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COMPARATIVE ANALYSIS OF NEARSHORE CONTAMINATED SITES IN LAKE ONTARIO: RANKING FOR ENVIRONMENTAL HAZARD

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NWRI CONTRIBUTION NO. 94-94

Comparative Analysis of Nearshore Contaminated Sites in Lake Ontario: Ranking for Environmental Hazard

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MANAGEMENT PERSPECTIVE

This paper uses data collected to quantify the degradation status of some nearshore sites in lake Ontario to rank the sites using a method based on graph theory. This method not only ranks the sites according to their pollution status, but also identifies which criteria are important for a proper assessment. Therefore, in future studies no efforts needs to be wasted on the collection of redundant data.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Le présent article traite de l'utilisation de données déjà recueillies pour quantifier le degré de dégradation de certains sites côtiers du lac Ontario, en vue de classer ces sites au moyen d'une méthode fondée sur la théorie des graphes. Cette méthode permet non seulement de classer les sites selon leur degré de pollution, mais encore de déterminer quels critères sont importants pour une bonne évaluation. Il ne sera donc plus nécessaire, dans le cadre des études à venir, de gaspiller des ressources pour la cueillette de données superflues.

ABSTRACT

A ranking method, based on partially ordered set theory, is applied to degraded inshore waters of Lake Ontario. This ranking method uses test data collected by Dutka et al. in bottom sediments. The outcome of this ranking analysis is displayed by Hasse diagrams. Hasse diagrams avoid the loss of information that occurs when data are aggregated into a ranking index. Both ranking schemes, Dutka et al.'s and ours have identified the same sites as the most degraded: Humber River STP outfall, Mimico Creek mouth and the harbour in Port Hope. In addition, we also identify Whitby Harbour and another site in Port Hope Harbour as degraded. These two sites, together with the Industries Area in Toronto and Lasco Steel in Whitby Harbour are degraded in a manner different from all other sites (because they have high toxicity). We also note that Cherry St. in Toronto (site 27) should be considered as degraded because of the high ranking in Fecal Coliforms (FC). Finally, the ranking method identifies two tests, namely Microtoxicity and Genotoxicity as important for ordering the sites.

RÉSUMÉ

Une méthode de classement fondée sur la théorie des ensembles partiellement ordonnés a été appliquée aux eaux côtières dégradées du lac Ontario. Cette méthode a permis d'utiliser les données expérimentales recueillies par Dutka *et al.* dans les sédiments du lac. Les résultats du classement sont donnés sous forme de diagrammes de Hasse, ce qui évite la perte d'information due au regroupement des données selon un indice de classement. Quelle que soit la méthode de classement utilisée, celle de Dutka *et al.* ou la nôtre, les sites les plus dégradés sont l'émissaire de la station d'épuration des eaux usées de Humber River, l'embouchure du ruisseau Mimico et le port de Port Hope. De plus, nous avons déterminé que le port de Whitby et un autre site du port de Port Hope sont également dégradés. Le type de dégradation de ces deux sites, de la zone industrielle de Toronto et de l'usine Lasco Steel du port de Whitby est différent de celui des autres sites, en raison de leur haute toxicité. Nous observons également que le site de la rue Cherry (site 27), à Toronto, devrait être considéré comme dégradé à cause de son rang élevé en ce qui concerne les coliformes fécaux. Finalement, notre méthode a permis de relever deux tests importants pour le classement des sites : le test de microtoxicité et le test de génotoxicité.

INTRODUCTION

Dutka et al. (1986) developed a list of complementary tests (microbiological, biochemical, and bioassays), which they call the "battery of tests", which can be used to quantify degradation of different sites. The information from these tests was summarized by Dutka et al. into an index used to rank the sites. The use of an index, however, has the disadvantage that information from each test is lost because it is aggregated. In this paper, we use a previously published ranking method (Halfon, 1983; Halfon and Reggiani, 1986; Halfon, 1989) that preserves the information from all tests performed at each site, and we apply it to the sediment samples of the Lake Ontario. Our method does not merge results from different tests, e.g. toxicity with quality tests, as it is done in the construction of a ranking index, and it helps to visualize the causal relation between properties and the final ranking. The method can be used to explain which tests are important in the ranking and which may be eliminated without loss of information. An index does not provide this information. Zitko (1992) approached the same problem from a statistical viewpoint using Principal Component Analysis to map 12 sediment quality parameters on 3 principal components to facilitate the visual identification of similar stations and samples.

DATA

Dutka et al. (1986) collected bottom sediments samples at a depth of two - three

centimetres at 50[1] sites along the Canadian shores of Lake Ontario, from Kingston to the Niagara River. Their investigation was aimed to be a snapshot (June 1985) of the state of degradation, therefore they did not perform any time series or pooling of samples.

The "Battery of tests":

Dutka et al. analyzed the bottom sediments with six tests. They did not employ the same tests everywhere, and some test results were negative at all sites. Six samples were taken from Port Hope Harbour at sites that are in an area of about 100 metres in diameter, therefore 55 samples from 50 sites are reported. The other samples were taken from 44 nearshore sites in Lake Ontario. The following tests were performed: 1) Fecal coliforms / E. coli (FC), 2) Coprostanol (COP), 3) Cholesterol (CHO), 4) Microtox (MT) and 5) Genotoxicity (GT). The microbiological and biochemical tests are described in detail by Dutka et al. (1986). Two interesting tests, as it will become clearer later, are the GT and CHO: The GT test consisted of colorimetric assays of enzymatic activities and the CHO procedure is found in the APHA standard methods (1985).

Scoring of the test results

Dutka et al. did not use the raw data to rank sites in Lake Ontario but assigned their data to classes and assigned scores to each class. Therefore, to compare our results with Dutka et al.'s we use their classes and scores (Table 1). All scores are presented in Table 2.

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[1] Dutka et al. took samples from 50, not 51 different sites as described in their paper

RANKING SITES

Ranking with aggregated scores

It is difficult to rank polluted sites using multiple measures of degradation. When multiple tests are used to rank a site, there might be different combinations of results. Data from Table 2 can be used to exemplify the three possibilities:

a) Some sites, for example 27 and 47, are equally degraded as also reported by Dutka et al. (1986) since the scores of the test results are the same (Table 2),

b) Some sites, for example 27, 25 and 4, can be ranked unequivocally (site 27 is worse than 25 which is worse than 4) since they are comparable for all tests, and

c) Some sites, for example 31 and 27, can not be ordered (ranked) in any way: Site 31 is less degraded than site 27 when the test FC is considered. Conversely, site 27 is less degraded than site 31 when COP and CHO are taken into account. In other words, these two sites are "incomparable"[2], since different processes of degradation are identified at these two sites.

To avoid the ambiguity that arises from incomparable sites, Dutka et al. (1986) summed the scores to obtain a degradation index. Sites with a high index were identified as degraded sites and not fit for drinking and/or swimming. Note that the use of an index hides the fact that sites are degraded in different ways, information is lost.

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[2] We also call this "a contradiction" or "an ambiguity"

Ranking with Hasse diagrams

The above mentioned loss of information is avoided if Hasse diagrams (Reggiani and Marchetti, 1975) are applied. The theory of Hasse diagrams has been discussed in text books (Harary, 1969; Preparate and Yeh, 1973; Davey and Priestley, 1990).

Halfon and Reggiani (1986), Halfon (1989), Brüggemann and Halfon (1990), Brüggemann and Münzer (1993), Steinberg et al. (1993), Brüggemann et al. (1994) and Münzer et al. (1994) applied this method to environmental problems. The aim of this method is to use a formal procedure to order (or rank) like in this example polluted sites according to test results of a test battery (a n-tuple)[3] as described by Dutka et al. (1986). In the ranking method by Hasse diagrams two conditions, antisymmetry and transitivity must be fulfilled at the same time for some objects to be said to be in an order relation. "Order is not a property intrinsic to a single object, it concerns comparison between pairs of objects: 0 is smaller than 1; "Mars is farther from the Sun than Earth..." (Davey and Priestley, 1990). Antisymmetry means 5 is bigger than 3 but 3 is not bigger than 5 and transitivity means that from $0 < 1$ and $1 < 1000$ we can deduce that $0 < 1000$. Furthermore, there are four descriptive terms of ordering relations, **strict** and **non-strict, total** and **non-total**. These relations are as fundamental to our purposes and in general in ecology as the previous two conditions of antisymmetry and transitivity. The statement "site x is more polluted by a chemical than site y" means that x is **strictly** more polluted than y. In general the statement "site x is polluted exactly as site y" can not be excluded, a **non-strict** order arises. If all pairs of objects can be compared, then a **total order** arises. However, the statement

[3] n-tuple is a vector with n elements and each element is the numerical result of an experiment in the battery of tests.

"site x is polluted by chemicals A and B and site y is more polluted by A and less polluted by B than x" means that there is an ambiguity between the pollution status of x and y. x and y are incomparable. The presence of such incomparable objects within an ordering scheme is explicitly denoted by the term non-total order or **partial ordering**. For the formal mathematical details see Davey and Priestley (1990). The following describe the rules inherent to the construction of Hasse diagrams for our purpose of ranking in ecology.

1) Hasse diagrams (Figs. 1 to 3) can be constructed with raw data as well as with scores (as done here). The use of scores diminishes uncertainty because the variation of raw data within the class defining interval do not change the score[4].

2) By convention, highly degraded sites are located on the top of the Hasse diagram. Less degraded sites are at the bottom.

3) The sites are represented by small circles, and are identified by numbers. Next to the circles, the corresponding scores (FC, COP, CHO, MT, GT) are provided to minimize mental effort to understand the ranking.

4) Some sites are ranked exactly the same. For example sites 27, 33, 46 and 47 have the same scores (Table 2); they are <u>equivalent</u> to each other. Thus, in the diagram only site 27 appears as a representative[5]. The other sites are indicated by extra lines at the bottom of the diagram.

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[4] Here an optimized definition of intervals lay outside of the scope of the paper, to compare our results with Dutka <u>et al</u>. we have to take his classification scheme.

[5] In mathematical terms: Sites 27, 33, 46, 47 are elements of the same equivalence class. The equivalence relation is: "Equality of the scores." Therefore it is sufficient to select one element of the equivalence class as "representative" of the whole class.

5) Sites that are "comparable" with respect to all tests [for example, site 27 is more degraded for all tests than site 25] are connected by lines. In the graph, the lines should be followed in one direction only, from top to bottom, or (exclusively) from bottom to top.

6) Sites that are not comparable are not connected ("incomparable" sites). For example sites 27 and 31 can not be compared.

7) For clarity, circles are arranged into levels. "Incomparable" sites can also be on different levels.

8) The presence of a connection between two circles, either directly or indirectly through other circles, indicates that the site on the superior level has ranked worse than the site located in a lower level with respect to all tests[6].

9) If possible, a circle is located at the top level, to be conservative, i.e., the site might be degraded.

These nine rules allow a user to understand a Hasse diagram. The Hasse diagrams that follow, Fig.s 1 to 3, point out relations among the data.

RESULTS

All five Dutka tests used as basis for ranking

The concept of "incomparability" is at the heart of Hasse diagrams, therefore some examples are discussed in more detail. Test results between stations 27 and 31 are really

[6] Comparable sites cannot be located on the same level because they have to be connected by a line (rule 5). By rules 2 and 8 they must be located on different levels

different. We have chosen these two stations to make a number of points. Even if station 27 might look less polluted than 31 (see below), some ambiguities are present, that need to be discussed in detail. Site 27 (Cherry Station, Toronto) and its equivalent elements 33, 46 and 47 and site 31 (STP outfall, Humber River) are located at the same level (Fig. 3) and are not connected by a line. Table 2 shows:

	FC	COP	CHO	MT	GT
site 27	5	0	0	0	0
site 31	4	5	4	0	0

Site 27 is one point worse than site 31, according to the first test, but four or five points better than site 31 according to the second and third tests. The Hasse diagram (Figure 1) demonstrates this contradiction, the two sites are "incomparable". Thus, even if site 31 seems to be more hazardous than site 27, because three tests show a rather high degradation, site 27 should nevertheless be regarded as suspect because of the higher ranking in FC. This information would be masked if a single index were used for ranking. The technique of Hasse diagrams does not exclude the assessment that site 31 might be more hazardous than site 27, but it reveals that the type of degradation is different. Note that Dutka et al. ranked site 31 as the second worst but site 27 as the 17th. No mention was made of the high level of FC at site 27. Furthermore, Fig. 1 shows that 31 other sites (25, 4, 6, 94, ..., 91, 93, ..., 11, 16, ..., 45; all these sites are connected with 27 in a downward direction) have the same kind of degradation pattern (rules 2, 5 and 8). This degradation is described by (i): they have non-zero test results for FC in a decreasing order from 25 to 45; and (ii) they have zeros in the four remaining tests.

Dutka et al. and we identify site 31 (Humber River STP outfall), 32 (Mimico Creek mouth) and 95 (Harbour, Port Hope) as the most degraded. These three incomparable sites are located at the top level of the Hasse diagram (Fig. 1) but they have different degradation patterns. Figure 1 shows the reason: Site 31 is degraded due to FC, COP and CHO; site 32 is degraded because of MT and site 95 has high scores for COP and MT.

Sites 18 and 9 are also at the top level (Fig. 1). Site 9 is comparably more degraded than the representative sites 2 and 11[7], respectively, (connected by a line), and is located at the top level of the Hasse diagram because of rule 9. The same argument holds for the site 18. Site 18 is "incomparable" with all other sites, except sites 60[8], 2 and 11. Sites 9, 18, and 23 (equivalent to 60) are degraded in a manner different from all other sites (because the toxicity test GT and/or MT has scores different from zero.) This is not true for almost all other sites. Hasse diagrams point out this fact graphically.

Analysis of most important tests for ranking

The ranking of sites depends on which tests are used. Usually the ranking changes if not all tests are employed. If, for example, GT were not used to rank, then sites 9, 18, 60 and 23 (mentioned above) would appear as almost not degraded (see below). The elimination of other tests might not change the ranking so drastically. If, for example, CHO and COP are ignored, then a new ranking, or in our methodology, a new Hasse diagram results. If - otherwise - MT

[7] There are other sites that have exactly the same scores as 2 and 11, respectively. Figure 1 shows all equivalent sites.

[8] As mentioned before, these sites are equivalent to others (see Fig. 1)

and GT are ignored, another Hasse diagram can be constructed. As an example, to assess the importance of some tests within our methodology, we compare three Hasse diagrams [all five tests (Fig. 1); only FC, MT, GT (Fig. 2); and only FC, COP, CHO (Fig. 3)]. A comparison of Fig.s 1 and 2 shows that the Hasse diagram of Fig. 2 retains almost all contradictions of the original Hasse diagram (Fig. 1). However the third Hasse diagram (Fig. 3) shows only few contradictions: almost all sites are comparable. Many sites are no more differentiated by the remaining tests. Our conclusion is that MT and/or GT are more important than COP and CHO because their elimination changes the Hasse diagram dramatically. For example, sites 9, 18, 23 and 60 are still indicated as highly degraded in Fig. 2 but not in Fig. 3. Furthermore, the bottom five levels of Fig. 2 are the same as in Fig. 1. The only difference is that sites 31 and 95 are ranked on the second level in Fig. 2[9].

DISCUSSION

Several benefits derive from this ranking analysis:

Identification of the most polluted sites: Typically the Hasse diagram technique lists more than one site as most environmentally degraded, each corrupted by a different combination of pollutants, therefore the sediment quality may be improved through different control options. Furthermore, this technique identifies the more important and the less important criteria to rank the sites, which leads to a reduction in costs in environmental monitoring. This identification is of great value for environmental studies, where uncertainty and sampling costs are often big

[9] This apparent trial and error procedure can be systematized. Bruggemann and Halfon have developed an algorithm that avoids the drawing and laborious analysis of many Hasse diagrams (to be published)

issues. Both ranking schemes, Dutka et al.'s and ours, have identified the same sites as the most degraded, and our analysis has pointed out additional locations not considered excessively degraded by Dutka et al. The ranking scheme using Hasse diagrams has also identified different degradation patterns that are not immediately evident when an index is used. The analysis of Hasse diagrams therefore allows the reconstruction of the ranking and facilitates the decision making process; it identifies which tests are needed in future surveillance projects. Tests that do not influence much the ranking of sites, such as COP and CHO were identified.

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FIGURE LEGENDS

1) Hasse diagram ranking 55 samples corresponding to 50 different sites in Lake Ontario according to the five tests (Fecal Coliforms, concentration of Coprostanol, concentration of Cholesterol, Microtox and Genotoxicity test) shown in Table 2. These tests are performed in the bottom sediments. The numbers within each circle identify a site. Next to each circle its individual tuple of scores are given. At the bottom of the picture, sites that occupy the same position in the Hasse diagram are identified (equivalent sites). Sampling locations are presented in Table 2. On the top of the diagrams there are the most degraded sites, on the bottom the least degraded ones. For the sake of simplicity the sites are organized in levels.

2) As in Fig. 1, but now only three tests: These tests are performed in the bottom sediments and they are Fecal Coliforms concentrations, Microtox and Genotoxicity tests;

3) As in Fig. 2, but now only three tests: These tests are Fecal Coliforms concentrations, Coprostanol and Cholesterol.

Table 1: Scores awarding scheme used to rank samples, based on suspected contained hazards [modified from Dutka et al. (1986)].

Fecal Coliform/E. coli (FC) Sediment 10/100 mL MPN	Scores
< .1	0
.1 - 100	1
100 - 500	2
500 - 2500	3
2500 - 10,000	4
> 10,000	5

Coprostanol (COP) Sediment mg/Kg	Scores
< .1	0
.1 - 1	1
1 - 3	3
3 - 5	5
5 - 7	7
> 7	10

Cholesterol (CHO) Sediment mg/Kg	Scores
< .1	0
.1 - 2	1
2 - 4	2
4 - 6	3
6 - 8	4
> 8	5

Microtox (MT) EC50/g wet wt or /mL	Scores
< .1	10
.1 - .2	8
.2 - .3	6
.3 - .4	4
.4 - 1000	2
> 1000	0

Genotoxicity (GT) Equivalent to ng/mL 4NQO*	Scores
0	0
0 - 200	2
200 - 400	4
400 - 600	6
600 - 800	8
> 800	10

* 4 Nitro Quinoline Oxide

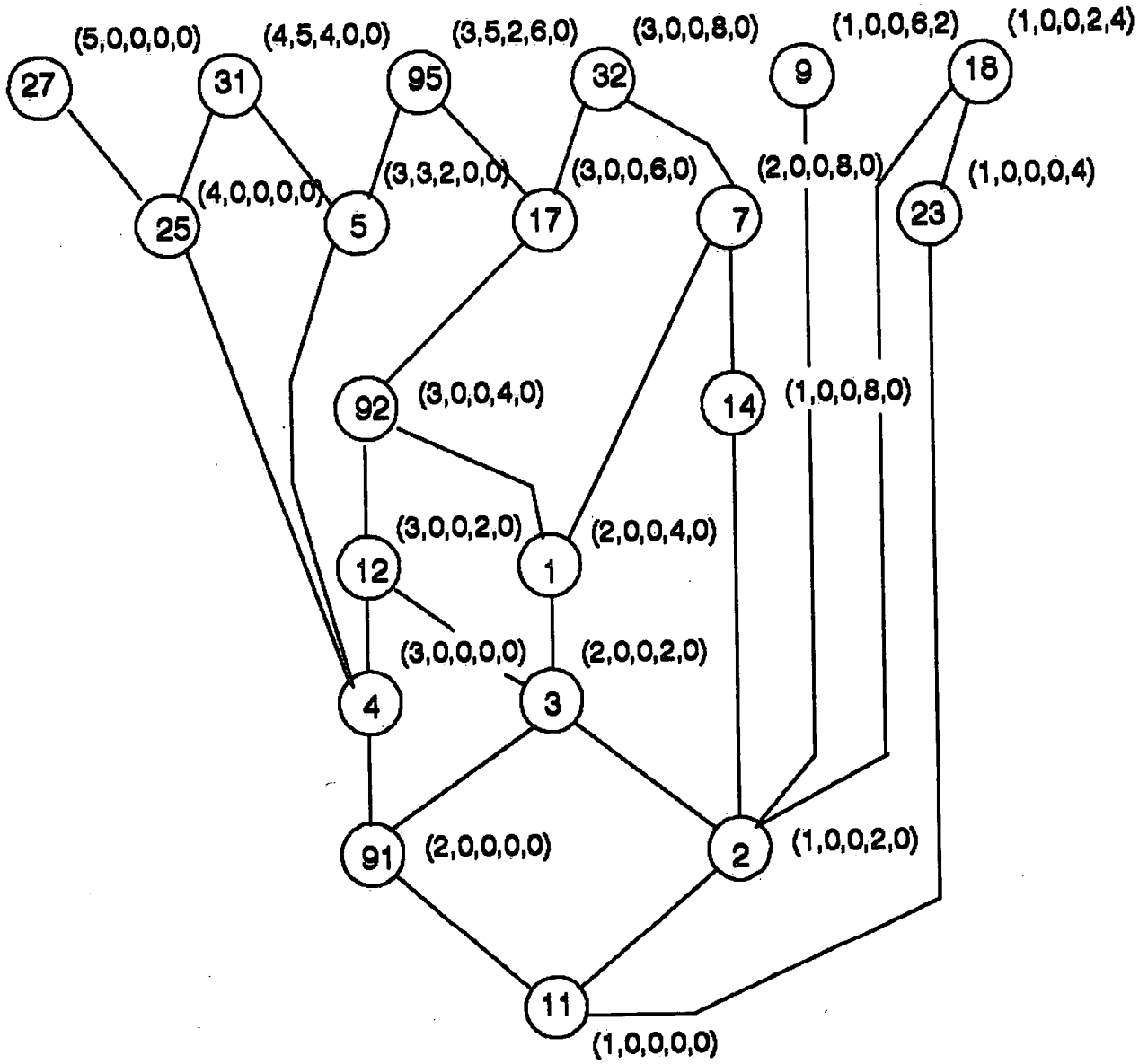
Table 2: Sediment Scores of 55 samples in Lake Ontario. The five tests used to rank the sites are 1) Fecal Coliforms, 2) Coprostanol, 3) Cholesterol, 4) Microtox and 5) Genotoxicity (See Table 1).

Hasse Diagram Identifier	Test results 1 FC	2 COP	3 CHO	4 MT	5 GT	Sampling Site
1	2	0	0	4	0	Cataraqui River, Kingston
2	1	0	0	2	0	Carruthers, Point, Kingston
3	2	0	0	2	0	Deseronto
4	3	0	0	0	0	Napanee River
5	3	3	2	0	0	Outfall area, Belleville STP
6	3	0	0	0	0	Moira River
7	2	0	0	8	0	Trent River
8	1	0	0	2	0	Coburg
95	3	5	2	6	0	Harbour - Port Hope (9A)[10]
91	2	0	0	0	0	Harbour - Port Hope (9D)
92	3	0	0	4	0	Harbour - Port Hope (9H)
93	2	0	0	0	0	Harbour - Port Hope (9I)
94	3	0	0	0	0	Harbour - Port Hope (9M)
9	1	0	0	6	2	Harbour - Port Hope (9T)
10	3	0	0	0	0	Breakwall - Port Hope
11	1	0	0	0	0	Newcastle
12	3	0	0	2	0	Bowmanville
13	3	0	0	0	0	Bowmanville Creek
14	1	0	0	8	0	Ruby Head
15	3	0	0	4	0	Marina Oshawa
16	1	0	0	0	0	Oshawa

[10] Label in Dutka et al. (1986)

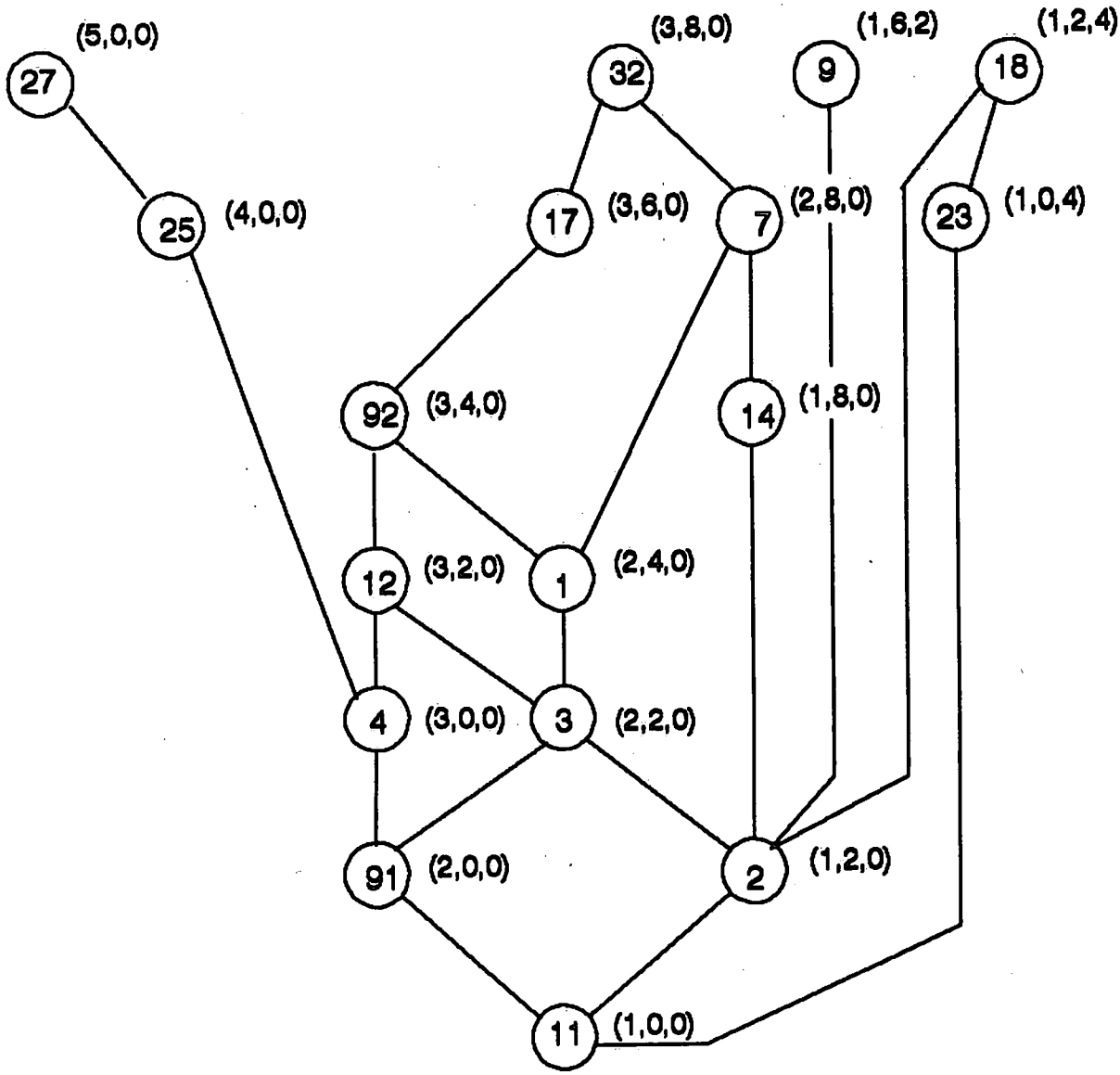
17	3	0	0	6	0	Corbett Creek, Whitby
18	1	0	0	2	4	Harbour Whitby
60	1	0	0	0	4	Lasco Steel (18A)
19	3	0	0	0	0	Duffin Creek
20	2	0	0	0	0	Rouge River
21	3	0	0	0	0	Highland Creek
22	3	0	0	0	0	Scarborough
23	1	0	0	0	4	Industries Area, Toronto
24	2	0	0	0	0	Between Toronto Islands
25	4	0	0	0	0	STP, Toronto
26	2	0	0	0	0	Harbour, Toronto
27	5	0	0	0	0	Cherry St., Toronto
28	2	0	0	0	0	Ontario Place, Toronto
29	3	0	0	0	0	Sunnyside Beach, Toronto
30	3	0	0	0	0	Humber River, Toronto
31	4	5	4	0	0	STP outfall, Humber River
32	3	0	0	8	0	Mimico Creek
33	5	0	0	0	0	Etobicoke Creek
34	2	0	0	0	0	Lakeview Generator
35	3	0	0	6	0	Mouth of Credit River
37	2	0	0	0	0	Opposite Gulf Oil Plant
39	2	0	0	0	0	16 Mile Creek
40	1	0	0	0	0	Bronte Creek
41	1	0	0	0	0	Petro Canada Pier
42	1	0	0	0	0	Spencer Smith Park
43	1	0	0	0	0	Entrance to Burlington Canal
44	1	0	0	0	0	Grimbsy Beach
45	1	0	0	0	0	Jordan Harbour
46	5	0	0	0	0	Mouth of Pourth Dalhousie
47	5	0	0	0	0	Inside of Bay, Port Dalhousie

48	3	0	0	0	0	Port Weller
49	2	0	0	0	0	Mouth of Niagara River
50	2	0	0	0	0	Mouth of Niagara River
51	2	0	0	0	0	Mouth of Niagara River



Equivalent samples:

{2,8}
{4,6,10,13,19,21,22,29,30,48,94}
{11,16,40,41,42,43,44,45}
{15,92}
{17,35}
{20,24,26,28,34,37,39,49,50,51,91,93}
{23,60}
{27,33,46,47}



Equivalent samples:

{2,8}
{4,5,6,10,13,19,21,22,29,30,48,94}
{11,16,40,41,42,43,44,45}
{15,92}
{17,35,95}
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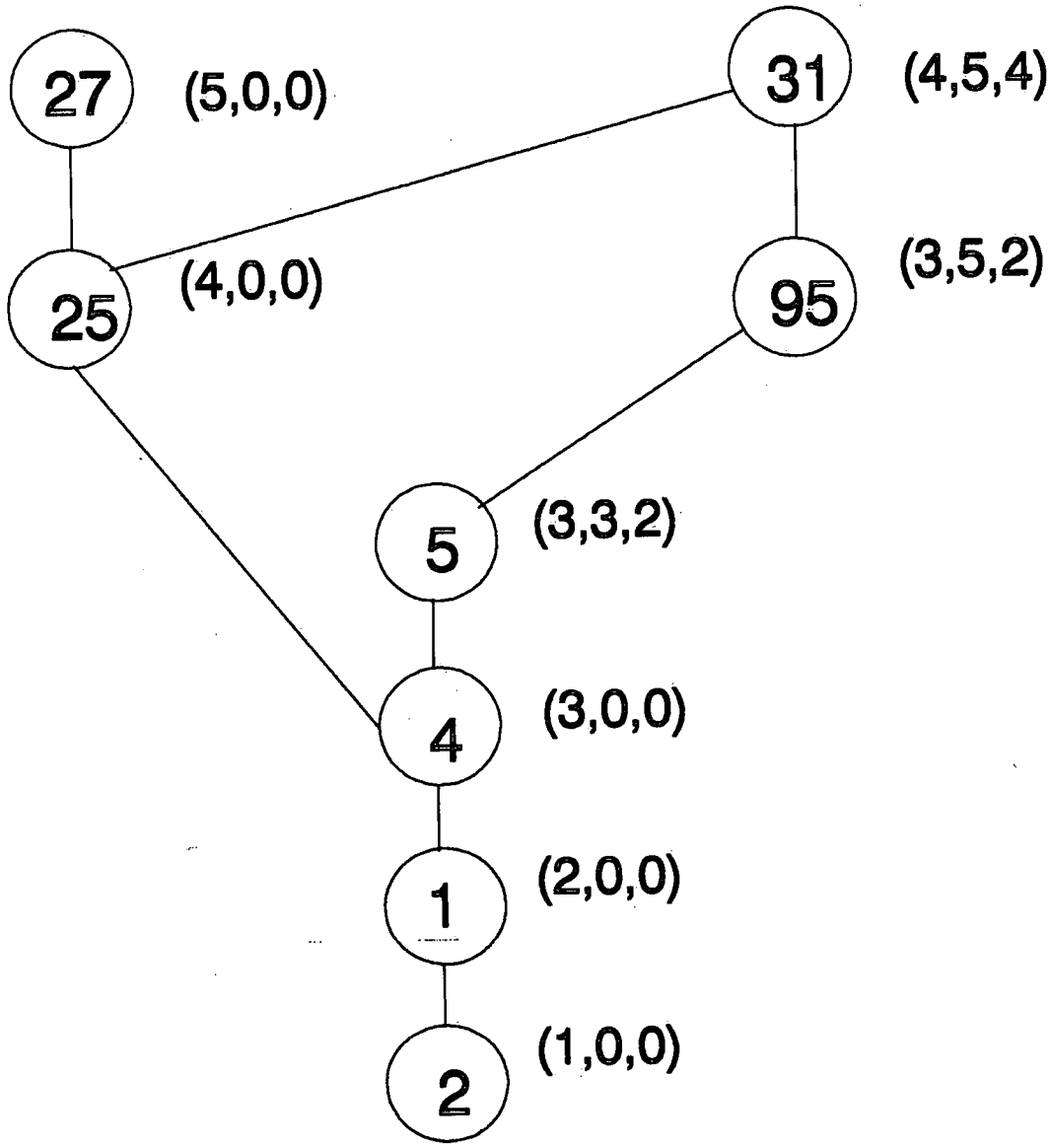
{25,31}
{27,33,46,47}



Equivalent samples:

{1,3,7,20,24,26,28,34,37,39,49,50,51,91,93}

{2,8,9,11,14,16,18,23,40,41,42,43,44,45,60}

{4,6,10,12,13,15,17,19,21,22,29,30,32,35,48,92,94}

{27,33,46,47}

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