利用综合评价方法和等级模型评价乐安江水体重金属污染

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摘要：采用 1992～1995 年在江西乐安江所获得的野外调查数据，对化学、毒理学和生态学数据的性质进行分析比较。分析了不同类型评价参数的性质和综合利用时存在的问题，并提出了三者综合的评价方法和一个等级模型，来评价江西省乐安江河流重金属污染及潜在的生态影响。结果表明对于复杂的河流生态系统，采用多指标综合评价方法是描述污染和预测污染生态效应的一种有效途径。

关键词：重金属污染；生态风险评价；多指标；综合方法

Assessing Heavy Metals Pollution in the Le′an River by Multi-index and an Integrative Model

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Abstract: The assessment of heavy metal pollution in river is an important topic in the fields of water quality research. The chemical, toxicological or ecological approaches have been extensively and independently used to assess ecological consequences of heavy metals pollution in many rivers. Independent application of each parameter to assess water quality has disciplinary limitation and, therefore, the integration of these assessments gives a better explanation to chemical pollution and the associated ecological effects in a river.

This paper compared the characteristics of chemical, biological and ecological data obtained from the field studies carried out in Le′an River, Jiangxi Province during 1992 to 1995. There were three types of data have been included in the assessment: chemical data include concentrations of heavy metals in river water, interstitial water, and sediment, toxic data included overall toxicity in different types of samples performed with luminobacterium *P. qinghanesis* 67 and *P. phosphoreum*, algae *C. vulgaris* and *S. obliqnus*, and invertebrate *D. magna*, as well as ecological data included the abundance and richness of aquatic and benthos species in the river.

The characteristics of different type of data and so-formed indicators used in traditional ecological risk assessment were evaluated. Their application in assessing or predicting ecological impact of heavy metals could result in differences. In the case study, the chemical data showed good accordance with ecological data, but neither chemical nor ecological data were in good accordance with toxic data. There were two major explanations to these disagreements. Firstly, the observed toxicity of the collected samples could not be attributed to heavy metals that were measured and there were other pollutants or acidity affecting

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the aquatic biota. Secondly, the chemicals in water and in sediment could not be totally bioavailable and the bioavailability depended on site-specific aquatic condition.

An integrative methodology and a hierarchical model were developed for assessing the potential ecological impact of heavy metal pollution in the river. In the approach, Nemerow Index was used to describe water pollution by multiple metals, Risk Index was used to describe sediment pollution by multiple metals, relative inhibition or death rate from acute toxicity tests of multiple species were classified into toxicity levels to indicate the toxicity associated with environmental samples, Shannon-Weaver Diversity Index was used to describe diversity of algae, crustacean, rotifer and protozoan communities and Margalef Diversity Index was used to describe diversity of benthonic macroinvertebrates. Based on these index, a hierarchical model was applied to rank the observed effects and the effects were divided into five classes: i.e. no-effect, slightly affected, moderately affected, strongly affected and seriously affected.

It was shown that the multi-index description and the proposed approach should be an effective way for understanding of metal pollution and its associated ecological impact in Le′an River. At upstream, water pollution occurred in raining season and should be mainly caused by zinc and it showed a moderate toxicity to *D. magna*. Both chemical pollution and toxicity to certain species did cause system deterioration.

Affected by the copper min discharge, river water was severely polluted by heavy metals and acidity and the aquatic ecosystem was severely deteriorated. However, neither river water nor sediment showed toxic effects in acute bioassay, indicating the metal pollutants, when measured in total concentration, were mostly in inert forms. Ecological consequence should be mainly associated with acidity.

At converging with Jishui River, which is a tributary discharging soluble metals to the river, chemical, biological and ecological data showed in good accordance and the ecosystem deterioration should be closely related with heavy metal pollutions.

Downstream of the river, concentrations of heavy metals in aqueous phase did not exceed the allowable criteria and ecosystem was gradually recovered. The ecosystem recovery should be due to the dilution effects, strong buffer capacity, as well as intrude of species from the lakeside. However, both water and sediment showed slight to moderate toxicity, indicating chemical pollution other than metals and the disturbance to sediment may result in potential ecological impact.

Key words: heavy metal pollution; ecological risk assessment; integrated approach

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目前,化学、生态学和毒理学等方法已被广泛应用于评价水环境中的重金属污染。然而,每一类方法都有它的优点和限制。化学方法得到的结果具有法律效率,便于将数据直接用于环境管理,但不能反映水体的毒性和生态状况[1]。总量测定也不能反映生物有效态的浓度和不同的环境效应[2]。水生生物已被用来监测不同水体的毒物影响和确定污染源[3],生物监测方法已被证实是一种确定复杂污染物生物效应的可靠方法[1~5],但缺乏和污染物浓度之间的对应关系。生态监测所得到的数据直接反映水生态系统的状况,但生态系统的退化受多种环境条件变化的影响。因此在实际研究工作中,很难用单一的评价方法,来解决复杂的环境问题,需要化学、生态和毒理学等多学科及多种评价方法的综合[6,7]。而目前关于如何利用化学、毒理学和生态学方法,以及实际应用于河流污染评价的工作尚少。

本文基于 1992～1995 年国际合作生态研究计划(CERP)课题所获得的数据,对乐安江化学、毒理学和生态学数据进行分析比较,提出了一个等级模型,来综合评价乐安江河流重金属污染状况。

1 研究方法

乐安江表层水中主要的污染物是重金属 Cu、Pb 和 Zn。对乐安江表层水中 3 种重金属浓度,水质评价标准采用国家《地面水环境质量标准》中的 Ⅱ 类标准(GB: 3838-88)和《渔业水质标准》(TJ35-79),即:Cu=

0.01mg/l,Pb=0.05mg/l,Zn=0.1mg/l，采用 Nemerow 水质指数公式进行综合[8]。

乐安江沉积物中主要的污染物也是重金属 Cu、Pb 和 Zn。乐安江沉积物重金属 Cu、Pb 和 Zn 的背景浓度分别为 45mg/kg、34mg/kg 和 117mg/kg，采用瑞典学者 Hakanson 的潜在生态风险性指数(Risk Index)公式对多种重金属污染物进行综合评价[9]。

原生动物、藻类和浮游动物群落多样性指数，采用香农-威纳多样性指数公式计算[10]。底栖无脊椎动物多样性指数利用马格莱夫指数公式计算[11]。

对乐安江河水和沉积物提取液进行了多指标毒性测试，包括发光菌(*Photobacterium phosphoreum* T3 和 *Vibro qinghaiensis* Q-67)、小球藻(*Chlorella vulgaris*)和斜生栅藻(*Scenedesmus obliqnus*)毒性测试，以及大型蚤(*Daphnia magna*)急性和慢性毒性测试，结果以相对抑制率或相对死亡率表示。

该文所有原始数据分别取自 CERP 数据库。

根据表层水的 Nemerow 指数值、沉积物生态风险性指数值、生物多样性指数值和毒性检验的相对抑制率或死亡率的大小，可把表层水和沉积物中重金属的污染及生态系统受影响程度分为：没有影响、轻微影响、中等影响、较强影响和严重影响 5 个等级[7]。针对乐安江河流污染的实际情况，乐安江表层水和沉积物的污染及对生态系统影响的等级划分见表 1。

表 1 化学、生态学和毒理学评价分类等级模型[7]

Table 1 Hierarchical model for chemical, ecological and toxicological assessments

效应 Impact	等级 Grade	水质指数值 Nemerow index	沉积物风险指数值 Hakanson index	生物多样性指数比值* Relative biodiversity index	相对抑制率或死亡率 Inhibition or death rate
没有影响 No impact	Ⅰ	<1	<20	1.0	0
轻微影响 Slight impact	Ⅱ	1～2	20～80	0.75～1.0	0～25%
中等影响 Moderate impact	Ⅲ	2～3	80～160	0.50～0.75	>25%～50%
较强影响 Strong impact	Ⅳ	3～5	160～240	0.25～0.50	>50%～75%
严重影响 Very strong impact	Ⅴ	>5	>240	<0.25	75%～100%

* 藻类、浮游动物和底栖动物的平均多样性指数比值(污染站位/对照站位)Relative Biodiversity Index was defined as the ratio of the averaged biodiversity index of algae, zooplankton and benthos at polluted site to that at control site

利用各指标及其分级，得出相应的环境质量评价结果，并在此基础上综合判断污染及其生态影响。不同评价的目的、方法，及其综合流程示于图 1。

2 结果与讨论

2.1 乐安江表层水化学污染评价

乐安江河水受到来自德兴铜矿的矿山酸性废水和洎水河河水的污染，主要的环境污染物是酸性废水和重金属铜铅锌的污染。利用 Nemerow 指数对河水中的重金属污染程度进行了评价，结果见图 2。在乐安江未受德兴铜矿矿山酸性废水污染的对照河段(A01)，由于其上游有一活性炭工厂排放一些含锌废水，河水受到轻微的污染。在洎口河段(A04)，由于德兴铜矿矿山酸性废水的影响，河水受到重金属的严重污染。另据文献报道，此河段河水中的 pH 值也相当低，并且丰水期比枯水期酸污染严重，河水 pH 分别为 3.24 和 4.25[22]。A05 至 A06 河段，由于河水的稀释、吸附沉淀等作用，表层水没有受到影响。在戴村河段(A07)，由于受到来自洎水河河水的重金属污染，表层水重金属污染相当严重。在 A08～A13 河段，表层水仍有轻微的污染。在蔡家湾(A13)之后，河水才恢复到正常水平。

2.2 沉积物污染评价

根据 Hakanson 的生态风险性(*RI*)指数公式，探讨了乐安江沉积物中重金属污染。从图 3 可以看出，海口(A01)沉积物基本上没有污染。洎口(A04)至虎山(A08)河段，具有很高的 *RI* 值，沉积物已经污染，并具有很强生态风险性。污染应该主要来自德兴铜矿酸性废水和洎水河。A08 至 A09 河段沉积物具有中等或轻

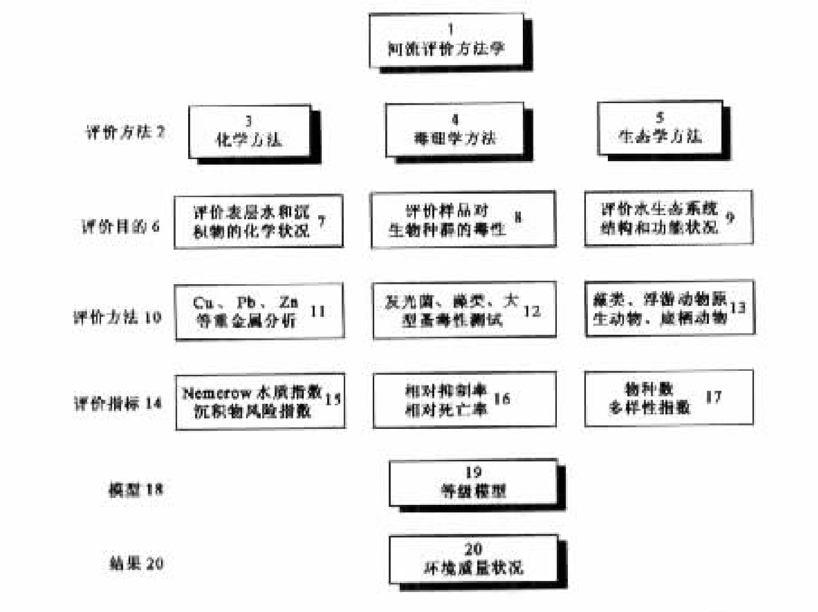

图 1　河流重金属污染评价方法学框图

Fig. 1　Methodology for the assessment of heavy metal pollution

1. Method for Ecological Risk Assessment (ERA); 2. Approaches in ERA; 3. Chemical Approach; 4. Toxicological Approach; 5. Ecological Approach; 6. Objectives of Assessment; 7. Chemistry of Water and Sediment; 8. Toxicity of Water and Sediment Samples; 9. Structure and Function of Aquatic Ecosystem; 10. Tasks; 11. Analysis of Heavy Metals; 12. Bioassay; 13. Ecological Survey; 14. Index; 15. Nemerow Index; 16. Inhibition or Death Rate; 17. Species Richness and Biodiversity; 18. Models; 19. Hierarchical Model; 20. Results; 21. Assessments

图 2　乐安江表层水重金属污染评价图

Fig. 2　The assessment of heavy metal pollution in surface water of Le′an River

1. Assessment of Surface Waters　Ⅰ. **没有影响** No impact　Ⅱ. **轻微影响** Slight impact　Ⅲ. **中等影响** Moderate impact　Ⅳ. **较强影响** Strong impact　Ⅴ. **严重影响** Very strong impact　A00～A18. **样点** Sample plot

微的污染,以后逐步减弱,在接近入湖口的蔡家湾(A13)至龙口(A16)河段沉积物表现为轻微污染。

2.3　生态学数据评价

1993 年 6 月(丰水期)和 1994 年 10 月(枯水期)分别对乐安江的浮游植物、浮游动物和底栖生物进行

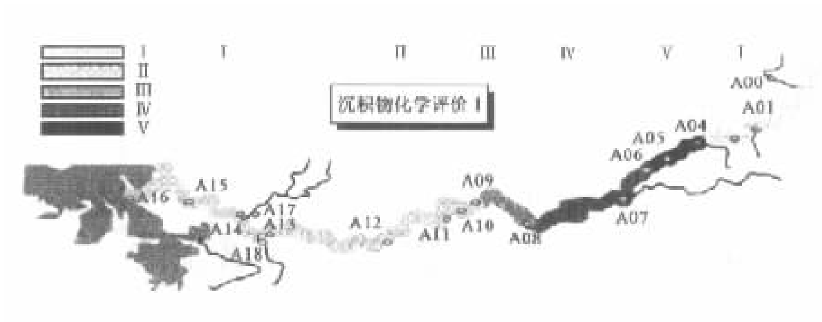

图 3 乐安江沉积物重金属污染评价

Fig. 3 The assessment of heavy metal pollution in sediment of Le'an River(1. Assessment of Sediments)

图例同图 2 Legend same as fig. 2

了野外调查[12,13]。根据藻类、浮游动物和底栖动物的多样性指数值,计算出三者的多样性指数与对照站位多样性指数的平均比值,然后进行生态影响等级划分(图 4)。结果表明,在 A04 采样站位,由于受到德兴铜矿矿山酸性废水的污染,该河段的水生生态系统被严重破坏。从 A05 至 A08 河段,生态系统较强地被破坏。在乐安江的下游(A13~A16),由于污染程度减轻,同时,来自鄱阳湖物种的迁移,该河段的生水生态系统逐渐恢复,只受到轻微的影响。

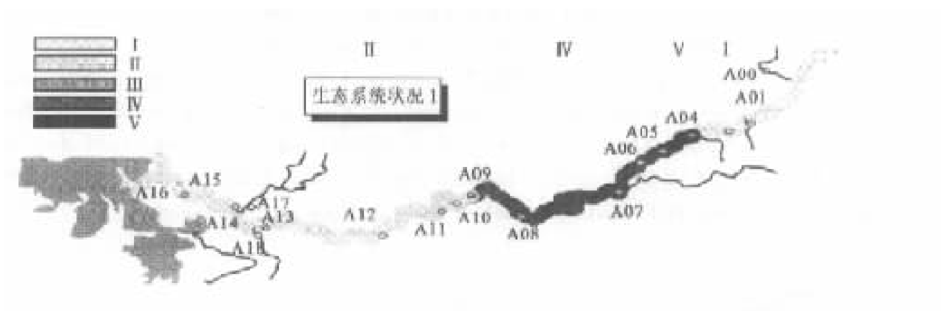

图 4 乐安江水生生态系统状况评价

Fig. 4 The assessment of the ecological characteristic in Le'an River(1. Assessment of Ecosystem)

图例同图 2 Legend same as fig. 2

2.4 表层水和沉积物提取液生物毒性评价

乐安江表层水 T3 发光菌和 Q67 毒性检验结果表明(图 5),A01 采样站位显示轻微的毒性,A04 和 A05 表层水没有毒性,在 A07 采样站位,表层水由于受到洎水河水的污染,显示极强的毒性,A08~A16 河段的河水显示轻到中等的毒性。

对于乐安江沉积物提取液进行生物毒性检验结果用几何平均值表示,结果绘于图 6。沉积物提取液大型蚤(*D. magna*)急性毒性检验表明,丰水期各河段沉积物都显示极强的毒性,枯水期只有 A07 河段的样品显示极强的毒性。

乐安江沉积物提取液的藻类(*C. vulgraris* 和 *S. obliqnus*)生长抑制实验表明,A01、A04 和 A05 样品没有或显示轻微的毒性,A07 样品显示中等的毒性,A08 样品没有毒性,A13 样品显示轻微的毒性。如果仅仅根据上述毒性评价结果,各类样品显示的毒性主要是来自洎水河的污染物,而不是德兴铜矿。

2.5 化学、毒理学和生态学方法评价结果的比较与综合

通过对乐安江河流重金属污染化学、生物和毒理学方法评价结果的综合比较,可知用不同评价方法来描述或预测重金属污染的生态影响,结果并不相同。其中化学和生态的数据之间相对一致,而部分采样点生物毒性数据并不和化学或生态数据重合。考虑到本文所收集的数据仅限于对该水体影响重大的重金属

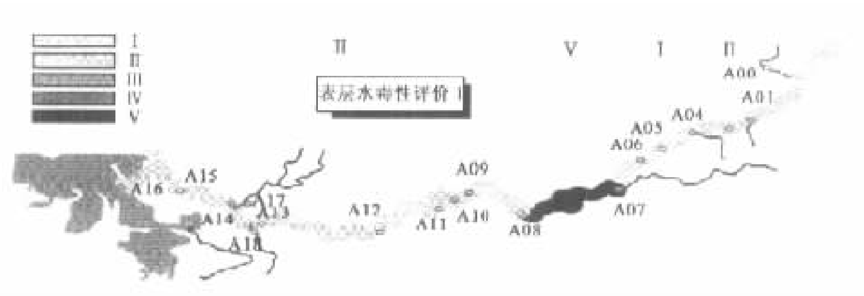

图 5　乐安江表层水生物毒性评价结果

Fig. 5　The assessment of biological toxicity of surface water in Le′an River(1. Bioassay of Waters)

图例同图 2 Legend same as fig. 2

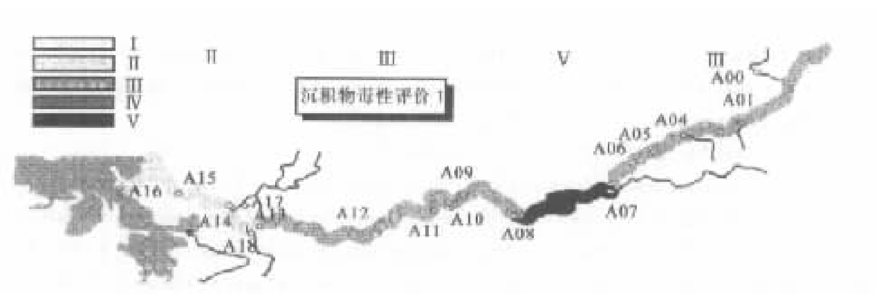

图 6　乐安江沉积物提取液成组生物检验结果

Fig. 6　The assessment of biological toxicity of sediment extracts in Le′an River(1. Bioassay of Sediments)

图例同图 2 Legend same as fig. 2

污染物,并没有排除其他污染物或污染效应,如酸度变化的影响。另一方面,化学分析和生物毒性测试结果的不一致,在一定程度上反映了天然水体中重金属污染物的毒性与其生物可给性密切相关。

基于化学、生态和毒理学评价结果,可以通过具体案例说明如何采用综合评价方法和等级模型对乐安江各河段的重金属污染及生态影响进行描述或预测。

在乐安江未受到矿山废水污染的对照站位 A01,丰水期表层水化学评价和生物检验评价,显示轻到中等程度的污染,而生态学评价表明生态系统没有受到影响。但沉积物大型蚤毒性检验显示中等的毒性,这可能与沉积物中高浓度 Zn 有关(Zn 对 *D. magna* 的 $EC_{50}=0.54$mg/L[14]),典型污染物的影响至关重要。

在 A04 河段,由于乐安江受到德兴铜矿酸性废水的污染,河水和沉积物被严重污染,同时,水生生态系统结构和功能被严重破坏,化学评价和生态学评价显示一致的结论。然而,河水和沉积物毒性检验显示轻到中等的毒性。这主要是由于沉积物中的重金属主要以惰性态,如硫化物形式存在[15]。

在 A07 河段,由于受到来自乐安江上游及洎水河的污染物,河水和沉积物被严重污染,化学、生物和毒性评价都显示相同的结论,河水和沉积物显示极强的毒性,对生态系统产生严重的影响,综合评价认为重金属污染是关键因素。

从 A08 到 A16 河段,化学评价结果表明表层水没有受到污染,而河水和沉积物的毒性检验以及生物学评价显示轻到中等影响。由于该河段河水和沉积物的缓冲容量、稀释作用,以及来自鄱阳湖生物物种迁移补充,生水生态系统逐渐得以恢复。然而,当一些水力条件(淘金、挖淤泥活动)和物理化学(pH、pε)条件发生改变时,沉积物中的重金属会产生潜在的生态影响。

3　结论

对于复杂的河流生水生态系统重金属污染的评价,采用单一的方法不可能得到全面的结果,多种方法

的综合评价是解决实际问题的有效途径。本文通过化学、毒理学和生态学方法对乐安江河流重金属污染的综合评价,指出乐安江河水和沉积物明显受到来自德兴铜矿和洎水河的污染,并对水生生态系统产生显著的影响。乐安江下游(A08)**至鄱阳湖河段沉积污染物,具有潜在的生态破坏作用。本研究结果同时表明化学、毒理学和生态学评价方法都有一些限制,各类方法评价结果之间存在一些差异,并对其原因做了说明。**

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