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A new assessment method for urbanization environmental impact: urban environment entropy model and its application

Tingping Ouyang · Shuqing Fu · Zhaoyu Zhu · Yaoqiu Kuang · Ningsheng Huang · Zhifeng Wu

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Abstract The thermodynamic law is one of the most widely used scientific principles. The comparability between the environmental impact of urbanization and the thermodynamic entropy was systematically analyzed. Consequently, the concept "Urban Environment Entropy" was brought forward and the "Urban Environment Entropy" model was established for urbanization environmental impact assessment in this study. The model was then utilized in a case study for the assessment of river water quality in the Pearl River Delta Economic Zone. The results indicated that the assessing results of the model are consistent to that of the equalized synthetic pollution index method. Therefore, it can be concluded that the Urban Environment Entropy model has high reliability and can be applied widely in urbanization environmental assessment research using many different environmental parameters.

Keywords Urbanization · Environmental impact assessment · Thermodynamic entropy · Urban environment entropy

T. Ouyang (✉) · S. Fu · Z. Zhu · Y. Kuang · N. Huang · Z. Wu
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Wushan,
Guangzhou, Guangdong 510640, China
e-mail: oyangtp@gig.ac.cn

Introduction

The thermodynamic law, which includes the first law, second law and third law, is one of the most widely used scientific principles. The first thermodynamic law represents the principle of energy conservation. Entropy is central to the second law of thermodynamics. Meanwhile, the third thermodynamic law is about the absolute entropy of substances (Fu et al. 1990). The second law of thermodynamics is the most meaningful law in physics. It is profound not only because it is a law that has got the most discussion yet a law that is most strange to us, but also because it gives us the clue to the understanding of life, i.e. the famous arrow of time. The time arrow points to the direction in which an isolated system gets more and more chaotic and disordered until its entropy gets to its maximum (Wang 1996). The second law points out that an isolated system will evolve in such a direction in which its entropy never decreases. The entropy is a variable indicating the disorder of the system. The bigger the entropy is, the lower the level of order of the system is. For an isolated system, the natural course of events takes the system to a more disordered (higher entropy) state. The entropy law implies that in the course of all processes in an isolated system, the quality of energy and matter deteriorates. It can also be expressed that the quality of a system is lower than it was before after a process has happened.

The concept of entropy has been applied to different research fields. Devins (1982) discussed the physical impact on the environment of energy. For the economic development and pollution, Rebane (1995) pointed out that the more developed the economy, the more serious the pollution, and the more quickly entropy increases. Leung and Yan (1997) discussed the transportation research under the entropy principle. The entropy principle was also applied to energy impact on ceramic targets (Smalley and Woosley 1999). Ren (2000) brought forward the conception of disaster entropy and applied it at a case study. Allan (2002) used the entropy principle to discuss the cost of complexity in industrial production. Jonathan and Costas (2002) applied the entropy method to dynamical fermions. Brohan et al. (2006) used the entropy law to estimate the uncertainty of regional and global observed temperature changes. Within the research field of climate change, some scientists used thermodynamic law to discuss the remained uncertainties (Collins et al. 2007). Unfortunately, little research has been done applying entropy law to the environmental impact assessment (He and Chen 2001). Though Wu et al. (2000) calculated the entropy in dissipative structure to discuss the developing direction of urban eco-system; almost no researcher used this theory to assess environmental impact of urbanization.

Urbanization is an adjustive process of the relationship between the humankind and the land. The primary purpose of urbanization is to improve the environment and to use all kinds of limited resources fully and effectively (Pugh 1995; Ouyang et al. 2005). Through the population agglomeration effect of urban development, a large number of rural people immigrate into urban areas. As a result, the urban population expands quickly. This population urbanization affects urban environment inevitably. This impact acts on every subsystem of the entire urban system. During the current developing phase in China, urbanization is mainly driven by industrialization (Chen and Chen 2002). Compared to industrialization, urbanization in terms of population can be quantified more easily. Therefore, it is a simple thought that population urbanization is the direct influencing factor on the state of an urban system. The function of population urbanization in urban systems is equivalent to the temperature in thermodynamic systems.

The impact of urban development on the environment is non-reversible. In a certain developing period, with the increase of urbanization levels, the natural environment becomes less ordered. On the contrary, the human environment probably becomes more and more steady and balanced (Bureau of Statistics of Guangdong Province (1988–2007). From a certain urban system state to another, the variation process may be different. However, once the original and final states are decided, the integrative variation of urban environment is stable. As a result, the impact of urbanization on urban environment is extremely similar to the effect of temperature to systematic entropy. Therefore, the primary purpose of this study is to establish a method for the urbanization environmental impact assessment based on the thermodynamic entropy law. Through a case study, the reliability and application of the established method was discussed.

Foundation of Urban Environment Entropy model

In the urbanization environmental impact research, a city is an open system that has both energy and matter exchanges with its environment. As discussed before, the urbanization environmental impact research system is similar to an open thermodynamic system. In an urbanization environmental impact research system, the urbanization level in terms of population is the independent variable for all changes while the environmental level is a dependent variable changing with the population urbanization level. In order to establish the Urban Environment Entropy model based on the entropy law to measure and assess the influence of urbanization on the urban environment, two assumptions should be stated.

Assumptions

Firstly, the relationship between urbanization level and urban environmental level is regarded as a kind of causality. It means that the urban environmental variation is a result of urbanization variations.

Secondly, the change of urbanization level is the exclusive reason for urban environmental impact. It means that the other factors are not considered when calculating Urban Environment Entropy to assess the impact of urbanization on the urban environment.

Definition

Within the thermodynamics, the entropy is defined as the heat added per unit temperature (Schroeder 2000; Baierlein 2003). Similarly, Urban Environment Entropy (simplified as UEE) can be defined as a function of the environmental effect of urbanization on an urban system in urbanization environmental impact research. It indicates the degree of influence of urbanization on the urban environment during the process of urbanization. Simply, UEE is the quotient of the changes of environmental level and urbanization level. It can be simply represented as the following equation:

$$\mathrm{UEE} = (\pm)\frac{dE}{dU},$$

where, E stands for the environmental level and can be represented by several groups of environmental indicators, and U stands for the urbanization level which is the urban population percent to total population of a certain study area. For the negative urban environmental indicators, the positive sign is chosen for calculation. On the contrary, the minus is used for positive urban environmental indicators.

Physical meaning

The positive value of UEE means urbanization has negative impact on urban environment. The urbanization leads to a decreasing quality in urban environment. The negative value of UEE indicates some positive effect of urbanization to urban environment. Urbanization can improve urban environmental quality to some extent. If the value of UEE is exactly equal to zero, it can be regarded that urban environment remains in a balanced state during this certain process of urbanization. The value of UEE indicates the degree of the influence of urbanization on urban environment. The larger the absolute value of UEE, the higher the impact of urbanization does on urban environment.

Calculation of Urban Environment Entropy

The calculation of the entropy change in thermodynamics considered several different changing processes (Fu et al. 1990). During the process of urbanization, the environmental impact included the assessment for the history and actuality. Along with the urban development, the environmental scientists would want to predict the environmental impact of urbanization. Therefore, the calculation of the UEE should include the following different practical conditions.

(1) Environmental indices are monitored at a certain time. That means the urbanization level is relatively steady. This situation is similar to the equal temperature change in the thermodynamics. The entropy change of a thermodynamic system is equivalent to the quotient between heat and temperature (Fu et al. 1990). Correspondingly, the UEE can be calculated by the quotient between the environmental change and the urbanization level. It can be represented by the following equation:

$$\mathrm{UEE} = (\pm)\frac{\Delta E}{U}$$

If the concentration of a certain pollutant and its standard or background value can be determined, the UEE of this pollutant during the process of urbanization can be calculated using the following formula:

$$\mathrm{UEE}_i = (\pm)\frac{\Delta E_i}{U},$$

Where, ΔE_i stands for the percentage of the difference between the measuring value of the ith pollutant and its standard or background value; U is the temporal urbanization level of the sampling location.

(2) During a certain developing period, the original and final values of the urbanization level and the urban environmental indices are known or can be acquired. According to the definition and the formula for the UEE, it can be calculated by the ratio between the variations of the urban environmental values and urbanization level. The formula can be written as following.

$$\mathrm{UEE}_i = (\pm)\frac{\Delta E_i}{\Delta U},$$

Where, ΔE_i stands for the variation of the urban environmental index and ΔU is the variation of the urbanization level during this period.

(3) Based on the known urbanization level and urban environmental situation, the environmen-

tal impact can be predicted when the urbanization level reaches to a certain degree. In general, a series of values for environmental parameters appeared along with the change of urbanization level. Therefore, a function between the environmental parameter and urbanization level can be found using statistic analysis. Then the UEE of the predicted environmental impact from a basic stage (urbanization level is U_1) to another (urbanization level is U_2) can be calculated through the integral method using the following formula:

$$\mathrm{UEE} = (\pm)\int_{U_1}^{U_2} \frac{E}{U}\, d\, U,$$

Where, E stands for the urban environmental level; U is the urbanization level; moreover, the urban environmental level is a function of the urbanization level as $E=f(U)$.

Application of the model – a case study

In the practical application, all different kinds of indicators of urban environment can be used to calculate the UEE for a certain period. In the present case study, a series of indices for river water quality were used to assess the practicability and dependability of the new established Urban Environment Entropy model.

Thirty river water samples were collected from the Pearl River Delta Economic Zone during the middle water level period of the hydrological year 2002. Several physicochemical parameters were determined for all the samples. The study area, the distribution of urbanization level and the sampling sites are illustrated in Fig. 1. The monitoring results were published in the Journal of Environmental Monitoring (Ouyang et al. 2005).

In the present study, the Urban Environment Entropy model was applied to assess the analytical

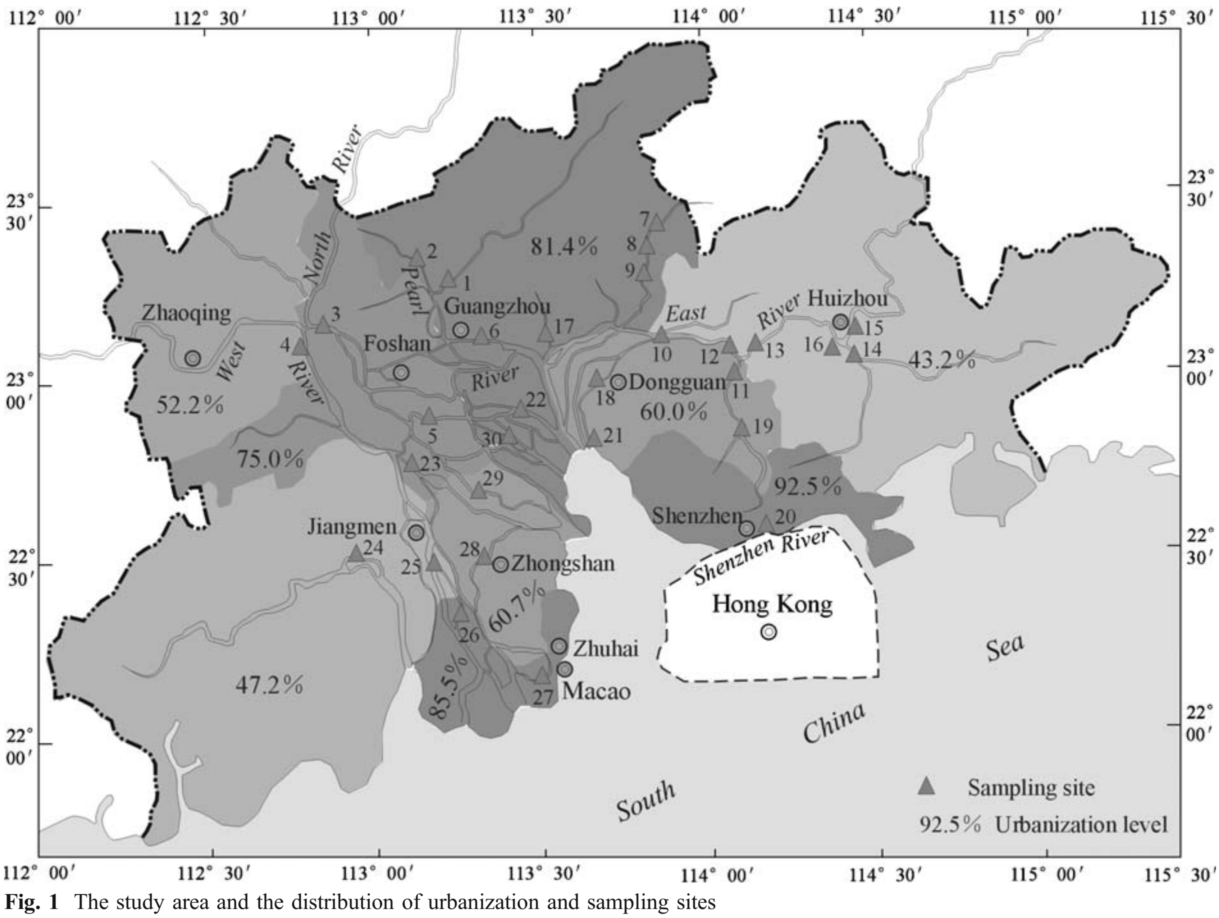

Fig. 1 The study area and the distribution of urbanization and sampling sites

results. Subsequently, the assessing results were compared with the results of integrative pollution index method published at Environmental Monitoring and Assessment (Ouyang et al. 2006) to certify the practicability and dependability of the Urban Environment Entropy model. The calculation of the UEE in this case study belongs to the first condition, mentioned before. The specific characteristic of urbanization must be considered during the course of calculation. Generally, the higher the urbanization level, the larger the impact does on urban environment. On the other hand, for the convenience of comparing the results from different assessing methods, the formula is slightly changed. In the present study, the percentage of difference between the analytical result and its standard is used to represent the environmental variation. Therefore, the calculating formula is changed to the following form:

$$\mathrm{UEE}_i = (\pm)\frac{\Delta E_i^s}{1-U}$$

Where, ΔE_i^s is the percentage of difference between the analytical result and the standard value for the ith parameter and U stands for the temporal urbanization level of a sampling site.

Considering the condition of river water pollution in the study area, the parameters, NH_4^+, DO, COD_{Mn} and TOC were chosen to calculate their UEE. According to the standards of surface water, the water quality reaches class II can be used for the source of drinking water (Bureau of National Environmental Protection 1989). Therefore, the water quality standards of class II were used for the UEE calculation. The population data of late 2001 were used to calculate the urbanization level. The results of Urban Environment Entropy for the above parameters are listed in Table 1.

Table 1 The Urban Environment Entropy of main parameters for every sampling site

Sampling no.	NH_4^+	DO	COD_{Mn}	TOC
1	0.596	0.112	0.061	0.073
2	0.559	0.149	0.074	0.079
3	−0.159	−0.166	−0.155	−0.187
4	−0.154	−0.149	−0.155	−0.174
5	−0.061	−0.163	−0.207	−0.207
6	2.048	0.149	0.065	0.117
7	−0.432	−0.350	−0.420	−0.474
8	−0.312	−0.330	−0.360	−0.466
9	−0.240	−0.330	−0.360	−0.442
10	−0.024	−0.240	−0.360	−0.413
11	3.437	−0.020	0.230	0.210
12	0.112	−0.186	−0.250	−0.251
13	−0.035	−0.210	−0.271	−0.291
14	4.657	−0.066	−0.128	−0.086
15	−0.432	−0.293	−0.383	−0.404
16	−0.500	−0.199	−0.341	−0.279
17	10.985	0.152	0.931	2.623
18	12.388	0.354	0.899	0.377
19	0.080	−0.033	−0.130	−0.126
20	5.957	0.071	0.471	0.479
21	−0.352	0.020	0.350	−0.268
22	−0.257	−0.022	−0.134	−0.162
23	−0.313	−0.079	−0.110	−0.236
24	−0.610	0.265	−0.032	−0.032
25	−0.402	−0.141	−0.238	−0.317
26	−0.375	−0.141	−0.212	−0.275
27	0.145	0.036	−0.036	−0.056
28	5.897	0.288	0.373	0.071
29	−0.346	−0.144	−0.167	−0.270
30	−0.257	−0.058	−0.120	−0.176

At the sampling sites 17, 18, 20, and 28, the Urban Environment Entropy of all parameters appeared to be positive values. In addition, the UEE values of ammonia were extremely large, more than 5.0 (Table 1). According to the definition and physical meaning of the UEE, the river water bodies at these locations can be regarded as seriously polluted. Urbanization had an extremely serious negative impact on the river water quality of these sampling sites. Positive UEE values appeared at sampling sites 6, 11, and 14 for all or some calculated parameters and their absolute values ranged from 1.0 to 5.0. It can be concluded that river water at these sampling sites was heavily polluted. During urban development, urbanization did a serious negative impact on these river water bodies. At sampling sites 1, 2, 12, 19, 21, 24, and 27, only a small part of the UEE values were positive. Moreover, their absolute values were relatively low. The river water quality was slightly affected by urbanization at these sites. As for the samples that were located far away from urban or industrial areas, the UEE values of all parameters were negative. Basically, urbanization did not disturb the river water quality of these locations. On the contrary, river water quality was improved to a certain extent due to the population emigration to urban areas and the increasing investment in environmental protection related to the economic development

(Bureau of environmental protection, Guangdong Province 1998–2003).

The application of the integrative pollution index method and its assessing results were published in the Environmental Monitoring and Assessment (Ouyang et al. 2006). As discussed, the equalized synthetic pollution index was more than 3.0 at sampling sites 17, 18, and 20. The water bodies at these locations were seriously contaminated. For the reason these sites are located within urban zones, it can be inferred that urban activities extremely deteriorated the river water quality. Meanwhile, the water bodies located at the 6, 11, 14, and 28 sampling sites whose pollution indexes were larger than 1.0 but less than 3.0 had heavy polluted water. The river water quality was affected to some serious extent. The waters of sampling sites 8, 19, 21, 22, 24, and 27 were slightly polluted. However, equalized synthetic pollution indices of the other samples were less than 0.2. The river water remained relatively clean and could match the requirements of drinking water sources. These other water bodies were almost not affected by the human activity because these sampling sites were located far away from developing urban and industrial areas.

From the discussion mentioned before and the detailed comparison of the results from the two methods illustrated in Fig. 2, it can be clearly seen that the integrative assessing results from the Urban Environment Entropy model and the equalized synthetic pollution index method are basically consistent. Only at sampling site 8 and 22, the ESPI indicated that the river water at these sites was slightly polluted. However, the results of UEE implied that the river water quality was not affected negatively by urbanization at these two sites because the UEE values of all the parameters were negative. Therefore, the relative error of the assessment was 6.67% for 30 samples. This kind of error may be caused by systematic error or accidental error of the experiment. Moreover, the error of assessing method is small enough to be ignored. Consequently, it can be concluded that it is feasible to apply the Urban Environment Entropy model in the assessment of urbanization environmental impact. The assessing results can be directly used to discuss the urban environmental problems.

Conclusion

Based on the simple introduction of thermodynamic theory and systematic analyses of the urbanization environmental impact, the authors think that the thermodynamic entropy law can be used as a reference for the assessment of urbanization environmental impact. The concept of Urban Environment Entropy was brought forward, and its physical meaning was defined in the present study. Before the establishment of Urban Environment Entropy model, two assumptions were stated. The calculation of the Urban Environment Entropy was discussed through three different circumstances, which included

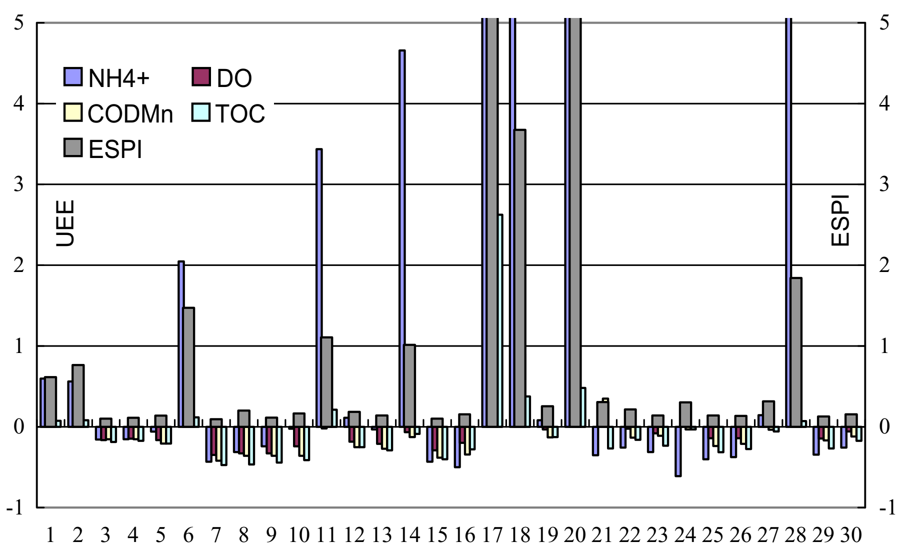

Fig. 2 Comparison of ESPI and UEE for every sampling site

historical and current condition assessments and the prediction of the future.

As a case study, the assessment of urbanization impact on river water quality in the Pearl River Delta Economic Zone was simply introduced to show the application of the new method. Comparison was performed between the results from the equalized synthetic pollution index method and the urban environment entropy model. The results indicated that low relative error exists between the two assessing results. This comparison proves the practicability and reliability of the urban environment entropy model.

As well known, the state of the urban system can be represented by many natural environmental factors such as urban water, urban land use, air and soil quality, and a series of socioeconomic indicators such as economic situation, quantity and quality of population, traffic and so on. For the application of the Urban Environment Entropy model, almost all the mentioned series of environmental indicators can be used to calculate their UEE to assess the urban environmental impact during urbanization process. Furthermore, the required database used for the Urban Environment Entropy model is relatively simple and easy to collect. In addition, the calculation procedure is both simple and convenient. Therefore, the Urban Environment Entropy model can be widely used in the urbanization environmental impact assessment research.

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