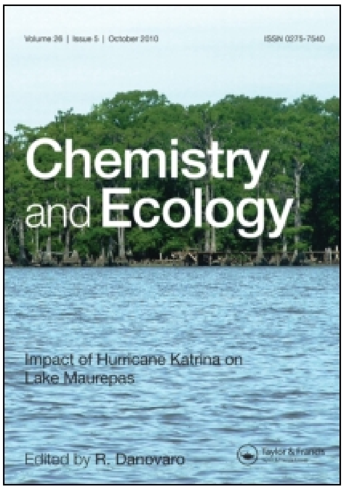

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MACROINVERTEBRATES AS BIOINDICATORS OF WATER POLLUTION IN STREAMS DRAINING DAIRY FARMING CATCHMENTS

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Runoff from intensive dairy farming systems can impair the quality of catchment waters, with potential ecological and human health implications. A water quality study was carried out in three streams in a predominantly dairy farming region, with the aim of assessing the effects of diffused- and point-sourced inputs on a number of water quality parameters and benthic macroinvertebrates. The results showed significant increases in streamwater biochemical oxygen demand (BOD), ammonium-nitrogen (NH_4-N) and molybdate reactive phosphorus (MRP) concentrations between the farm reaches. These changes in water quality appeared to be due largely to the point-sourced inputs from farmyards, and had a significant effect on the ability of the water to support a healthy and diverse community of invertebrates. The results also showed that concentrations of dissolved oxygen (DO) and ammonium in streamwater were the two most important parameters studied that were inversely related to the invertebrate scores.

Keywords: Farm pollution; water quality; ammonium-nitrogen; biochemical oxygen demand; dissolved oxygen; benthic invertebrates

1. INTRODUCTION

The intensification of dairy farming over recent years has led to concern that it can be causing significant ecological damage to the aquatic

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environment (NRA, 1992). Pollution events such as spills of slurry or silage effluent have shown up in the statistics increasingly over the past 20 years (SOAFD, 1991) and have often been reported as causing severe ecological damage in aquatic systems, resulting in, for example, fish kills and sewage fungus growth. The everyday activities on dairy farms such as milking, yard washing and slurry spreading may also have adverse effects which have gone unreported previously but are now attracting attention (Webb and Archer, 1994). Traditionally waters have been monitored in terms of their chemistry, and EU directives concerning water quality specify chemical limits in waters used for specific interests, *e.g.*, Drinking Water Directive (80/778/EEC), the Directive for the Protection of Fisheries (78/659/EEC) (Howarth, 1988). It has been suggested that traditional chemical spot sampling may miss pollution from farms that can be of an occasional or periodic nature (Mason, 1991). However, monitoring of biological communities living in the stream gives an indication of the water quality over a period of time. Benthic macroinvertebrate communities have been shown to be good indicators of organic pollution, and as such have been widely used to assess water quality (*e.g.*, Armitage *et al.*, 1983; Schofield *et al.*, 1990; Marneffe *et al.*, 1996). The fauna living on the streambed respond to changes in water quality (Marneffe *et al.*, 1996), and the resulting species composition is likely to reflect both the physical (*e.g.*, particulate material, colour) and chemical (*e.g.*, nutrients) nature of the watercourse as a whole. Some groups of macroinvertebrates are very sensitive to the oxygen depletion that arises as a consequence of any organic/nutrient enrichment and so will not survive under these conditions, while other groups thrive only when the competition has been removed by enrichment (Crawford *et al.*, 1992).

Recently a major study assessing the impact of various farming systems (*e.g.*, arable, beef, dairy, mixed arable-beef) on catchment water quality was undertaken in southwest and northeast of Scotland. The results showed that outputs from even a single farm produced detectable increases in streamwater nitrate (Hooda *et al.*, 1997a) and phosphate (Hooda *et al.*, 1997b) concentrations. The work presented in this paper involved a survey of benthic macroinvertebrates and associated water quality/environmental components in three streams draining farm-sized catchments, and formed a part of the same study. Industrial and municipal waste inputs to watercourses are known to have a significant impact on the benthic macroinvertebrates (Griffiths, 1991; Crawford *et al.*, 1992). It is commonly perceived that grassland-farming systems are environmentally benign, but the impact of runoff from such systems on macroinvertebrates in catchment waters is relatively unknown. This work was therefore designed primarily to (a) study the impact of low level chronic water pollution from cattle farms on benthic macroinvertebrates and (b) to assess the usefulness of biological monitoring in detecting changes in chemical water quality.

2. STUDY CATCHMENTS AND METHODS

2.1. Catchments and Land Use

The three farms (45-71 ha) were well known to the authors having been part of the initial project (Hooda *et al.*, 1996). All three- farm catchments (Caddell, Killoch and Logan) are in the Ayrshire region, with altitude varying from 75 to 280 m. Annual precipitation in the catchments shows a large variation, ranging from 1100 – 1700 mm. The three catchments are in one of the most intensive dairy farming regions in the UK, and maintained grassland is the near-exclusive agricultural land use on the study farms (Fig. 1). Swards are cut for silage as well as being rotationally grazed by cattle and stocked with sheep during the winter months (December – March), when the cattle are housed.

Caddell is a dairy farm that lies in a subcatchment of the River Garnock. The farm boundaries form only a small part of the whole catchment. The farm buildings are situated near to the stream bank (Fig. 1) and slurry is spread on surrounding fields, some of which are adjacent to the stream. It is a second order stream with the flow varying from 2 l s^{-1} at base flow to about 1000 l s^{-1} at flood. Killoch lies within the catchment of the River Irvine and is also a dairy farm, but the stream is some distance from the farm buildings and any input of organic material comes from the fields and cattle entering the water (Fig. 1). This first order stream is much smaller with the flow ranging from less than 1 l s^{-1} to 50 l s^{-1} in times of flood. The farm lies almost entirely within the catchment of the stream. Logan is part of the River Ayr catchment, there is no dairy at the farm and all the cattle are young calves and non-milking cows. However normal slurry and silage

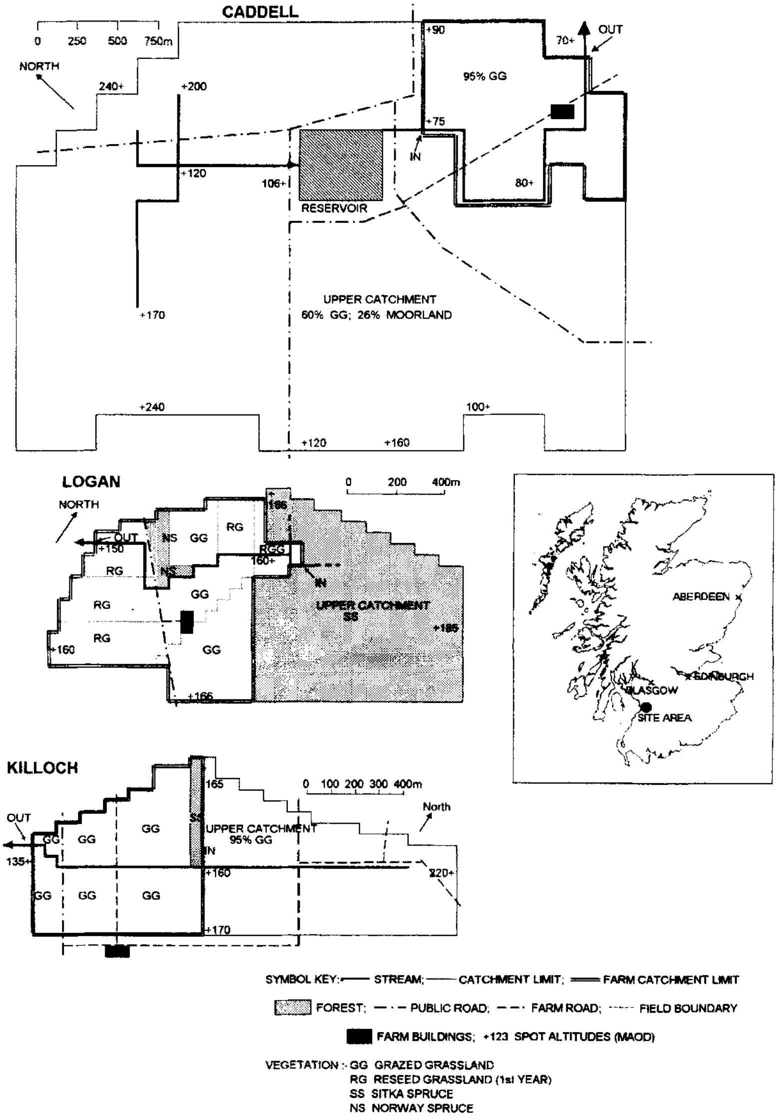

FIGURE 1 Cellular diagrams for the study catchments in SW Scotland. The "IN" and "OUT" points denote upstream and downstream sampling stations, respectively.

activities still take place. The stream is also first order and is a similar size to that at Killoch. The farm forms about 50% of the catchment, with its headwaters being within a coniferous forest plantation (Fig. 1).

2.2. Macroinvertebrate Sampling and Water Analysis

The samples were taken in the spring and late summer of 1994 and 1995. Each stream was sampled from two sites, upstream and downstream of the farms, on four occasions between May 1994 and September 1995. The benthic macroinvertebrates were sampled by means of a square ended pond net using the 3-minute 'kick sample' technique. This is the most commonly used sampling technique in the water industry (Furse *et al.*, 1981) and is used widely by various environmental protection agencies in the UK (Fozzard *et al.*, 1994). Large stones were removed from the net and the remaining contents transferred to a bottle. Samples were sorted in the laboratory and preserved in 10% formaldehyde. The macroinvertebrates were identified to family level and the sites were scored using the Biological Monitoring Working Party (BMWP) score system (Armitage *et al.*, 1983). There was no attempt to estimate abundance levels for the different families. The BMWP score was developed for the whole of Britain in 1978 to assess the effect of organic matter on lotic waters using macroinvertebrates as indicators, and is widely used by the Scottish Environment Protection Agency for routine monitoring work (CRPB, 1991). Each family is given a score between 1 and 10 depending on its pollution tolerance, one for pollution tolerant groups and 10 for clean water groups. The total score of all the families is added together to give the BMWP score. The Average Score Per Taxon (ASPT) is used to help reduce biases due to differences in sampling sites and seasons. The ASPT score is simply the BMWP score divided by the number of families counted in the sample.

Temperature, electrical conductivity (EC), dissolved oxygen (DO) and stream flow were measured at the time of sampling. Temperature was measured by means of an Orme Scientific mercury thermometer (76 mm, −10° to 110°C). A Jenway Model 4070 conductivity meter was used for measuring the conductivity. The flow was estimated using a stage-height and correlating this with a previously calculated relationship between the stage-height and stream flow as described by Hooda *et al.* (1997a). Unfiltered water samples were tested for the 5-day biochemical oxygen demand (BOD_5) (Anon, 1988). Filtered (0.45 μm) aliquots were analysed for nitrate-nitrogen (NO_3^-) ammonium-nitrogen (NH_4^+) and molybdate reactive phosphate (MRP), using standard procedures (Greenberg *et al.*, 1992).

3. RESULTS AND DISCUSSION

3.1. Water Quality and Macroinvertebrate Scores

Although all three farms studied were dairy enterprises, they were contrasting in terms of direct inputs to the streams. Field drainage, farmyard runoff and/or effluent discharges from the farms have impaired the water quality as demonstrated by the increasing concentration of most water quality parameters between the farm reaches (Tab. I). In addition to runoff from fields, the Caddell stream received farmyard runoff, midden drainage, milking-parlour washing and silage effluent in varying amounts through drains almost continuously. This was reflected in the chemical analyses of the streamwater, with BOD, ammonium-N and molybdate reactive phosphorus (MRP) concentrations at the downstream sampling station being consistently larger than at the upstream location. Winter growths of sewage fungus were common in the stream and in summer heavy growths of the algae *Oedogonium* spp. indicate eutrophic conditions. The water quality had a conspicuous effect on stream ecology, as the benthic fauna downstream from the farm was limited to a few pollution-tolerant groups such as oligochaetes, chironomids and leeches. Consequently BMWP/ASPT scores decreased within the farm reaches (Tab. II, Fig. 2). The upstream sampling site was generally in better condition than below the farm, as was shown by the lower BOD values (Tab. I) and the greater diversity of high scoring pollution-sensitive organisms such as the stonefly, *Chloroperlidae* spp., resulting in higher ASPT values than at the downstream site (Fig. 2).

The Killoch stream had none of the point-sourced inputs that affected the Caddell stream, although cattle did have access to the water for drinking purposes and slurry was spread on fields directly adjacent to the stream. Nevertheless BOD, nitrate, ammonium and MRP concentration showed some variations between the farm reaches, indicating diffused-sourced inputs and dilution-associated effects (Tab. I). Overall, the water quality and faunal populations were generally of a good standard with BOD being consistently below 2.5 mg l^{-1} as recommended for class RE1 rivers (DoE, 1994). As a result, the BMWP/ASPT scores showed little change between the upstream and downstream sampling stations (Fig. 2), with good populations of mayflies, stoneflies,

TABLE I Results of various chemical and physical measurements for the three farm catchments at upstream (U/S) and downstream (D/S) stations

Catchment		*BOD* $mg\ L^{-1}$	NO_3-*N* $mg\ L^{-1}$	NH_4-*N* $mg\ L^{-1}$	*MRP* $\mu g\ L^{-1}$	*Temp.* (°*C*)	*EC* $\mu S\ cm^{-1}$	*pH*	*DO* %	*Q* $L\ s^{-1}$
					May 1994					
Caddell	U/S	1.9	1.04	41.0	116	9.5	208	7.4	96	27
	D/S	7.0	0.92	157.0	533	9.5	217	7.8	81	35
Killoch	U/S	0.6	0.91	0.19	95	11.5	484	8.0	100	8
	D/S	2.2	1.28	0.21	82	12.2	511	8.3	100	11
Logan	U/S	0.9	0.36	0.63	27	13.0	88	6.7	95	3
	D/S	1.3	0.43	1.45	44	12.0	673	7.9	90	5
					September 1994					
Caddell	U/S	1.7	1.16	1.86	188	12.6	208	5.7	98	81
	D/S	4.5	0.72	2.68	195	12.6	210	6.4	95	103
Killoch	U/S	1.8	1.17	0.13	431	11.2	480	8.1	100	14
	D/S	1.6	1.14	0.54	382	11.8	533	8.1	99	18
Logan	U/S	2.2	0.54	0.79	33	10.2	109	7.3	91	21
	D/S	42.4	0.81	78.0	157	10.6	218	7.4	57	23
					May 1995					
Caddell	U/S	2.8	1.02	3.05	166	11.2	176	7.5	96	5.6
	D/S	5.7	0.98	9.68	483	11.4	180	7.5	88	5.7
Killoch	U/S	0.7	0.96	0.23	79	13.7	378	7.9	90	0.3
	D/S	1.6	1.22	0.84	95	13.5	401	8.0	81	0.4
Logan	U/S	2.6	0.61	0.76	27	10.8	151	6.8	90	0.4
	D/S	4.9	0.63	0.89	44	10.0	336	7.2	88	0.5
					September 1995					
Caddell	U/S	2.6	0.14	3.0	94	12.5	357	7.3	95	3.4
	D/S	4.8	0.78	11.0	352	12.7	368	7.5	86	3.9
Killoch	U/S	1.8	0.95	0.42	138	11.4	500	8.0	90	1.1
	D/S	1.9	0.92	0.39	154	11.8	558	8.0	90	1.4
Logan	U/S	2.1	0.29	0.12	46	12.1	120	6.7	100	2.1
	D/S	3.0	0.51	1.18	76	12.4	478	7.5	85	2.5

EC, electrical conductivity; DO, dissolved oxygen; Q, streamflow.

TABLE II Average biological scores for the three farm streams at upstream (U/S) and downstream (D/S) locations

Catchment		*Number of families*	*BMWP*	*ASPT*
Caddell	U/S	9.7 (2.0)	43.5 (13.5)	4.4 (0.5)
	D/S	6.5 (3.1)	24.5 (16.9)	3.5 (0.7)
Killoch	U/S	9.0 (0.8)	46.5 (2.1)	5.2 (0.3)
	D/S	11.0 (2.6)	55.2 (13.0)	5.0 (0.2)
Logan	U/S	8.0 (2.1)	40.7 (10.5)	5.1 (0.3)
	D/S	8.2 (3.6)	37.5 (21.1)	4.1 (1.5)

The values in parentheses are standard deviations for the four measurements made between May-94 and Sept-95.

caddis flies and beetles as reflected by the number of invertebrate families (Tab. II), despite disturbance of the water by cattle.

Logan generally was also a clean stream with little input from the farm buildings; however the usual cattle and slurry activities take place, with open access to the stream for cattle. The BOD, nitrate, ammonium and MRP concentrations were generally low (Tab. I) and diversity of fauna fairly high, again with a similar range of organisms to Killoch (Tab. II). There was however one exception, in the autumn of 1994 a pipe from the silage pit carried effluent directly into the stream between the up- and downstream stations. This led to severe pollution, which included sewage fungus and an almost total elimination of fauna except for the most pollution-tolerant worms, leeches and chironomids. By the early summer of 1995, however, the source of the problem, the silage, had been removed and the fauna quickly recolonised the waters as indicated in the biological scores (Fig. 2). Chemically the most obvious sign of pollution was the BOD of 42 mg l^{-1} (Tab. I) which led to reduced dissolved oxygen saturation levels of 56%, compared to over 90% at the upstream station. The situation repeated itself in the late summer of 1995 when drainage from the nearby stored silage crop again escaped into the stream. The consequences, however, were less severe than during the previous year (Tab. I, Fig. 2), although this may be partly due to the relatively longer period between the pollution incidence and the sampling date.

The results of this study showed that the input of organic material from farmyard runoff to small streams has a significant effect on the ability of the water to support a healthy and diverse community of invertebrates. The continuous, semi-continuous or intermittent input of these medium strength pollutants, as in the Caddell stream, is probably

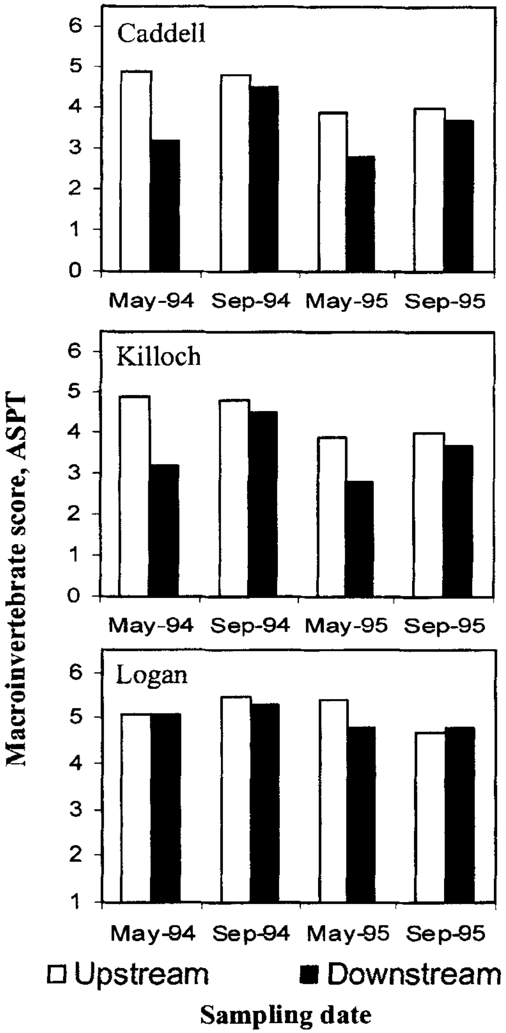

FIGURE 2 The impact of diffused and point-sourced inputs on the invertebrate score, ASPT, between the upstream and downstream reaches.

far more common than the catastrophic failure of slurry stores and silage pits which make up many of the reported farm pollution incidents (SOAFD, 1991). These findings (*e.g.*, ASPT/BMWP scores, BOD, ammonium) are consistent with other studies on the effects of livestock farming on water quality in the U.K. (*e.g.*, Schofield *et al.*, 1990;

McCahon *et al.*, 1991; Rutt *et al.*, 1993). In arable and livestock farms with no point-sourced inputs of organic effluents/waste, the ASPT scores are generally above 5, indicating good water quality in terms of a healthy and diverse community of invertebrates (Yorke, 1994), as seen in the Killoch stream. Point-sourced inputs of organic waste/effluents to aquatic systems cause well-known organic enrichment effects, ranging from mild eutrophication, through excessive algal growth to dense sewage fungus and, in extreme cases, the eventual 'death' of the stream (Abel, 1989; Marneffe *et al.*, 1996). All these stages have been seen in the Caddell stream. In the event of point-sourced organic/nutrient inputs the benthic invertebrates community shifts to pollution-tolerant organisms as seen in the Caddell and Logan streams, and the recovery of pollution-intolerant species may not be immediate and would depend upon the severity and length of pollution occurrence (Crawford *et al.*, 1992). However, the impact of point-sourced pollution on the benthic invertebrates during high-flow may not be as obvious as compared to times of low flow. Pollutants other than nutrients/organic effluents have also been found to reduce the diversity of invertebrates. For example, a survey of benthic invertebrates in three southland (New Zealand) streams changed in the sections within developed pastures in such a way as to suggest pollution, although no point sources were present. It was suggested that dips and drenches used on sheep in the developed pastures could be partly responsible for some of the changes (Scott *et al.*, 1994).

The effect of effluent entering the water on the benthic fauna is to reduce the diversity and composition of the groups of species that exist in this environment. The results from Killoch and Logan suggest that drainage from grassland fields and even cattle entering the water to drink has little obvious effect (Tab. II), although species diversity may be reduced, allowing a reduced number of sensitive species such as mayflies to coexist with oligochaetes and leeches. Where point-sourced runoff/discharge enters a watercourse the impact is more serious, with the effluent causing an environment of low dissolved oxygen and nutrient enrichment, as noted in some samplings at Caddell and Logan. Under such situations pollution-tolerant species are excluded to the benefit of a few hardy opportunistic ones that grow to profusion in the competition-free waters. This can have a serious effect on fisheries and general amenities if this situation continues for a long period of time.

3.2. Correlations Between Macroinvertebrates and Water Quality Parameters

Table III summarises results of the correlation analysis of various water quality parameters and the invertebrate scores. As expected, the concentration of BOD in streamwater was inversely correlated with the invertebrate scores. Increasing inputs of oxygen-demanding carbonaceous material increase BOD, causing a depletion in DO concentration that, in turn, puts stress on invertebrates and other forms of aquatic life, as indicated by a positive correlation between the BMWP/ASPT scores and dissolved oxygen (Tab. III). Ammonium-N in streamwater also had an inverse relationship with the invertebrate scores, *i.e.*, ammonium being detrimental to the benthic invertebrate community. Ammonia (NH_3) is the form of nitrogen most responsible for toxic effects in fish and other aquatic life (USEPA, 1994). Ammonia dissolved in water exists as an equilibrium of molecular ammonia (NH_3) and ionised ammonium (NH_4^+), and toxicity to aquatic organisms is largely attributable to ammonia with ammonium being relatively less toxic. This equilibrium is dependent upon the system pH and temperature. With a water temperature of 10–12°C and a pH value of about 7.5 as observed in the study streams when ammonium concentration was high (Tab. I), up to 1.5% of total ammonium is expected to exist in molecular ammonia (NH_3) form (USEPA, 1985). Some of the ammonium concentrations (Tab. I) were therefore likely to yield aqueous ammonia that would be far in excess of concentrations known to cause toxicity to fish and other aquatic

TABLE III Correlation coefficients of chemical and biological parameters, based on data pooled from the three farm catchments ($n = 24$)

	ASPT	*BMWP*	*BOD*	*NO_3-N*	*NH_4-N*	*MRP*
ASPT						
BMWP	0.79***					
BOD	−0.69***	−0.57**				
NO_3-N	NS	NS	NS			
NH_4-N	−0.58**	−0.56**	0.49*	NS		
MRP	−0.48*	−0.44*	NS	0.43*	0.46*	
DO	0.63**	0.56**	−0.81***	NS	−0.53**	NS

Levels of significance $p \leq 0.05$ = *, $p = \leq 0.01$ = **, $p \leq 0.001$ = ***, $p > 0.05$ = non significant (NS).

organisms (USEPA, 1985). Although excessive phosphorus can affect the invertebrate community through eutrophication, the negative correlations of MRP with the invertebrate scores are due at least partly to the source of MRP, BOD and ammonium being the same, *i.e.*, point-sourced farm effluents, as indicated by their positive correlations (Tab. III). This is further supported by the findings that a significant percentage of phosphorus outputs from these farm-catchments is contributed by point-sourced inputs (Hooda *et al.*, 1997b). However, ammonium together with other nutrients, notably MRP, may also have adversely affected the invertebrate population and diversity through nutrient enrichment.

The inverse relationship between the ammonium and DO (Tab. III) concentrations was not unreasonable. Just as bacterial decomposition of organic wastes depletes DO in receiving waters, in-stream nitrification of ammonium when it occurs causes an additional oxygen demand. Biological nitrification of 1.0 mg l^{-1} of ammonium consumes 4.6 mg l^{-1} of oxygen. It appears therefore that the large concentrations of ammonium observed in some of the samples affected the invertebrate community by a combination of direct toxicity effects of ammonia, nutrient enrichment and oxygen depletion. Overall, it seems that inputs of farm effluents from point sources, which are rich in both carbonaceous material and ammonium, were the main cause for the observed changes in the BMWP/ASPT scores between the catchment reaches. The ASPT gave stronger correlations than the normal BMWP scores, which agrees with the argument that ASPT gives a better picture of the state of the water, due to reducing errors in sampling (Armitage *et al.*, 1983).

4. CONCLUSIONS

The result of the present study showed that the concentrations of water quality parameters, notably BOD, ammonium and MRP, increased between the catchment reaches, indicating significant pollution from the farms. These changes in water quality were particularly obvious where point-sourced inputs of drainage from farmyards entered the streams, and had a considerable effect on the benthic invertebrate communities. The examination of benthic macroinvertebrates performed in this work is a relatively simple procedure, and appeared to be an effective method of assessing the effects of farm waste pollution on catchment water ecology.

The study also showed that measurements of DO and ammonium concentrations largely reflected the ecological nature of the catchment waters. The latter component, however, is likely to have little influence on aquatic ecology particularly when inputs are of a diffused-source origin, *i.e.*, low ammonium concentration and/or environmental conditions for ammonium conversion to ammonia not being favourable (*e.g.*, low temperature, acidic waters).

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