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Inferring pollution states based on community structure of Benthic Macroinvertebrates in streams

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Abstract – Species abundance distributions (SADs) are an efficient means of assessing community structure to define macroecological states and ecological integrity in responding to environmental impacts. Rank abundance distributions of benthic macroinvertebrate communities collected from streams with different levels of pollution in Korea were obtained and used to confirm water quality classification based on empirical assessment. The pollution states were broadly divided into weak and strong pollution groups according to SAD models, log-normal distribution and geometric series, respectively. A lower γ value in the log-normal distribution also differentiated weak pollution from strong pollution. Lower coefficient variation in the SAD slopes was further suitable in dividing less and slightly polluted states within the weak pollution group. Within the strong pollution group, a mixture of log-normal distribution to geometric series separated, polluted and severely polluted states. Higher correlation coefficients were observed between γ and other water quality parameters, as well as community and biological water quality indices. Similar patterns in SADs were presented between spring and fall; however, γ values of the less polluted state differed between seasons. Overall, developing SADs of related parameters is an efficient method of addressing ecological integrity that could serve as a reference system describing anthropogenic impact in streams.

Key words: Community structure / geometric series / log series / log-normal distribution / species abundance distribution

Introduction

Community assemblages are constrained by surrounding environmental factors, which makes them useful for evaluation of ecological integrity (Stevenson, 1997; Bunn and Davies, 2000; Diaz *et al.*, 2004). Benthic macroinvertebrates are considered to be suitable taxa for the evaluation of stream ecosystems (Hynes and Coleman, 1968; Rosenberg and Resh, 1993; Wright *et al.*, 2000). As is well known, fish, macroinvertebrates and diatom are considered the most suitable group to assess biological water quality (Hellawel, 1986). Benthic macroinvertebrates characteristically respond to the impact of pollution from watershed areas based on taxonomic diversity, sedentariness in survival range, and long life cycles (Resh and Rosenberg, 1984; Rosenberg and Resh, 1993; Chon *et al.*, 2002; Allan and Castillo, 2007; Park *et al.*, 2007) and have been widely used for indicators of the short- and long-term environmental changes, especially in running waters in the mountain areas (Hering *et al.*, 2006; Park *et al.*, 2007). Although benthic macroinvertebrates present ecological integrity fairly well, community data are highly complex and difficult to analyze since communities consist of diverse species varying in a non-linear manner in response to numerous natural and anthropogenic factors (Merritt and Cummins, 1996; Lake, 2000; Diaz *et al.*, 2004). Conventional community indices such as diversity and evenness, and biological water quality indices have been proposed for assessment of ecological state and pollution level (Armitage *et al.*, 1983; Cao *et al.*, 1996). However, these parameters are highly condensed and constrained in the sense that ecosystem quality is expressed by single terms only. Since communities consist of numerous species, more in-depth information on ecological integrity can be obtained from extended dimensions of community structure based on abundance of all species present in ecosystems concurrently. Multi-metrics (Index of Biotic integrity) and predictive models, including River Invertebrate Prediction and Classification System (RIVPACS), have also been introduced to present ecological integrity by reflecting diverse aspects of structure and function in communities (Reynoldson *et al.*, 1997; Wright *et al.*, 2000;

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Blocksom, 2003). In this case, however, criteria are mainly based on empirical evaluation of presence of specific taxa pertaining to sample sites *in situ* to present diversity, tolerance, composition, etc. Studies justifying these types of empirical observations with structure property of communities, however, have not been extensively reported except diversity index which presents a pattern of overall abundance of all species sampled at the same site.

In addition to diversity, species abundance distribution (SAD) describes the number of individuals encountered within a community for each species. Similar to diversity index, abundance for all species is considered, however, species ranks are arranged according to degree of abundance (McGill *et al.*, 2007). Since Raunkiær (1909) and Motomura (1932) first used SAD to evaluate structures of communities and biodiversity, numerous studies of SAD have been conducted to evaluate various taxa, including plants (Forster and Warton, 2007) and terrestrial animals (Ford and Lancaster, 2007). SADs have recently been reported for freshwater macroinvertebrates communities subjected to different levels of pollution (Qu *et al.*, 2008). Kim *et al.* (2013) further reported the stability of SADs and their persistence across seasons in temperate zones.

There has been considerable improvement in fitting mathematical and statistical models to SADs collected from field data. Fisher *et al.* (1943) suggested a log series model to describe the community using a histogram of species number in insect communities (Williams, 1964). Considering the commonness and rarity of community members, Preston (1948, 1962) proposed a log-normal model of species abundance based on the canonical hypothesis. May (1975) discussed modes in the model regarding statistical consequences of large numbers. Other models have been developed by considering biological (*e.g.*, competition) and physical (*e.g.*, neutrality) processes since the 1990s. MacArthur (1960) suggested models based on biological hypotheses including the overlapping and particulate-niche model. Tokeshi (1990a) proposed niche occupation in community establishment and addressed logical coherence to niche subdivisions such as random fraction, random assortment and dominance decay. Neutral theory was further developed by Bell (2000) and Hubbell (2001), who investigated whether species similarity without ecological constrains from biological aspect could explain the diversity of numerous natural communities mainly due to dispersal ability of individuals among local communities.

SADs have recently been used as indicators to present the ecological state of communities. Considering that individual species are diverse and have unique responses to disturbances in communities, SADs would be suitable for evaluating the environmental impacts of communities based on their structural properties. May (1981) observed that log-normal patterns tend to be replaced by geometric or log series patterns due to organic pollution, confirming a model of the effects of fertilizers on diatom communities (Patrick, 1963) and a grassland community (Williams, 1978). Undisturbed marine benthic communities could also be used as a criterion for detecting organic pollution (Gray and Mirza, 1979; Gray and Pearson, 1982). Warwick (1986) used the cumulative patterns of abundance and biomass with species rank to show the impact of pollution gradient. Nummelin (1998) and Hill *et al.* (1995) further compared SADs of disturbed forest with adjacent undisturbed forest assuming no β diversity between sites. Quality assessment in disturbed sites was investigated by marine benthic-species abundance (Rosenberg *et al.*, 2004). Furthermore, SADs were found to be useful for revealing the states of benthic macroinvertebrate communities in freshwater across different levels of pollution (Qu *et al.*, 2008; Kim *et al.*, 2013). In benthic macroinvertebrate communities, geometric series served as indicators of pollution states, whereas a majority of sample sites in less polluted streams matched the log-normal distribution.

In this study, we extended the results of previous studies (Qu *et al.*, 2008; Tang *et al.*, 2010; Kim *et al.*, 2013) to further investigate whether the patterns of SADs would be suitable for presenting pollution impacts and consistent through different seasons. We hypothesized that structure property of communities could be associated with water quality classification and aimed toprovide objective justifications for the empirical decision according to field conditions. We presented the pattern of SAD curves to reflect the structural characteristics of benthic macroinvertebrate communities in response to the impact of pollution. The model parameters and variations observed in SADs were suitable in defining pollution states from a community structure aspect.

Materials and methods

Field sampling

To present macroinvertebrate communities across different levels of pollution, 14 sampling sites were selected in two major (Nakdong and Han) and one local (Suyeong) river basins in the Southern Korean peninsula (Table 1). Community data in different levels of pollution were collected monthly at four sites. Less polluted sites were selected at BCN and BSL in the Baenae Stream, a tributary of the Nakdong River (Qu *et al.*, 2008). The two sites are located in typical mountainous streams with large substrates (boulders and cobbles) and higher discharge fluctuations. Additionally, NSJ, which was located at the main channel of the Nakdong River basin, was also added to present the impact of pollution. Site NSJ, which is located in a suburban area, showed an intermediate level of pollution owing to residential and agricultural pollution (Tang *et al.*, 2010) (Table 1). Community data from a severely polluted site, JHU, was also obtained for Yangjae Stream, a tributary of the Han River in Seoul, Korea. This stream flows through the metropolitan and agricultural areas in the city, and has primarily been polluted with organic material (Table 1). Communities from seasonal collection are additionally selected in streams with different pollution levels. In Daechon Stream in the Nakdong

Table 1. Site description, sampling methods and water quality parameters (mean ± S.E.) at different sample sites in three river basins in Korea.

Sites	River	Location	No. of samples	Periods	Conductivity (μs cm^{-1})	BOD5 (mg L^{-1})	Area
Monthly collection							
BCN	Nakdong	35°31′ 07.72″N, 128°01′01.97″E	78	05.11–13.07	24.7 (± 0.6)	0.98 (± 0.13)	Mountain
BSL	Nakdong	35°30′11.3″N, 128°59′45.8″E	23	10.04–12.04	34.0 (± 1.2)	1.31 (± 0.20)	Mountain
NSJ	Nakdong	35°51′5.27″N, 128°23′46.68″E	43	07.11–12.08	263.4 (± 10.1)	2.42 (± 0.14)	Suburban
JHU	Han	37°24′–37°29′N, 126°57′–127°04′E	41	Apr 96–00.03	–	–	Residential
Seasonal collection							
DUK	Nakdong	35°14′27.25″N, 129°3′24.66″E	6	04.11–06.01	39.2 (± 2.3)	1.24 (± 0.20)	Residential/Mountain
DAG	Nakdong	35°15′5.64″N, 129°2′36.65″E	5	04.11–05.09	113.8 (± 16.7)	2.87 (± 0.44)	Residential/Mountain
DDK	Nakdong	35°14′59.32″N, 129°3′24.30″E	6	04.11–06.01	148.5 (± 17.1)	3.18 (± 0.32)	Residential/Mountain
DKS	Nakdong	35°14′59.32″N, 129°3′24.30″E	5	04.11–05.09	158.6 (± 27.2)	3.28 (± 0.44)	Residential/Mountain
HJD	Nakdong	35°8′30.31″N, 128°59′0.66″E	5	04.11–05.09	435.0 (± 70.3)	11.63 (± 4.38)	Industry
OCU	Suyeong	35°16′46.78″N, 129°4′47.38″E	5	04.11–05.09	45.6 (± 4.8)	1.80 (± 0.49)	Residential/Mountain
YBK	Suyeong	35°21′45.44″N, 129°6′15.78″E	5	04.10–06.10	60.0 (± 11.0)	1.38 (± 0.34)	Mountain
ONS	Suyeong	35°16′40.26″N, 129°5′9.65″E	5	04.11–05.09	142.2 (± 39.3)	3.33 (± 0.88)	Residential
YSC	Suyeong	35°17′2.76″N, 129°06′19.31″E	15	May 99–06.10	199.4 (± 19.6)	3.66 (± 0.71)	Suburban
THP	Suyeong	35°13′17.6″N, 129°08′39.9″E	17	Oct 98–06.10	561.2 (± 53.4)	7.00 (± 0.74)	Industry

BOD, biochemical oxygen demand.

River basin, community data from four sites (DUK, DAG, DDK, and DKS) with variable pollution state were collected. The site HJD in the Hakjang Stream in the Nakdong River basin has been heavily affected by domestic and industrial pollution (Table 1). Sample sites in the Suyeong River in the Busan Metropolitan area were additionally selected to present different levels of pollution with less polluted sites (OCU and YBK) and intermediately polluted sites (YSC and ONS) located in agricultural and residential areas(Kwon and Chon, 1991; Yoon and Chon, 1996). Additionally, THP in the Soktae Stream in the Suyeong River basin (Table 1) was selected to present severe impacts of industrial pollution. The Soktae Stream passes through the watershed area and is subject to a wide range of pollution sources, including domestic sewage, agricultural practices and small-scale industry in Busan (Qu *et al.*, 2008).

Sampling was conducted monthly or seasonally according to sample sites using a Surber sampler (30 × 30 cm^2 for streams, or 50 × 50 cm^2 for rivers, 500 μm mesh). There were three–five replications of all samples, and sampling was conducted from April 1996 to July 2013 (Table 1). Water quality parameters such as biological oxygen demand (BOD) and conductivity were measured concurrently during the sampling period. The specimens were mostly identified to species or to the lowest possible taxonomical level using the procedures described by Merritt and Cummins (1996), Brigham *et al.* (1982), Pennak (1978) and Yoon (1995) for general taxa, Brigham *et al.* (1982) and Brinkhurst (1986) for Oligochaeta, and Wiggins (1996) for Trichoptera. However, Chironomidae was not identified to the species level owing to difficulty conducting classification and was therefore not included in the analysis. After classification of the specimens, the diversity and dominance were determined according to the Shannon (Shannon and Weaver, 1949) and dominance index (McNaughton, 1967). Additionally Ephemeroptera, Plecoptera and Trichoptera (EPT) richness (percentage of all species of EPT) and the revised biological monitoring working party (BMWP) and average score per taxa (ASPT) (Hawkes, 1998) were used to assess the biological water quality (Table 2).

SAD

Three conventional models of SADs, a log-normal distribution (Preston, 1948; Magurran, 2004), a log series (Fisher *et al.*, 1943) and a geometric model (Motomura, 1932; May, 1975; Magurran, 1988), were selected to fit the field data describing benthic macroinvertebrate communities collected from the sampling sites.

Log-normal distribution

$$S(R) = S_0 \exp\left(-a^2R^2\right) \qquad (1)$$

where, $S(R)$ is the number of species in the Rth octave (*i.e.*, class) in abundance of the symmetrical curve, a is a constant, and S_0 is the number of species in the modal

Table 2. Community and biological water quality indices (mean ± (S.E.), range) at different sample sites in three river basins in Korea.

Sites	Density (m^{-2})	No. of species	Shannon diversity	Dominance	BMWP	ASPT	Pollution state
Monthly collection							
BCN	1056.2 (± 87.2)	25.9 (± 0.7)	2.52 (± 0.08)	0.65 (± 0.02)	110.7 (± 2.5), 48.0–147.6	7.60 (± 0.05), 6.0–8.4	Less
BSL	1156.8 (± 168.7)	25.3 (± 1.2)	2.45 (± 0.10)	0.68 (± 0.03)	80.7 (± 4.2), 12.5–105.0	7.31 (± 0.08), 6.6–7.9	Slightly
NSJ	4011.4 (± 1135.5)	7.5 (± 0.5)	0.92 (± 0.07)	0.95 (± 0.01)	31.9 (± 2.1), 7.2–64.6	4.96 (± 0.15), 2.1–6.7	Polluted
JHU	2605.7 (± 403.5)	4.2 (± 0.2)	0.93 (± 0.05)	0.96 (± 0.01)	13.4 (± 0.7), 7.2–25.1	3.34 (± 0.06), 2.9–4.1	Severely
Seasonal collection							
DUK	372.6 (± 114.3)	21.0 (± 3.9)	2.94 (± 0.23)	0.58 (± 0.05)	119.4 (± 11.0), 82.9–153.8	7.37 (± 0.12), 6.9–7.7	Less
DAG	916.8 (± 333.4)	16.2 (± 3.0)	2.19 (± 0.32)	0.71 (± 0.09)	65.9 (± 6.8), 44.4–87.3	6.44 (± 0.33), 5.6–7.5	Slightly
DDK	2593.2 (± 646.6)	10.3 (± 1.2)	1.22 (± 0.15)	0.91 (± 0.04)	39.7 (± 3.9), 24.5–48.7	4.92 (± 0.28), 4.1–5.7	Polluted
DKS	3657.0 (± 2001.4)	9.0 (± 1.5)	1.22 (± 0.41)	0.86 (± 0.07)	30.5 (± 3.8), 17.4–38.5	4.66 (± 0.43), 3.5–5.8	Polluted
HJD	6177.4 (± 1480.0)	5.4 (± 0.6)	0.25 (± 0.11)	0.98 (± 0.01)	13.1 (± 1.7), 9.3–19.4	3.65 (± 0.32), 2.8–4.6	Severely
OCU	804.2 (± 153.1)	22.0 (± 1.8)	2.87 (± 0.3)	0.59 (± 0.09)	125.8 (± 9.1), 96.9–141.1	7.31 (± 0.08), 7.0–7.5	Less
YBK	156.0 (± 29.6)	18.4 (± 2.5)	2.69 (± 0.24)	0.63 (± 0.04)	76.0 (± 6.9), 46.0–78.9	7.28 (± 0.31), 6.1–7.9	Slightly
ONS	848.8 (± 347.0)	11.4 (± 0.9)	1.37 (± 0.26)	0.87 (± 0.05)	41.1 (± 3.7), 30.7–53.3	4.91 (± 0.23), 4.4–5.7	Polluted
YSC	681.4 (± 178.3)	10.9 (± 1.3)	1.75 (± 0.13)	0.78 (± 0.03)	45.7 (± 5.5), 7.2–37.3	5.34 (± 0.19), 4.1–6.5	Polluted
THP	1303.9 (± 375.0)	5.1 (± 0.4)	0.94 (± 0.15)	0.90 (± 0.03)	13.5 (± 1.8), 7.2–37.3	3.48 (± 0.14), 2.9–5.3	Severely

octave (Preston, 1948; May, 1975). In this study, a truncated log-normal distribution was used to fit the community data as described by Magurran (2004). The parameter α expresses the inverse of the width of distribution, $(2\sigma^2)^{1/2}$, while γ was calculated by R_n/R_{max} (R_n = the modal octave of the individuals curve; R_{max} = the octave in the species curve containing the most abundant species) and has considered a good measure of diversity (Magurran, 2004).

Log series

$$\alpha x, \frac{\alpha x^2}{2}, \frac{\alpha x^3}{3}, \ldots, \frac{\alpha x^n}{n} \qquad (2)$$

where, α is the index of diversity, n is the 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 = total number of species and N = total number of individuals).

Geometric series

$$n_i = NC_k(1-k)^{i-1} \qquad (3)$$

where, n_i is the number of individuals in the ith species, k is the proportion of the available resource that each species utilizes, N is the total number of individuals, and C_k is a constant (Magurran, 2004). Parameters (*i.e.*, α and γ in the lognormal distribution; k in geometric series) in the models were estimated based on iterative calculations (May, 1975; Magurran, 2004).

Statistical analyses

After estimation of the parameters, the Kolmogorov–Smirnov test for goodness of fit (Sokal and Rohlf, 1995) was conducted according to the methods proposed by Magurran (2004) for the SAD models (Qu *et al.*, 2008; Kim *et al.*, 2013). Analysis of variance and a multiple comparison test (Tukey's HSD (honest significant difference) test) were applied to identify differences in parameters according to different SAD. Additionally, Pearson's correlation coefficients were calculated to evaluate the relationships among parameters, including water quality parameters community indices and biological water quality indices (Zar, 1984). A $P < 0.05$ was considered to indicate statistical significance.

Results

Water quality and biological indices

Water quality parameters at the sampled sites are presented relative to different pollution impacts in Tables 1 and 2. The minimum conductivity, 24.7 μS cm^{-1}, was observed at BCN in the Nakdong River, whereas the maximum level was measured at HJD in the Nakdong

Table 3. Proportion of benthic macroinvertebrate communities fitting to species abundance distribution (SAD) models (Kolmogorov–Smirnov test ($P > 0.05$)) and model parameters (mean ± S.E.) for log-normal distribution (α and γ) and geometric series (k).

Site	Pollution state	No. of samples	Best fitting model: Log-normal distribution (%)	Log series (%)	Geometric series (%)	γ	α	k
Monthly collection								
BCN	Less	78	88.5	6.4	5.1	0.83 (± 0.02)	0.31 (± 0.01)	0.29 (± 0.01)
BSL	Slightly	23	86.9	4.4	8.7	0.85 (± 0.02)	0.30 (± 0.01)	0.31 (± 0.01)
NSJ	Polluted	43	25.5	4.7	69.8	1.79 (± 0.09)	0.22 (± 0.01)	0.39 (± 0.02)
JHU	Severely	41	0.0	0.0	100.0	1.64 (± 0.07)	0.28 (± 0.01)	0.31 (± 0.01)
Total		185	54.1	4.3	41.6			
Seasonal collection								
DUK	Less	6	100.0	0.0	0.0	0.69 (± 0.06)	0.36 (± 0.02)	0.34 (± 0.03)
OCU	Less	5	60.0	20.0	20.0	0.80 (± 0.05)	0.30 (± 0.02)	0.32 (± 0.02)
Subtotal	Less	11	80.0	10.0	10.0	0.74 (± 0.06)	0.33 (± 0.03)	0.33 (± 0.02)
DAG	Slightly	5	100.0	0.0	0.0	0.99 (± 0.12)	0.31 (± 0.05)	0.28 (± 0.01)
YBK	Slightly	5	80.0	20.0	0.0	0.69 (± 0.10)	0.42 (± 0.02)	0.35 (± 0.03)
Subtotal	Slightly	10	90.0	10.0	0.0	0.84 (± 0.13)	0.37 (± 0.04)	0.32 (± 0.02)
YSC	Polluted	15	40.0	13.3	46.7	1.15 (± 0.07)	0.31 (± 0.03)	0.31 (± 0.02)
ONS	Polluted	5	80.0	0.0	20.0	1.21 (± 0.25)	0.28 (± 0.03)	0.38 (± 0.10)
DKS	Polluted	5	20.0	0.0	80.0	1.73 (± 0.38)	0.27 (± 0.08)	0.34 (± 0.06)
DDK	Polluted	6	0.0	0.0	100.0	1.79 (± 0.16)	0.20 (± 0.02)	0.36 (± 0.05)
Subtotal	Polluted	31	35.0	3.3	61.7	1.47 (± 0.18)	0.27 (± 0.04)	0.35 (± 0.04)
THP	Severely	17	5.9	0.0	94.1	1.66 (± 0.12)	0.27 (± 0.02)	0.32 (± 0.02)
HJD	Severely	5	0.0	0.0	100.0	2.50 (± 0.13)	0.16 (± 0.01)	0.29 (± 0.04)
Subtotal	Severely	22	3.0	0.0	97.0	1.70 (± 0.07)	0.26 (± 0.01)	0.31 (± 0.01)
Total		74	40.5	5.4	54.1			
Grand total		259	50.2	4.6	45.2			

Subtotal: samples collected at each site; Total: monthly and seasonal collections; Grand total: average between monthly and seasonal collection.

River basin and THP in Soktae Stream of the Suyeong River basin, which had values of 435.0 and 561.2 $\mu S\ cm^{-1}$, respectively (Table 1). BOD varied similarly according to the degree of pollution ranging 0.98 mg L^{-1} (BCN) and 11.6 mg L^{-1} (HJD).

Community and biological water quality indices were also differentiated according to pollution levels (Table 2). The minimum and maximum BMWP ranged from 7.2 to 153.8. At BCN, DUK and OCU, the average BMWP values were higher than 100, whereas the values were lower than 60 at other sites. The minimum and maximum species richness ranged from 3 to 39, which was generally in accordance with water quality and biological indices (Table 2). Sample sites with higher species richness also showed higher Shannon diversity, with the maximum level of 3.93 being recorded at BCN with minimum dominance index 0.26.

According to Ferreira *et al.* (2004) and Rocha *et al.* (2015), four pollution states were determined based on the biological water quality indices, BMWP and ASPT, less polluted and slightly polluted for weak pollution, and polluted and severely polluted for strong pollution (Table 2). The pollution states could be broadly divided into weak and strong groups according to the values of 60 and 6 for BMWP and ASPT, respectively. BMWP appeared to be better at differentiating less and slightly polluted states within the weakly polluted group because it contained information regarding the richness of pollution-sensitive species in the family level, whereas ASPT tended to be more representative of the overall tolerance in pollution impact. Chemical indicators including conductivity and BOD5 were additionally used for confirming the level of pollution along with field information. Communities with BMWP values higher than 100 (BCN; 110.7, DUK; 119.4 and OCU; 125.8) were further selected as "less polluted" state, whereas sites with BMWP values less than 100 (BSL (80.7) and YBK (76.0)) were considered to be in "slightly polluted" states within the weak pollution group. Three sites, HJD, THP and JHU, showed extremely low values of BMWP (around 13) and ASPT (around 3.5) and were therefore selected as "severely polluted" areas, whereas the remaining sites (NSJ, DDK, DKS, ONS and YSC), which had scores higher than 15, were considered to be in the "polluted"state within the strong pollution group.

Species abundance patterns

Statistical tests were conducted separately for each model, and the best matching one (*i.e.*, highest P value based on the Kolmogorov–Smirnov goodness test) was selected as the fitting model (Table 3). Among 294

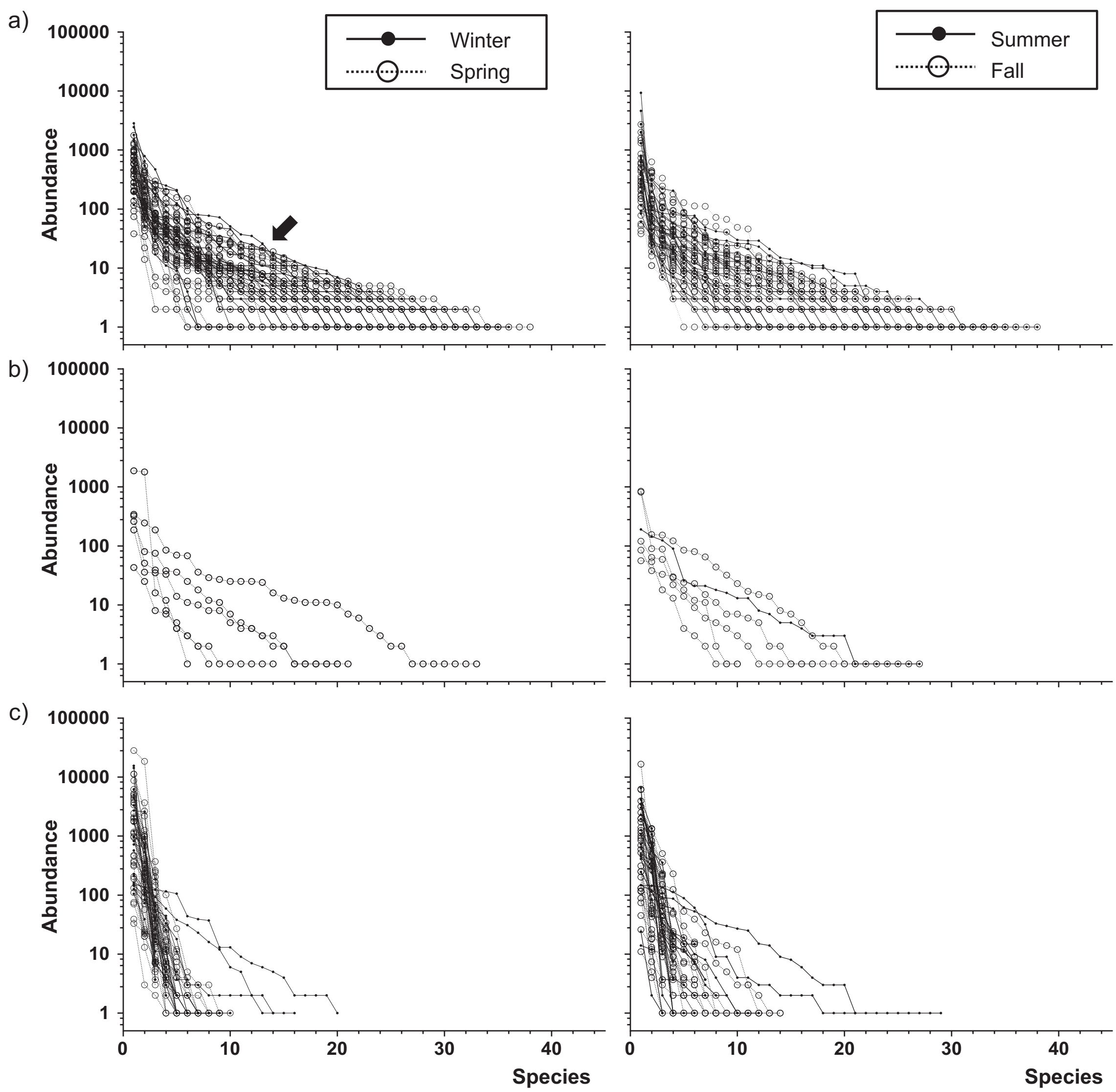

Fig. 1. SAD curves fitting three models in different seasons. (a) log-normal distribution, (b) log series and (c) geometric series. Winter and summer collections are superimposed for spring (left pannel) and fall (right pannel) collections, respectively. Abbreviation: SAD, species abundance distribution.

samples, the proportion of the best matching model was 50.2% for log-normal distribution, 45.2% for geometric series and 4.6% for log series. During monthly sampling, the matching proportions were 54.1, 41.6 and 4.3% for geometric series, log series and log-normal distribution, respectively. Seasonal samples showed a similar trend, with a slight increase being observed in geometric series (Table 3).

Figure 1 shows the SAD curves fitted to different models in winter and spring (left panel), and summer and fall (right panel). The SAD patterns were generally similar across seasons as long as the SADs were fitted to the same model (Fig. 1). In the log-normal distribution, SAD values were in a broad range, with spring and fall samples being widely included within the same model (Fig. 1(a)). During winter, the species richness increased while the slopes of SAD decreased relative to the spring SADs (see dotted (spring) and solid (winter) arrows in Fig. 1(a)). Only a few summer and winter samples deviated from communities collected in fall and spring, especially for geometric series (Fig. 1(c)).

Water quality parameters and biological indices were differentiated according to the SAD models. Figure 2 compares the indices according to different SAD models. Specifically, the conductivity and BOD5 data distribution range (means of water quality indices) were significantly higher in geometric series than in data showing log-normal distribution and log series (Fig. 2(a) and (b)). Data distributions for the number of species, Shannon diversity and evenness were significantly lower in geometric series than in log-normal distribution and log series (Fig. 2(c)–(e)) while the dominance index showed significance in the opposite direction (Fig. 2(f)). Biological water quality indices, EPT% (richness), BMWP and ASPT, showed similar distribution patterns, being lower with geometric series and higher with the two other models

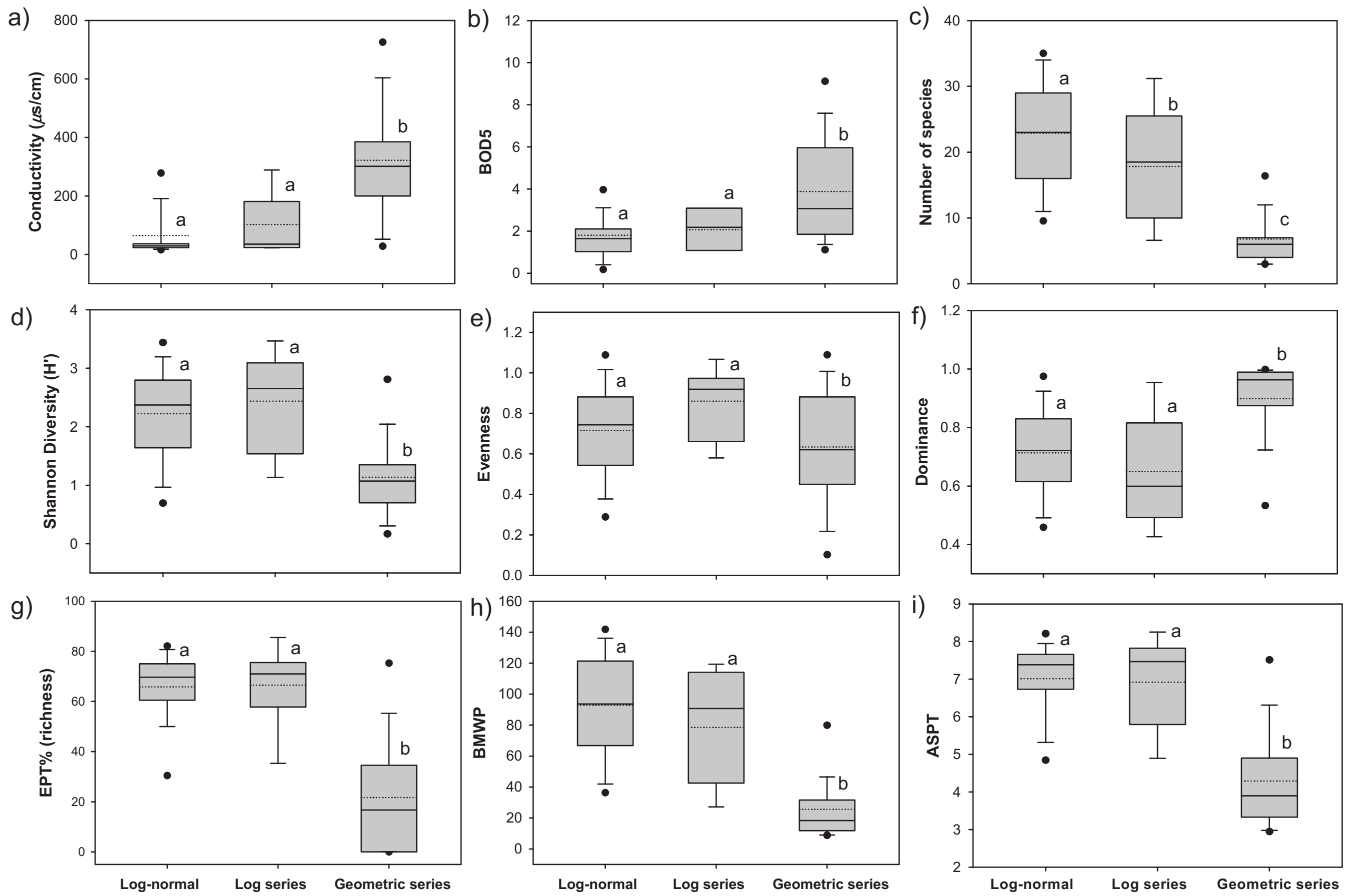

Fig. 2. Mean value (broken line), and box and whiskers plots of water quality parameters and biological water quality and community indices according to three different models. The boxes in the figure represent the 25–75% range and the whiskers 5–95%, while lines in the box indicate median values of the distribution. Significant differences were identified based on multiple comparison analysis (Tukey's HSD). Different letters on the bar indicate significant differences. (a) conductivity; $P < 0.001$, (b) BOD5; $P < 0.001$, (c) number of species; $P < 0.001$, (d) Shannon diversity; $P < 0.001$, (e) dominance; $P < 0.001$, (f) BMWP; $P < 0.001$, and (g) ASPT; $P < 0.001$. Abbreviations: ASPT, average score per taxa; BOD, biochemical oxygen demand, BMWP, biological monitoring working party.

(Fig. 2(g)–(i)). Overall, the geometric series indicated pollution and was associated with low water quality and community indices, whereas log-normal distribution represented high indices. Although log series were not observed frequently, they tended to be close to log-normal distribution. Significant differences between the two models were only observed in the number of species, with higher average value in log-normal distributions than in log series. Additionally, the mean number of species differed significantly among all three models (Fig. 2(c)). Although statistical significance was not observed, the Shannon diversity and evenness in the log series tended to be higher than in the log-normal distribution (Fig. 2(d) and (e)).

Consequently, communities fitted to the three types of SAD models were divided according to pollution states in both monthly and seasonal collections (Table 3). At less and slightly polluted sites (BCN and BSL), the community data were mostly fitted to a log-normal distribution with, 88.5 and 86.9% of best fitting, respectively, in monthly collections (Table 3). In contrast, all samples collected at the severely polluted site, JHU, were associated with geometric series (Table 3). It should be noted that "pollution" and "severe pollution" were differentiated according to the proportion of log-normal distribution and geometric series. While 100% of the samples belonged to geometric series for severe pollution at JHU, a substantial proportion (25.5%) matched log-normal distribution and the rest was in accord with geometric series (69.8%) at NSJ.

A similar pattern was also observed in seasonal collections. Log-normal distribution was mostly fitted to less (80%) and slightly polluted (90%) sites (Table 3). A less polluted site, DUK, matched the log-normal distribution with 100%. All samples from severely polluted sites were fitted to geometric series with 97%, except one case in THP. In the polluted states, fitting was split, with 61.7% being observed for geometric series and 35.0% for log-normal distribution (Table 3). This trend of mixed proportions between geometric series and log-normal distribution can be useful for differentiating pollution and severe pollution from a community structure aspect

Table 4. Pearson's correlation coefficients among water quality parameters, biological water quality and community indices and model parameters in species abundance distributions (SADs).

	BOD5	BMWP	ASPT	EPT% (richness)	Abundance	Species richness	Dominance	Shannon diversity	*k* value	α value	γ value
Conductivity (µs cm^{-1})	0.553**	−0.864**	−0.871**	−0.837**	0.201**	−0.855**	0.704**	−0.706**	0.100	−0.364**	0.685**
BOD5		−0.506**	−0.555**	−0.533**	0.183*	−0.498**	0.362**	−0.409**	−0.029	−0.341**	0.471**
BMWP			0.890**	0.818**	−0.113	0.949**	−0.752**	0.781**	−0.130*	0.312**	−0.653**
ASPT				0.907**	−0.203**	0.831**	−0.707**	0.719**	−0.077	0.357**	−0.669**
EPT% (richness)					−0.184**	0.813**	−0.698**	0.725**	−0.121	0.329**	−0.643**
Abundance						−0.059	0.448**	−0.387**	−0.104	−0.778**	0.599**
Species richness							−0.760**	0.788**	−0.152*	0.280**	−0.641**
Dominance								−0.959**	0.332**	−0.602**	0.765**
Shannon diversity									−0.347**	0.551**	−0.744**
k value										−0.091	0.134*
α value											−0.834**

ASPT, average score per taxa; BOD, biochemical oxygen demand; BMWP, biological monitoring working party; EPT, Ephemeroptera, Plecoptera and Trichoptera.
$^{**}P < 0.05$; $^{*}P < 0.01$.

within the strong pollution group. However, log series were fitted to field data in substantially lower frequencies of 0.0–20.0% for each site. No matching to log series was found in the severely polluted state (Fig. 2).

Three different SAD parameters, α and γ from the log-normal distribution model and *k* from geometric model, are presented in relation to the different pollution states in Table 3. Parameter γ in the log-normal distribution increased as the pollution level increased. However, the values were mainly divided into two broad groups of pollution levels, weak (less and slightly polluted) and strong (polluted and severely polluted), similar to the division by BMWP (see section 'Field sampling'). This trend was commonly observed in both monthly and seasonal samples (Table 3). Overall, the average γ values ranged from 0.69 to 0.85 and 0.69 to 0.99 at the less polluted and slightly polluted sites, respectively, whereas the values ranged from 1.15 to 1.79 and 1.64 to 2.50 at polluted and severely polluted sites, respectively. According to Tukey's HSD test ($P < 0.05$), the samples were significantly divided into a "less-slightly polluted" group and "polluted-severely polluted" group according to γ. However, the parameters *k* and α did not differ significantly across pollution levels, showing overall ranges of 0.28–0.39 and 0.16–0.42 on average, respectively.

Correlation analysis

The Pearson's correlation coefficients were obtained to characterize the relationships among SAD parameters, water quality parameters (conductivity and BOD5), biological water quality indices (BMWP, ASPT and EPT %), and community indices (dominance and Shannon diversity) (Table 4). With the exception of *k*, SAD parameters showed significant correlations with water quality parameters and biological indices. The γ values showed higher correlation coefficients (> 0.6), mostly with water quality parameters (conductivity), biological water quality (BMWP, ASPT and EPT%), and community (species richness, diversity and dominance) indices. The *a* value also showed significant correlations, but were generally lower than γ values (in absolute). Specifically, these values ranged from 0.28 to 0.36, except for the correlation coefficients of abundance (− 0.78), dominance (− 0.60) and diversity (0.55). The *k* values showed low correlation coefficients for most parameters (Table 4). Overall, γ in the log-normal distribution model was suitable for presenting pollution states because it was highly correlated with water quality parameters. The water quality parameter was also highly correlated with other community indices. Conductivity showed coefficients higher than 0.8 ($P < 0.05$) with biological water quality and community indices. BOD5 was also significantly correlated with most indices, but showed relatively lower values than conductivity. The biological water quality indices, BMWP, ASPT and EPT%, were also significantly correlated with species richness, dominance and diversity (Table 4).

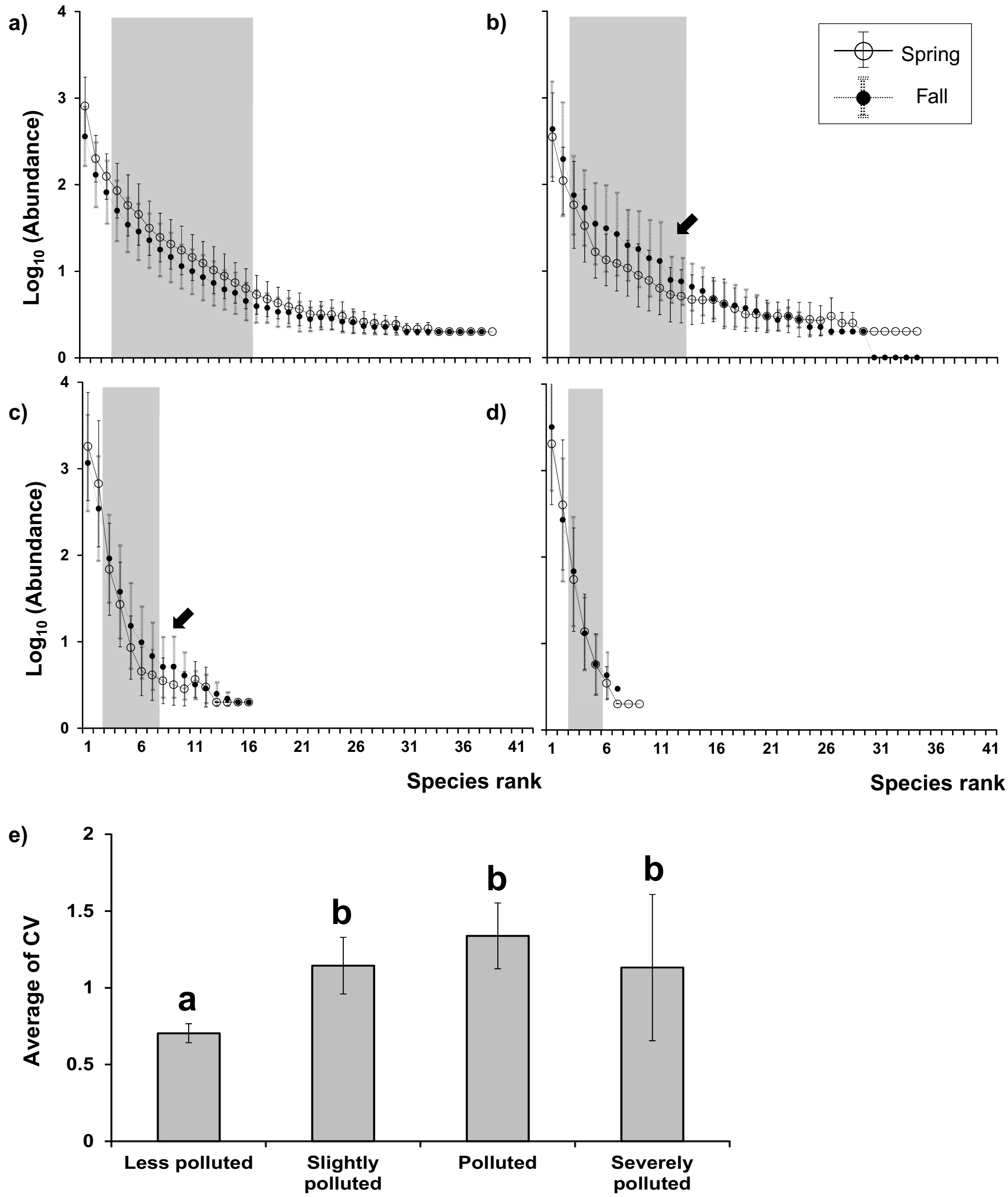

Fig. 3. SAD curves with mean and S.D. of abundance from each rank of samples across different levels of pollution; (a) less polluted, (b) slightly polluted, (c) polluted and (d) severely polluted (grey bars indicate the range of intermediate ranks), and (e) difference in average CV calculated by CVs of abundance from each rank in middle ranked species. Bars indicating the S.D. and different letters standing for statistical significance (Tukey's HSD test; $P < 0.05$). Abbreviations: CV, coefficient of variance; SAD, species abundance distribution; S.D., standard deviation.

SAD curves and seasonal comparison

SADs were further compared between spring and fall using a similar number of samples from areas characterized by each pollution level. SAD slopes with average and variations of abundance were obtained as log scale across different levels of pollution (Fig. 3). Natural environmental disturbances were minimized based on comparison with other seasons in the temperate zone (*e.g.*, summer flooding, winter drought), and spring and fall would be suitable for presenting communities under stable field conditions.

As stated above, the SADs were generally similar in both seasons under each pollution state. At less polluted sites (BCN, DUK and OCU), SADs showed a universal pattern of a hollow curve along the *x*-axis, peaking at the top ranked species decreasing with lower slope for intermediately ranked species, and flat tail part for rare species

Table 5. Average species abundance distribution (SAD) parameters in spring and fall across different levels of pollution.

Pollution state	Model	Parameter	Season		P value
			Spring	Fall	
Less polluted	Log-normal	α value	0.30 (±0.01)	0.34 (±0.01)	0.254
	Log-normal	γ value	0.83 (±0.02)	0.74 (±0.03)	0.021*
Slightly polluted	Log-normal	α value	0.31 (±0.03)	0.33 (±0.2)	0.278
	Log-normal	γ value	0.83 (±0.06)	0.82 (±0.05)	0.660
Polluted	Geometric series	k value	0.38 (±0.02)	0.39 (±0.07)	0.165
	Log-normal	α value	0.27 (±0.02)	0.31 (±0.04)	0.157
	Log-normal	γ value	1.26 (±0.18)	1.12 (±0.13)	0.867
Severely polluted	Geometric series	k value	0.33 (±0.03)	0.39 (±0.04)	0.260

*Statistical significance (t-test; $P < 0.05$).

(Fig. 3(a)) (Magurran, 2004; Qu *et al.*, 2008; Kim *et al.*, 2013). SADs at the slightly polluted sites (BSL, DAG and YBK) presented relatively steeper slopes with shorter tails compared with less polluted sites. It should be noted that higher variation of SAD curves was also observed at slightly polluted sites than less polluted sites (Fig. 3(b)). At the polluted sites (NSJ, YSC, ONS, DDK, and DKS), SAD curves showed steeper slopes with shorter tails than at less and slightly polluted sites (Fig. 3(c)). SAD curves were even steeper at severely polluted sites (HJD, JHU and THP), with minimal species richness (Fig. 3(d)). Although the trends in SADs were similar between spring and fall, slight deviations were also observed. In less polluted sites, the average abundance of mid-ranked species was higher in spring whereas the abundance of mid-ranked species was higher in fall than in spring at slightly polluted and polluted states (see arrow in Fig. 3). Although the slopes in spring and fall were different, these differences were not statistically significant due to high variation in slopes (t-test, $P > 0.05$).

The three parameters in SAD models were compared with spring and fall. Based on the fitness test results (Table 3), the k values of geometric series were checked to determine if the values could differentiate polluted and severely polluted states, whereas α and γ of the log-normal distribution were useful for comparing less, slightly and polluted states (Table 5). Most parameters did not differ significantly between seasons, except for the less polluted state, for which the parameters were significantly different ($P = 0.021$), being 0.83 in spring and 0.74 in fall. Overall, the γ values were divided into two groups based on pollution states, being lower in less and slightly polluted sites (0.74–0.83) and higher in polluted sites (0.12–1.26). The values of k and a were similar, ranging from 0.14 to 0.69 (average, 0.35) and 0.20 to 0.58 (average, 0.33), respectively (Table 5).

Pollution state characterization

SAD slopes varied according to pollution states. The range of standard deviation of slope was substantially narrower for samples observed to be in the less polluted state (Fig. 3(a)) than other states (Fig. 3(b)–(d)). Considering the variability was more clearly differentiated in the middle range in the rank, the coefficient of variation (CV) of SAD slope for the intermediately-ranked species were more clearly differentiated (shades in Fig. 3(a)–(d)). The upper limit of the intermediate ranks was determined according to the number of species matching the break point between steep and flat slopes in SADs fitted to the log-normal distribution (Fig. 1). The approximate top 10% of the total rank was the upper limit of the intermediate rank, which matched a density of around 100 individuals per 0.27 m^2. Subsequently, the approximate upper 40% of the total rank was the lower limit, showing density lower than five individuals per 0.27 m^2. To fit sampled communities to geometric series when break points were not observed, the upper and lower limits were determined based on the densities observed in the case of log-normal distribution. The approximate top 20 and 50% of the total species rank became the upper and low limit, respectively, based on the increased density under polluted conditions.

CVs for the slopes of the intermediately ranked species were differentiated according to different pollution states (Fig. 3(e)), being significantly lower in the less polluted state than the slightly and higher polluted states ($P < 0.001$). It was noteworthy that the level of SD markedly increased from less pollution to slight pollution (Fig. 3(b)). Although statistically the same, CVs tended to be higher in the slightly polluted and polluted states than in the severely polluted state. Overall, these findings indicated that the rank abundance of species in the community, especially in the intermediate rank, was variable after the pollution increased from the less polluted state.

In summary, by integrating results for SADs, model fitting, parameter (γ) differences, and CVs of SADs could be used for newly characterizing pollution states in a systematic way based on community structure properties (Fig. 4(a)). The pollution states according to empirical judgmentcould initially be divided into weak and strong pollution groups based on the SAD model fitting, log-normal distribution and geometric series, respectively. Significant differences in γ value serves as a criterion for differentiating weak and strong pollution (Table 3). The distribution of γ values appeared to be in a narrow range (0.48–1.35) for weak pollution whereas γ values were broadly distributed over a long range (0.57–3.28) for strong pollution (Fig. 4(b)). The curves were fitted to

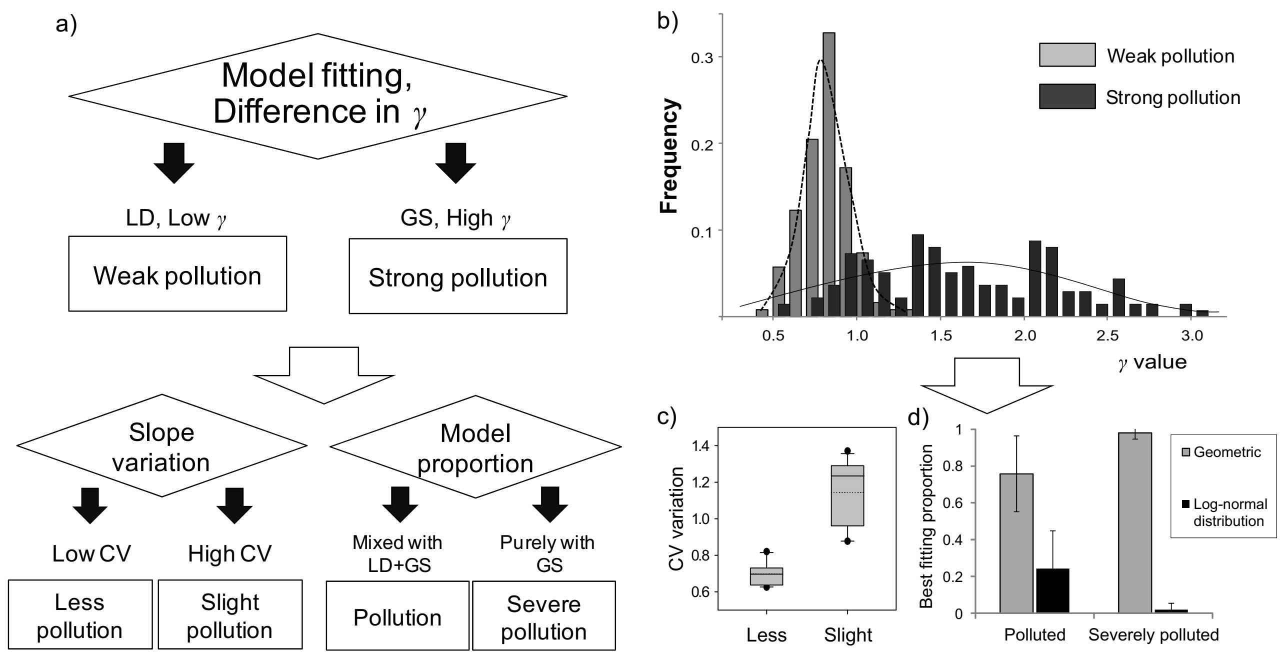

Fig. 4. Characterizing pollution states depending on community structure analysis based on SADs. LD indicates a log-normal distribution model and GS indicates a geometric series model, respectively. (a) Decision diagram of pollution state using community structure information and (b) application of decision diagram for community data to Korean streams. Abbreviation: SAD, species abundance distribution.

Gaussian function and were substantially different for the weak ($\mu = 0.78$, $\sigma = 0.19$, $r^2 = 0.95$) and strong pollution ($\mu = 1.53$, $\sigma = 0.96$, $r^2 = 0.43$) according to the curve fitting tool from Matlab 2009.

Discussion

Species abundance patterns based on macroinvertebrate communities in streams were suitable in objectively defining pollution states according to empirical judgment based on water quality indices such as BMWP and ASPT. Whereas less and slightly polluted sites mostly showed log-normal distributions patterns, disturbances caused by pollution produced community patterns with geometric series (Gray and Mirza, 1979; May, 1981) as confirmed with freshwater macroinvertebrate communities (Qu *et al.*, 2008; Tang *et al.*, 2010; Kim *et al.*, 2013) (Fig. 2 and Table 3). It is worth noting that the two groups primarily reflected pollution levels from the structural aspect, with a log-normal distribution being observed for the group of weak polluted state and geometric series for the severely polluted state (Table 3).

The CVs of SADs for the intermediately ranked species could be used to distinguish between less and slightly polluted states within the weak pollution category, with significantly higher values being observed for the slightly polluted state than the less polluted state (Figs. 3 and 4(c)). At the intermediately disturbed state, variations in species richness and productivity were reportedly higher in the stream macroinvertebrate community, which was in accordance with the results of previous studies (Townsend *et al.*, 1997; Lake, 2000). To the best of our knowledge, this is the first report addressing the significance of CVs in SAD curves for presenting community organization.

To compare CVs for SAD, we used more than 30 samples collected from areas with different levels of pollution in stable seasons, including spring and fall. However, further study is required to determine how many samples would be needed to accurately determine CVs for characterization of pollution states under field conditions. The parameter γ of the log-normal distribution was also used to distinguish between weak and strong pollution (Tables 3 and 4). It should also be noted that the strong polluted state determined by empirical observations were divided into the polluted and severely polluted states, and was characterized by a mixture of geometric series and log-normal distribution (Table 3 and Fig. 4(d)). Since the structural properties are known, more objective diagnosis of the pollution state is possible from a community organization aspect, and realistic management policies can be established for assessment and sustainable management of aquatic ecosystems.

Although SADs are efficient in characterizing community structure, disadvantages were also reported regarding the taxonomy and loss of information (McGill *et al.*, 2007). A substantial effort will be required for identifying all organisms in the sampled communities in order to determine rank and abundance required in SADs. Especially identification would be a problem with the highly diverse taxa such as Chironomidae, which was not reported in this study. It is noteworthy, however, that classification to exact species would not be required in producing SADs as long as ranks are identified to different species regardless of finding exactspecies name for all organisms. This would relieve the rigorous requirement of taxonomic classification. Further studies on classification improvement including molecular taxonomy however,are warranted for obtaining more comprehensive information on SADs.

It is also noteworthy that SADs are also suitable in expressing water quality and ecological state with index (γ) used in the SAD model as shown in this study (Table 3). Beside community parameters, multi-metrics would be another option in expressing ecological integrity (Reynoldson *et al.*, 1997). By combining selective indices according to important aspects in community responses to environmental impacts, all aspects are considered in community structure and functioning including diversity, richness, tolerance and composition (Barbour *et al.*, 1999). Consequently metrics had the advantage of presenting ecological integrity in a comprehensive manner with multimetrics (Reynoldson *et al.*, 1997; Barbour *et al.*, 1999). However, metrics are still based on heuristic judgments mainly according to observers' field experience pertaining to the sample sites. Since SADs accordingly represent structure properties and provide objective basis for empirical judgment (in this case BMWP and ASPT) in this study (Fig. 4), SADs could be efficiently utilized to justify water quality criteria judged by multi-metrics and predictive models including RIVPACS and Australian River Assessment System. The future study is warranted in evaluating relationships between SADs and multi-metrics across different levels of pollution.

It should be noted that the γ value in the log-normal distribution differed seasonally in the less polluted state (Table 5). Considering that the γ value ($R_n/R_{\max}$) indicates the proportion of species of modal octave to species with the maximum abundance (Magurran, 2004), spring communities had higher species richness relative to modal octaves. Species showing a modal octave primarily corresponded to the intermediate ranks in SADs, indicating that higher γ values represented higher species richness with higher evenness (*i.e.*, lower slopes in rank abundance distribution) (Magurran, 2004). Communities in spring showed relatively higher evenness among a broad range of intermediately ranked species. This could be explained by community development in different seasons within 1 year in Korea. Communities are more stable in temperate zones during spring, which is in the premonsoon period, than in the postmonsoon period (Brewin *et al.*, 2000). The results of the present study suggest that the flood impact on communities remains until fall.

Not many communities were found to fit log series in contrast with log-normal distribution in our result. Qu *et al.* (2008) found that the proportion of log series (15.2%) was higher than the proportion shown in the present study; however, they conducted SAD fitting independently for each model and reported the fitting proportion for each model instead of determining the one of best fitting model. We analyzed our data using the same method as Qu *et al.* (2008) and found that the log series fitting was substantially higher (48.8%; Supplementary Table S1) than when all data were analyzed together, as well as the results reported by Qu *et al.* (2008). This was due to the higher proportion of weakly polluted sites in the present study. Specifically, 13.6% of the total sites were weakly polluted in the study conducted by Qu *et al.* (2008), while 47.1% were in the present study. As discussed above, the log series were closer to log-normal distribution for less and slightly polluted states (Fig. 2). In this study, we evaluated the final outcome of the most suitable model *in situ*. If the fitting was obtained separately for each model, the overall tendency of SAD could be revealed according to statistical distributions. Accordingly, further study is warranted to better characterize statistical fitness and SAD shaping under field conditions with consideration of sampling theories (*e.g.*, unbiasedness, sampling efficiency).

Although not many samples were shown with a log series, community compositions could still be characterized according to this model (Fig. 1). Extreme abundance of a dominant species group was not observed in a log series because the slopes for the most and intermediately dominant species were not as sharply divided as in the cases of log-normal distribution. It should be noted that, although taxa composition varied according to spatial differences (*e.g.*, habitat, altitude, river basin, etc.), overall curve patterns of community structures according to the ranks were markedly consistent and the stable SAD shaping was addressed accordingly in response to disturbances (Fig. 3).

Three conventional models were used for fitting in this study, log-normal distribution and log series as statistical models and geometric series for biological processes (Magurran, 2004). However, more models have been introduced by elaborating physical (*e.g.*, Hubbell, 2001) and biological (Tokeshi, 1993) processes. Focusing on biological properties (*e.g.*, niche-preemption models), Tokeshi (1993, 1999) defined SAD models and applied them to benthic macroinvertebrate communities. Across different levels of pollution, it was reported in benthic macroivertebrate communities that the dominant decay model was suitable for addressing SADs in the less polluted state, whereas the random fraction and random assortment model fit the polluted state better for benthic macroinvertebrates (Tang *et al.*, 2010). However, physical processes could also be examined since the log-normal-like distribution and geometric-like distribution would also be possible using neutral theory based on the zero-sum multi-nominal distribution (Hubbell, 2001). Based on the results from our field collections, we need more information regarding how biological or physical processes should be involved in producing SADs. We mainly checked the associations between field data and obtained model results according to statistical parameters in this study. Nevertheless, statistical fitting to conventional models could be still used to reasonably express community states relative to pollution impacts. Further tests are required to investigate how the environmental and biological selective pressure of species (*i.e.*, tolerance, competition) could be inter-linked with biological and physical processes in expressing SADs. Additionally, more examinations are required to enable application of our method in the field for assessment and monitoring, including evaluation of river networks as well as expression of biological properties such as trait (Magurran and Henderson, 2012).

To present the patterns of community structure, other methods such as species accumulation curve (Colwell *et al.*, 2004) and rarefaction curve (Raup, 1975; Roesch *et al.*, 2007) have been applied. However, fundamental differences exist between SAD and these methods. While biodiversity could be presented in an accumulative manner, especially over a broad area (or sampling efforts) in accumulation and rarefaction curves, SAD is more focused on specific species compositions pertaining to the selected sampling sites. Whereas species accumulation and rarefaction curves would be more applicable in estimating global ecological integrity according to the spatial scale, SADs convey information specific to local topographic conditions and environmental impacts in sampling areas. Further studies including size effect and sampling efficiency are warranted in the relationships between SAD, SAR (species-area relationship) and other community structure measurements in order to address ecological integrity more properly in depth, in the future (Magurran and McGill, 2011; Heino, 2013).

Conclusions

In this study, SAD was demonstrated to be a useful method for characterizing the impact of pollution on benthic macroinvertebrate communities. Overall, the SADs were stable in different pollution states. According to the comprehensive results for SADs, including model fitting (log-normal distribution and geometric series), parameter (γ) differences, and CVs, pollution states could be newly characterized based on community structural properties (Figs. 2 and 4). Initially, the pollution states could be divided into weak (less and slightly polluted) and strong (polluted and severely polluted) groups based on model fitting, log-normal distribution and geometric series, respectively. Statistical differences in γ value could be also a criterion for differentiating weak and strong pollution (Table 3). Subsequently, CV for SAD slopes separated less polluted state from slightly polluted state within the weak pollution group (Figs. 3 and 4). Within the strong pollution group, a mixture of log-normal distribution with the geometric series could differentiate the polluted state from the severely polluted state (Fig. 4 and Table 3). Once the structural properties are known, more accurate diagnosis is possible from a community structure aspect based on changes in community abundance, enabling realistic management policies to be established for assessment and sustainable management of aquatic ecosystems. SADs revealed that the model patterns, parameters and variations in slopes are useful indicators for differentiating pollution states from the community structure aspect that would be feasible as reference systems for monitoring ecological integrity under stressful conditions.

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Supplementary Table S1. Kolmogorov–Smirnov test results for goodness of fit to species abundance distribution (SAD) models of benthic macroinvertebrate communities collected at all sites.

	Sampling time	Geometric series	Log series	Log-normal distribution		Sampling time	Geometric series	Log series	Log-normal distribution
BCN	2005.11.	0.432**	0.150	0.085	JHU	1996.04.	0.150	0.541*	0.598*
	2006.05.	0.220**	0.214**	0.113		1996.05.	0.147	0.588*	0.600*
	2006.06.	0.178*	0.169*	0.090		1996.06.	0.032	0.609**	0.353
	2006.07.	0.173*	0.159	0.096		1996.07.	0.045	0.374	0.440
	2006.08.	0.580**	0.338**	0.109		1996.09.	0.040	0.493	0.644**
	2006.10.	0.335**	0.125	0.090		1996.11.	0.118	0.716**	0.537*
	2006.11.	0.275**	0.149	0.091		1996.12.	0.041	0.345	0.377
	2006.12.	0.076	0.251**	0.152		1997.01.	0.042	0.630**	0.444
	2007.01.	0.198	0.238*	0.095		1997.02.	0.080	0.338*	0.428**
	2007.02.	0.495**	0.170	0.119		1997.04.	0.212	0.578**	0.641*
	2007.03.	0.313**	0.101	0.116		1997.05.	0.058	0.580*	0.503
	2007.04.	0.447**	0.219**	0.095		1997.06.	0.060	0.482**	0.423
	2007.05.	0.590**	0.344**	0.143		1997.07.	0.055	0.735**	0.420**
	2007.06.	0.404**	0.127	0.109		1997.08.	0.322	0.611*	0.629*
	2007.07.	0.387**	0.159	0.084		1997.09.	0.165	0.451	0.506
	2007.08.	0.477**	0.274*	0.145		1997.10.	0.074	0.393	0.321
	2007.09.	0.561**	0.207*	0.095		1997.11.	0.171	0.274	0.320
	2007.10.	0.301**	0.076	0.118		1997.12.	0.202	0.335	0.333
	2007.11.	0.208**	0.148	0.136		1998.01.	0.050	0.276	0.328
	2007.12.	0.147	0.145	0.134		1998.02.	0.030	0.343	0.336*
	2008.01.	0.254**	0.138	0.108		1998.03.	0.043	0.268	0.296
	2008.02.	0.059	0.146	0.103		1998.04.	0.092	0.341*	0.448
	2008.03.	0.461**	0.126	0.087		1998.05.	0.117	0.327	0.349
	2008.04.	0.512**	0.178	0.126		1998.06.	0.038	0.424*	0.352
	2008.05.	0.313**	0.153	0.097		1998.07.	0.105	0.274	0.245
	2008.06.	0.343**	0.095	0.087		1998.08.	0.223	0.391	0.293
	2008.07.	0.284**	0.098	0.081		1998.10.	0.079	0.390**	0.383
	2008.08.	0.406**	0.147	0.065		1998.11.	0.098	0.456**	0.504**
	2008.09.	0.288**	0.121	0.104		1998.12.	0.117	0.652**	0.391**
	2008.10.	0.505**	0.308**	0.213		1999.01.	0.264	0.641*	0.686**
	2008.12.	0.597**	0.294**	0.082		1999.02.	0.228	0.596	0.566
	2009.01.	0.451**	0.142	0.062		1999.03.	0.289	0.573*	0.612*
	2009.03.	0.287**	0.196**	0.065		1999.05.	0.088	0.427	0.426*
	2009.04.	0.245**	0.111	0.077		1999.06.	0.270	0.571	0.584
	2009.05.	0.179	0.100	0.080		1999.07.	0.141	0.428**	0.509
	2009.06.	0.272**	0.281**	0.167		1999.08.	0.127	0.296	0.304
	2009.07.	0.231*	0.140	0.113		1999.09.	0.049	0.594*	0.387
	2009.08.	0.475**	0.286**	0.222*		1999.11.	0.016	0.435*	0.469*
	2009.09.	0.215	0.082	0.096		2000.01.	0.125	0.376	0.314
	2009.11.	0.343**	0.123	0.096		2000.02.	0.115	0.590*	0.599**
	2010.01.	0.309**	0.101	0.059		2000.03.	0.060	0.366	0.442
	2010.02.	0.216**	0.124	0.083	DUK	2004.11.	0.123**	0.125	0.166
	2010.03.	0.521**	0.193**	0.059		2005.02.	0.282**	0.121**	0.077
	2010.04.	0.437**	0.214**	0.059		2005.04.	0.391**	0.269	0.118
	2010.05.	0.445**	0.232**	0.089		2005.07.	0.309**	0.147	0.109
	2010.06.	0.318**	0.217**	0.085		2005.09.	0.321**	0.091	0.053
	2010.07.	0.513**	0.187	0.117		2006.01.	0.251**	0.122*	0.061
	2010.08.	0.648**	0.312**	0.076	DAG	2004.11.	0.120**	0.417	0.170
	2010.09.	0.270**	0.148	0.131		2005.02.	0.395	0.186	0.132
	2010.10.	0.334**	0.128	0.102		2005.04.	0.192**	0.247	0.171
	2010.11.	0.391**	0.135	0.088		2005.07.	0.300**	0.153*	0.106
	2011.01.	0.419**	0.222**	0.094		2005.09.	0.214**	0.184*	0.152
	2011.03.	0.217*	0.073	0.104	DDK	2004.11.	0.458	0.284**	0.168
	2011.04.	0.329**	0.119	0.058		2005.02.	0.165	0.463**	0.257
	2011.05.	0.513**	0.154*	0.049		2005.04.	0.131	0.430**	0.256
	2011.06.	0.440**	0.201*	0.077		2005.07.	0.131	0.324	0.210
	2011.07.	0.563**	0.257**	0.101		2005.09.	0.121	0.227	0.140
	2011.08.	0.387**	0.140	0.091		2006.01.	0.037	0.249	0.268
	2011.09.	0.405**	0.146	0.088	DKS	2004.11.	0.041	0.332**	0.207

Table S1 (*Contd*)

	Sampling time	Geometric series	Log series	Log-normal distribution
	2011.10.	0.528**	0.167*	0.064
	2011.11.	0.294**	0.174*	0.101
	2011.12.	0.250**	0.137	0.082
	2012.01.	0.110	0.199**	0.067
	2012.04.	0.202**	0.122	0.122
	2012.05.	0.528**	0.144	0.059
	2012.06.	0.376**	0.108	0.078
	2012.07.	0.524**	0.130	0.088
	2012.08.	0.550**	0.180**	0.127
	2012.09.	0.435**	0.128	0.084
	2012.10.	0.309**	0.136	0.066
	2012.12.	0.049	0.105	0.094
	2013.01	0.148	0.283**	0.110
	2013.02	0.122	0.235**	0.094
	2013.03	0.134	0.132	0.088
	2013.04	0.111	0.288**	0.119
	2013.05	0.413**	0.162*	0.093
	2013.06	0.614**	0.177*	0.064
	2013.07	0.606**	0.179*	0.072
BSL	2010.04.	0.461**	0.289**	0.092
	2010.05.	0.321**	0.153	0.086
	2010.06.	0.232**	0.086	0.087
	2010.07.	0.458**	0.205**	0.107
	2010.08.	0.408**	0.210	0.120
	2010.09.	0.233**	0.109	0.076
	2010.11.	0.403**	0.176*	0.100
	2011.01.	0.472**	0.325**	0.079
	2011.02.	0.591**	0.160*	0.086
	2011.03.	0.441**	0.134	0.052
	2011.04.	0.305**	0.113	0.081
	2011.05.	0.364**	0.207*	0.117
	2011.06.	0.375**	0.261**	0.135
	2011.07.	0.296**	0.152	0.091
	2011.08.	0.111	0.116	0.139
	2011.09.	0.303**	0.091	0.088
	2011.10.	0.414**	0.171*	0.065
	2011.11.	0.377**	0.101	0.063
	2011.12.	0.489**	0.131	0.105
	2012.01.	0.135	0.246*	0.186
	2012.02.	0.424**	0.157	0.093
	2012.03.	0.297**	0.187*	0.096
	2012.04.	0.222**	0.174	0.095
NSJ	2007.11.	0.415**	0.288**	0.139
	2007.12.	0.252	0.338**	0.188
	2008.01.	0.157	0.427**	0.245
	2008.02.	0.154	0.362*	0.247
	2008.03.	0.228	0.281	0.310
	2008.04.	0.224	0.266	0.314
	2008.05.	0.009	0.404	0.515*
	2008.06.	0.480**	0.422**	0.238
	2008.07.	0.463**	0.373**	0.161
	2008.08.	0.073	0.337	0.343*
	2008.10.	0.034	0.257	0.317
	2008.11.	0.140	0.380**	0.276
	2008.12.	0.024	0.224	0.303
	2009.01.	0.133	0.435**	0.299
	2009.02.	0.045	0.318	0.403*
	2009.03.	0.250	0.481**	0.342*
	2009.04.	0.121	0.297*	0.226
	2009.05.	0.108	0.399	0.467*
	2009.06.	0.062	0.401*	0.354
	2005.02.	0.272	0.352**	0.213
	2005.04.	0.157	0.504	0.285
	2005.07.	0.207	0.242	0.221
	2005.09.	0.130	0.146**	0.152
HJD	2004.11.	0.121	0.255	0.285
	2005.02.	0.222	0.335*	0.264**
	2005.04.	0.055	0.514	0.528*
	2005.07.	0.041	0.385*	0.516
	2005.09.	0.142	0.384*	0.320
ONS	2004.11.	0.518**	0.337	0.189
	2005.02.	0.355	0.280*	0.220
	2005.04.	0.228	0.282	0.197
	2005.07.	0.070**	0.231	0.149
	2005.09.	0.404**	0.157	0.123
YBK	2004.10.	0.470**	0.134	0.080
	2005.05.	0.280**	0.073	0.108
	2005.10.	0.318**	0.249	0.173
	2006.05.	0.375**	0.205*	0.137
	2006.10.	0.221**	0.092	0.064
ONS	2004.11.	0.518**	0.337	0.189
	2005.02.	0.355	0.280*	0.220
	2005.04.	0.228	0.282	0.197
	2005.07.	0.070**	0.231	0.149
	2005.09.	0.404**	0.157	0.123
YSC	1999.05.	0.108	0.257	0.285
	2000.05.	0.167	0.359	0.242
	2000.10.	0.029	0.632**	0.393
	2001.05.	0.126	0.195	0.252
	2001.10.	0.108	0.131	0.211
	2002.05.	0.319**	0.277*	0.186
	2002.10.	0.261	0.163	0.232
	2003.05.	0.394**	0.361*	0.205
	2003.10.	0.496**	0.272**	0.146
	2004.05.	0.162	0.179	0.085
	2004.10.	0.345**	0.230**	0.085
	2005.05.	0.086	0.237	0.219
	2005.10.	0.258*	0.288*	0.199
	2006.05.	0.208	0.198	0.234
	2006.10.	0.066	0.155	0.191
THP	1998.10.	0.143	0.651**	0.340
	1999.05.	0.142	0.537**	0.576**
	1999.10.	0.044	0.429**	0.253
	2000.05.	0.217	0.480**	0.442**
	2000.10.	0.343	0.437	0.499*
	2001.05.	0.018	0.259	0.343
	2001.10.	0.017	0.382	0.518*
	2002.05.	0.132	0.392	0.358
	2002.10.	0.070	0.270	0.388*
	2003.05.	0.305*	0.262	0.234
	2003.10.	0.141	0.390	0.434*
	2004.05.	0.199	0.356*	0.242
	2004.10.	0.049	0.366	0.399
	2005.05.	0.051	0.395	0.531*
	2005.10.	0.086	0.584*	0.526*
	2006.05.	0.110	0.199	0.313
	2006.10.	0.179	0.279	0.285

Table S1 (*Contd*)

Sampling time	Geometric series	Log series	Log-normal distribution	Sampling time	Geometric series	Log series	Log-normal distribution
2009.08.	0.027	0.401	0.494*				
2009.09.	0.287	0.332*	0.239				
2009.10.	0.112	0.338*	0.236				
2009.11.	0.146	0.516**	0.306*				
2010.01.	0.121	0.353*	0.276				
2010.02.	0.170	0.271	0.309				
2010.03.	0.147	0.436**	0.290				
2010.04.	0.291	0.277	0.346				
2010.05.	0.323*	0.292*	0.165				
2010.06.	0.394**	0.417**	0.177				
2010.07.	0.001	0.521*	0.481				
2010.09.	0.122	0.117	0.171				
2010.11.	0.041	0.269	0.335*				
2011.01.	0.052	0.221	0.278				
2011.03.	0.042	0.198	0.250				
2011.06.	0.273	0.548*	0.642**				
2011.08.	0.098	0.346	0.496				
2011.09.	0.065	0.333	0.447*				
2011.11.	0.291	0.407*	0.480**				
2012.04.	0.281	0.339	0.319				
2012.05.	0.529**	0.402**	0.142				
2012.06.	0.332	0.539**	0.287				
2012.07.	0.433**	0.269	0.178				
2012.08.	0.390**	0.376**	0.229				