Environmental RTDI Programme 2000–2006

Evaluation of the Use of the Sodium Dominance Index as a Potential Measure of Acid Sensitivity (2000-LS-3.2.1-M2)

WATERAC

Synthesis Report

(Main Report available for download on www.epa.ie/EnvironmentalResearch/ReportsOutputs)

Prepared for the Environmental Protection Agency and Council for Forest Research and Development

by

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DISCLAIMER

WATER QUALITY

The Water Quality Section of the Environmental RTDI Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in this area. The reports in this series are intended as contributions to the necessary debate on water quality and the environment.

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Executive Summary

The identification of acid-sensitive waters currently uses coarse methods of designation, i.e. pH (<5.5) and low alkalinity (<10 mg/l $CaCO_3$). While these measures are clearly indicative of low buffering capacity, they are extremely variable within any one catchment, depending on flow conditions and geology. The contribution of sodium (Na^+) to the sum of the major cations (Sodium Dominance Index, SDI, or Weathering Index) in river waters has been proposed as an indicator of the acid sensitivity of rivers in upland Scotland, particularly where sea-salt inputs dominate the base cation composition. The extent of the SDI is considered a quantitative indication of catchment weathering rate, incorporating the effects of diverse geological composition. This project set out to evaluate the efficacy of the SDI approach to site designation under Irish conditions. Two hypotheses were tested:

1. That the SDI is more stable across the range of stream flows than the two most commonly used indicators and is thus a better indicator of stream sensitivity to acidification than pH or alkalinity, and

2. That there is a graded response by the stream macroinvertebrates to values of the Index, and hence some ecological underpinning of the chemical relationship.

These hypotheses were tested by examining the water chemistry of 257 sites across Ireland, encompassing a range of underlying geologies, during base flow. A further subset of 65 sites were sampled at both base and elevated flow and a number of more detailed hydrological events were monitored at a smaller number of sites. pH, conductivity, hardness, alkalinity and the SDI were determined for each site, together with a range of environmental variables, including geology type, presence or absence of forest, distance from the south-west of Ireland and distance from the sea. The study found that the SDI varied less than other indicators of sensitivity at the catchment scale among sites across a range of geologies and land use. The SDI was highly correlated with existing indicators and less variable when compared at sites during base and elevated flow. Therefore, when used alone, alkalinity readings could allow grant aid and increased forestry plantations on catchments, which could be deemed acid sensitive by the SDI. Although the SDI showed some variation at the beginning of a flood event, this variation seemed to decline after about 5–6 h of elevated flow, when it again showed less variation than pH or alkalinity. It appears that a threshold level of the SDI of 50–60 is indicative of sensitivity to acidification as measured by the acid-neutralising capacity (ANC) and alkalinity. Some evidence of a response in biology across the SDI bands was detected with sites with SDI values >50 and those <20 showing distinct communities. However, there were no consistent differences between the fauna from forested and non-forested sites. Given the errors associated with the measurement of pH, compared to base cations, the SDI could perhaps provide a more reliable measure of acid sensitivity; however, further work is required to validate these data within each catchment in the context of risk assessment under the Water Framework Directive, before the SDI is implemented as an indicator of sensitivity.

1 Project Background, Aims and Objectives

1.1 Introduction

Plantation forests cover 10% of the Irish landscape, with the planted area projected to reach 17% by 2010. This has raised concerns as to the possible effects such new plantations and associated forestry practices may have on aquatic resources because of the direct links between catchment land use and the ecology and functioning of aquatic ecosystems (Hynes, 1975; O'Halloran and Giller, 1993; Giller and Malmqvist, 1998). Many Irish river systems rise in or pass through forested catchments.

In the UK, coniferous forestry exacerbates the acidification of soft waters draining geologically sensitive areas which receive atmospheric pollutants (Hynes, 1975; Giller and Malmqvist, 1998). This anthropogenically mediated acidification occurs where atmospheric deposition of strong acid anions (SO_4^{2-} and NO_3^-), accompanied by H^+ and NH_4^+, exceeds the buffering capacity of the soil resulting in the leaching of Ca^{2+}, Mg^{2+} and Al^{3+}. Whilst forestry-related hydrochemical changes have been noted in the east and west of Ireland (Allott *et al.*, 1997; Kelly-Quinn *et al.*, 1997a,b), it is considered that plantation forests do not lead to acidification and the related problems in the south of Ireland (Giller and O'Halloran, 2004).

While the deposition of acidifying ions has declined by 40% in European Environment Agency (EEA) membership countries (EEA, 2000), there is still considerable concern about the impacts of acidifying ions on surface water quality and its associated ecology. Whilst plantation forests and their management can influence water quality in a number of ways (e.g. nutrients or energy inputs) and in different stages of the forest cycle, it would be helpful to appraise the sensitivity of sites to forestry prior to planting. The present study therefore focused on an evaluation of the Sodium Dominance Index (SDI) as a measure of stream sensitivity to acidification and hence the identification and regulation of potential sites for forest development.

The Irish Forest Service introduced regulations that all applications for grant aid in acid-sensitive areas required an assessment. These regulations were largely targeted at the protection of salmonid waters. The designation of sensitivity was (and is currently) based on alkalinity values from a minimum of four occasions at intervals not greater than 4 weeks apart between February and May. Where the minimum alkalinity of the run-off water is <8 mg $CaCO_3$/l no afforestation is permitted. In areas where concentrations exceed 15 mg $CaCO_3$/l, afforestation is permitted, and if the values fall in between, full, partial, or no afforestation may be allowed.

The methods used for designating acid-sensitive sites are currently coarse: alkalinity varies across flow conditions and there is a poor relationship between peak acidity and lowest alkalinity values (e.g. in Wicklow, Kelly-Quinn *et al.*, 1997a,b). In addition, many sites might be designated as sensitive based on alkalinity, yet ecological data do not show negative impacts (e.g. Munster area, Giller *et al.*, 1997; Giller and O'Halloran, 2004). What is needed is a measure that is both relatively stable and independent of season and flow. The contribution of sodium (Na^+) in river waters to the sum of the major cations (Sodium Dominance Index or Weathering Index) has been proposed by White *et al.* (1998, 1999) as an indicator of the acid sensitivity of rivers of upland Scotland, particularly where sea-salt inputs dominate the base cation composition (as is the case in much of Ireland). The SDI is calculated as the relative contribution of sodium to the major cations as follows:

$$SDI = \frac{[Na^+]}{[Na^+]+[Ca^{2+}]+[Mg^{2+}]} * 100$$

Base cations (particularly Ca^{2+}) may be derived from weathering of the underlying geology (e.g. limestone). Increases in their concentrations relative to sodium infer an increased acid neutralising capacity to the catchment, and conversely, high sodium dominance infers reduced neutralising capacity. As weathering rates ($mmol_c$/ha/year) increase, the SDI value declines in response. As such, the SDI provides a quantitative value of the weathering upstream of the sampling point.

1.2 Scale of Approach

There are three spatial scales that are important in examining the acidification issue, in terms of identifying sensitive catchments and in developing tools for amelioration of problems in this context. At the supra-catchment or regional scale, the objective is to identify potentially sensitive areas to help plan forest development with minimum impact on water quality and ecology (e.g. fisheries). Because of Ireland's geographical position and prevailing weather systems, the deposition of acidifying compounds is low although local-scale ammonium deposition may be very important in the future (EPA, 2000). In this context, national-scale evaluation of the SDI has been undertaken in the present project.

At smaller scales, research efforts have been largely focussed on preventing or mitigating against acidification and ensuring that acidification is not exacerbated locally (Hildrew and Ormerod, 1995). This can lead, for example, to planting regimes being controlled in sensitive catchments. This project examined a number of catchments at low and high flow in an attempt to evaluate the temporal responses of the SDI and to look at a range of important variables which might influence the SDI value, and hence its use as a tool in designating sites.

At the reach scale, there have been a number of recent attempts to devise and implement methods of riparian management to ameliorate the effects of forestry on acidification (e.g. Ormerod *et al.*, 1993; Mitsch and Mander, 1997). At this scale, it is also possible to investigate the stability of the SDI over a range of stream conditions, an important approach that has been adopted in the present study to evaluate further the efficacy of the SDI as an indicator of sensitivity of the catchment.

According to White *et al.* (1999), the SDI is preferable to base-flow measurements of pH for a number of reasons. Firstly, pH is notoriously difficult to measure accurately in low ionic strength waters (this has implications for alkalinity tests). On the other hand, base cations are relatively straightforward to measure and more variable between catchments (but note that base cations are highly variable with discharge due to dilution). Finally, the expression of the results as an index based on ratios 'smoothes' out small variations. The values of the SDI indicative of acid-sensitive conditions remain to be defined however. The limited data analysed by Kelly-Quinn *et al.* (1999) suggested that sites with low pH and alkalinity would have SDI values greater than 40.

1.3 Objectives of the Study

The overall objectives of this project were to test if the SDI offers a better approach to designating sites than current methods employed, and secondly whether there is any relationship between the SDI values and the ecological character of streams. This was approached by undertaking studies at a national scale at base-flow level, a subset of sites at base and elevated flow and a series of detailed studies at a number of intensive sites during the course of several hydrological events.

Two key hypotheses were tested:

1. That the SDI is more stable than other potential hydrochemical indicators across the range of stream flows and is thus a better indicator of stream sensitivity to forest-mediated acidity, and

2. That there is a graded response by the stream macroinvertebrates to values of the Index.

These hypotheses were tested through a number of work packages as detailed in Cruikshanks *et al.* (2005).

2 Site Selection and Methodology

2.1 Site Selection

Site selection for the extensive sampling was undertaken in detailed consultation with the EPA/COFORD. A total of 257 potential sites were identified across Ireland (192 non-forested and 65 forested), which ranged in elevation from 50 m to <300 m above sea level (Fig. 2.1). All sites were of good water quality with a minimum EPA rating of Q4 and above, indicating no evidence of organic pollution or eutrophication based on macroinvertebrate fauna (EPA, 2000). Site selection was also weighted, based on the base cation weathering index map obtained from Aherne and Farrell (2000). This weighted sampling ensured that the required large-scale geographical spread of sites was achieved along with sufficient replication across the SDI scale. The finalised site selection criteria are summarised in Table 2.1. Full site details are available in Cruikshanks *et al.* (2005).

Following the completion of the extensive sampling phase a subset of sites was selected, based on a range of SDI values from the extensive sampling, and sampled at base and elevated flow conditions to examine the temporal stability in the SDI. The 65 sites were sampled with a wide geographical spread between 12 February 2003 and 19 June 2005, during base and elevated flow conditions.

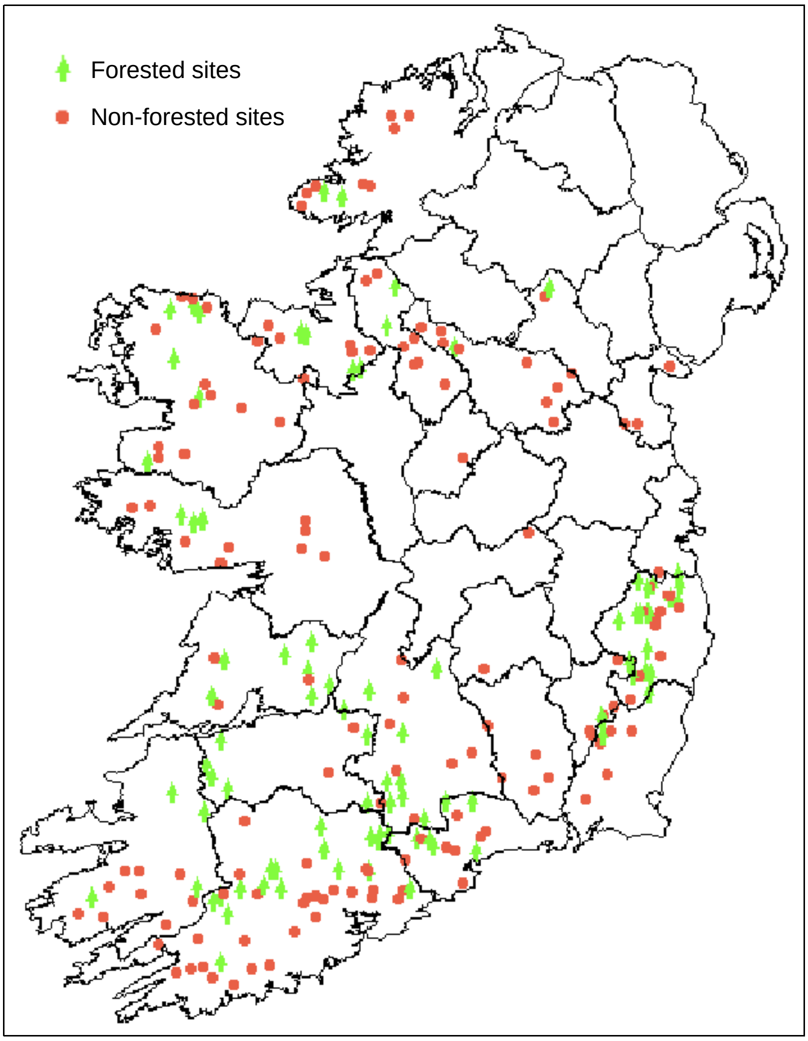

Figure 2.1. Location of all sampled sites.

Table 2.1. Summary of site selection criteria.

Aim	Collect data from areas where a paucity of suitable data exists
Total number of sites	192 non-forested and 65 forested
Sampling basis	Base cation weathering index (Aherne and Farrell, 2000) (mol_C/ha/year) sites allocated to the following categories 200–500 (n = 80); 501–1000 (n = 60); 1001–2000 (n = 40); >2001 (n = 20).
University sampling areas	Division of the country into two areas
Site sampling areas	No sites to be sampled in Northern Ireland
Access to forested sites	COFORD/Coillte access enabled
Site details	
Site altitude	>50 m and <300 m
Site length	50 m
Site quality	Q value greater than or equal to Q4
Stream order	Sites located on 2nd to 4th order streams (avoiding 1st and >4th order)
Definition of 'forested' sites	Presence of closed canopy forestry in catchment (>20% if possible)
Riparian zone	Intact
Water sample collection	Non-turbulent areas (glides)
Biological sample collection	Multi-habitat using kick sampling

The detailed sampling during several separate hydrological events at the reach scale was undertaken at three forested and five non-forested sites (see Cruikshanks *et al*., 2005 for details).

2.2 Water Sampling and Chemical Analysis

Base-flow data collection was undertaken after 7 days of little or no rainfall (<0.22 mm). Elevated flow samples were collected from 65 sites, between February 2003 and June 2005, following periods of heavy rain. The reach sampling was undertaken using Sigma samplers that were programmed to collect samples after flow actuation. In most cases, the pre-event level was 0.09 m and the enabling level was 0.14 m: a stream rise of 5 cm. (Further details are given in Cruikshanks *et al.*, 2005.)

Measurements of pH and conductivity were made in the field using meters and all other determinants were measured in the laboratory, usually within 12 h following collection (no later than 24 h after the event). A summary of analytical methods is given in Table 2.2 and full details are given in Cruikshanks *et al.* (2005).

Inter-calibration exercises involving an independent accredited laboratory were conducted to ensure the quality and standardisation of the water chemistry

Table 2.2. Summary of the analytical methods used and units of expression.

Parameter	Method	Unit
pH	pH meter	units pH
Conductivity	Conductivity meter	µS/cm @25°C
Alkalinity	Depended on pH: Gran titration or standard titration	mg/l $CaCO_3$
Calcium	Ion chromatography	mg/l Ca^{2+}
Magnesium	Ion chromatography	mg/l Mg^{2+}
Sodium	Ion chromatography	mg/l Na^{+}
Potassium	Ion chromatography	mg/l K^{+}
Chloride	Ion chromatography	mg/l Cl^{-}
Colour	Colorimetry	mg/l Pt^{+}/Co
Organic carbon	Colorimetry/conversion equation	mg/l DTOC
Aluminium	Colorimetry	mg/l Al^{3+}

analyses in the laboratories at UCD and UCC. The subsequent results of a suite of analyses showed close agreement (largely within the 95% confidence limits) and any differences in the two results had a minor influence on the values of the SDI. The data set was also scanned for possible errors by testing ionic balance where a full suite of ions was analysed. Data considered to be out of line were tested, by plotting alkalinity against pH or the various cations against conductivity and alkalinity. Some data were rejected on this basis.

2.3 Biological Sampling

A subset of 65 of the extensive sites was selected for macroinvertebrate sampling covering the following SDI bands: 0–10, 20–30, 40–50, 60–70 and >80, with around six paired forested and non-forested sites selected within each range.

Macroinvertebrates were collected in both spring and autumn 2003 using 3-min multi-habitat kick sampling together with a 1-min hand search/stone wash. This approach attempted to ensure that the maximum biodiversity was sampled at each site. A 50-m reach was surveyed for different habitat types – riffles, glides, pools, backwaters, vegetated areas and margins. The time allotted to sampling each habitat type was weighted according to the percentage representation of each in the 50-m reach. Three replicate samples were taken at each site together with descriptions of the respective habitats. A complete list of the sites is presented in the electronic database and sampling and sorting methods are given in the full report (Cruikshanks *et al.,* 2005).

Invertebrates were sorted and identified to species level for all the major insect groups (except Diptera – genus/family), as well as Mollusca (snails), Turbellaria (flatworms) and Hirudinea (leeches). The total number of taxa and their relative abundance were assessed for each site.

2.4 Statistical Analysis

Summary statistics were calculated and standard tests (including ANOVA and correlation analysis) were conducted to compare hydrochemical values between site types (e.g. forested and non-forested, geological classes and SDI classes) and to examine for relationships between parameters.

Two-Way Indicator Species Analysis (TWINSPAN) was used to classify sites based on macroinvertebrate species assemblages (Hill, 1979), while the Indicator Value (IndVal) method and the Multi-Response Permutation Procedure (MRPP) (carried out using PC-ORD) validated the Indicator Species and Cluster Groups derived from TWINSPAN, respectively. The relationships between the faunal data set and the physico–chemical parameters (Ter Braak, 1991) was examined using Canonical Correspondence Analysis (CCA) carried out using Ecological Community Analysis™ 2.0 (ECOM™ 2.0).

For hydrological event calculations, the factors contributing to loss of buffering during a selection of the events were examined using the methodology outlined in Kahl *et al.* (1992). Values of 100% indicate that only dilution is affecting buffering (i.e. reducing alkalinity). Lower values indicate titration by an acid anion.

3 Results

3.1 Extensive Water Chemistry Survey

Full details of the hydrochemical results for the 257 extensive sites are presented in Cruikshanks *et al.* (2005). Some analyses were confined to 248 of these sites. In the following section, the major findings and relationships only are highlighted.

3.1.1 pH and conductivity

The pH at base flow ranged from 4.9 to 8.8 with most (84%) values in the circum-neutral range (pH 6.5–7.5). The majority of sites with pH values <7 were located in the west (north-west and south-west) and some in the east (Fig. 3.1). Low conductivity values were associated with poorly buffered areas (e.g. granite) whilst higher values were linked with well-buffered areas (e.g. limestone).

Data for the cation composition of the extensive sites are illustrated in Fig. 3.2. Calcium dominated the sites located in well-buffered limestone areas whereas sodium dominated those sites located in poorly buffered areas. Most (90–100%) of the calcium was from non-marine sources in over 98% of the sites. In contrast, 50% of the magnesium recorded at 86 sites was of marine origin. At the remaining sites, marine-derived magnesium accounted for 10% (34 sites) to 40% (37 sites) of the total

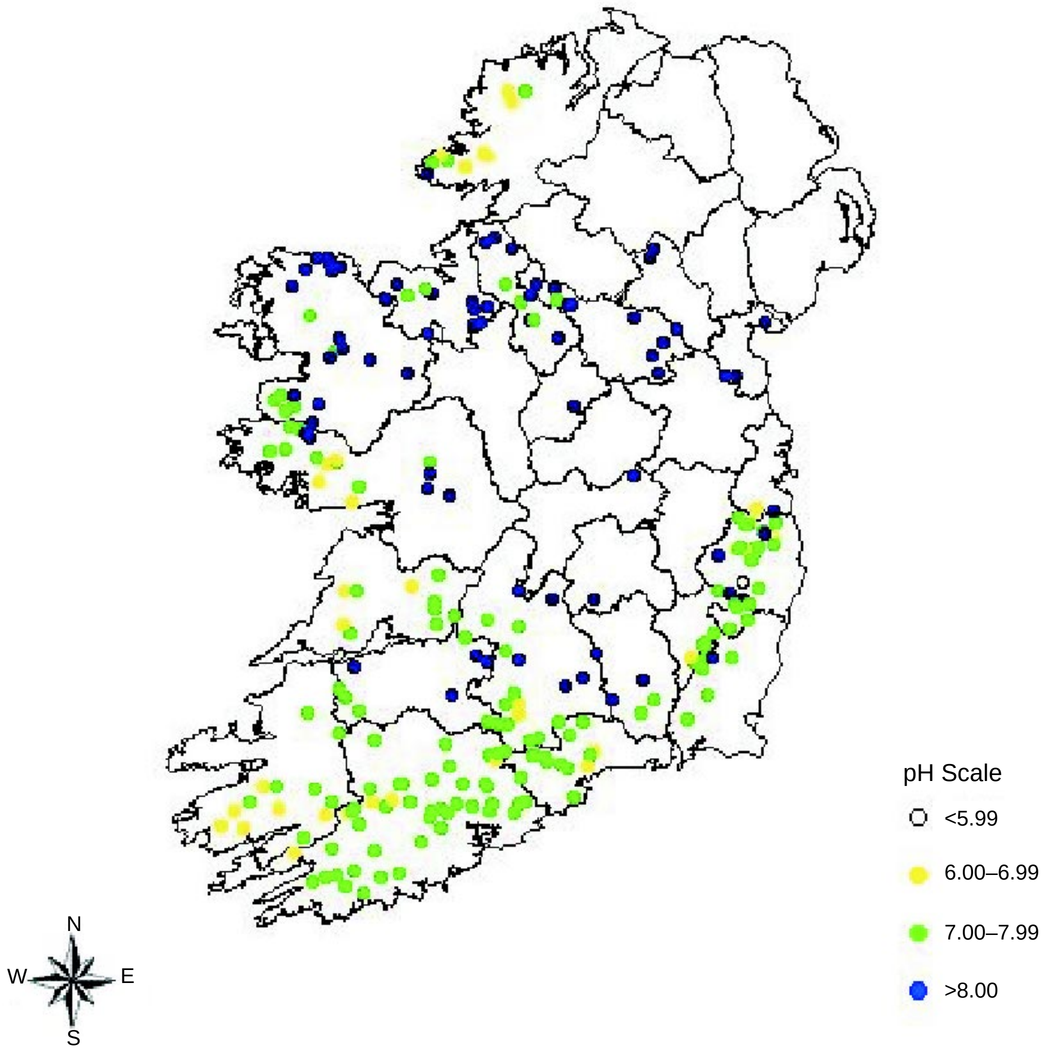

Figure 3.1. pH values (base flow) across the range of extensive sites.

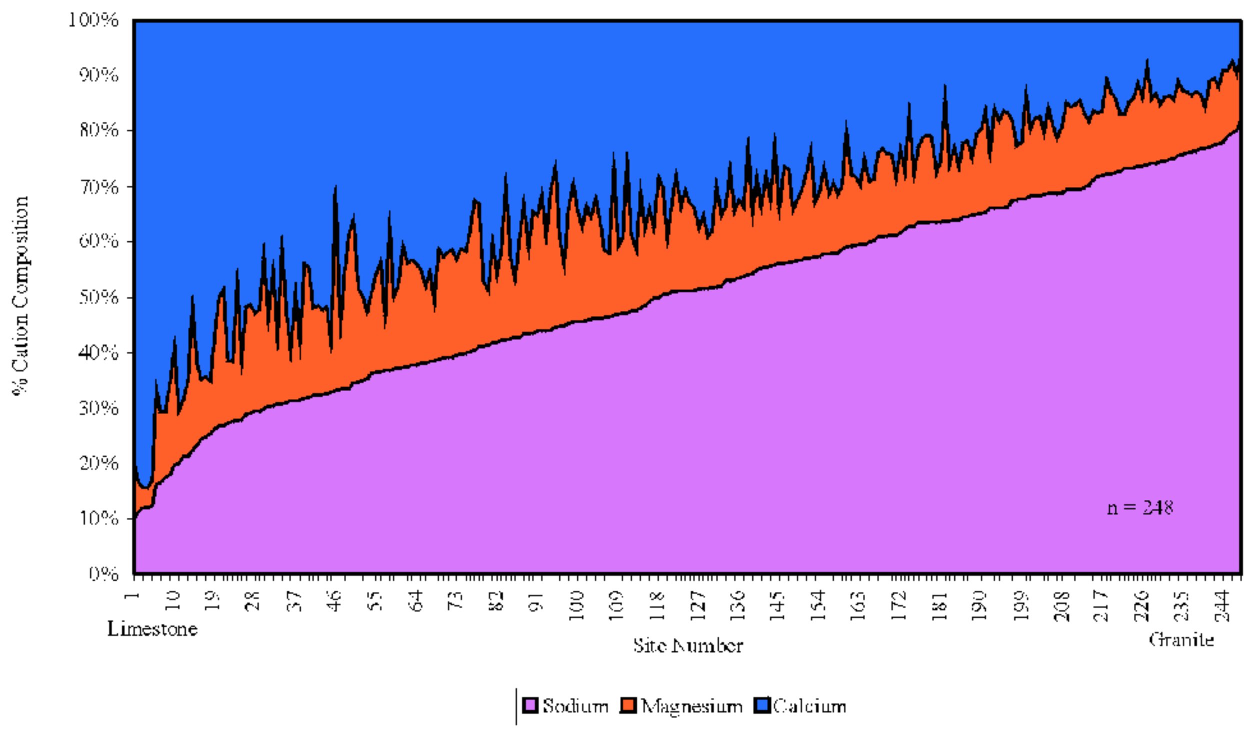

Figure 3.2. The percentage cation composition (calculated in terms of mmol/l) at extensive sites.

concentration. Potassium contributed less than 3% of the major cation concentration at the majority (80%) of sites.

3.1.2 Sodium Dominance Index

Figure 3.3 shows the spatial distribution of SDI values for all sites sampled. Values ranged from 10.1 (Yellow River, Co. Meath) to 81.9 (Cashla River, Co. Galway). The highest values of the Index were recorded in upland sites in Wicklow, Donegal, Galway and Kerry.

Sites were assigned to one of 13 groups based on dominant watershed geology. A strong relationship between the SDI and geology is clear from Fig. 3.4. Significant differences were detected (ANOVA $F_{12,182}$ = 9.323, $P < 0.001$) across the geological groups for the non-forested sites with the lowest values recorded on limestone and values steadily increasing to the more weather-resistant rocks such as granite. No significant difference in the SDI was detected between the non-forested and forested sites in any of the geological groups.

A highly significant negative linear relationship was evident between pH and the SDI (Fig. 3.5) for non-forested and forested sites combined ($r = –0.729$, $P < 0.01$, $R^2 = 0.532$, $n = 248$). There was no separation of non-forested and forested sites and the slopes of the two lines were not significantly different.

The SDI–alkalinity relationship ($r = –0.826$, $P < 0.01$, $n = 248$) is summarised in Fig. 3.6, and here again there was no clear separation of forested and non-forested sites in the overall pattern. The slopes of the two lines were not significantly different. With the exception of two points, all forested sites recorded alkalinity values below 50 mg $CaCO_3$/l.

The relationship between the alkalinity of potentially acid-sensitive sites and SDI values was also examined; a significant correlation was found ($r = –0.721$. $P < 0.01$, $n = 187$), although considerable scatter was evident.. The slopes of the lines for the forested and non-forested sites were not significantly different.

The acid-neutralising capacity (ANC) was calculated for 117 sites from the present extensive study, using Gran titration alkalinity values, total aluminium and DOC concentrations according to the methodology outlined by Foster *et al.* (2001). A significant relationship between ANC and the SDI was evident ($r = –0.671$, $R^2 = 0.594$, $P < 0.01$, $n = 117$, Fig. 3.7).

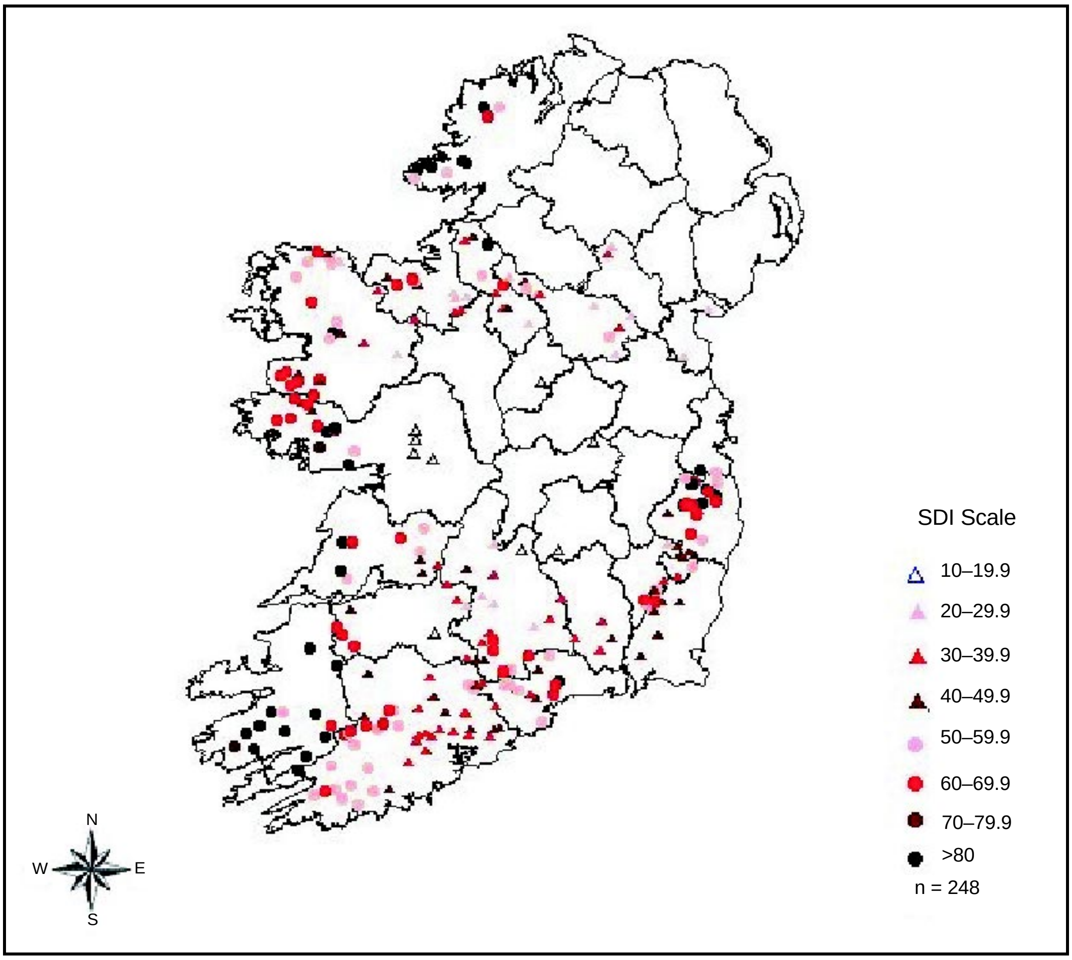

Figure 3.3. Spatial distribution of SDI results for the extensive sites.

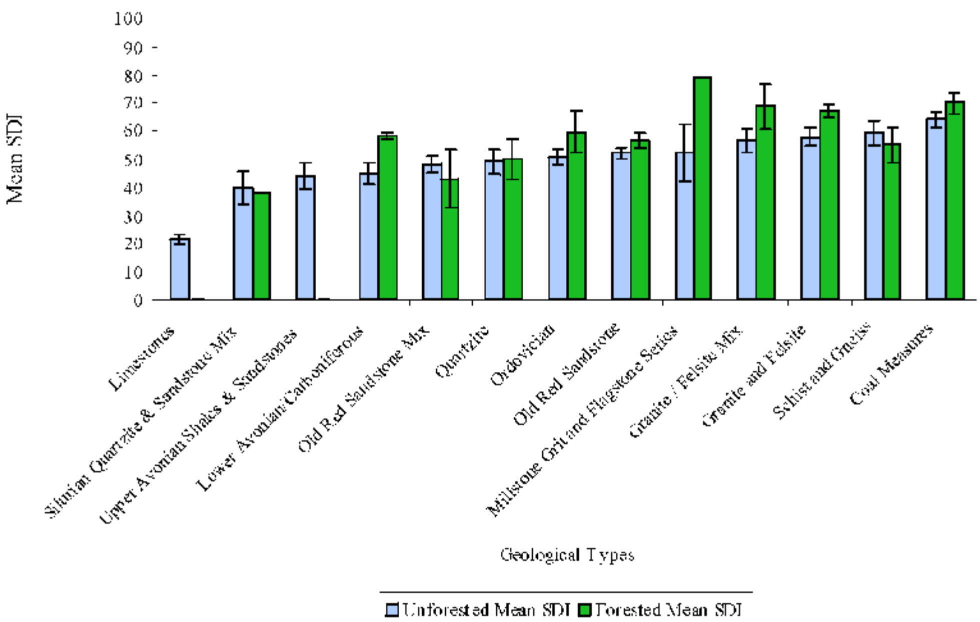

Figure 3.4. Mean SDI (±SE) results for sites grouped according to dominant watershed geology (no forested sites were sampled in limestone areas).

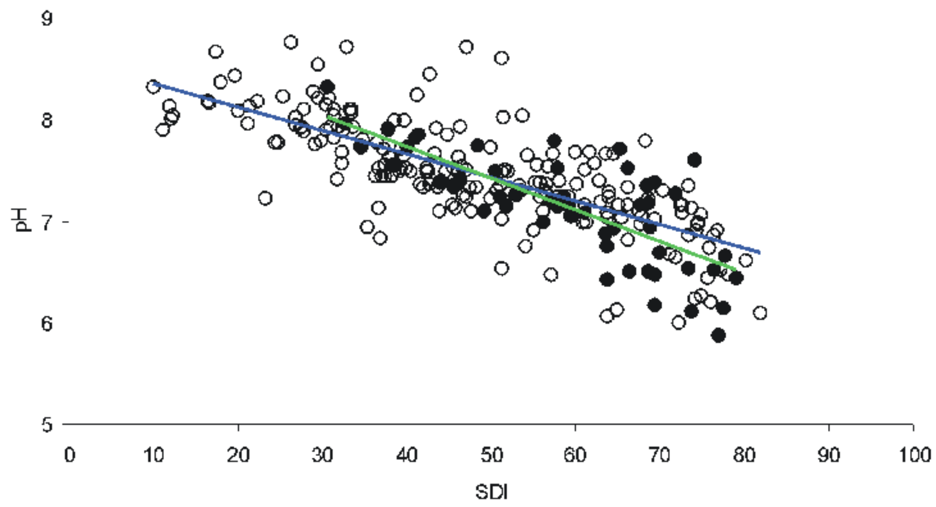

Figure 3.5. Relationship between base-flow pH and the SDI for non-forested (open circles, dark blue trend line) and forested sites (filled circles, green trend line), n = 248 sites. The two lines represent the relationship between pH and the SDI for forested and non-forested sites.

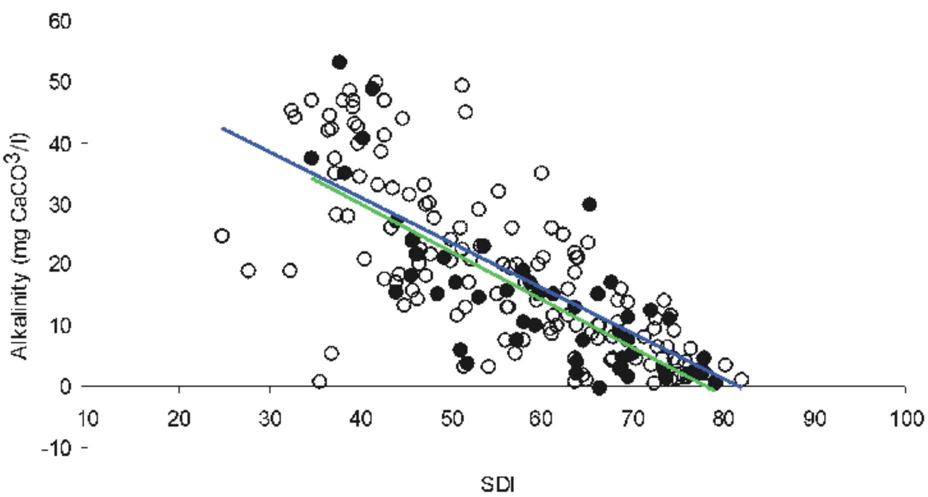

Figure 3.6. Relationship between alkalinity (<50 mg $CaCO_3$/l) and the SDI for non-forested (open circles, dark blue trend line) and forested sites (filled circles, green trend line), n = 186 sites. The two lines represent the relationship between alkalinity and the SDI for forested and non-forested sites.

3.2. Influence of Flow on the SDI

SDI values increased during rainfall events at all sites except ten. Generally there was less than a 15-unit SDI difference between low and elevated water levels. Most of the sites that did show a substantial increase in the Index at elevated flow were located in catchments with mixed geology. Overall, the variation in the SDI was substantially less than that for alkalinity. No significant differences were found in the SDI between base flow and elevated flow at non-forested or forested sites when examined separately within each geological type (one-way ANOVA, $P > 0.05$) except for forested sites ($F_{1,4} = 10.75$, $P = 0.031$) on schist and felsite. Likewise, there was no significant effect of forest cover on the SDI ($P > 0.05$, Mann–Whitney) on the elevated and base-flow values.

Figure 3.8 illustrates the general nature of changes in the SDI and alkalinity during rainfall events. Alkalinity fell sharply and the SDI tended to rise as flow increases but

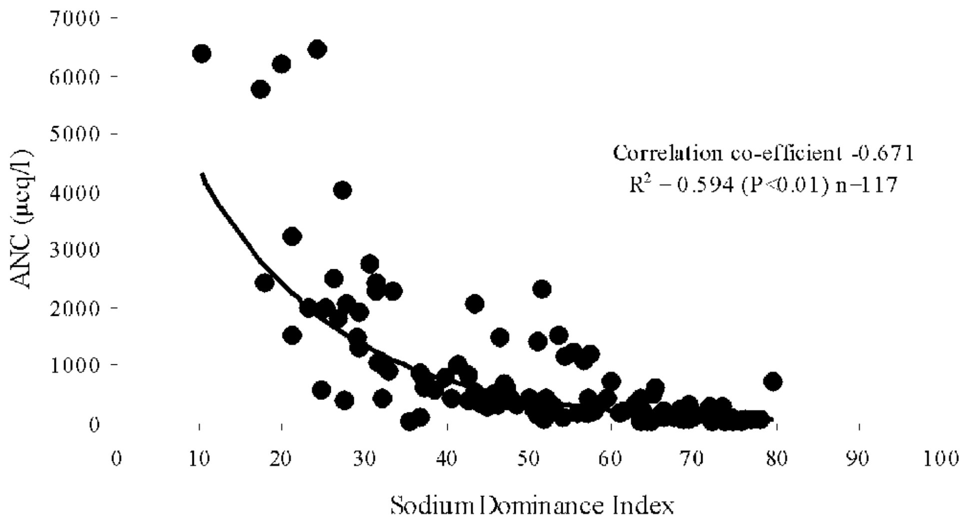

Figure 3.7. Relationship between ANC and the SDI for 117 WaterAc extensive study sites.

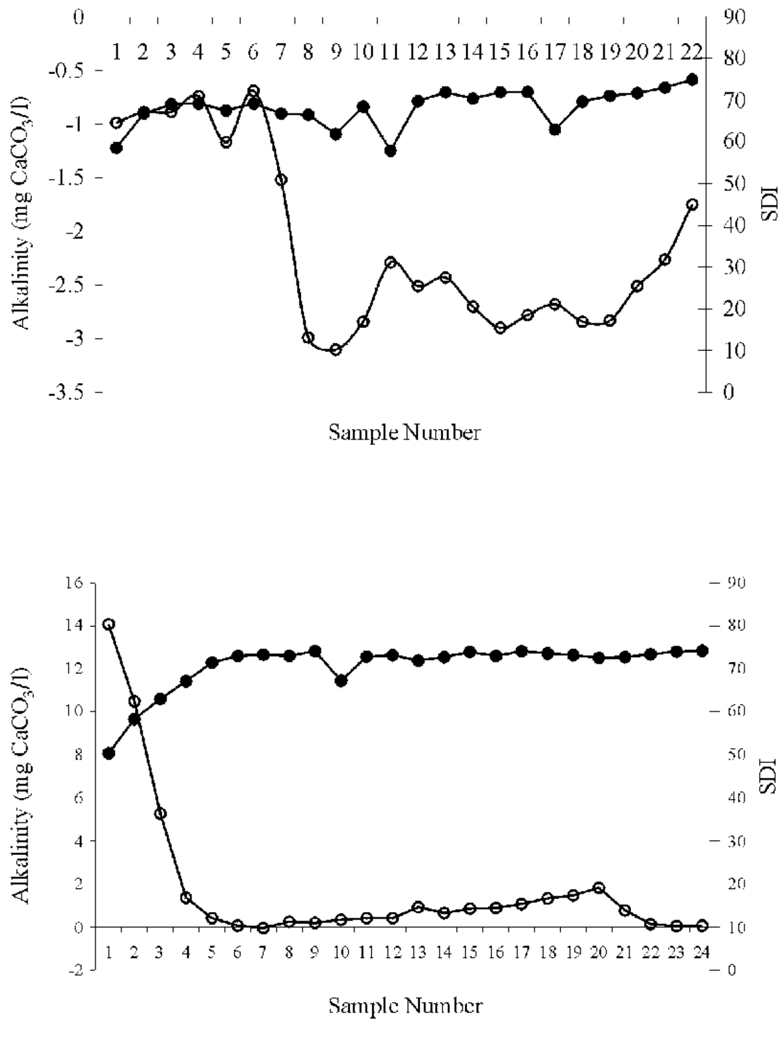

Figure 3.8. Hydrochemical trends during event on 22 June 2004 in Annalecka River (30% forest cover) (top) and Glendassan River (5% forest cover) (bottom). The SDI (filled circles) and alkalinity (open circles). Samples were taken in sequence during the flow events following rainfall.

as found in the more extensive comparison between base flow and increased flow described above, the coefficient of variation was highest for alkalinity (3.44–836%) and least for the SDI (2.21–20.5% – the highest value related to one event and most were significantly lower).

The greatest change in both the SDI and alkalinity occurred within the first few hours of the event. The data collected for the Cork sites included flow recording. Spearman rank correlation analyses indicated significant (r_S = 0.7–0.78, $P < 0.01$) relationship between change in flow and change in the Index. In fact this was the only significant relationship detected. A more detailed examination of the underlying factors influencing the SDI values during flow events is given in the full report (Cruikshanks *et al.*, 2005).

3.3 Biological Patterns

3.3.1 Taxon numbers and faunal composition

A total of 237 taxa were recorded over the two seasons representing 75 families. The number of taxa recorded per site ranged from 33 to 78. A total of 33 taxa were present in over 50% of the 65 sites sampled. Trichoptera was the most diverse group (48 species) followed by the Coleoptera (41 species). Ephemeroptera were represented by 19 species while 18 plecopteran species were recorded. There were 17 genera/subfamilies of Diptera, two crustacean orders, namely Malacostraca and Entomostraca, with four and two species recorded respectively, while the Annelida were represented by six Hirundinae species. Fourteen gastropod species and two lamellibranch species were also recorded. (Full details are available in the electronic data set.)

A number of general biological patterns were identified in relation to water chemistry and SDI values. The Ephemeroptera constituted an increasing proportion of the community with progression from sites with an SDI >80 to those in the 30–40 SDI band (Figure 3.9). In contrast, Plecoptera increased in proportion with increasing acid sensitivity (particularly at highly forested sites). While crustacean and molluscan numbers decreased predictably with increasing acid sensitivity, the representation of dipteran larvae generally increased. The pattern was similar for both seasons.

3.3.2 Multivariate analyses

TWINSPAN of the spring faunal data set (non-forested sites only) resulted in seven validated groups (Groups 1–7). Group 7 consisted mostly of acid-tolerant sites with a mean SDI of 21.6 (SDI range 7.6 to 59.7). Groups 1–6 tended to have a higher mean SDI (50.1–74.9), reflecting largely acid-sensitive conditions. The SDI did not distinguish between Groups 1–6. When all sites (spring data) were included in TWINSPAN no distinctive patterns between forested and non-forested sites were found. Analysis of the autumn faunal data (non-forested sites)

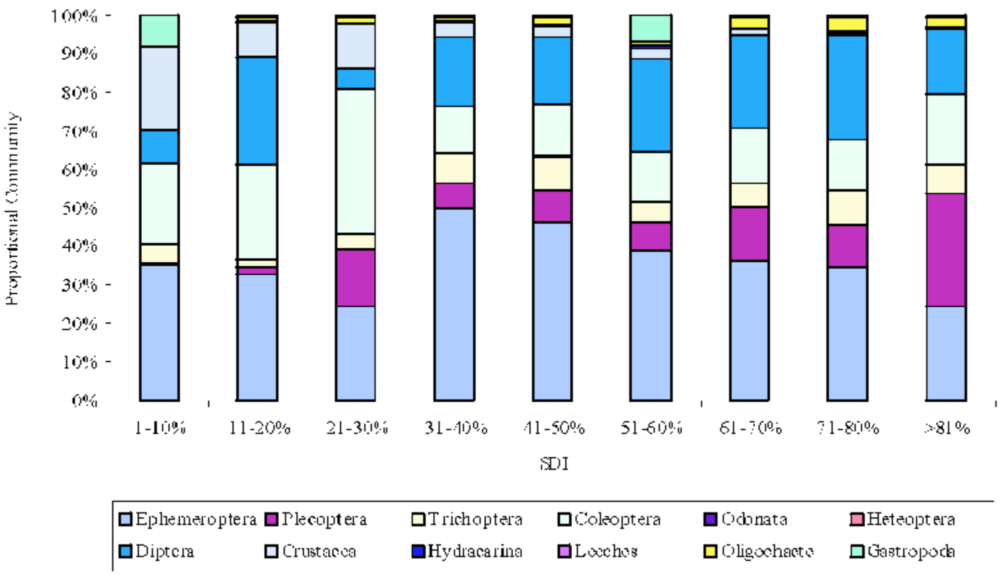

Figure 3.9. Spring macroinvertebrate community composition over the SDI gradient.

yielded relatively similar results with again seven groups. The mean SDI values in Group 7 were 23.8 (range from 12.7 to 35.5). Groups 1–6 consisted of moderately to highly sensitive sites. Mean SDI values for Groups 1–6 ranged from 38.8 to 60.3. (Further details and dendrograms are given in Cruikshanks *et al.,* 2005.)

A significant correlation between the physico–chemical parameters and the spring faunal data set for the non-forested sites was demonstrated by CCA. However, the eigenvalues were low, with the four axes explaining only 27.27% of the cumulative data variation. According to the CCA plot (Cruikshanks *et al*., 2005), SDI, elevation, slope and boulder substrate were all strongly associated with the most acid-sensitive sites. Forward selection indicated the SDI (% variance 9.06%, $P < 0.01$), slope (% variance, 8.76%, $P < 0.01$) and mud substrate (% variance, 4.86%, $P < 0.01$) as the three most important variables in the spring data set. The autumn data also showed low eigenvalues with the total cumulative data variation explained at 29.19%. The SDI, slope and elevation were indicated as being important variables on the CCA plot for the autumn analysis. Forward selection noted slope (% variance, 8.05%, $P < 0.01$), SDI (% variance, 7.05%, $P < 0.01$) and magnesium (% variance, 3.53%, $P < 0.01$) as the three most important variables in autumn.

3.3.3 Relationships between SDI and faunal data

Taxon numbers and abundances were examined over an SDI and forestry gradient with all sites grouped into SDI classes of 10–19, 20–29, 30–39, 40–49, 50–59, 60–69 and >70. The total taxon richness in the spring data set was significantly negatively correlated with the SDI for all sites combined and for forested sites alone (Table 3.1). The trend did not hold for the autumn data (Table 3.2). The correlations with ephemeropteran and trichopteran richness (decrease) were only significant for the spring period (non-forested site data) (Table 3.1). Plecopteran

Table 3.1. Correlations of taxon number and other biological metrics with SDI for spring.

Spring parameters		Correlation	Regression	P value
Total taxa *vs* SDI	Non-forested	–0.792	$R^2 = 0.627$	P = 0.034*
	Forested	–0.790	$R^2 = 0.625$	P = 0.061
	All sites	–0.859	$R^2 = 0.738$	P = 0.028*
Total number of Ephemeroptera *vs* SDI	Non-forested	–0.868	$R^2 = 0.753$	P = 0.011*
	Forested	–0.667	$R^2 = 0.445$	P = 0.148
	All sites	–0.795	$R^2 = 0.633$	P = 0.059
Total number of Plecoptera *vs* SDI	Non-forested	0.214	$R^2 = 0.046$	P = 0.645
	Forested	–0.797	$R^2 = 0.583$	P = 0.058
	All sites	–0.817	$R^2 = 0.668$	P = 0.047*
Total number of Trichoptera *vs* SDI	Non-forested	–0.743	$R^2 = 0.552$	P = 0.042*
	Forested	–0.887	$R^2 = 0.786$	P = 0.018*
	All sites	–0.916	$R^2 = 0.840$	P = 0.010**
EPT *vs* SDI	Non-forested	–0.87	$R^2 = 0.875$	P = 0.011*
	Forested	–0.279	$R^2 = 0.117$	P = 0.593
	All sites	–0.939	$R^2 = 0.906$	P = 0.005**
E/P *vs* SDI	Non-forested	–0.213	$R^2 = 0.0572$	P = 0.648
	Forested	–0.605	$R^2 = 0.3675$	P = 0.202
	All sites	–0.230	$R^2 = 0.0706$	P = 0.611
C/D *vs* SDI	Non-forested	–0.825	$R^2 = 0.925$	P = 0.004**
	Forested	–0.716	$R^2 = 0.565$	P = 0.110
	All sites	–0.846	$R^2 = 0.823$	P = 0.016*

*Significant to 0.05 level.
**Significant to 0.01 level.

Table 3.2. Correlations of taxon number and other biological metrics with SDI for autumn.

Autumn parameters		Correlation	Regression	P value
Total taxa *vs* SDI	Non-forested	–0.392	R^2 = 0.156	P = 0.385
	Forested	–0.556	R^2 = 0.526	P = 0.252
	All sites	–0.677	R^2 = 0.571	P = 0.144
Total number of Ephemeroptera *vs* SDI	Non-forested	–0.369	R^2 = 0.156	P = 0.415
	Forested	–0.693	R^2 = 0.526	P = 0.127
	All sites	–0.755	R^2 = 0.571	P = 0.083
Total number of Plecoptera *vs* SDI	Non-forested	0.823	R^2 = 0.817	P = 0.023*
	Forested	0.138	R^2 = 0.000	P = 0.794
	All sites	0.753	R^2 = 0.854	P = 0.051
Total number of Trichoptera *vs* SDI	Non-forested	–0.147	R^2 = 0.022	P = 0.753
	Forested	–0.707	R^2 = 0.749	P = 0.116
	All sites	–0.765	R^2 = 0.844	P = 0.076
Ephemeropteran abundance *vs* SDI	Non-forested	–0.525	R^2 = 0.425	P = 0.226
	Forested	–0.210	R^2 = 0.060	P = 0.689
	All sites	–0.503	R^2 = 0.406	P = 0.250
Plecopteran abundance *vs* SDI	Non-forested	0.375	R^2 = 0.508	P = 0.407
	Forested	0.401	R^2 = 0.161	P = 0.431
	All sites	0.573	R^2 = 0.328	P = 0.179
Trichopteran abundance *vs* SDI	Non-forested	–0.729	R^2 = 0.531	P = 0.063
	Forested	0.526	R^2 = 0.276	P = 0.284
	All sites	–0.385	R^2 = 0.148	P = 0.394

*Significant to 0.05 level.
**Significant to 0.01 level.

taxon richness increased with increasing SDI and this relationship was the only significant one in autumn.

Analysis of variance (two-way) on the spring data showed differences in total taxon richness between SDI bands ($F_{6,50}$ = 2.721, P = 0.023). This was not repeated in the autumn. No significant effects of the SDI were found when the analysis was run using spring and autumn ephemeropteran taxon richness. Plecopteran species richness demonstrated significant differences between SDI bands in both seasons (spring – $F_{6,50}$ = 3.732, P = 0.004; autumn – $F_{6,52}$ = 4.108, P = 0.002), generally species richness increased with increasing SDI. Trichopteran richness differed between bands in the spring ($F_{6,50}$ = 3.749, P = 0.004) but was not repeated in the autumn. There was no significant interaction between forestry and SDI bands for these taxonomic groups.

In terms of abundance both the spring (two-way ANOVA, $F_{6,50}$ = 2.721, P = 0.023) and autumn ($F_{6,52}$ = 3.354, P = 0.007) data showed significant differences in total taxon abundance between SDI bands. Neither forestry nor the forestry SDI band interaction were significant. A similar finding applied to the Ephemeroptera in both seasons (spring – $F_{6,50}$ = 2.355, P = 0.044; autumn – $F_{6,52}$ = 3.233, P = 0.009). Plecopteran and trichopteran abundances showed no significant effect of forestry or SDI bands in the spring. However, significant differences in plecopteran ($F_{6,52}$ = 3.903, P = 0.003) abundance between SDI bands were detected in the autumn data set.

In general, most of the significant differences in both taxon richness and abundances could be attributed to differences between the lowest SDI band (<20) and the two highest, 60–70 and >70.

A number of other biotic metrics were examined in relation to the SDI. Mean EPT (the sum of ephemeropteran, plecopteran and trichopteran abundance) and mean E/P (ephemeropteran divided by plectopteran abundance) were both correlated to mean SDI within each band of SDI. An additional metric, crustacean/dipteran (C/D), was also tested. This new index was proposed based on the trends in the representation of the Crustacea and Diptera noted in the data.

The relationships between these metrics and the SDI for spring and autumn faunal data are shown above in Tables 3.1 and 3.2. While the negative relationship between EPT and SDI was significant for all sites and non-forested sites considered separately, it did not hold for forested sites in spring. For the autumn data, the relationship was significant for all sites combined. The negative relationship between the SDI and C/D was significant for all sites combined and the non-forested sites in both seasons. There were no significant correlations between the E/P and SDI in this study.

4 Discussion

The growing desire to develop plantation forestry further in Ireland has led to questions as to how to designate sites for future development. The protection of water quality, and in particular salmonid water quality, has become an important objective. In view of the ecological importance of soft waters for salmonid production, it is critical that measures are taken to avoid increased rates of acidification, particularly those relating to changes in land use. This necessitates the identification of acid-sensitive waters. Currently, the Irish Forest Service uses alkalinity readings in deciding whether to grant-aid afforestation on potentially acid-sensitive catchments. Measures of alkalinity, hardness and pH are known to be extremely variable over time and are greatly influenced by stream flow rate (as also found in the current study), and thus it has become apparent that a more stable indicator of acidification is required.

The SDI has previously shown great potential to deal with varying geologies underlying catchments and adverse temporal flows (i.e. spates or flooding) which occur following periods of rainfall and snow melt (White *et al.*, 1999) and compares well with the Critical Load approach (Smart *et al.*, 2000). The base-flow relationships noted in the present extensive study of over 200 sites have confirmed these earlier findings and have indicated the strong potential of the Index as an indicator of acid sensitivity in Ireland.

A strong relationship was found between the SDI and geology. The lowest SDI values were recorded on limestone, with values steadily increasing with progression on to the more weather-resistant rocks such as granite. However, within any geology type, no significant difference was found in the value of the SDI between the non-forested and forested sites, suggesting that the Index does not detect acid impact. However, it is important to note that despite the relatively large number of sites sampled in this study, few of the forested sites would be deemed impacted, based on their pH, alkalinity or biology (especially in their absence of Ephemeroptera). Accordingly, it might be difficult to detect such a forest effect on the SDI.

A negative linear relationship between pH and the SDI was found for both non-forested and forested sites and there was no difference in the relationship if the sites were forested or not. Low SDI sites (i.e. well buffered) were generally associated with high conductivities and *vice versa* with no clear separation of forested and non-forested sites in the overall pattern.

Not surprisingly, high alkalinity sites had low SDI values. However, here again there was no clear separation of forested and non-forested sites in the overall pattern. Accordingly, the SDI is giving similar outcomes in terms of sensitivity and as previously stated may not detect impact.

It was clear from the limited data available on the ANC that the ANC values approached zero at an SDI value of 60. In terms of risk assessment, sites would fall within the ‘at risk’ category; however, some sites within an SDI value of 50–60 lie close to zero ANC and would be considered to be ‘probably at risk’. These figures are greater than the value of 40 for the SDI previously reported on the limited data set by Kelly-Quinn *et al.* (1999), but it appears to represent an important threshold in relation to the ANC. In the same way, when the SDI is plotted *versus* alkalinity an SDI band of 50–60 seems to be the threshold for the identification of sensitive sites.

In general, the SDI seemed stable in the face of flow change compared to alkalinity and conductivity. However, there was some evidence, at some sites, of a significant percentage change in the SDI during high flow. Of particular note are sites on mixed geology where low flow is probably influenced by reach geology/soil, whereas high flow is more influenced by watershed characteristics. Changes in the SDI between base and elevated flow were found to be unrelated to changes in pH, alkalinity, hardness, calcium or sodium. The absence of clear relationships may be in part due to the fact that the majority of sites exhibited only small changes in the SDI. For those sites showing stability of the Index, it is probable that rainfall simply dilutes the base cations but maintains the relative proportions of each.

The hydrological events were opportunistically sampled and involved sites from both acid-sensitive and moderately buffered areas. In general, the pattern of change in both alkalinity and the SDI during the monitored events was fairly similar. As with the base and elevated flow data, the coefficient of variation was highest for alkalinity and least for pH and the SDI. The greatest change in both the SDI and alkalinity occurred within the first few hours of the event. Using the Cork site data, a significant correlation was detected between change in flow and change in the Index. The results overall suggested that dilution of basic cations, particularly at the commencement of the event, was driving changes in the SDI.

The 237 taxa recorded in the study representing a total of 75 families, inclusive of both seasons, are broadly typical of upland streams in Ireland and confirm that the quality for the sites was good, in terms of EPA Q values. The Ephemeroptera represented an increasing proportion of the community as the SDI varied from >80 to those in the 30–40 SDI band. In contrast, Plecoptera demonstrated a trend of increasing abundance with increasing acid sensitivity (particularly at highly forested sites). TWINSPAN analysis of the spring faunal data set yielded seven validated groups: those with a mean SDI of 21.6 (SDI range 7.6–59.7) depicting mostly acid-tolerant sites (Group 7), and a second group (Groups 1–6) with higher mean SDI values ranging from 50.1 to 74.9, largely acid-sensitive conditions. Although these bands overlap in the 50–60 SDI range it is clear that, similar to the chemical data, the macroinvertebrate community is showing a broadly similar pattern of change around a threshold SDI value of 60. Interestingly, an analysis of autumn faunal data for the non-forested sites yielded relatively similar results, suggesting that this pattern may be applicable year around.

A general trend of decreasing taxon richness with increasing SDI was found throughout the data set in the spring, but not for autumn data. However, there was some variation across season and land use. For example, the correlation with ephemeropteran richness and the SDI was only significant for the spring period (non-forested site data). The autumn sampling indicated the best relationship with plecopteran taxon richness. No significant difference in ephemeropteran richness was noted between SDI bands for non-forested sites but a difference was significant for the forested sites. A significant difference was detected between SDI bands for trichopteran taxon richness again at non-forested site. Significant differences were also noted in total abundance of macroinvertebrates and Ephemeroptera along the SDI gradient for both the non-forested and forested sites.

While the relationship between EPT and the SDI was significant for all sites in spring and autumn and non-forested sites in spring, for the autumn data the relationship was significant for all sites combined. The relationship between the SDI and C/D, a new index, was significant for all sites combined and the non-forested sites in both seasons. Pair-wise comparison of the C/D values between classes suggested that C/D in SDI bands >40 were significantly different from the values in the lower SDI bands.

5 Conclusions

In conclusion, based on the present large-scale study, the SDI clearly offers a valuable and effective alternative indicator of stream sensitivity to acidification and hence for the assessment of possible sites for afforestation (Cruikshanks *et al.*, 2005). The variation in the SDI across a range of geologies and land use and in relation to changes in stream flow was significantly lower than found with other indicators of sensitivity at the catchment scale. The Index is more stable than alkalinity, in the majority of hydrological events. However, at the beginning of extreme events, the SDI can show some change and this is the only stage in the hydrological event that should be avoided. The SDI will diagnose the acid susceptibility of a catchment or sub-catchment at base flow, whereas alkalinity readings can sometimes indicate moderate sensitivity (8–12 mg $CaCO_3$/l) at base flow. Therefore, when used alone, alkalinity readings could allow grant aid and increased forestry plantations on catchments, which could be deemed acid sensitive by the SDI. There was, however, some variation in the SDI at the individual site scale. However, this variation seems to decline after about 5–6 h of elevated flow, when it again shows less variation than pH or alkalinity. It appears that a threshold SDI level of 50–60 is indicative of sensitivity to acidification as measured by the ANC and alkalinity.

Some evidence of a response in biology across the SDI bands was detected. TWINSPAN distinguished best between those sites with mean SDI values >60 and those <20; between these two extremes, the site groupings were characterised by a mix of SDI values. However, there were no consistent differences between the fauna from forested and non-forested sites. Further work is required to validate these data within each catchment in the context of risk assessment under the Water Framework Directive. The links with the fauna will require further analysis and more detailed consideration. In particular the contribution of river typology (RIVTYPE after Kelly-Quinn *et al.*, 2004) may well help to elucidate more fully the relationship between the SDI and fauna and this may lead to the identification of indicator species, ideally with a graded response to the SDI. Given the errors associated with the measurement of pH, compared to base cations, the SDI is perhaps a more reliable measure of acid sensitivity.

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