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專　論

台北水源特定區污染潛勢空間變異性分析及土地利用管制策略研擬

Assessing Spatial Variability of Pollution Potential and Creating Land-Use Management Strategies in the Taipei Water Specific Area

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摘　要

本研究應用輸出係數法及自然分級法評估台北水源特定區污染潛勢之空間變異性，依照數值高程資料將研究區域切割成 22 個子集水區，其中有 6 個子集水分區屬於高污染潛勢區域，建議須採取較嚴格的土地利用管制策略。本研究評估結果顯示，若將高污染潛勢區域之土地利用型態稍作變化，將 50%農地及 50%社區變更為林地時，高污染潛勢區域則可以縮小，由原先的 6 個子集水區降到僅有 2 個子集水區屬於高污染潛勢區域。本研究所提出之土地利用管制策略可以供台北水源特定區管理單位參考之用。

關鍵詞：非點源污染，污染潛勢，集水區管理，自然分級法。

ABSTRACT

This study applies the export coefficient and natural breaks classification methods to assess the spatial variability of pollution potential in the Taipei Water Specific Area (TWSA). This work divides the TWSA into twenty-two subwatersheds based on digital elevation data, among which there are six subwatersheds with grade A pollution potential which is the highest level. Stricter land-use policy should be implemented in subwatersheds with larger pollution potential. If these subwatersheds implement land-use management

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strategies and change 50% of farmlands and 50% of built-up areas to forested areas, the number of subwatersheds with grade A pollution potential can be reduced from six to two. The land-use management strategies addressed in this study can be useful for classifying land-use restrictions in the TWSA.

Keywords: Finite Mixture Model, Heavy Metal, Soil Pollution.

I. Introduction

As Taiwan's population and urban development have increased, environmental pollution problems have become increasingly significant. Human activity in environmentally vulnerable areas increases the risk of damaging water quality and the ecological environment (Lin *et al.*, 2000; Lu *et al.*, 2001; Chang *et al.*, 2008a). Land-use management strategies are important for establishing protective measures necessary for the protection of vulnerable watersheds. Because land resources are limited, it is impossible to prohibit all activities in a watershed. Classified land-use restrictions are therefore increasingly necessary for protecting the watershed environment and sustaining land resources (Wang, 2001; Chang *et al.*, 2008b; Chang and Hsu, 2009; Chang and Hsu, 2011).

Export coefficients represent the annual average total amount of pollutants in a system from a specific area. The use of applied export coefficients in determining pollution from non-point sources is a well-developed method that has been applied in environmental studies (Johnes, 1996; Townsend and Douglas, 2000; Khadam and Kaluarachchi, 2006; Kay *et al.*, 2008; Do *et al.*, 2011). Export coefficients have been efficiently combined with Geographic Information Systems (GIS) to study non-point source pollution, owing to the compatibility, integration capability, and easy implementation of this method (Mattikalli and Richards, 1996; Liu *et al.*, 2008; Gurel *et al.*, 2011). In previous studies, the results produced for non-point source pollution have been widely used to identify critical pollution regions by GIS (Worrall and Burt, 1999; Erturk *et al.*, 2006; Liu *et al.*, 2009). However, there has been little discussion about applying cartographic classification methods and export coefficient modeling to create land-use management strategies for mitigating pollution potential.

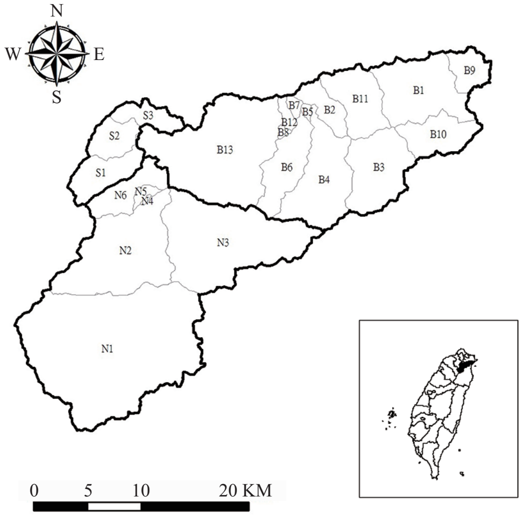
The natural breaks classification method is one of the most common for the classification or ranging of interval data in cartography. It is based on the subjective recognition of gaps in distribution, where there are significantly fewer observations. Developed by George Jenks, the natural breaks classification method minimizes variation within classes and maximizes variation between classes (Jenks, 1967; Luan *et al.*, 2011). This technique is most useful when the data set has more than one modal value. Luan *et al.* (2011) utilized the natural breaks classification method to identify break points of the habitat suitability index for the wild Amur tiger in China. Raikow and D'Amico (2011) demonstrated the effectiveness of this method in determining the temporal variation in spatial sources of discharge in a watershed.

The case area in this study is the Taipei Water Specific Area (TWSA), an important water source area in northern Taiwan. The land-use activities in this area result in the spatial variability of pollution potential. While there are limited resources available in water source areas, it is important to develop an approach that identifies the target subwatersheds with relatively high pollution potential. Therefore, this study applies the natural breaks classification and export coefficient methods to analyze the spatial variability of pollution potential in this area, and uses these findings to address classified land-use restrictions. Areas with high pollution potential should implement higher land-use restrictions than other areas. This study also addresses several land-use management strategies for reducing pollution potential and assesses the efficiency of each strategy.

II. Methods

2.1 Site description

As shown in Figure 1, the TWSA comprises three basins: the Bei-Shih Creek Basin, the Nan-Shih Creek Basin, and the Sin-Dian Creek Basin. It covers an area of 697.57 km^2. The Fei-Tsui reservoir, which provides water for around five million people in northern Taiwan, is located in the Bei-Shih Creek Basin. This study divides the TWSA into twenty-two subwatersheds based on their drainage area, which are determined from digital elevation models supplied by a GIS tool. Land-use data for the subwatershed areas are obtained from the National Land Surveying and Mapping Center, Taiwan (Taiwan NLSC, 2011). The Center conducted a nationwide land use investigation during 2006-2008 based on non-cloud aerial photographs and SPOT-5 satellite images. Table 1 lists the areas and area percentages of different land-uses in the TWSA. More than 90% of the land in this area is forest. The percentages of forest in the Bei-Shih Creek Basin and the Nan-Shih Creek Basin are larger than that of the Sin-Dian Creek Basin. Conversely, the percentage of built-up area in the Sin-Dian Creek Basin is larger than those of the Bei-Shih Creek Basin and the Nan-Shih Creek Basin. The percentage of farmland area in the Sin-Dian Creek basin is greater than the other two basins. Additionally, the Bei-Shih Creek Basin has the most non-irrigated farmlands without vegetative cover.



Note:
B1~B13 are the subwatersheds in the Bei-Shih Creek Basin;
N1~N6 are the subwatersheds in the Nan-Shih Creek Basin; and
S1~S3 are the subwatersheds in the Sin-Dian Crrek Basin.

Fig. 1 Case area: the Taipei Water Specific Area.

2.2 Pollution potential assessment

This study applies the export coefficient method, a popular method for assessing the amount of non-point source pollution (Griffin *et al.*, 1980; Pegram and Bath, 1995; Taebi and Droste, 2004), to analyze the pollution potential in the twenty-two subwatersheds. Due to the specific climatic and physiographic characteristics of individual watersheds, agricultural and urban land-uses can exhibit a wide range of variability in nutrient and sediment export. Site-specific numbers are used by preference if they are available. Pollution loads can be calculated by Eqn. (1).

$$P = \sum_{i=1}^{n} A_i E_i \qquad (1)$$

where P is the the nutrient load (kg/yr); A_i is the

Table 1 Areas and area percentages of different land-uses in the TWSA.

Land-use	Bei-Shih Creek Basin		Nan-Shih Creek Basin		Sin-Dian Creek Basin		Total	
	Area (km^2)	Area percentage	Area (km^2)	Area percentage	Area (km^2)	Area percentage	Area (km^2)	Area percentage
Built-up area	4.38	1.4%	1.75	0.5%	4.13	9.1%	10.26	1.5%
Forest	277.14	87.5%	328.65	98.0%	33.66	74.6%	639.45	91.7%
Farmland	18.84	5.9%	1.44	0.4%	5.77	12.8%	26.05	3.7%
Non-irrigated farmlands without vegetative cover	4.24	1.3%	1.02	0.3%	0.12	0.3%	5.38	0.8%
water area	12.39	3.9%	2.58	0.8%	1.46	3.2%	16.43	2.3%
Total	316.9	100%	335.44	100.0%	45.14	100%	697.57	100.0%

Table 2 Export coefficients for different land-use activities.

Land-use	Pollution export per year per area (kg/year/ha)				
	BOD	TN	TP	NH3-N	SS
Built-up area	50.0	8.5	5.0	4.25	500.0
Forest	5.0	3.0	0.2	1.5	85.0
Farmland	18.0	26.0	4.0	13.0	120.0
Non-irrigated farmlands without vegetative cover	5.5	26.0	4.0	13.0	60.0

Note: the coefficients are referring to a local investigation (Wen *et al.*, 2011).

Table 3 Score for the subwatersheds with different pollution exports per year per unit area.

Pollution export per year per unit area	Score			
	1	2	3	4
BOD (kg/year/ha)	<5.31	5.32-6.61	6.62-9.96	>9.97
TN (kg/year/ha)	<3.51	3.52-4.36	4.37-5.93	>5.94
TP (kg/year/ha)	<0.34	0.35-0.54	0.55-0.75	>0.76
NH_3-N (kg/year/ha)	<1.76	1.77-2.18	2.19-2.97	>2.98
SS (kg/year/ha)	<86.80	86.81-96.40	96.41-111.43	>111.44

Note: the classification is determined by the natural breaks classification method (Jenks, 1967).

area of land-use class i (ha); and E_i is the export coefficient for land-use class i (kg/ha/yr). GIS software is used in this study to process the database and map layers. Several studies reviewed published export coefficient data of various land-use types (Wen *et al.*, 2001; Lin, 2004). The export coefficient for different land-use activities are obtained from a previous study for this research (Wen *et al.*, 2001), as shown in Table 2.

The natural breaks classification method is used in this study as a priority setting and conservation plan for the water source area. Each subwatershed has different pollution loads per unit area per year. According to the five pollution loads (BOD loads, TN loads, TP loads, NH_3-N loads, and SS loads) per unit area per year, each of these twenty-two subwatersheds is given five scores (ranging from 1-4) by the natural breaks classification for each pollution load, as shown in Table 3. The sum of the five scores represents the

Table 4 Sum of scores for different grades of pollution potential.

Grade of pollution potential	Sum of scores of each pollutant for subwatersheds
A	18-20
B	15-17
C	10-14
D	5-9

Note: the classification is determined by the natural breaks classification method (Jenks, 1967).

Table 5 Land-use management strategies.

Subwatershed	Land-use management strategies
the Bei-Shih Creek and Nan-Shih Creek Basins	I. improve land in all the farmlands to have zero pollution exports II. change 100% of farmlands to forest in subwatersheds with grade A pollution potential III. change 50% of farmlands to forest in subwatersheds with grade A pollution potential
the Sin-Dian Creek Basin	IV. improve land in all the built-up areas to have zero pollution exports V. change 100% of built-up areas to forest in subwatersheds with grade A pollution potential VI. change 50% of built-up areas to forest in subwatersheds with grade A pollution potential

subwatershed's pollution potential. The larger the sum of the five scores, the higher the overall pollution potential for the subwatershed. By the natural breaks classification method, each subwatershed is assigned a grade (A, B, C or D, with A representing the highest and D representing the lowest pollution potential), as shown in Table 4.

2.3 Land-use management strategies

As farmlands contribute a certain portion of pollution due to fertilization, they are major pollution sources in the Bei-Shih Creek and Nan-Shih Creek Basins. Built-up areas with large impermeable regions comprise the greatest pollution problem for the Sin-Dian Creek Basin. Because the major pollution sources are different for each of these basins, this study addresses several land-use management strategies according to the pollution problems specific to each subwatershed.

Table 5 lists all the land-use management strategies addressed in this study. In the Bei-Shih Creek and Nan-Shih Creek Basins, land-use management strategies include the following: strategy I- improve land in all the farmlands to have zero pollution exports; strategy II- change 100% of farmlands to forest in subwatersheds with grade A pollution potential; and strategy III- change 50% of farmlands to forest in subwatersheds with grade A pollution potential. As for the Sin-Dian Creek Basin, land-use management strategies include the following: strategy IV- improve land in all the built-up areas to have zero pollution exports; strategy V- change 100% of built-up areas to forest in subwatersheds with grade A pollution potential; and strategy VI- change 50% of built-up areas to forest in subwatersheds with grade A pollution potential.

Table 6 Numbers, areas, and area percentages of subwatersheds with different grades of pollution potential.

Subwatershed	A grade pollution potential			B grade pollution potential			C grade pollution potential			D grade pollution potential			total		
	No.	Area (km^2)	%	No.	Area (km^2)	%	No.	Area (km^2)	%	No.	Area (km^2)	%	No.	Area (km^2)	%
Bei-Shih Creek Basin	4	42.59	13.4%	1	2.16	0.7%	5	123.99	39.1%	3	148.25	46.8%	13	316.99	100%
Nan-Shih Creek Basin	0	0	0%	0	0	0%	2	3.11	0.9%	4	332.33	99.1%	6	335.44	100%
Sin-Dian Creek Basin	2	25.16	55.7%	1	19.98	44.3%	0	0	0%	0	0	0%	3	45.14	100%
Total	6	67.75	9.7%	2	22.14	3.2%	7	127.1	18.2%	7	480.58	68.9%	22	697.57	100%

Note: % is area percentage of subwatersheds with different grades of pollution potential.

III. Results and discussion

3.1 Spatial variability of pollution potential

Table 6 shows the number, area, and area percentage of subwatersheds with different grades (A, B, C, and D) in the three subwatersheds in the TWSA. Under the present land-use activities in the TWSA, there are 6, 2, 7, and 7 subwatersheds with grade A, B, C, and D pollution potential, respectively. The areas of subwatersheds with grade A, B, C, and D pollution potential are 67.75, 22.14, 127.1, and 480.58 km^2, respectively. About 9.7% of the areas have relatively high pollution potential (grade A pollution potential).

The numbers of subwatersheds with grade A pollution potential in the Bei-Shih Creek, Nan-Shih Creek, and Sin-Dian Creek Basins are 4, 0, and 2, respectively. The areas of subwatersheds with grade A pollution potential in the Bei-Shih Creek and Sin-Dian Creek Basins are 42.59 and 25.16 km^2, respectively. No subwatersheds in the Nan-Shih Creek Basin have grade A or grade B pollution potential. Moreover, the area percentage of the subwatersheds with grade A pollution potential in the Sin-Dian Creek Basin is higher than those in the Bei-Shih Creek Basin and Nan-Shih Creek Basin. The results show that the pollution potential and the damage risk on the water-related environment is the greatest in the Sin-Dian Creek Basin. The lowest risk area is the Nan-Shih Creek Basin.

The pollution potential of these twenty-two subwatersheds displays spatial variability, as shown in Figure 2. The findings can provide a useful reference for classified land-use restriction strategies, especially when considering the limited resources available for the entire watershed. Higher land-use restrictions should be first implemented in subwatersheds with grade A pollution potential. On the contrary, subwatersheds with grade D pollu-

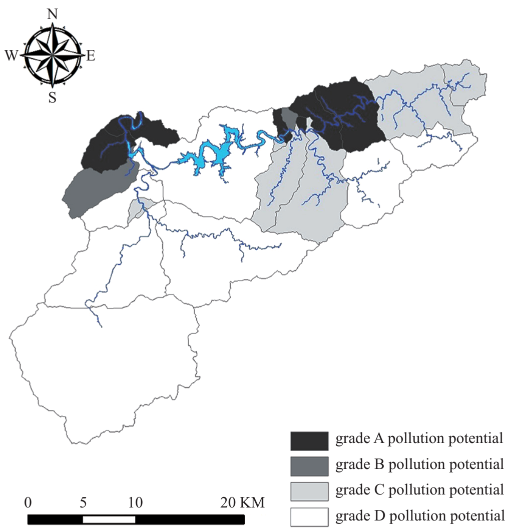


Fig. 2 Spatial variation of pollution potential under the present land-use activities in the TWSA.

Table 7 Present pollution exports and the pollution removal rates under different land-use management strategies.

Subwatershed	Strategy	Pollution export per year(kg/year)					Pollution removal rate				
		BOD	TN	TP	NH_3-N	SS	BOD	TN	TP	NH_3-N	SS
Bei-Shih Creek Basin	Present situation without any land-use management strategies	196,714	146,873	16,965	73,437	2,826,210	-	-	-	-	-
	I	162,802	97,889	9,429	48,945	2,600,130	17.24%	33.35%	44.42%	33.35%	8.00%
	II	187,575	130,704	14,293	65,352	2,801,605	4.65%	11.01%	15.75%	11.01%	0.87%
	III	192,145	138,789	15,629	69,394	2,813,908	2.32%	5.50%	7.87%	5.50%	0.44%
Nan-Shih Creek Basin	Present situation without any land-use management strategies	176,228	106,479	8,432	53,239	2,904,425	-	-	-	-	-
	I	173,636	102,735	7,856	51,367	2,887,145	1.47%	3.52%	6.83%	3.52%	0.59%
Sin-Dian Creek Basin	Present situation without any land-use management strategies	47,932	28,923	5,094	14,461	562,570	-	-	-	-	-
	IV	27,282	25,412	3,029	12,706	356,070	43.08%	12.14%	40.54%	12.14%	36.71%
	V	30,562	26,800	3,241	13,400	402,380	36.24%	7.34%	36.37%	7.34%	28.47%
	VI	42,721	28,286	4,538	14,143	514,513	10.87%	2.20%	10.91%	2.20%	8.54%

Note: the land-use management strategies I-VI are explained in Table 5.

tion potential can allow for less restricted land-use activities.

3.2 Efficiency of land-use management strategies

According to the major pollution problems in the three subwatersheds of the TWSA, this study addresses several land-use management strategies. Table 7 summarizes the present pollution exports and the pollution removal rates of BOD, TN, TP, NH_3-N, and SS under different land-use management strategies in the three creek basins investigated in this study. The results show that the pollution removal rates are usually less than 7% when implementing the addressed land-use management strategies in the Nan-Shih Creek Basin. Because the area percentage of forests is high in the Nan-Shih Creek Basin, it is difficult to reduce pollution exports based only on land-use management. Other watershed conservation practices should be implemented for efficient lowering of pollution exports and the damage to the watershed environment. For BOD and SS, the efficiency of pollution removal in the Sin-Dian Creek Basin is better than that in the Bei-Shih Creek Basin. Conversely, for TN, TP and NH_3-N, the efficiency of pollution removal in the Bei-Shih Creek Basin is better than that in the Sin-Dian Creek Basin. The result indicates that changing farmland areas to forested areas is helpful for reducing nutrients, and changing built-up areas to forested areas is useful for decreasing the damage from organic pollution and solids.

Because the Nan-Shin Creek Basin has no subwatersheds with grade A pollution potential, land-use management strategies II and III cannot be implemented in this basin. In the Bei-Shih Creek Basin, the efficiency of pollution removal under land-use management strategy I is better than those under land-use management strategies II or III. In the Sin-Dian Creek Basin, the efficiency of pollution removal under land-use management strategy IV is better than those under land-use management strategies V or VI. However, the feasibility of land-use management strategies I and IV are low because achieving zero pollution discharge on farmlands and built-up areas in a watershed is difficult to implement.

Table 8 Change of subwatershed's grades of pollution potential under different land-use management strategies.

Grades of pollution potential	Bei-Shih Creek Basin				Nan-Shih Creek Basin		Sin-Dian Creek Basin				Whole study area	
	Present situation	Strategy I	Strategy II	Strategy III	Present situation	Strategy I	Present situation	Strategy IV	Strategy V	Strategy VI	Present situation	Strategy III and Strategy VI
	Subwatersheds number											
A	4	0	0	1	0	0	2	0	0	1	6	2
B	1	0	2	2	0	0	1	1	1	2	2	4
C	5	2	6	7	2	1	0	1	1	0	7	9
D	3	11	5	3	4	5	0	1	1	0	7	7
	Subwatershed area (km^2)											
A	42.59	0	0	12	0	0	25.16	0	0	13.98	67.75 (9.7%)	25.98 (3.7%)
B	2.16	0	14.16	5.2	0	0	19.98	19.98	19.98	31.16	22.14 (3.2%)	36.36 (5.2%)
C	123.99	15.04	127.03	151.54	3.11	0.42	0	13.98	13.98	0	127.1 (18.2%)	154.65 (22.2%)
D	148.25	301.95	175.8	148.25	332.33	335.02	0	11.18	11.18	0	480.58 (68.9%)	480.58 (68.9%)

Note: the land-use management strategies I-VI are explained in Table 5.

Table 8 shows the change of the subwatersheds with grade A, B, C, and D pollution potential under different land-use management strategies. The results show that the number of subwatersheds with grade A pollution potential in the Bei-Shih Creek Basin can be reduced from four to zero under land-use management strategies I and II; and from four to one under strategy III. For the Sin-Dian Creek Basin, the number of subwatersheds with grade A pollution potential can be reduced from two to zero under land-use management strategies IV and V; and from two to one under strategy VI. As changing 100% of farmland and built-up areas to forest is not easy to implement, strategies III and VI are more feasible. If both the land-use management strategies III and VI are implemented in the TWSA, the number of subwatersheds with grade A pollution potential can be reduced from six to two, and the percentage of area with grade A pollution potential can be reduces from 9.7% to 3.7%.

IV. Conclusion

Land-use management is increasingly important for protecting a watershed environment. The major findings in this study are as follows:

(1) This study assesses the spatial variability of pollution potential of the subwatersheds in the TWSA, and can be an important reference for classified land-use restrictions.

(2) The pollution potential is larger in the Sin-Dian Creek Basin than those of the Bei-Shih Creek and Nan-Shih Creek Basins because of a higher degree of urbanization.

(3) This study specifically provides several land-use management strategies for these three creek basins according to the major pollution problems of each subwatershed. Farmland is the major pollution problem in the Bei-Shih Creek Basin, while built-up areas are the major pollution problem for the Sin-Dian Creek Basin.

(4) When changing farmlands to forests, the efficiency of nutrients removal is high. However,

changing built-up areas to forests is more helpful for decreasing organic pollution and solids.

(5) Land-use management is not the only way for reducing a watershed's pollution potential. For sustained improvement in the watershed environment, other watershed conservation practices should be considered and implemented in the TWSA, including the reduction of potentially damaging risks from pollution exports.

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