

# Species abundance distribution of benthic chironomids and other macroinvertebrates across different levels of pollution in streams

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**Abstract** – Chironomid assemblages collected from seven different streams in South Korea were investigated. The subfamily composition of chironomids was clearly differentiated across different levels of organic pollution. Species abundance distributions (SADs) of chironomid communities were compared with the total macroinvertebrate communities across different levels of pollution. The number of species with minimal range of abundance was lower in SADs for chironomid communities compared with total communities. The log normal distribution was accepted for both total and chironomid communities, while the geometric series was relatively more suitable for chironomids and the log series were more fitted to total communities. The  $a$  values in the log normal distribution increased in chironomid communities across different levels of pollution, while  $\gamma$  values increased at the polluted sites for both chironomid and total communities. In the Power law analysis, the parameter decreased in chironomid communities. The dominance decay model was more fitted to chironomid communities in clean conditions while random fraction and assortment models were more suitable for the polluted sites.

**Key words:** Chironomid / species abundance distribution / macroinvertebrates / log normal distribution / power law analysis / random fraction / random assortment / dominance decay

## Introduction

The family Chironomidae (Diptera) is a conspicuous component of freshwater communities, where they often exhibit high diversities and abundances (Resh and Rosenberg, 1984; Pinder, 1986; Armitage *et al.*, 1995; Raposeiro *et al.*, 2009). Chironomids thus make a significant contribution to community diversity at any sampling site. Consequently, they have been proposed as relevant water quality indicators, and are likely to be as sensitive as (or even more sensitive than) other biological indicators such as the well-known EPT (the species richness of Ephemeroptera, Plecoptera and Trichoptera), Ephemeroptera or Trichoptera taxa, Oligochaeta abundance, etc. (Saether, 1979; Resh and Jackson, 1993; Rosenberg, 1993; Barbour *et al.*, 1996, 1999; De Bisthoven *et al.*, 2005; Arimoro *et al.*, 2007; Carew *et al.*, 2007). Although some methods have been proposed for running waters (Schmid, 1992; Ruse, 1995; Lods-Crozet *et al.*, 2001; Calle-Martinez

and Casas, 2006; Rossaro *et al.*, 2006), previous bioassessment methods based on chironomids were mostly developed for lentic ecosystems such as lakes or reservoirs (Saether, 1979; Wiederholm, 1980; Aagaard, 1986; Rossaro *et al.*, 2007; Hamerlik and Bitusik, 2009). Species abundance patterns deserve special attention when dealing with the structural response of communities to disturbances. Since Chironomidae colonize a very wide range of habitats, and all functional feeding groups are found within the family (Armitage *et al.*, 1995), community patterns in Chironomidae such as species abundance distributions (SADs) could provide useful information for characterizing community responses to stressful conditions in aquatic ecosystems.

Since SADs have been studied by Raunkiaer (1909) and Motomura (1932), numerous research have dealt with various taxa representing marine communities (Gray and Mirza, 1979; Gray, 1981; Hughes, 1984; Magurran and Henderson, 2003), terrestrial plants (del Moral, 1999; Begon *et al.*, 2006; Forster and Warton, 2007) and terrestrial animals (Fisher *et al.*, 1943; Syrek *et al.*, 2006; Ford

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and Lancaster, 2007). Extensive reviews can also be found in May (1975), Tokeshi (1993), Magurran (2004), May *et al.* (2007), and McGill *et al.* (2007).

Regarding chironomid communities, various SAD models have been proposed by Tokeshi (1990, 1993, 1995, 1999), who reported that the random fraction and assortment models were successfully fitted to the chironomid communities based on individual data (Tokeshi, 1990). Using chironomids collected from a large river, Fesl (2002) reported that the observed communities did not fit the various niche-oriented models including the geometric series, whereas the distribution of functional feeding groups in chironomids fitted the random fraction model. In contrast, Ruse (1995) found that the abundance patterns of larval and pupal chironomids from a chalk stream were best described by a log series model. Alternatively, Dimitriadis and Cranston (2007) studied estuarial systems, where abundance patterns of chironomid communities fitted geometric series. SADs were also checked for different life stages. Boerger (1981) collected emerging chironomids from a muskeg stream and reported there were more rare species than expected from Preston's log-normal distribution, while the community pattern, excluding the rare species, did not differ significantly from the log normal model.

Earlier studies on SADs in chironomids have considered the impact of different stream types, covering unpolluted (Schmid, 1992; Ruse, 1995), muskeg (Boerger, 1981) and estuarial (Dimitriadis and Cranston, 2007) ecosystems. Previous research has been also carried out at sites under stressful conditions subjected to organic pollution (Calle-Martinez and Casas, 2006), or sediment clogging (Carew *et al.*, 2007) and river regulation (Penczak *et al.*, 2006). However, these studies mostly aimed at defining indicator groups for a selected range of disturbances (Saether, 1975, 1979; Wiederholm, 1980; Rossaro *et al.*, 2006). No extensive analysis has examined the SADs of chironomids in response to organic pollution, in comparison with total benthic macroinvertebrates. Dimitriadis and Cranston (2007) recently checked the SADs of Chironomidae exposed to a salinity gradient, and reported an overall satisfactory fit was achieved with the geometric series. Recently, the SADs of total benthic macroinvertebrates in polluted streams were evaluated by Qu *et al.* (2008), who found that the SADs were useful for depicting the ecological status of the sampling sites. As a continuation of this study, we investigated the SADs in chironomid communities and compared them with the structural properties of the total communities across different levels of pollution.

## Materials and methods

### Study area

Data sets were built upon benthic macroinvertebrates collected at the 14 sampling sites in six streams (Main channel in the Nakdong River Basin, and streams of

Baenae, Daechon, Onchon, Hakjang, and Kumsan), including one large (Nakdong) and two short (Suyong and Kumsan) river basins in Korea from 2004 to 2008 (Fig. 1, Table 1). The sampling sites represented different levels of pollution (Table 1). An unpolluted site (B; BCN) was selected from the Baenae Stream, a tributary located in the middle course of the Nakdong River Basin. The Baenae stream is located in a mountainous area (Fig. 1) and is relatively unpolluted (see Table 1). However, due to an increase in summer tourism since the 1990's there has been a corollary increase in the level of disturbance (Oh and Chon, 1991a, 1991b, 1993).

The Keumsan stream (three successive sites; S1(KBK), S2(KMI), S3(KUP)) also located in a mountainous area was additionally selected to represent unpolluted conditions (Fig. 1). The Onchon stream originates in a mountainous area and passes through a residential area (Kwak *et al.*, 2002), thus presenting a range of unpolluted (O1; OCU) to polluted sites (O2; ONS) (Table 1). Since the early 2000s, a recovery project has been conducted by the local government in this stream.

The Daechon Stream was selected to reflect the impact of different levels of organic pollution. It is a tributary of Nakdong River Basin that passes through a mountainous area. The middle section of the stream has been heavily polluted by the many restaurants in the area. Two sites (D2 (DDK) and D3 (DKS)) were polluted by domestic sewage (Song *et al.*, 2005; Qu *et al.*, 2008), while D1 (DUK) was unpolluted in the upstream area. The site D4 (DAG), located further downstream from D2 and D3 (Fig. 1), showed a recovering status (see Table 1).

Two streams were selected to represent polluted and severely polluted sites. Four sampling sites (N1 (NSJ), N2 (NKJ), N3 (NJP), and N4 (NMK)) located in the main stream of the Nakdong River Basin represented the polluted state (Table 1). The sampling sites were located in the lower river basin in suburban area. Along with the sampling site in the Baenae Stream, the sample sites in the main channel of the Nakdong River have been surveyed for the national LTER (Long-Term Ecological Research Project in Korea) since 2005.

The Hakjang Stream in the Nakdong River Basin is a tributary of the Nakdong River Basin within Busan city and was selected to represent severe pollution. The site K (HJD) in the Hakjang Stream has been heavily affected by domestic and industrial pollution (see BOD and BMWP values in Table 1). The sampling procedure details were summarized in Table 2. Seasonal samplings were carried out from winter 2004 to spring 2007 in the Daechon and Onchon Streams, while monthly samplings were conducted at sites B, N1 and N2 from March 2005 to August 2008. In total, 176 samples were analysed.

### Community data

Benthic macroinvertebrates including chironomids were collected using a Surber net (sampling area = 30 × 30 cm<sup>2</sup>, mesh size = 100 μm). Three collections mainly

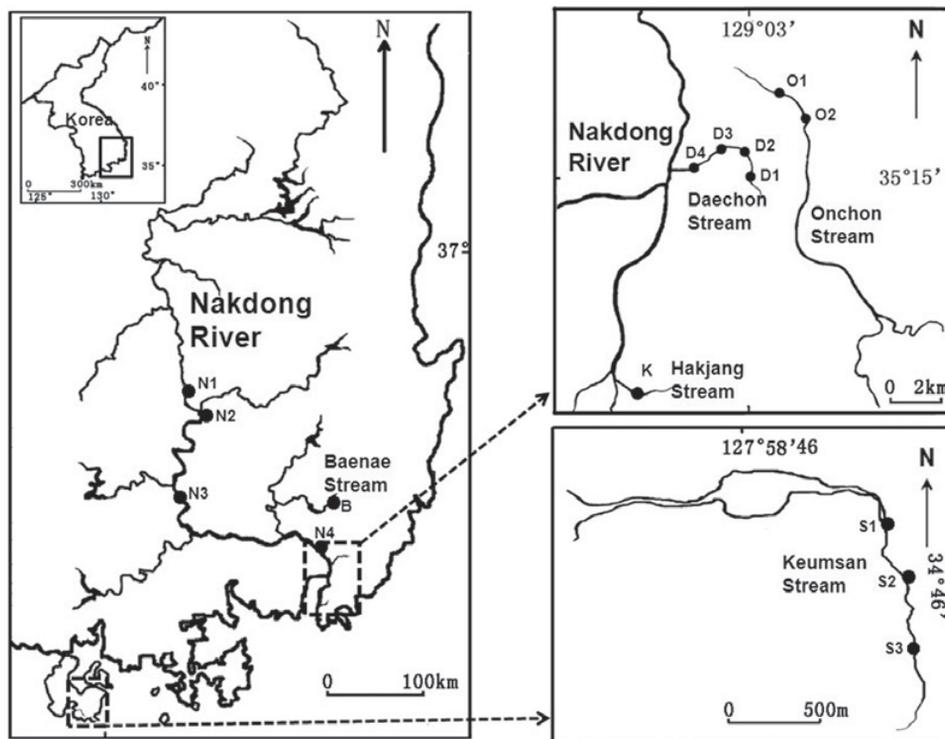


Fig. 1. Location of sample sites in different streams in Korea.

Table 1. Environmental factors, Biological Monitoring Working Party (BMWP), and pollution states at the sample sites.

Streams	Sites	BOD ( $\text{mg}\cdot\text{L}^{-1}$ )	Turbidity (NTU)	Conductivity ( $\mu\text{S}\cdot\text{cm}^{-1}$ )	BMWP*	Pollution level
Baenae	B	$1.15 \pm 0.80$	$0.84 \pm 0.95$	$23.86 \pm 6.66$	121 (68–157)	Low
Keumsan	S1	$2.23 \pm 0.25$	$0.65 \pm 0.39$	$31.79 \pm 14.69$	111 (87–131)	Low
	S2	$3.41 \pm 1.60$	$0.69 \pm 0.70$	$48.06 \pm 29.76$	121 (96–162)	Low
	S3	$3.17 \pm 0.51$	$1.11 \pm 1.60$	$33.00 \pm 20.37$	111 (93–130)	Low
Daechon	D1	$2.02 \pm 2.34$	$5.54 \pm 8.54$	$41.36 \pm 7.66$	110 (61–180)	Low
	D2	$6.88 \pm 5.68$	$4.16 \pm 3.97$	$176.76 \pm 73.21$	37 (17–52)	Intermediate
	D3	$4.52 \pm 3.36$	$2.87 \pm 2.31$	$211.90 \pm 97.31$	43 (15–76)	Intermediate
	D4	$2.56 \pm 1.63$	$0.96 \pm 0.78$	$161.03 \pm 75.16$	76 (44–116)	Intermediate
Onchon	O1	$2.75 \pm 1.70$	$2.43 \pm 1.31$	$72.82 \pm 43.29$	128 (95–162)	Low
	O2	$3.78 \pm 2.68$	$7.72 \pm 10.41$	$237.51 \pm 147.3$	41 (24–54)	Intermediate
Nakdong	N1	$9.84 \pm 4.75$	$12.01 \pm 10.28$	$311.95 \pm 56.21$	52 (20–75)	High
	N2	$8.70 \pm 5.49$	$10.90 \pm 12.01$	$316.25 \pm 64.73$	40 (35–50)	High
	N3	$7.38 \pm 6.81$	$10.03 \pm 6.21$	$452.25 \pm 107.17$	53 (30–82)	High
	N4	$8.89 \pm 6.64$	$17.61 \pm 26.42$	$329.29 \pm 120.78$	26 (7–50)	High
Hakjang	K	$31.80 \pm 23.86$	$12.92 \pm 9.03$	$480.44 \pm 189.20$	19 (9–36)	Extreme

\* Number in parenthesis is range.

covering riffle zones were conducted as replicates at each site. Chironomid samples were sorted from the benthic macroinvertebrates and preserved in 85% alcohol in the laboratory. The larvae were further hand sorted under a stereo-microscope and counted separately. For coarse identification, sorted individuals were classified into several possible species groups based on similar morphological characters; such as body seta, body color, body shape, the location of eye, etc. Subsequently, at least 1–5 individuals from each possible species groups were picked out and dissected into head and body to mount into slides by CMC-10 solution (Master Company, Inc., Illinois). Fine classification was conducted under the compound micro-

scope by checking the mounted slides. In most cases the specimens were identified to species or to the lowest possible taxonomical level following the keys of Sasa (1979, 1984), Ree and Kim (1981), Cranston (1982), Wiederholm (1983, 1986), Sasa and Kikuchi (1995), Epler (2001), Klink and Moller Pillot (2003), Langton and Visser (2003), Wilson and Ruse (2005), Nittsuma and Yamamoto (2005) and Tang (2006). Part of the adult samples collected by sweep net or reared in the lab and the pupal samples collected at the same place were further used to confirm the larval status.

As many researchers have mentioned, classification of all collected larvae is practically impossible (Kawai *et al.*,

**Table 2.** Sampling methods and description of the sample areas.

Streams	Sites	Sampling frequency	Sampling periods	No. of samples	Area
Baena	B	Monthly	May., 05–Aug., 08	31	Mountain
Keumsan	S1	Seasonal	Spr., 07–Aug., 08	7	Mountain
	S2	Seasonal		7	Mountain
	S3	Seasonal		7	Mountain
	S4	Seasonal		7	Mountain
Daechon	D1	Seasonal	Win., 04–Spr., 07	11	Residence/Mountain
	D2	Seasonal		11	Residence/Mountain
	D3	Seasonal		11	Residence/Mountain
	D4	Seasonal		11	Residence/Mountain
Onchon	O1	Seasonal	Win., 04–Spr., 07	11	Mountain
	O2	Seasonal		11	Residence
Nakdong	N1	Monthly	Mar., 05–Aug., 08	14	Suburban
	N2	Seasonal	Spr., 05–Spr., 06	4	Suburban
	N3	Seasonal	Spr., 05–Spr., 06	4	Suburban
	N4	Monthly	Mar., 05–Mar., 08	25	Suburban
Hakjang	K	Seasonal	Win., 04–Spr., 07	11	Industry

1989; Rabeni and Wang, 2001), since there are numerous specimens with small-sized individuals. Subsampling was conducted if the number of individuals of some samples exceeded 300, according to Barbour *et al.* (1999). In each subsample, 100–300 individuals were identified for this study.

A biological index, the revised BMWP (Hawkes, 1997), was used to characterize the sites according to the identified communities. Environmental variables were also measured at each sampling time during the collection of communities. Water temperature ( $^{\circ}\text{C}$ ), dissolved oxygen (DO,  $\text{mg}\cdot\text{L}^{-1}$ ), conductivity ( $\mu\text{S}\cdot\text{cm}^{-1}$ ), turbidity and other environmental factors were measured *in situ* with multifunction probes. BOD<sub>5</sub> was checked according to Standard Methods (APHA, AWWA and WPCF, 1985).

### Data analysis – Species abundance distribution (SAD)

Considering that not all small chironomid larvae can be identified, we chose models that are robust when dealing with missing rare species. In this regard the log normal distribution (Preston, 1948; May, 1975) and the power law (Pueyo, 2006b) were used for analysis. The truncated log normal distribution assumes that rare species are not fully surveyed during the sampling, and the model would show a truncated pattern in the lower side of octaves in abundance (Preston, 1948; May, 1975; Magurran, 2004). Consequently, this model could be applicable when small and rare species are not extensively collected.

The log normal distribution (Preston, 1948; May, 1975) presents frequency of species arranged on the logarithm scale of species abundance in the normal distribution:

$$S(R) = S_0 \exp(-a^2 R^2) \quad (3)$$

where  $S(R)$  is the number of species in the  $R$ th octave (*i.e.* class) in abundance to the right and left of the symmetrical curve and  $S_0$  is the number of species in the modal octave. Parameter  $a$  indicates the inverse width of the distribution:  $a = (2\sigma^2)^{-1/2}$  where  $\sigma$  is the standard deviation of the

observed values after taking the logarithm (Preston, 1948; May, 1975). In this study, the truncated log normal distribution was used to fit the community data based on Magurran (2004). After estimation of the parameters, the Kolmogorov-Smirnov test (Sokal and Rohlf, 1995) was used to check fitness of field data in the benthic invertebrate communities (Qu *et al.*, 2008).

The universality residing in the power law has been demonstrated to reveal structural properties in the sampled communities. In the power law analysis, the slopes between species and log abundance could be represented by excluding the maximal or minimal ranges in abundance (Pueyo, 2006b). The power law is based on the following relationship (Pueyo, 2006a, 2006b):

$$p(n) \propto n^{-\beta} \quad (4)$$

where  $p(n)$  is the probability density of  $n$  individuals in communities, and  $\beta$  is a constant. According to Pueyo (2006b),  $p(n)$  is replaced with  $f(n)$  as a continuum of probability densities, and the value in each bin  $j$  was estimated in our study as:

$$f(n_j) = \frac{1}{2^j} \frac{s_j}{S} \quad (5)$$

where  $s_j$  is the number of species in bin  $j$  for the abundance class (in this case, interval = 2),  $2^j$  indicates the width of bin  $j$ , and  $S$  is the total number of species. For each bin  $j$  the (logarithmically) central value is  $n_j = 2^{j+1/2}$ . The maximum likelihood estimation was used to estimate the  $\beta$  values. The detailed method can be found in Pueyo (2006b) and Qu *et al.* (2008).

Two other traditional models widely used in analyzing SADs are the geometric and log series. We also checked the models for comparative purposes. In the geometric series species abundance, ranked from most to least abundant, is expressed as (Motomura, 1932; May, 1975; Magurran, 1988, 2004):

$$n_i = NC_k (1 - k)^{i-1} \quad (1)$$

where  $n_i$  is the number of individuals in the  $i$ th species,  $k$  is the proportion of the available resource that each species

**Table 3.** The chironomid subfamilies/tribes composition across different levels of pollution.

Pollution level	Subfamilies (%)*					Dominant species		
	Podo. %	Tany. %	Diam. %	Ortho. %	Chiro. %	1st	2nd	3rd
Low	0.09	9.38	0.14	46.13	44.26	<i>Tanytarsus brundini</i>	<i>Parametrioctenus stylatus</i>	<i>Polypedilum surugense</i>
Inter-mediate	0	7.43	4.72	50.02	37.83	<i>Chironomus flaviplumus</i>	<i>Micropsectra atrofasciatus</i>	<i>Orthocladius yugashimaensis</i>
High	0	2.75	1.06	36.43	59.76	<i>Cricotopus triannulatus</i>	<i>Polypedilum cultellatum</i>	<i>Tanytarsus mendax</i>
Extreme	0	0	0	3.93	96.07	<i>Chironomus flaviplumus</i>	<i>Paratrachocladus rufiventris</i>	-

\* Podo.: Podonominae, Tany.: Tanyopodinae, Diam.: Diamesinae, Ortho.: Orthocladiinae, Chiro.: Chironominae.

utilizes,  $N$  is the total number of individuals, and  $C_k$  is a constant ensuring  $\sum n_i = N$  (see Magurran, 2004).

The log series originally proposed by Fisher *et al.* (1943) is presented as:

$$\alpha x, \frac{\alpha x^2}{2}, \frac{\alpha x^3}{3}, \dots, \frac{\alpha x^n}{n} \quad (2)$$

where  $\alpha$  is the index of diversity,  $n$  is species sequence from the minimum to the maximum, and  $x$  is estimated from the iterative solution of  $S/N = (1-x)/x[-\ln(1-x)]$  ( $S$ , the total number of species, and  $N$ , the total number of individuals).

The SAD models proposed for Chironomidae (Tokeshi and Townsend, 1987; Tokeshi, 1990) were also tested using the chironomids sampled in this study. The random fraction (RF) model was the basic concept for this type of model, and various models were subsequently created to accommodate diverse situations in niche preemption. In the RF model all species in an assemblage have the same probability of being selected for subsequent niche division by other invading species. The niche is first divided at random into two fractions, one of which is randomly chosen and divided at random into further two fractions. This type of fractioning continues to produce more fractions until niche space for the species with the lowest rank is formed (Tokeshi, 1990). The random assortment model (RF) refers to a situation where abundances of different species are not mutually related. Niche space is restricted in size only by its immediate, larger neighbor on the niche-rank axis. This relationship can be expressed as:

$$N_i = 1$$

$$N_i = r_i N_{i-1} \quad (i, \text{ integer greater than } 1)$$

where  $N_i$  is the niche size (abundance) of rank  $i$  and  $r_i$  is an independent uniform random variable between 0 and 1 (Tokeshi, 1990).

The dominance decay (DD) model refers to a situation where new species always take a portion of niche space already occupied by the most dominant species (Fesl, 2002). Consequently the model is conducted toward the negation of dominance and converges towards equitable abundances of constituent species (Tokeshi, 1990).

The RF, RA and DD models were applied to the field data. For fitting the models to the field data, 10 000 assemblages were simulated in accordance with the number of species collected in the field. The 95% confidence limits

were obtained from the simulation models and were used for checking the field data. The detailed method can be found in Tokeshi (1990), Fesl (2002) and Magurran (2004).

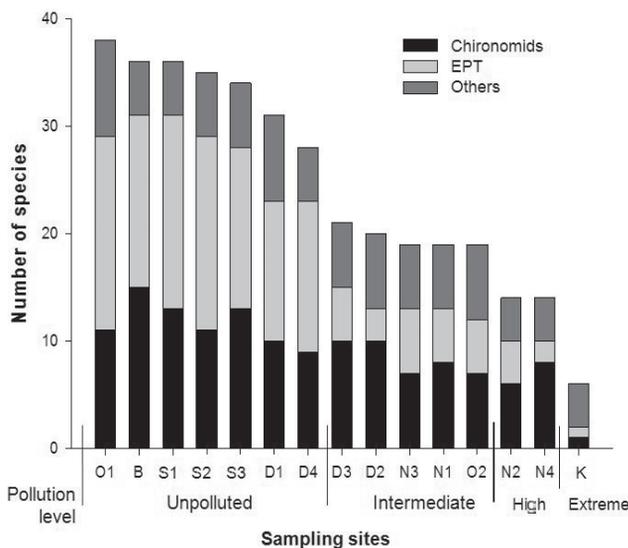
## Results

### Composition of chironomid communities

In total, 85 chironomid species were collected during the survey periods, including one species from the subfamily Podonominae, nine Tanyopodinae, four Diamesinae, 36 Orthocladiinae, and 35 Chironominae. Subfamily composition was clearly differentiated across the various levels of pollution (Table 3). At the unpolluted sites, Orthocladiinae were most dominant, followed by Chironominae. This was contrasted with the polluted sample sites, where Chironominae were distinctively dominant. At the severely polluted site, Chironominae abundance was extremely high (> 96.7%), while dominance of Chironominae decreased to 59.8%, followed by Orthocladiinae with 36.4% at the highly polluted sites (Table 3). At sites with intermediate levels of pollution Orthocladiinae were the most dominant followed by Chironominae, which was similar to the case of unpolluted sites (Table 3). Tanyopodinae and Podonomiinae were present at low densities across the different levels of pollution during the study periods.

Dominant species were variable with different levels of pollution (Table 3). Sites with low levels of pollution, for instance, were characterized by the following dominant species: *Tanytarsus brundini*, *Parametrioctenus stylatus* and *Polypedilum surugense*. *Cricotopus triannulatus*, *Polypedilum cultellatum* and *Tanytarsus mendax* were dominant at sites with high levels of pollution. At the most severely polluted site, K, *Chironomus flaviplumus* and *Paratrachocladus rufiventris* were selectively dominant.

Figure 2 outlines species richness for all species, the chironomid, and EPT (Ephemeroptera, Plecoptera and Trichoptera) communities across the different levels of pollution. The sample sites were arranged according to the order of total species richness from left to right in the figure. The first group in the left-hand side of Figure 2, from site O1 to D4 (unpolluted state) showed the highest total species richness at close to 40. Species richness in chironomids was a little over 10. A substantial EPT



**Fig. 2.** The number of species collected in total, chironomid and EPT across different levels of pollution (monthly averages).

richness was observed in this group. The number of species was a little higher (15–20) than for chironomids.

The second group of sites, with intermediate pollution, showed a lower species richness in total communities, with around 20 species. The number of chironomid species, however, remained around 10. It was notable that EPT richness decreased substantially ( $< 5$ ). The polluted sites showed lower species richness (around 15 species) and lower EPT richness (2–3). The decrease in species richness for total communities at the intermediately polluted sites was mainly caused by the decrease in EPT species.

At the polluted sites total species richness decreased further to around 10 on average. The number of chironomid species, however, was fairly stable from clean to polluted sites with around 10 species. At the extremely polluted site (K), located in the far right-hand side of Figure 2, richness decreased greatly to a minimum of seven species. Chironomid richness also decreased to three species, and only a few EPT species were collected.

### 3.2. SADs in total and chironomid communities

SAD was compared between chironomid and total macroinvertebrate communities. The number of species was presented according to the individuals in the octaves using  $\log_2$  for both total benthic macroinvertebrates and chironomids (Fig. 3). The patterns between the two communities were characteristically different. For the total communities, most curves showed truncated patterns at the unpolluted sites: relatively higher levels of the number of species were observed at the minimal range of octaves (the far left hand side of the plots in Fig. 3). At the intermediately polluted sites, however, the truncated pattern was not clear, and the number of species was mostly in the maximal range at the minimum level of the octaves (*i.e.*, left hand side of the figure) (*e.g.*, N1–N4 in Fig. 3).

In chironomids, however, the SADs were substantially different from the total communities (Fig. 3). The truncated patterns were usually not observed: the minimal number of species was found at the minimal range of octaves. The number of species gradually increased with the increasing level of octaves, and subsequently decreased after the level of octaves reached the peak in the middle area of the octaves. These patterns in chironomids were similarly observed across the different levels of pollution, although the height of peaks tended to decrease for the polluted sites. At the extremely polluted site, K, this trend was not observed for chironomids. Only three species were recorded at this site.

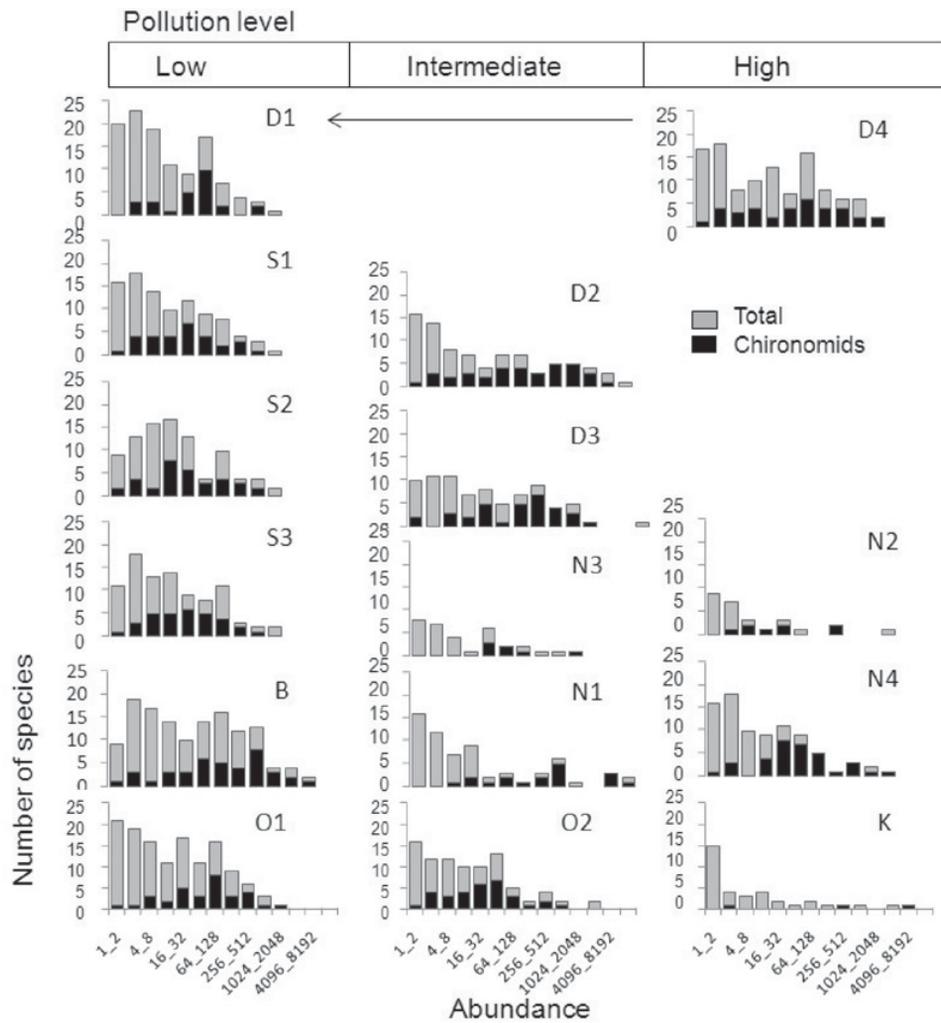
### Model fitting

When the log normal model was applied to total communities and to chironomid communities according to Magurran (2004), all samples were statistically fitted to this model for both total and chironomid communities (Table 4). The other models, however, were selectively accepted. The geometric series was mostly rejected using samples from total communities, while the model was mostly accepted using the chironomid communities across the different levels of pollution. The log series showed the reverse situation: the model was mostly rejected for the chironomid communities while the model was accepted using the majority of the total communities (Table 4). It was notable that the severely (K) and highly polluted (*e.g.*, D2–D3, N1–N4) sites were not acceptable using the geometric series for the total communities. This study, however, further showed that the geometric series was fitted to the chironomid communities.

The parameters  $a$  and  $\gamma$  in the log normal distribution were also obtained across different levels of pollution (Table 5). The  $a$  and  $\gamma$  values were in the range around 0.2 (0.175–0.291) and 1.0 (0.672–1.207) respectively (Table 5). In chironomid communities the  $a$  values were consistently higher than in the total communities across different levels of pollution ranging from 0.146–0.377. The parameter  $a$  represents inverse of width of distribution ( $a = (2\sigma^2)^{-1/2}$ ) (May, 1975; May and McLean, 2007). The increase in  $a$  values reflected that the chironomid communities had a relative low range in distribution of the octaves.

In both total and chironomid communities, however, the  $a$  values did not show differentiation in responding to different levels of pollution. However, the severely polluted site (*e.g.*, K; 0.175) showed the lowest value. The occurrence of the low value for this site would be exceptional since the level of species richness was extremely low (Fig. 3).

In contrast to the  $a$  values, the  $\gamma$  values differed according to the different levels of pollution. In total communities, the  $\gamma$  values tended to increase from unpolluted (*e.g.* Baena Stream, Keumsan Stream, O1 in Onchon stream; 0.707–0.853) to polluted sites (*e.g.*, Hakjang Stream, Main stream in the Nakdong River Basin, D2 and D3; 0.755–1.207) (Table 5). The increase in the



**Fig. 3.** The number of species related to abundance in octaves for total and chironomid communities across different levels of pollution in streams.

**Table 4.** Statistical values of Kolmogorov-Smirnov test for goodness of fit for the SAD models applied to total and chironomid communities.

Streams	Sites	Log normal		Geometric series		Log series	
		Total	Chironomid	Total	Chironomid	Total	Chironomid
Baenae	B	0.0575	0.0759	0.2028**	0.0842	0.0409	0.2336**
Keumsan	S1	0.0388	0.0823	0.2165**	0.0427	0.0444	0.2043**
	S2	0.0381	0.0758	0.2109**	0.0766	0.0496	0.1929**
	S3	0.0238	0.0392	0.2385**	0.0949	0.0385	0.1839*
Daechon	D1	0.0380	0.0577	0.2770**	0.1613	0.0723	0.3145**
	D2	0.0510	0.0898	0.2020**	0.1122	0.1024*	0.1980**
	D3	0.0543	0.1453	0.5208**	1.0001**	0.0775	0.2470**
	D4	0.0445	0.0947	0.1651**	0.0383	0.0340	0.1579*
Onchon	O1	0.0354	0.0314	0.1787**	0.0688	0.0235	0.2312**
	O2	0.0243	0.0448	0.4288**	0.1608*	0.1176**	0.1536
Nakdong	N1	0.0690	0.0993	0.3649**	0.0548	0.2363**	0.2489**
	N2	0.0733	0.2610	0.4954**	0.0883	0.2703**	0.1541
	N3	0.0633	0.2385	0.3361**	0.3737*	0.0958	0.4884**
	N4	0.0154	0.0780	0.3803**	0.1269	0.0768	0.2640**
Hakjang	K	0.1094	0.4821	0.6146**	0.0228	0.3526**	0.2774

\*Significant ( $\alpha = 0.05$ ).

\*\*Highly significant ( $\alpha = 0.01$ ).

**Table 5.** Parameters in the log normal distribution in total and chironomid communities in different streams.

Streams	Sites	Total			Chironomid		
		$D_{\max}$	$a$	$\gamma$	$D_{\max}$	$a$	$\gamma$
Baena	B	0.0575	0.237	0.853	0.0759	0.254	0.947
Keumsan	S1	0.0388	0.285	0.716	0.0823	0.345	0.721
	S2	0.0381	0.285	0.722	0.0758	0.305	0.789
	S3	0.0238	0.288	0.707	0.0392	0.343	0.754
Onchon Daechon	O1	0.0354	0.254	0.781	0.0314	0.292	0.823
	O2	0.0243	0.250	0.834	0.0448	0.304	0.816
	D1	0.0380	0.291	0.672	0.0577	0.377	0.606
	D2	0.0510	0.192	1.083	0.0898	0.228	1.197
Nakdong	D3	0.0543	0.222	1.010	0.1453	0.250	0.994
	D4	0.0445	0.229	0.890	0.0947	0.240	1.077
	N1	0.0690	0.193	1.080	0.0993	0.245	1.114
	N2	0.0733	0.266	0.878	0.2610	0.324	1.284
Hakjang	N3	0.0633	0.260	0.924	0.2385	0.410	0.806
	N4	0.0154	0.270	0.755	0.0780	0.305	0.787
	K	0.1094	0.175	1.207	0.4821	0.146	-

$\gamma$  values at the polluted sites was also observed in chironomid communities (Table 5). For the clean sites the value ranged between 0.606–0.947, while the values were higher at the polluted sites with a range from 0.787–1.284. The  $\gamma$  values ( $R_N/R_{\max}$ ) indicate the ratio of the octave for the most abundant species ( $R_{\max}$ ) in species curve and the modal octave ( $R_N$ ) in individual curve (May and McLean, 2007). While the  $a$  values were higher for chironomids, the  $\gamma$  values in chironomid communities were similar (0.606–1.284) to the  $\gamma$  values in total communities (0.672–1.207).

### Power law analysis

As stated previously, the power law as proposed by Puyco (2006b) is robust in dealing with rare species. According to the maximum likelihood method, the  $\beta$  values were generally in the higher range (1.29–1.49) for total benthic macroinvertebrate communities (Table 6). No clear difference was observed for the different levels of pollution. In chironomids, however, the values were consistently lower compared with the unpolluted sites, ranging from 0.87–1.27 with the exception of one sampling site, N3. The low levels of slopes indicated that the proportion of the medium range in log abundance was relatively higher in chironomid communities. This is understandable when considering that the number of species was relatively higher in the mid range of the octaves in chironomids (Fig. 3). Similar to the case for the total communities, differences in the values was not clearly observed for different pollution levels for chironomid communities (Table 6).

At site N3 the  $\beta$  value was exceptionally high at 1.61. This was due to the exceptional dominance by the selected chironomid species at site N3. The density of the primary dominant species was 781 individuals.m<sup>-2</sup>, while density of the secondary dominant species was exceptionally low at 76 individuals.m<sup>-2</sup>. The density of the least abundant species was also low at 19 individuals.m<sup>-2</sup>. This discrepancy in densities among species contributed to the

increase in  $\beta$  values at N3. Considering the field sampling conditions, this might be an exceptional case.

In fact, the  $\beta$  values were exceptionally variable at sample sites in the main channel of the Nakdong River (site N1–N4). While the values were in the minimal range, between 0.87–0.93 at site N1 and N2, the values at site N3 and N4 were maximal at 1.25–1.61. This indicated that community structure was exceptionally variable in chironomid communities in this area compared with other areas.

The  $\beta$  values calculated from the linear regression appeared to decrease slightly for both chironomid and total communities when compared to values obtained from the maximum likelihood estimation (Table 6). The variability in the values among the sample sites was similar. In case of the sample sites in the main channel of the Nakdong River (N1–N4), however, the difference in the  $\beta$  values within the channel tended to slightly decrease compared with the case from the maximum likelihood estimation.

### Testing proposed SADs for chironomids

Considering the unique position of chironomids in benthic macroinvertebrate communities, the selected models were specifically tested using Chironomidae. At unpolluted sites, the deduced decay (DD) model tended to slightly overestimate the species numbers, however, the model appeared to be most suitable for field data compared to the other models (Fig. 4). The random fraction (RF) and random assortment (RA) tended to underestimate the values of species numbers at unpolluted sites (Fig. 4). The DD model tended to overestimate the number of species for the low ranking (*i.e.* low abundance) species (*e.g.*, sites S3, D1, O1). The results from RF and RA models showed the increase in discrepancy as the rank decreased (right side on the  $x$  axis in the figure).

At intermediate to highly polluted sites, however, the suitability of the models appeared to change. At intermediate pollution level the distance between the field data and model results were similar. The DD models tended to

**Table 6.** Statistics of power law analysis applied to SAD models in total and chironomid communities in different streams.

Streams	Sites	Total						Chironomids						Excluding Chironomids					
		Maximum likelihood estimation			Linear regression			Maximum likelihood estimation			Linear regression			Maximum likelihood estimation			Linear regression		
		N	S	$\beta$	95% C.I.*	$R^2$	N	S	$\beta$	95% C.I.	$R^2$	N	S	$\beta$	95% C.I.	$R^2$	N	S	$\beta$
Baena Keumsan	B	23179	135	1.29	1.17–1.40	1.21	0.98	12437	40	1.09	0.85–1.33	0.95	0.92	10742	95	1.36	1.18–1.53	1.33	0.97
	S1	4039	95	1.46	1.35–1.56	1.39	0.98	1413	30	1.23	0.92–1.53	1.05	0.9	2626	65	1.50	1.39–1.60	1.43	0.98
	S2	5442	92	1.37	1.22–1.52	1.28	0.97	2082	34	1.17	0.89–1.44	1.01	0.94	3360	58	1.44	1.25–1.63	1.33	0.95
Onchon	S3	4172	91	1.37	1.23–1.52	1.34	0.98	1500	32	1.23	0.91–1.54	1.04	0.89	2672	59	1.47	1.33–1.62	1.39	0.97
	O1	9539	130	1.41	1.29–1.52	1.34	0.97	4984	32	1.16	0.89–1.43	0.97	0.90	4555	98	1.42	1.33–1.52	1.36	0.99
	O2	10282	88	1.37	1.28–1.47	1.31	0.99	2566	32	1.27	1.02–1.52	1.10	0.93	7716	56	1.40	1.29–1.52	1.33	0.98
Daechon	D1	4231	114	1.49	1.38–1.61	1.43	0.98	1359	26	1.14	0.62–1.66	1.00	0.84	2872	88	1.55	1.45–1.64	1.49	0.99
	D2	26504	84	1.30	1.22–1.38	1.23	0.99	13963	36	1.05	0.85–1.25	0.95	0.95	12541	48	1.33	1.23–1.43	1.24	0.97
	D3	25252	79	1.32	1.23–1.42	1.26	0.98	6967	33	1.14	0.91–1.37	1.00	0.92	18285	46	1.32	1.24–1.40	1.28	0.99
Nakdong	D4	14092	111	1.30	1.17–1.42	1.21	0.98	7920	36	1.04	0.82–1.25	0.97	0.95	6172	75	1.34	1.17–1.50	1.26	0.99
	N1	22886	65	1.33	1.18–1.48	1.23	0.96	15269	18	0.98	0.78–1.18	0.93	0.94	7617	47	1.47	1.31–1.63	1.37	0.97
	N2	1488	27	1.39	1.17–1.60	1.28	0.96	353	8	0.87	0.52–1.23	0.87	0.95	1135	19	1.39	1.07–1.71	1.28	0.95
Hakjang	N3	1830	33	1.44	1.29–1.60	1.33	0.97	994	7	1.61	0.98–2.24	1.30	0.98	836	26	1.48	1.30–1.65	1.39	0.97
	N4	5137	85	1.47	1.37–1.58	1.41	0.98	4234	34	1.25	1.02–1.48	1.10	0.91	903	51	1.56	1.44–1.69	1.49	0.99
	K	77923	37	1.37	1.25–1.48	1.27	0.98	7197	3	0.93	0.61–1.25	1.00	1.00	70726	34	1.39	1.24–1.54	1.29	0.98

\* 95% confidence interval.

overestimate the species numbers, while the RF and RA models underestimated the value similar to what is shown in the DD model results. For the RF and RA models, however, one case matched well to field data (*i.e.*, site O2), while the DD model still overestimated at this sample site (Fig. 4).

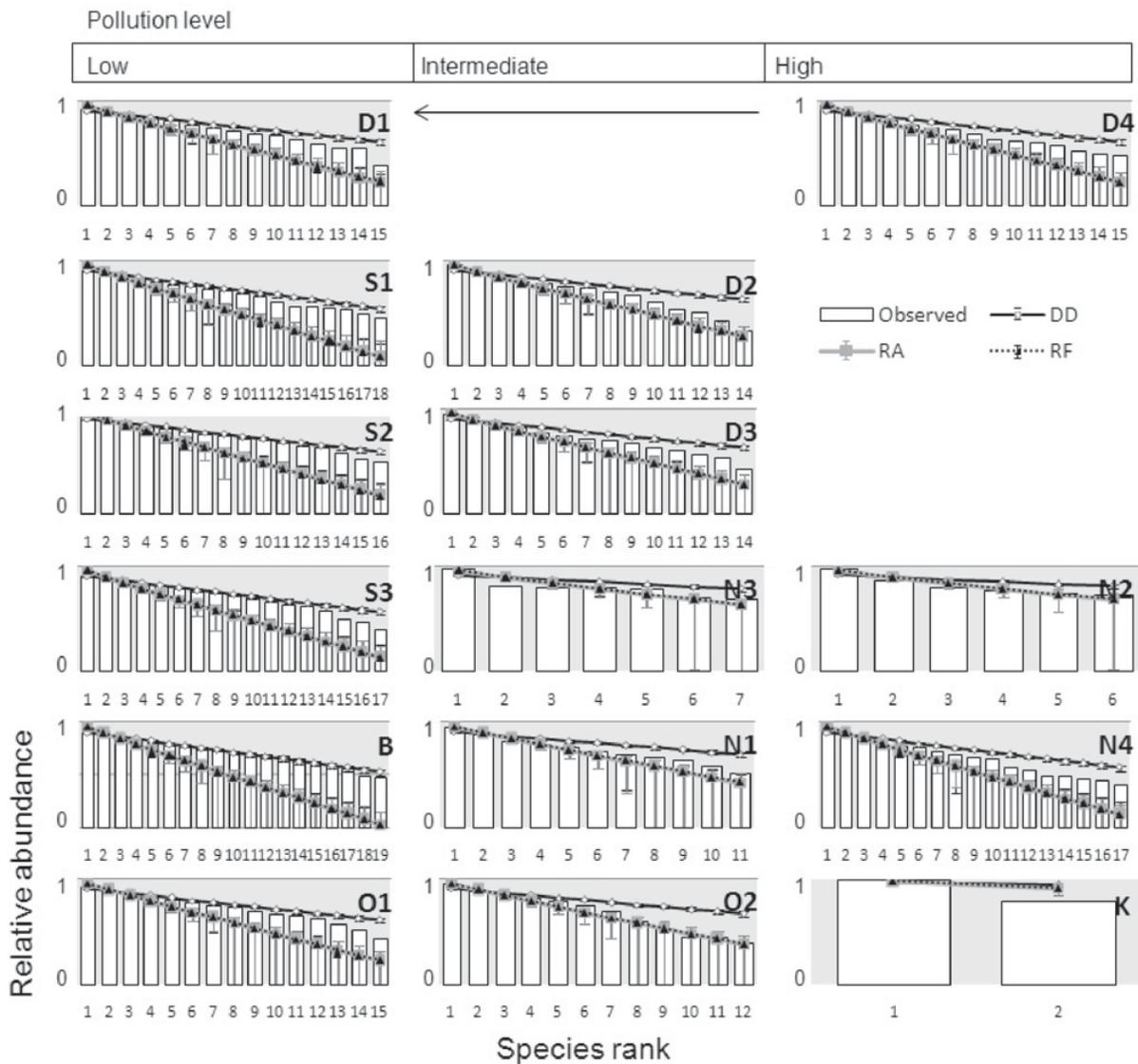
At highly polluted sites, the RF and RA models appeared to be more suitable for the field data than the DD model. While the DD model still overestimated the number of species at most sample sites, the RF and RA models were closer to the field data as shown at site N2 (Fig. 4). At site N4, however, results from all models did not agree with the field data. At the severely polluted site, K, the three models were similar with each slightly overestimating the number of individuals of the secondary dominant species. The number of species was exceptionally low in this case, and results may need confirmation from more sample sites in similar conditions (Fig. 4). The relative abundance obtained from the RF and RA models were similar across the different levels of pollution.

### Discussion

Our results demonstrated that SADs as applied to both total macroinvertebrates and chironomids could efficiently reveal structural changes in communities in response to disturbance. The distinctive appearance of dominant species (Table 3) was in accordance with previous studies defining the indicator groups as they relate to the different habitat conditions (Saether, 1979; Wiederholm, 1980; Hellawell, 1986; Calle-Martinez and Casas, 2006; Penczak *et al.*, 2006; Rossaro *et al.*, 2006; Carew *et al.*, 2007). For both total and chironomid communities the log normal model appeared most suitable. Although this model would not identify the dynamic processes in community development, the model was confirmed again to be widely fitted to field data (Diserud and Engen, 1999; Magurran, 2004; May *et al.*, 2007).

In the study of chironomids, identification of all specimens is a problematic issue. The collection of chironomids required a dense mesh 100–200  $\mu\text{m}$  in size and numerous small-sized individuals are frequently collected, while missing some small individuals is unavoidable (Storey and Pinder, 1985; Tokeshi, 1995). Although chironomid larvae play an important role in the benthic fauna, taxonomic difficulty often forces the investigators to treat them at higher levels, most often covering the (sub)-family or tribe (Armitage and Blackburn, 1985; Hilsenhoff, 1988), genus (Balloch *et al.*, 1976; Warwick, 1993), or uncertain classified species (Kwon and Chon, 1991; Youn and Chon, 1999).

Since application of the truncated log normal distribution assumes insufficient sampling of rare species, the model was suitable for checking the SADs in chironomids. Overall fitting to log normal distribution in total communities and the selected acceptance with the geometric and log series were generally in accordance with results from Qu *et al.* (2008).



**Fig. 4.** Comparison of SAD models applied to abundance (normalized) in relation to the rank of species in chironomid communities across different levels of pollution in streams. Low, intermediate, and high and severe levels in pollution (vertical bars shown with the model curves indicating 95% confidence intervals).

This study also showed that the parameters in the log normal distribution would present the structural differences in communities responding to pollution. The  $\gamma$  values in the log normal model tended to increase for polluted sites in both total and chironomid communities. The increase in  $\gamma$  values implied that the tolerant species were selectively adapted to polluted conditions and became increasingly dominant. Consequently, the tendency for dominance would be stronger at polluted sites as increase in the  $\gamma$  values suggested.

The structural difference between the total benthic macroinvertebrates and chironomid communities in the richness-abundance (in octave) relationships may have originated from sample collection issues (Fig. 3). The species number was characteristically high for the low abundance in the total communities. In total communities, there are numerous taxa besides Chironomidae, and there would

be a higher chance of rare species being present. Drifting would be a source of rare species in streams. Trichoptera, especially Hydropsychidae, were most frequently collected in small numbers (1–2 individuals) over a broad range at unpolluted sites. Ephemeroptera, including Ephemeridae and Ephemerellidae, were also often observed at the intermediately and highly polluted sites in minimal numbers. Considering that these species in Ephemeroptera and Trichoptera are usually found in unpolluted areas, the species may have drifted down from upstream and could contribute to the increase in number of species with low numbers in total communities (Fig. 3). At polluted sites, the species from upstream were also found in low abundance including 1–2 rare species from the Ephemeroptera, Diptera and Trichoptera. Besides insect species, species in Hirudinea were also widely collected in minimal numbers from intermediate to extremely polluted sites.

In this study,  $\beta$  values in the Power analysis were not highly variable between the different levels of pollution. In Qu *et al.* (2008), the  $\beta$  values increased at recovering sites. The parameters were measured at one site at different times in this case, reflecting the recovery of water quality. In this study, however, this type of parameter change was not observed. The  $\beta$  values may be variable depending upon the diversity of habitat conditions at sample sites. More consideration is needed to check community response and the scale free structure in communities in the future.

The change in suitability of the DD, RF and RA models to different levels of pollution was also noticeable. While the DD model was more fitted to unpolluted sites, the RF and RA models tended to be more suitable for polluted sites (Fig. 4). This indicated that random effects would play an important role in disturbing conditions. Tokeshi (1987) also mentioned that random effects would contribute greatly in determining species abundance of chironomids. At site N4 (also highly polluted), however, all the models did not fit the field data (Fig. 4). Communities collected at N4 were exceptional. Some species with the lower modal octave in individual curves were more frequently collected and consequently the octave for  $R_N$  was lower than the octave for  $R_{max}$ : about eight species with lower octave ( $17\text{--}32 \text{ individuals.m}^{-2}$ ) including *Chironomus flaviplumus*, *Cryptochironomus rostratus* and *Tanytarsus mendax* were abundantly collected at N4. In this case  $R_{max}$  usually belonging to the octave was  $33\text{--}64 \text{ individuals.m}^{-2}$ . This contributed to a decrease in the  $\gamma$  values (Table 5), indicating that some species ranked at low–intermediate levels were abundantly collected. This type of species distribution was not suitable for applying the proposed SAD models for chironomids.

The DD model, however, was useful at unpolluted sites. In this case the degree of niche preemption may be not strong since the DD model supports negation of dominance (Tokeshi, 1990). This indicated that dominance was unfavorable and niche division occurred for the most dominant species. Further research is required in checking how the subdivision pattern of niche will occur in aquatic conditions in this study. In fact, a wide variety of SAD models have been proposed including random fraction or assortment (Tokeshi, 1990, 1993, 1999; Fesl, 2002), log series (Ruse, 1995), geometric series (Dimitriadis and Cranston, 2007). This indicated that chironomid communities would show diverse SAD patterns in adapting to competition for resources and for environmental disturbances at study sites. Our study confirmed a wide variety in SADs, including the DD model adaptable to unpolluted sites. The mechanism of niche sharing among the residing species, however, needs to be further considered.

## Conclusions

Comparative studies on SADs between total macroinvertebrates and chironomids were useful in revealing structural properties in communities responding to disturbance. The number of rare species was relatively higher

in total communities, while the number of rare species was low and gradually increased to peak in the middle ranges of octaves in chironomid communities. Both total and chironomid communities were fitted to the log normal distribution, and the change in parameter ( $\gamma$ ) would be useful for community structure in diagnosing polluted sites. When the models proposed for chironomids were tested, the most suitable model was the DD model for clean conditions. The suitability changed to RF and RA models for polluted sites, indicating an increase in randomness of community establishment in disturbed conditions. Comparative studies of SADs in chironomids and macroinvertebrates would provide significant insight into changes in community structure and ecological assessment of water quality.

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