation in the area of silty sediment and the area of low fauna diversity Autumn surveys of the Boulby sand patch 1970-1993.

derived fauna groupings from 1990, which represent a significant decline in the resident benthic fauna community. The EQS is divided into two parts, 1 and 2, both of which must be satisfied if the discharge is to comply with it. Part 1 of the EQS defines the critical size of the impacted zone "A", in the immediate vicinity of the discharge, whereas part 2 describes a wider permissable boundary for the intermediately impacted zone "B" (Fig. 1).

The results of the MDS analysis of the benthic fauna data from 1991-1993 provide a means of testing the accuracy and applicability of the Boulby EQS (Fig. 4). During this period there were two occasions in 1991 and 1993, when total annual discharge exceeded 145,000 tonnes and one occasion in 1992 when the discharge complied with this discharge limit (Fig. 2). MDS analysis of the benthic fauna data from 1991 and 1993 demonstrated a significant disturbance of the Boulby fauna community, as defined by the established EQS. The larger impacted areas in 1991 and 1993 are highlighted as distinct groups of stations on the MDS plots (Fig. 4). In 1992 however, the majority of the Boulby fauna community was shown to recover leaving only the outfall stations 33 and 147 and stations 34 and 231 close by, significantly impacted by the discharge.

Appendix 1 contains the details of the MDS-derived fauna groupings from 1991-1993. The average abundances of the top 10-12 taxa per sample were presented for each survey year. A total of six groups have been defined. The first two groups regularly include stations from the three reference areas along with five Boulby stations 21, 22, 23, 152 and 157. These contain similar "background" fauna communities which may be considered to be outside the sphere of influence of the discharge. The fauna is both diverse and abundant, with consistently high numbers of *Magelona mirabilis*, *Venus striatula* and *Tellina fabula* and sporadically high numbers of *Spiophanes bombyx* and *Abra alba*. The last two species are known to exhibit a natural cycle of abundance in this geographical location (Shillabeer and Tapp, 1990). The third group represents the deep water station 83 from the north eastern edge of the Boulby sand patch, which had a diverse fauna, with high numbers of *Nucula turgida*, *Venus striatula* and *Tellina fabula* in 1992 and 1993 and *Abra alba* and *Amphiura sp.* in 1992 only. Group four stations from Boulby are characterised by an intermediate sparse fauna, which were dominated by *Tellina fabula* in 1992 and 1993 and also by *Abra alba* in 1993. Finally the fifth and sixth groups represent intermediately impacted and impacted fauna zones "B" and "A" in the vicinity of the outfalls (Fig. 1). The key, intermediate stations in zone B include 47,54, 56 and 146, while zone A is generally characterised by the impacted stations 34, 44 and 231. The outfall stations 33 and 147, within zone A, are considered to be grossly impacted.

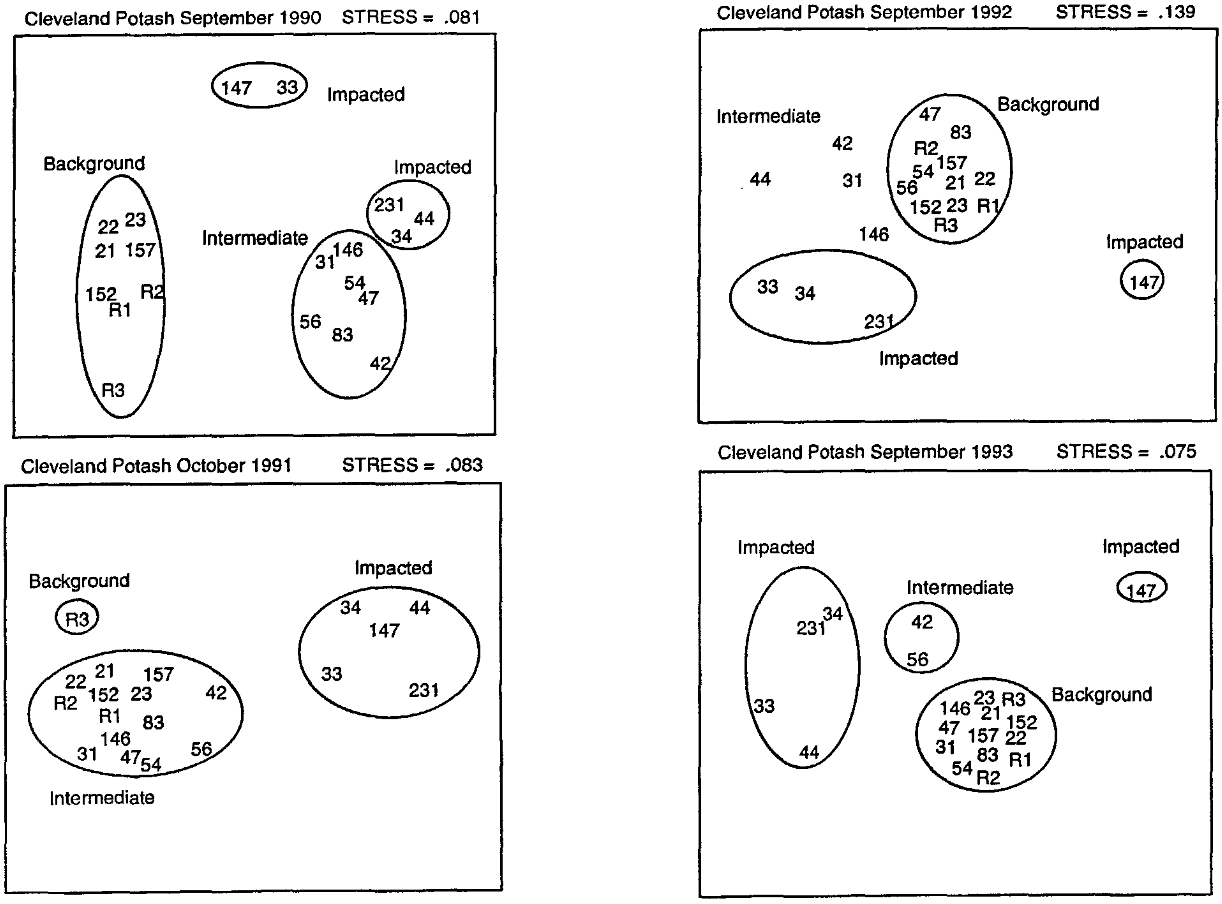

Figure 4

Multi-dimensional scaling plots 1990-1993.

According to parts 1 and 2 of the EQS for Boulby (Table 2), the 1991-1993 results represented in Figure4 can be summarised as follows:

Part 1) In 1991, three zone A stations 34, 44 and 231 were grouped with the outfall stations 33 and 147, because of the sparse nature of their fauna. The same grouping was repeated in 1993 except that outfall station 147 was isolated as a separate group because the sample was completely devoid of fauna, excluding it from the MDS analysis. This represents a significant disturbance of the Boulby fauna community in 1991 and 1993. In 1992 only two zone A stations 34 and 231 grouped with outfall station 33 and station 147 was again empty. Therefore there was no significant disturbance in 1992. NOTE: If the 1993 fauna conditions were to persist in 1994 this would constitute a significant disturbance of the Boulby community requiring further action.

Part 2) In 1991 and 1993 there was no coherent grouping of the representative zone A stations 23, 31, 42 and 44, as there was in 1990. On both occasions, station 23 grouped with the background stations, station 44 was impacted and stations 31 and 42 were intermediately impacted. Therefore the criteria for part 2 of the EQS were not applicable in 1991 and 1993. In 1992 only one station 146 in zone B grouped with zone A stations 31, 42 and 44. The remaining representative zone A station 23 was grouped with the background stations. This is further evidence to support the recovery of the Boulby fauna community in 1992.

DISCUSSION

The principal aims of an ecological monitoring programme include the identification and evaluation of the environmental effects of pollution, with a view to the assessment or control of exposure of pollution to either man or specified organisms (Portmann, 1976). With the advent of ecologically based Environmental Quality Standards these programmes now have the potential for predicting environmental impacts and setting appropriate environmental standards to combat them. These standards should be properly considered because a failure to comply with them may be met by a considerable financial penalty for the discharger. The formula for an ecologically based EQS for sewage sludge disposal areas has already been proposed by the UK Ministry of Agriculture, Fisheries and Food (Rees and Pearson, 1992). Comparisons are made between impacted or "Treatment" stations and "Reference" stations outside the area of influence, in terms of fauna abundance, number of taxa or biomass data. The data may then be substituted into the following equation [(Treatment/Reference)-1]*100 and the results compared with a natural variation or baseline noise which is calculated as [(Reference 1/Reference 2)-1]*100. Reference station 1 is defined as being just outside the area of influence and Reference station 2 is more distant still. A significant deviation in the Treatment results from the baseline noise over a period of at least three years is considered to represent an environmental impact. The Treatment/Reference formula has been applied to data from Boulby (Cotter and Rees, 1993). The Treatment station was represented by the outfall station 33 and Reference stations 1 and 2 were taken as stations 56 and 83. The untransformed Treatment/Reference ratio failed to detect the ecological impact demonstrated by MDS analysis of the 1970-1989 data (Craig *et al.*, 1993). This problem was overcome by log transformation of the ratio. However further inadequacies in the formula have been identified at other marine disposal areas, which are due to high baseline noise (Rees, pers. comm.; Shillabeer, in press). Cotter and Rees (1993) concluded that it would be preferable to base an EQS on a complete set of ecological data, including physico-chemical information and multivariate measures of benthic fauna community structure. This approach should be more accurate than employing univariate techniques to derive an individual number or statistic such as fauna abundance, number of taxa, biomass or diversity index, to represent a complex data set.

In 1990 an Environmental Quality Standard (EQS) was described specifically for the discharge of insoluble mining effluent to the Boulby sand patch, based on the structure of the resident macrobenthic invertebrate fauna community, as defined by the multivariate statistical technique MDS (Field *et al.*, 1982). A limit for the annual discharge of 145,000 tonnes of insoluble material was also set by the NRA, in order to permit the achievement of the EQS. Since the introduction of the EQS, breaches have coincided with increases in insoluble material above the discharge limit in 1991 and 1993. The 1991 total annual discharge was 170,000 tonnes, representing a 17 % increase above the discharge limit and in 1993 the annual total was 156,000 tonnes which corresponded to an 8 % increase. The discharge limit therefore appears to be set correctly, at a level which marks the threshold of an environmental impact as defined by the EQS.

CONCLUSION

The EQS for the Boulby sand patch is the first ecologically based standard to be used by the UK National Rivers Authority to regulate a marine discharge. The results reported in this paper clearly indicate the scale of background knowledge that is required before an EQS can be defined using ecological data. Such standards may be derived for any discharge whose environmental effects have been properly deduced by a sustained ecological monitoring programme. Ecologically based EQSs are highly applicable in real environmental situations and in many cases they will be more meaningful than standards derived from toxicological data.

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APPENDIX 1

Details of the MDS – derived fauna groupings from 1991-1993.

Year	Phyla	Taxa	Group					
			Ref 1	Ref 2 & 3	Deep	Mollusc dominated	B Interned Impact	A Impact
1991	Annelida	Nephtys sp. (juv)	5.3	3.0	–	–	1.1	0.3
		Spiophanes bombyx	1.0	2.3	–	–	0.4	0.0
		Spio filicornis	8.0	0.7	–	–	0.0	0.0
		Magelona mirabilis	1.7	4.4	–	–	0.0	0.0
		Cirratulidae unident	0.7	4.1	–	–	0.0	0.2
		Chaaetozone setosa	0.3	8.0	–	–	0.0	0.0
	Crustacea	Bathyporeia sp.	41.0	1.3	–	–	1.1	0.0
		Pontocrates arenanius	8.7	0.0	–	–	0.0	0.0
	Mollusca	Nucula turgida	0.0	3.4	–	–	0.6	0.0
		Tellina fabula	0.3	8.4	–	–	7.9	0.3
		Mean no. indivs/sample	75.3	47.6	–	–	20.0	2.8
		Mean no. species/sample	13.3	14.8	–	–	8.5	1.7
		No. Boulby stations/group	0	5	–	–	7	5
1992	Annelida	Nephtys assimilis	0.0	0.9	4.0	3.2	0.8	0.0
		Nephtys sp. (juv)	1.7	3.2	2.0	4.6	2.0	0.0
		Spiophanes bombyx	21.0	15.7	5.0	1.4	0.3	0.2
		Magelona mirabilis	12.3	30.2	0.0	4.4	0.3	0.5
		Cirratulidae unident	0.7	5.0	1.3	0.2	0.5	0.0
		Chaetozone setosa	0.3	4.5	0.7	0.2	0.0	0.0
	Crustacea	Ampelisca brevicornis	0.0	0.1	0.3	2.2	5.3	0.0
	Mollusca	Nucula turgida	0.0	4.5	30.7	3.4	0.0	0.0
		Venus striatula	0.7	44.4	20.0	1.0	0.0	0.0
		Tellina fabula	1.3	24.6	12.0	26.2	4.8	0.2
		Abra alba	0.7	14.7	168.3	94.4	25.5	0.5
	Echinoderm	Amphiura sp. (juv)	0.0	1.8	9.3	3.2	0.8	0.0
		Mean no. indivs/sample	53.7	188.1	289.7	164.6	67.5	3.2
		Mean no. species/sample	15.7	25.2	28.0	19.6	11.5	2.0
		No. Boulby stations/group	0	5	1	3	4	4
1993	Annelida	Nephtys sp. (juv)	–	4.4	3.3	2.5	1.5	0.0
		Spiophanes bombyx	–	3.0	4.3	1.3	0.3	0.1
		Spio filicornis	–	0.1	3.0	0.8	0.0	0.0
		Magelona mirabilis	–	24.5	1.3	1.0	0.0	0.1
		Chaetozone setosa	–	4.6	1.0	0.0	0.0	0.0
	Crustacea	Bathyporeia sp.	–	2.1	1.0	1.8	0.3	0.0
	Mollusca	Nucula turgida	–	2.5	18.7	0.5	0.0	0.0
		Venus triatula	–	15.6	9.0	0.5	0.0	0.0
		Tellina fabula	–	41.8	44.0	61.5	8.3	0.4
		Abra alba	–	0.9	1.0	2.0	12.5	1.0
		Mean no. indivs/sample	–	117.9	108.7	81.0	32.5	3.0
		Mean no. species/sample	–	17.1	17.0	11.8	9.0	2.3
		No. Boulby stations/group	–	5	1	4	2	5