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A COMPARISON OF AN INDEX FUNCTION AND A VECTORIAL APPROACH METHOD FOR RANKING WASTE DISPOSAL SITES

by

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MANAGEMENT PERSPECTIVE

The water quality of the Upper Great Lakes Connecting Channels is dependent on pollution loadings and land usage. Waste disposal sites near the Connecting Channels should have appropriate geological characteristics to contain pollution loadings and reduce the impact to the nearby Channels. This study uses a novel ranking method, based on set theory and systems analysis, to integrate information about land use, the geological characteristics of the waste sites and pollution impact; this information is used to identify the most environmentally hazardous waste sites and sites that need more studies. The results and insights of this new method are compared with results obtained by a standard ranking analysis using an index function and weight factors. The advantage of the new method is that critical contradictions in the data are identified by the ranking procedure itself. A ranking analysis can not be performed without first critically analyzing the data looking for inadequacy, as done in this paper, while other ranking schemes, that use indices to measure performance, do not include the identification of possible shortfalls in the data during the performance of the ranking procedure.

PERSPECTIVE ADMINISTRATIVE

La qualité de l'eau des canaux reliant les Grands Lacs d'amont est fonction des charges de pollution et de l'utilisation des terres. Les décharges de déchets situées près des canaux devraient posséder les caractéristiques géologiques appropriées pour retenir les charges de pollution et réduire leur impact sur les canaux situés à proximité. Cette étude utilise une nouvelle méthode de classement, basée sur la théorie des ensembles et l'analyse des systèmes, pour intégrer l'information sur l'utilisation des terres, les caractéristiques géologiques des décharges et l'impact polluant; cette information est utilisée pour déterminer les décharges les plus dangereuses pour l'environnement, ainsi que les sites qui nécessitent de plus amples études. Les résultats obtenus à l'aide de cette nouvelle méthode sont comparés à ceux que l'on a obtenu au moyen d'une analyse de classement standard faisant appel à une fonction d'indice et à des facteurs de pondération. L'avantage de la nouvelle méthode est de déterminer les contradictions critiques dans les données dans la procédure de classement elee-même. Une analyse de classement depeut être effectuée sans que les inexactitudes dans les données ne soient d'abord décelées par une analyse, comme cela est fait dans le présent rapport; les autres systèmes de classement, qui utilisent des indices pour mesurer la performance, ne comprennent pas la détermination des éventuelles lacunes des données pendant la procédure de classement.

ABSTRACT

A ranking method based on system principles is used to rank 38 waste disposal sites in the Detroit, St. Clair and St. Mary's River areas according to environmental hazard as part of the Upper Great Lakes Connecting Channels Study. A vectorial approach is used for partial ordering and in this study, 38 sites have been ranked according to 30 criteria related to their geological and pollution characteristics. The ranking is displayed using Hasse diagrams which show which sites are the most hazardous to the nearby Connecting Channels. The results and insights of this new method are compared with results obtained by a standard ranking analysis using an index function and weight factors. Here we show the advantage of using the new ranking scheme rather than other commonly used figure of merit schemes; the advantage is that critical contradictions in the data are identified by the ranking procedure itself. A ranking analysis can not be performed without first critically analyzing the data looking for inadequacy, as done in this paper, while figure of merit schemes do not include the identification of possible shortfalls in the data during the performance of the ranking procedure.

RÉSUMÉ

Une méthode de classement basée sur des principes systémiques a servi à classer 38 décharges dans la région des rivières Détroit, Sainte-Claire et Sainte-Marie, en fonction des risques environnementaux qu'elles représentent, dans le cadre de l'étude sur les canaux reliant les Grands Lacs d'amont. Une approche vectorielle a été utilisée pour effectuer un classement partiel et, dans cette étude, les 38 sites ont été classés en fonction de 30 critères reliés à leurs caractéristiques géologiques et leurs caractéristiques de pollution. Ce classement est présenté sur des diagrammes de Hasse, qui montrent quels sites sont les plus dangereux pour les canaux situés à proximité. Les résultats de cette nouvelle méthode sont comparés à ceux obtenus à l'aide d'une analyse de classement standard faisant appel à une fonction d'indice et à des facteurs de pondération. Le rapport montre les avantages du nouveau modèle de classement par rapport aux anciens, couramment utilisés; sont principal avantage est d'identifier les contradictions critiques dans les données au moyen de la procédure de classement même. Une analyse de classement ne peut être effectuée sans faire auparavant une analyse critique des données pour y déceler les inexactitudes, comme cela est fait dans ce rapport; les modèles courants ne comprennent pas la détermination des lacunes éventuelles des données pendant la procédure de classement.

INTRODUCTION

Ranking waste sites, in terms of their environmental hazard by prespecified criteria, has been the subject of much research (1,2,3,4). In this paper a novel and formal procedure (5), based on set theory and systems analysis, is used to rank waste disposal sites using the information available from a variety of geologic and water pollution tests (1). Partial ordering (5) is a vectorial approach which recognizes that not all sites can be directly compared with all other sites in terms of environmental hazard and that when many criteria are used contradictions in the ranking of sites are bound to exist. These contradictions might not be discovered using the standard figure of merit approach where a single index of hazard is computed. With the present approach contradictions are solved in a holistic way using decision theory. Results are displayed on paper or on a TV monitor driven by a desk top personal computer using Hasse diagrams (6,7), a useful graphic tool commonly used in algebra to display lattices (e.g., a genealogical tree is a special case of a Hasse diagram).

Geological and pollution data of 38 sites were collected by GTC Geologic Testing Consultants Ltd. (1) for the Ontario Ministry of the Environment. The 38 sites are located in Canada west of longitude 82° for the counties of Lambton, Essex and Kent as well as that area immediately surrounded by Algoma Steel and the Cherokee Landfill site in the Algoma district. Some sites are located on the eastern side of Lake St. Clair and of the St. Clair River; the sites marked with the letter L are located in Lambton County, near the St. Clair river, those with the letter K are in Kent county, near Lake St. Clair, those with the letter E in Essex County, near the Detroit River and those with the letter A in the Algoma district near the St. Mary's River. The set of data collected by GTC includes a summary of the geological conditions at the sites, an outline on the operation of waste disposal and waste containment facilities and a detailed evaluation of the potential environmental impact of each waste site. GTC developed a system of prioritization of the sites according to a figure of merit index (Table 1) and also analyzed 41 waste disposal sites without certificate of approval and without a definitive site description. Not enough data were given in the report (1) to include these sites in the present analysis.

The ranking method used in this study is based on the hypothesis that a set of numbers is generally necessary to create a ranking file; these numbers can be considered the elements of a vector, the "vector performance" or "vector distance". This "vector approach method" is different from the "scalar approach method", generally used in ranking studies and also used by GTC, where a single number (a scalar performance index) is said to be sufficient to interpret the data, to compare sites and rank them according to their environmental hazard.

The proposed method has some advantages and some weaknesses over the scalar approach. The main point is that rather than inventing new methods of decision making, i.e. to develop new indices, we could make a more realistic contribution by using methods to classify and evaluate reality using large data sets. A second point is that by analyzing and comparing all data the sites can be ranked in logical separate levels. The main weakness is that the subjectiveness of the choice of the attributes to be included in the analysis remains. Two basic assumptions are used for this ranking: (i) sites which have a poor geological setting in relation to the expected pollution impact are more hazardous than those that have more appropriate characteristics, such as clay soils, far from large rivers or lakes and with little potential for off-site leachate migration; (ii) sites which receive large volumes of waste with little engineered waste containment facilities and are located in location with inappropriate geological conditions are even more hazardous.

THEORY

A given number of criteria are used to evaluate each site, these criteria may be called attributes. Once several attributes are chosen the next step is to assign them weighting factors. This step can be left to the expert (8) and can be included or bypassed in the vectorial procedure; GTC (1) provided the weighting factors (Table 2). The weighting factors imply the concept of tolerance for each attribute; the assignment of weights may be necessary when the attributes have some uncertainty or measurement errors associated with them. In this case the total range of an attribute is divided, or quantized, in equal or nonequal parts or categories, for example five, with given boundary values. The first category of an attribute now includes elements that fall between its limits, the same is valid for the other four categories. The more important the attribute, the larger the number of categories and viceversa. Thus, an attribute which is split in few categories (limit case is 2) is considered not important. In this study GTC divided all attributes in three categories; thus, in the present study all attributes have the same weight.

The number of attributes should be minimal to reduce the number of experiments to be performed for each site or minimize field information to be collected; this condition implies that the properties of the attributes should be independent of one another. The attributes and their values can be expressed in a simple mathematical form: Each waste site is linked to a set of numbers, each number corresponding to the result of a single test; the numbers so defined are the elements of the vector distance and the ranking is defined in such a way to decrease as the environmental hazard decreases. Inclusion of the qualitative attributes should be discouraged as it will be shown in the following sections.

The ranking procedure

The formal mathematical and logical development of the method can be found in (5). A BASIC program to display results with a desk top personal computer is available from the author. The hazard levels are determined by comparing the test data for each site with all the others according to prespecified logical rules. These rules are the definition of binary relations between pairs of set elements and are based on principles of lattice and graph theory developed during the 1970's (5,6,7,9); the methodology is therefore well established and the procedure is described here with an example.

A set is partially ordered if contradictions exist in the test data that prevent us to rank the contaminants in a chain (Fig. 1a). If contradictions exist for the ranking of two sites, then the two sites may be assigned to the same hazard level (Fig. 1b) depending also on their relative ranking with the other sites in the list.

Two examples

a) Let C1 and C2 be two sites and VC1 and VC2 their respective vector distances. If every component of VC1 is lower than the corresponding one of VC2, C2 is obviously the safer of the two. Should any two successive sites C2, C3; C3, C4; ... of the considered set (C1, C2, ...) behave in the same fashion we could draw the diagram (Fig. 1a) known in set theory as the Hasse diagram. Here C1 is better than C2; C2 better than C3, and so on. The sites can be ranked in a chain. Unfortunately, such a situation, so simple to be understood and sketched, is seldom verified in reality. Consider, for example, the site C1 having as components for the vector distance the numbers [4,4] and the sites C2 and C3 characterized by the components [2,3] and [3,2]. Both C2 and C3 are better than C1 because they have smaller components than C1. Nevertheless, they are incomparable to each other (C2 is better than C3 as far as the first component is concerned, but the opposite is true for the second component, see Fig. 1b). Under these circumstances, it is not immediately apparent which of the two sites C2 and C3 is environmentally safer. With a larger number of sites and a larger number of tests the ranking becomes even more complicated.

b) In the general case, the formal ranking procedure can be explained by analyzing an example data set (Table 3); this data set contains only 6 attributes for each site while the real analysis includes up to 30 attributes for each site (Table 2). The data sets are marked #1; #6; #23; #24; #28; and #38. The Hasse diagram for these six data sets can be derived as follows: Assume that the six sites are positioned at the vertices of a regular polygon, in this case an hexagon (see Fig 2). Now, compare one site, e.g. #1 with all others (#6, #23, #24, #28, #38) one at the time. In principle, four outcomes can result from these comparison; they are

#1 = #6	case A
#1 >/ #6	case B
#1 \< #6	case C
#1 and #6 are incomparable	case D

The notation >/ (greater or equal; case B) means that each element of #6 is greater or equal than each element of #1, i.e $\#6_1$ >/ $\#1_1$; $\#6_2$ >/ $\#1_2$; ... with the constraint that the sign = can not be verified for all elements since this is case A. If the symbol >/ is interpreted as a parental relation (father-son; father-grandson; grandfather-grandson, etc.) within a family, the Hasse diagram becomes a genealogical tree. The lines represent the direct relation father-son and each two successive levels represent the passage of a generation.

Now if for example #1 = #6 (case A), then the hexagon becomes a pentagon. If B is true then #6 and #1 will be connected with an oriented line from #6 to #1; for case C (valid in the present example) the elements are connected with a line from #1 to #6. In case D the two elements are not connected. In the same manner we compare the pairs #1-#23, #1-#24, #1-#28 and #1-#38 and oriented lines are drawn accordingly. The next step is to compare the pairs #6-#23, #6-#24, #6-#28 and #6-#38; and so on until #24-#28; #24-#38 and finally #28-#38. When this analysis is completed, then we have Fig. 2b, or the relation diagram. The next step is to eliminate all redundant oriented lines. For example the line #38-#23 in Fig. 2b is redundant since the lines #38-#28 and #28-#23 already exist. Likewise, we can eliminate #28-#6 (the information is contained in #28-#23 and #23-#6); #24-#6; #38-#6 and #38-#1. Fig. 2c shows the diagram after all eliminations have been done. The next step is to rotate the diagram so that the oriented lines are directed towards the bottom of the page (fig. 2d). In this way, also the the arrows become redundant. In the final drawing the number of horizontal levels which contain the incomparable elements must be minimal and therefore the elements #28 and #24 and the elements #23 and #1 must be in the same level.

DATA

GTC (1) prepared a report for the Ontario Ministry of the Environment (MOE) where they described the geology, hydrogeology and physiology of the areas perceived by MOE as most likely to contain waste sites that could negatively impact the water quality of the Detroit River, St. Clair River, St. Mary's river and Lake St. Clair. GTC also developed comparative assessment criteria on which each site could be evaluated and ranked each site according to the developed criteria and environmental impact.

The complete waste site inventory of the Sarnia-Windsor / Sault Ste. Marie area was provided in (1) and includes 45 active sites with MOE certificates of approval, 14 inactive sites with canceled or revoked Certificates of approval and 41 inactive sites. The present study is restricted to 38 active sites since a number of disposal wells were either never used or closed in 1981. The elements of the vector distance used to rank 38 sites are presented in Tables 1 and 2.

In the GTC report the attributes were divided into seven groups: geologic information, hydrologic information, hydrogeologic information, geochemical information, on site monitoring, water characterization and containment, and health and safety. The division into this seven groups was convenient for the analysis of the raw data but this division is not suitable for the present ranking analysis because of its many subgroups in the geologic and pollution characterization sections; here the information about the waste sites is divided into two groups: geologic information and pollution impact. The first 18 components (Tables 1 and 2) include geological information and the other 12 components include information on on site monitoring, waste characterization and containment and health and safety criteria.

Table 1 shows that GTC used both quantitative and qualitative criteria and that availability of data was an important weighting factor for some qualitative criteria such as adequacy of surface water monitoring, availability of site soil data or details of waste site decommissioning plans. These criteria were assigned (1) weights of 1, 2 or 3 according to the respective available knowledge, detailed, intermediate or sparse. The inclusion of qualitative criteria is important to determine the lack of data but it might confuse the ranking scheme since a "no data" attribute raises the hazard estimate of a site. Here, ignorance about the waste sites is included in the ranking scheme only after an analysis of the sites is performed according to the available geologic and pollution characterization data (Table 3). The final ranking (Fig. 8) does not include the qualitative waste site assessment criteria marked with an asterisk in Table 1 for reasons explained in the next section.

RANKING PROCEDURE AND ASSUMPTIONS

The analysis of the data (1) and prioritization of the waste sites is accomplished in four stages:

a) The first step is to rank sites according to what is known about the geology of the waste sites using attributes 1,2,3,6,7,9,13,14 and 18. Some sites might be more suitable than others for receiving pollution; for example, fine grained and low permiability materials are generally preferred as ideal sediment types; depth of overburden is important in the Sarnia-Windsor area because the overburden protects the fresh water aquifer.

b) The second step is to rank sites according to the water burden using attributes 22,24,25,26,28,29 and 30; polluted sites should be ranked higher, or more hazardous, than sites receiving less pollution or with high degree of engineered waste containment. Problems exist when some sites, geologically not suitable, receive high level of pollution, these sites should be ranked the highest.

c) For each of these two steps the implications of the inclusion of qualitative data are considered. Lack of data on a site which does not receive pollution is not as important as the lack of data on sites heavily polluted. Conversely in an area of low pollution a lack of surface and groundwater monitoring data is not as important as in an area highly polluted or in area polluted and with low engineering waste containment. The point is some that the relation between attributes must be considered in the ranking analysis and not only the relative values independently of each other. The ranking analysis based on system method takes these factors into consideration. The GTC report did not consider this aspect and high weights were given to the attributes of sites with unknown characteristics.

d) The final aspect is to consider all geologic and pollution characterization data together and prepare a final ranking of the waste disposal sites using attributes 1,2,3,6,7,9,13,14,18,22,24,25,26,28,29 and 30. This ranking includes all known information and is compared with the rankings of the previous three stages and with the ranking prepared by GTC.

RESULTS

Figure 3 shows the priority ranking in form of a Hasse diagram (5) according to GTC: The sites at the bottom of the figure are the least hazardous to the environment. This Hasse diagram does not include lines connecting the circles since GTC used a different (scalar) ranking method and no analysis of contradictions in the data was performed. The numbers in each circle are labeled (Table 1) and the lines between the circles mean that the given sites can be directly compared with each other following any path (see second example in the Theory section for a full explanation of the development of a Hasse diagram). By definition the sites on the same level are noncomparable (see example in Fig. 1b).

The Hasse diagram shows that the 38 sites have been ranked in four levels by GTC; the four sites which are the most environmentally hazardous using their priority criteria are E-7, A-1, L-1, L-3 and L-7. A second priority group includes the sites E-5, E-6, L-21, L-13, E-3, L-29, L-19, L-5, E-1 and L-8. According to GTC the first priority group includes sites with a definite potential for impact on human health and safety while the second priority group include those sites which require immediate investigation in order to determine the potential for impact either on the environment or human health and safety.

Analysis of the known geological characteristics

a) Figure 4 shows the ranking according to available geological knowledge of the waste sites (criteria 1,2,3,6,7,9,13,14 and 18, Tables 2 and 3). The highest ranking site, or the site with the worst known geology, is E-5, followed by K-1, L-3, E-7, L-26 and L-2. Conversely, the best sites are L-4, L-5, L-8, L-9, L-10, L-12, L-17, L-19, L-25, L-29 and K-3.

The site L-4 has a very particular geology with so many contradictions in the data (Table 3) that it can not be included in the ranking scheme for environmental hazard; site L-4 has sandy soils (too permeable) with 30-45 metres of overburden (good) and it is close to a minor surface water receptor (might disperse pollution) but it has low potential for offsite leachate migration (good property). Overall site L-4 has a quite good geology and therefore it is located at the bottom of the figure even if not connected by any lines to the ranking tree. In Fig. 4 we can note that all K sites have a similar geology and that they almost form a separate hierarchy (found by following the lines connecting the circles) within the larger ranking of all sites. For example, K-1 is at the second highest hazard level but is sufficiently different from E-5 to be the head of its own hierarchy. L-26 is also at the head of its own hierarchy and therefore it also has a different geology from E-5, K-1 and L-3 since it is not connected by any line to these three sites. Nevertheless, from a hazard point of view L-26 has a better geology than these three sites.

b) Figure 5 shows the ranking of the waste sites if all the quantitative and qualitative information about the geology of the sites is used (criteria 1-18, Table 1). The ranking scheme has collapsed from six levels to four because of the large number of contradictory qualitative criteria (4,5,8,10,11,15,16,17) included in the analysis. The worst sites are now E-7, K-1 and E-5 followed by L-2, L-3, L-26, K-4 and E-6. L-4 and L-29 are incomparable with all the other sites but analysis of their data show them to be low in ranking.

Analysis of the impact of pollution independently of the geology of the sites

c) Figure 6 shows the ranking of the sites if only the known information (criteria 22,24,25,26,28,29,30) about contaminant loadings is used. The 38 sites are ranked in nine levels. The higher third includes the sites A-1, E-1, E-6, L-19, L-1, L-21, E-5, E-7 and E-4 followed by L-2, L-9, A-2, L-29 and L-31.

The least hazardous sites are L-4, L-6, L-12, L-14 and L-16 which also have some of the best geological characteristics (Fig. 4).

d) Figure 7 shows the ranking of the waste sites using all quantitative and qualitative criteria about pollution characterization and containment (criteria 19-30). The ranking scheme has collapsed from nine levels to three because the qualitative criteria 19,20,21,23 and 27 included in the analysis increase the contradictions in the data set. The worst sites are now the four sites L-1, L-21, E-6 and A-1. This ranking contains results equal to those observed by using only known information about the pollution in the sites. Of these four sites E-6 has the worst geological characteristics. A second set of priority includes sites that might have a pollution problem, L-19, L-31, L-7, L-26, K-1, L-13, E-1, E-4, L-3, L-8, E-5, E-7 and E-3. Out of this second set of sites L-26, K-1, E-1, E-5 and E-7 are located in areas with poor geological characteristics and the last three might be worrisome.

Analysis of the known geological characteristics and known pollution impact.

e) Figure 8 shows the ranking of all sites according to all quantitative criteria, both geological and pollution related (attributes 1,2,3,6,7,9,13,14,18,22,24,25,26,28,29,30). According to this analysis the worst waste sites, for a combination of poor geology and pollution contamination, are E-5 and K-1 followed by E-1, E-7, E-6 and K-4. All these sites were also identified by GTC consultants and ranked priority I and II; the sites K-1 and K-4 were ranked priority III. As noted before the K sites have distinguished individual geology and they form an separate hierarchy within the larger hierarchy. According to the present study sites K-1 and K-4 should be moved to priority II class because of their poor and unknown geology and possibility of contamination even if K-1 and K-4 are relatively pollution free. The other sites are contaminated and therefore the poor geology and the large levels of pollution might cause a high ranking.

A few sites, L-4, L-5, L-19, L-29 and L-31, do not belong to any hierarchy because of contradictions in the data and are displayed at the bottom the figure. L-5, L-19 and L-19 should be the subject of additional research given their contradictory geology.

Another interesting aspect in Fig. 8 is that the hierarchy is not uniformly connected but that at each hazard level new hierarchies start, for example K-1, E-1, E-7, E-6, L-3, L-21, A-1, L-1 and L-26 are all at the head of a hierarchy. This observation is important in determining the rank of a given site and in combining the effects of the geological characteristics with pollution influences. For example A-1 is ranked Priority I by GTC but here A-1 is ranked Priority III (third level from top in Fig. 8). Figure 6 shows that A-1 is ranked high in term of pollution but Fig. 4 shows that A-1 is ranked low in term of geology, i.e. A-1 has a good geology in relation to other waste sites. The high level of pollution might therefore not be that crucial. The same observation is valid for L-1, L-3, and L-7 (all ranked priority I by GTC and priority III here.

A ranking of the sites was also attempted by using all quantitative and qualitative criteria (attributes 1-30, Table 2). Unfortunately, the geological and pollution data are so contradictory that 22 out of 38 sites do not belong to any hierarchy and the other 16 sites are divided into five hierarchies. Clearly the inclusion of the qualitative criteria 4,5,8,10,11,12,15,16,17,19,20,21,23 and 27 in a global analysis introduces so much uncertainty in any ranking scheme to make them completely unreliable if used uncritically. This contradictory evidence is not immediately evident in ranking schemes using a figure of merit scheme and might produce spurious ranking. These results point to the advantage of using the new ranking scheme rather than the commonly used figure of merit. The new ranking method clearly points out that the ranking analysis can not be performed without critically analyzing the data looking for contradictions, as done in this paper, rather than using figure of merit schemes which can not identify possible shortfalls in the data.

DISCUSSION

The proposed method may seem long and difficult for interpreting geologic and exposure data and to rank waste sites according to their environmental hazard. The truth is that the reality we wish to represent is difficult to classify; when reality is simple (elements in a chain) there are no problems of visual display. We should be avoiding some procedures that are apparently simpler (scalar indices) because we may run the risk that we gain simplicity by distorting the reality. For example, the ranking scheme used by GTC (1) had a maximum possible score of 116 points and a minimum of 30 points for a range of 86 points. Nevertheless, the data contained so many contradictions that 26 out of 38 sites had a score between 80 and 100 (Table 3) with resulting low discrimination.

The ranking procedure using a vectorial approach is applicable to a variety of problems in environmental toxicology. Once data have been collected, a computer can process them in a few seconds and point out contradictions within a data set. A graphical display program has been developed for desk top computers and is available on request. The number of different classification levels is directly proportional to the number of sites and inversely proportional to the number of criteria; in fact the more criteria considered at the same time, the higher the probability of contradictions in the data and therefore the fewer the discrimination levels. Quantitative information, but only if it is unambiguous, is also better that vague criteria such as "detailed knowledge of waste types."

The Hasse diagrams show that using all quantitative information a meaningful ranking of the 38 waste sites according to environmental hazard is possible. Furthermore, should a new site be chosen for waste disposal and comparable information about its geological properties and pollution loadings collected, it can be easily ranked and compared with other known sites. The availability of the program in microcomputer form make the routine applicability easy to this or other similar ranking problems, for example ranking the effects of toxic contaminants (10).

The development of a suitable index for environmental risk has been widely discussed in the literature (3,4). An index is a suitable scalar function of the vector distance components with the best sites having the lowest index. Since an index is a scalar quantity, problems concerned with the noncomparability of sites cannot arise since the sites can always be ranked and represented as a chain in a Hasse diagram. Unfortunately, the choice of a particular index, or figure of merit, affects the results (8); therefore, the development of this new method which does not require an *a priori* definition of an index.

A simple example can clarify the previous arguments: Let C' and C" be the vector distance components of a site C and let F=C'+2C" be the chosen index. The site C2 previously considered has the components $C'_2=2$ and $C''_2=3$; thus $F_2=2+2x3=8$. Analogously, for the site C3, $C'_3=3$; $C''_3=2$ and $F_3=3+2x2=7$. As $F_3<F_2$, the site C3 would be considered safer than C2. Conversely, if the index were G=2C'+C", then $G_2<G_3$ and C2 would have to be considered safer than C_3. The conclusions are opposite to each other. They depend only on the index chosen. As a consequence, every time the definition of an index cannot be firmly grounded on a theoretical basis, the results can be completely inaccurate and the index becomes biased towards a subjective meaning.

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FIGURE LEGENDS

Figure 1 a) Hasse diagram of ranked sites C1-C4. C1 is less hazardous than C2, C2 less than C3, etc. b) Hasse diagram of partially ordered sites. Both C2 and C3 are better than C1 but they are incomparable with each other. Thus, it is not immediately clear which site should be chosen as the safest.

Figure 2 The formal procedure to rank sites according to environmental hazard is explained using six sites from Table 1. See text for additional explanations. a) set sites at vertices of regular polygon. b) rank site with one another. c) remove redundant lines d) rotate diagram and eliminate arrows, i.e. Hasse diagram.

Figure 3 Thirty eight sites have been ranked according to the 30 criteria presented in Tables 2 and 3. Four priority levels have been identified by GIC. Circles represent the sites. See text for further details.

Figure 4 The same 38 sites shown in Fig. 3 are ranked according to the known geological characteristics (attributes 1,2,3,6,7,9,13,14 and 18. Table 1). Six hierarchical levels have been identified by the partial ordering method with one site, L-4, out of the hierarchy. Circles represent the sites and lines indicate that these sites can be directly compared. See text for further details.

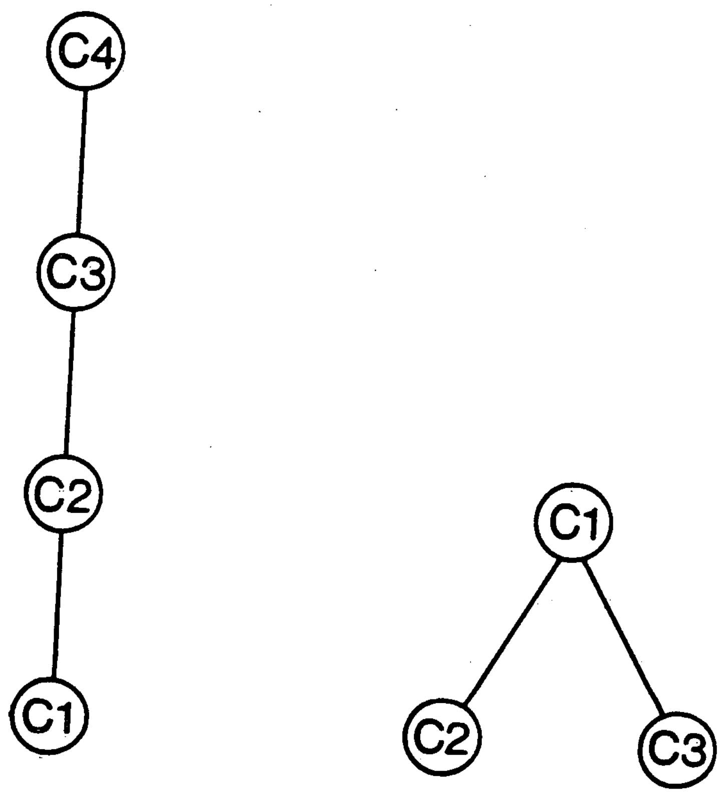
Figure 5 The same 38 sites shown in Fig. 3 are ranked according to the known and unknown (qualitative) criteria (attributes 1-18, Table 1). Four levels have been identified by the partial ordering method with two sites, L-4 and L-29, out of the hierarchy. Circles represent the sites and lines indicate that these sites can be directly compared. See text for further details.

Figure 6 The same 38 sites shown in Fig. 3 are ranked according to the known pollution impact (attributes 22,24.25,26,28,29 and 30, Table 1). Nine priority levels have been identified by the partial ordering method. Circles represent the sites and lines indicate that these sites can be directly compared. Note that L-52 is missing from the figure since it has the same rank as L-1; also L-9 and A-2 rank the same as L-2; K-3, K-4 and K-5 are missing since they have the same rank as K-1; A-1 has the same rank as E-1.

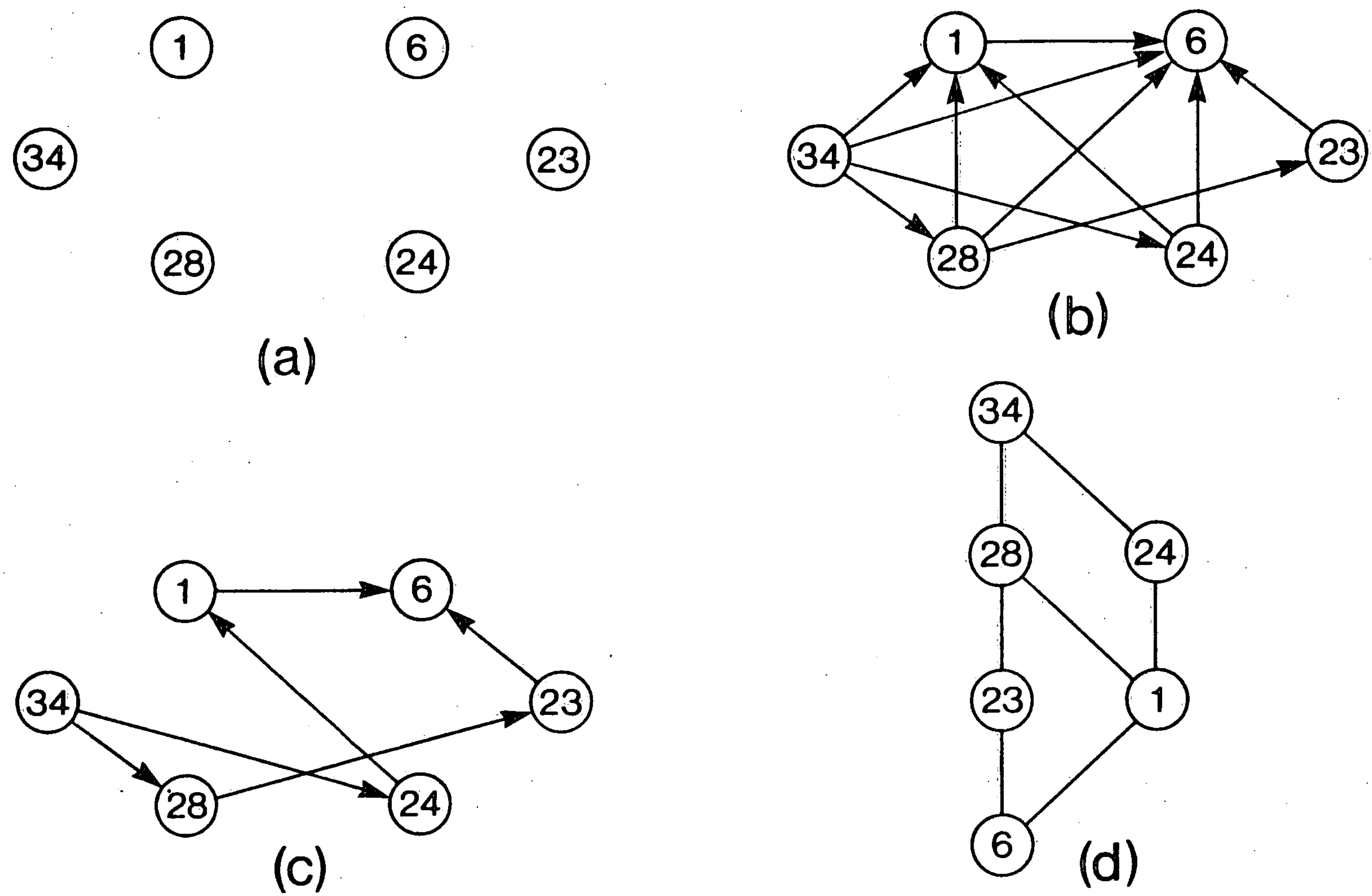
Figure 7 The same 38 sites shown in Fig. 3 are ranked according to the known and known pollution characteristics (criteria 19-30, Table 1). Three levels have been identified by the partial ordering method. Circles represent the sites and lines indicate that these sites can be directly compared. Note that L-9 is missing from the figure since it has the same rank as L-2; also K-3, K-4 and K-5 are missing since they have the same rank as K-1.

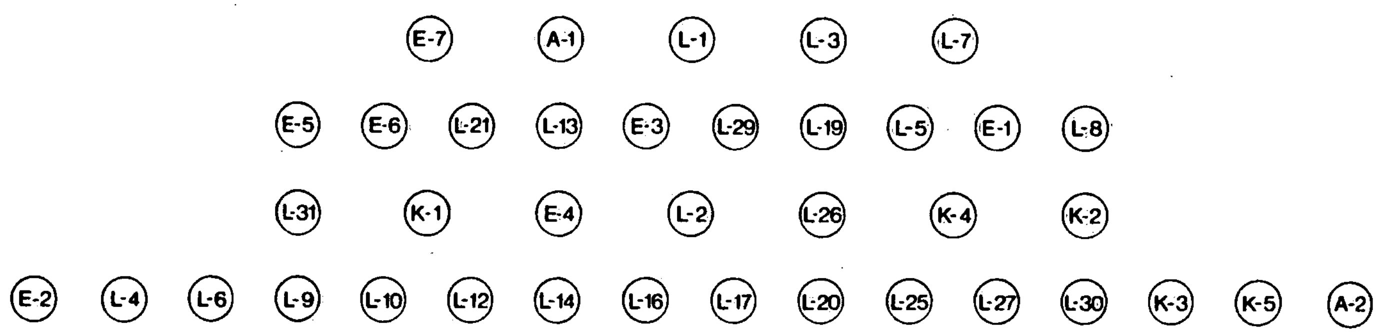
Figure 8 The same 38 sites shown in Fig. 3 are ranked according to all known geologic and pollution criteria (attributes, 1,2,3,6,7,9,13,14,18,22,24,25,26,28,29 and 30, Table 1). Four levels have been identified by the partial ordering method with five sites L-4, L-5, L-19, L-29 and L-31 out of the hierarchy. Circles represent the sites and lines indicate that these sites can be directly compared. See text for further details.

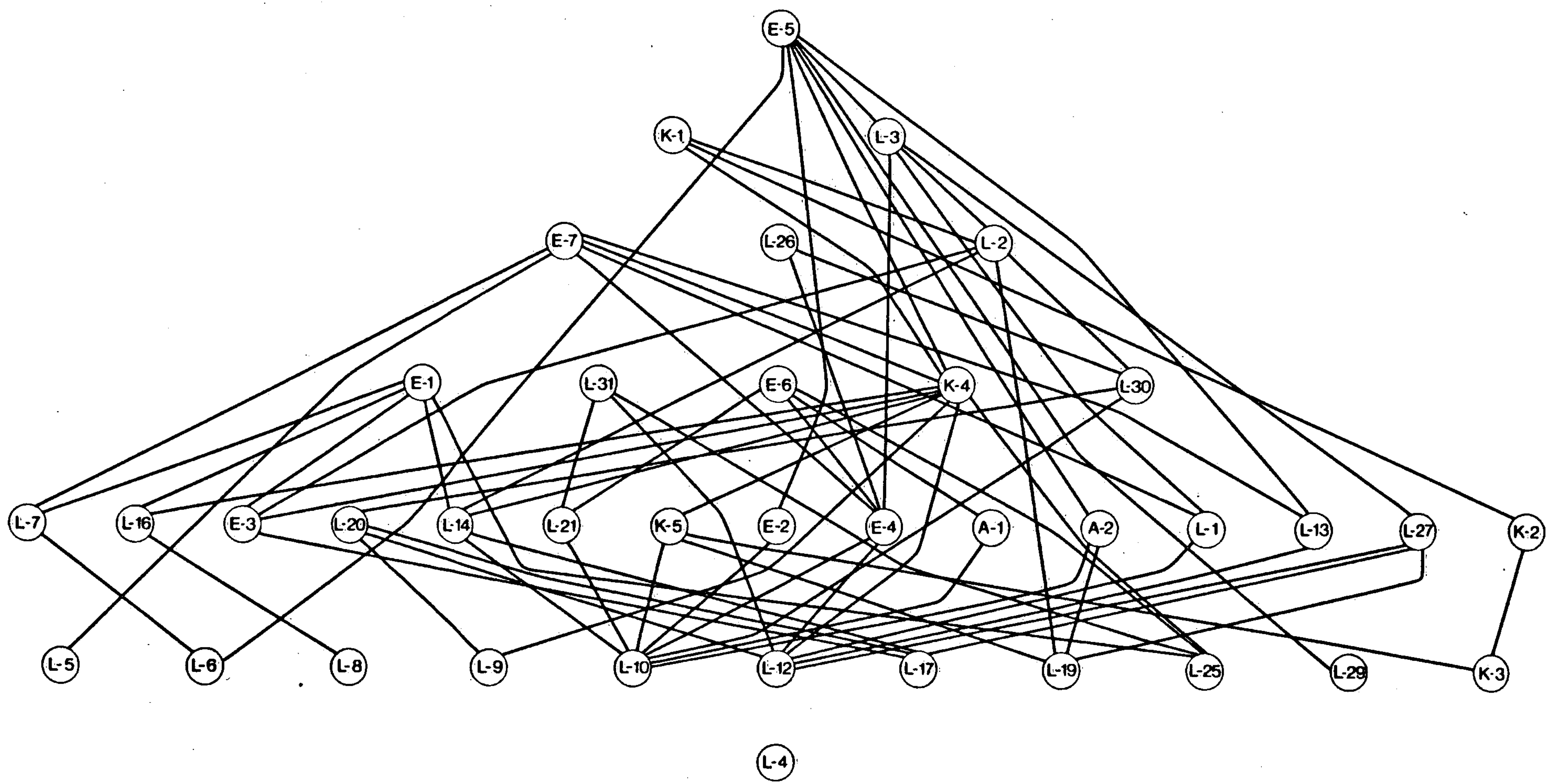
Fig I



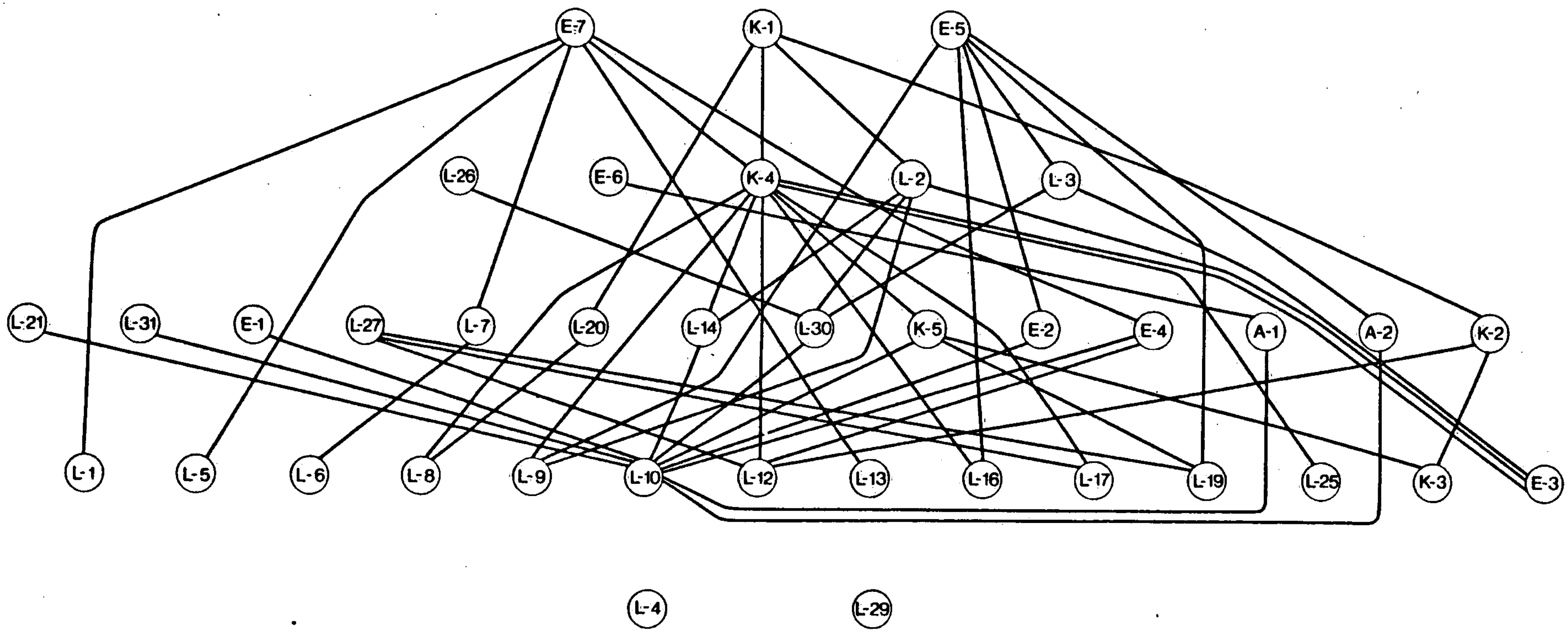
(a) (b)


1
6
34
23
28
24
(a)
1
6
34
23
28
24
(b)
1
6
34
23
28
24
(c)
34
28
24
23
1
6
(d)


E-7 A-1 L-1 L-3 L-7
E-5 E-6 L-21 L-13 E-3 L-29 L-19 L-5 E-1 L-8
L-31 K-1 E-4 L-2 L-26 K-4 K-2
E-2 L-4 L-6 L-9 L-10 L-12 L-14 L-16 L-17 L-20 L-25 L-27 L-30 K-3 K-5 A-2



E-5
K-1
L-3
E-7
L-26
L-2
E-1
L-31
E-6
K-4
L-30
L-7
L-16
E-3
L-20
L-14
L-21
K-5
E-2
E-4
A-1
A-2
L-1
L-13
L-27
K-2
L-5
L-6
L-8
L-9
L-10
L-12
L-17
L-19
L-25
L-29
K-3
L-4


E-7
K-1
E-5
L-26
E-6
K-4
L-2
L-3
L-21
L-31
E-1
L-27
L-7
L-20
L-14
L-30
K-5
E-2
E-4
A-1
A-2
K-2
L-1
L-5
L-6
L-8
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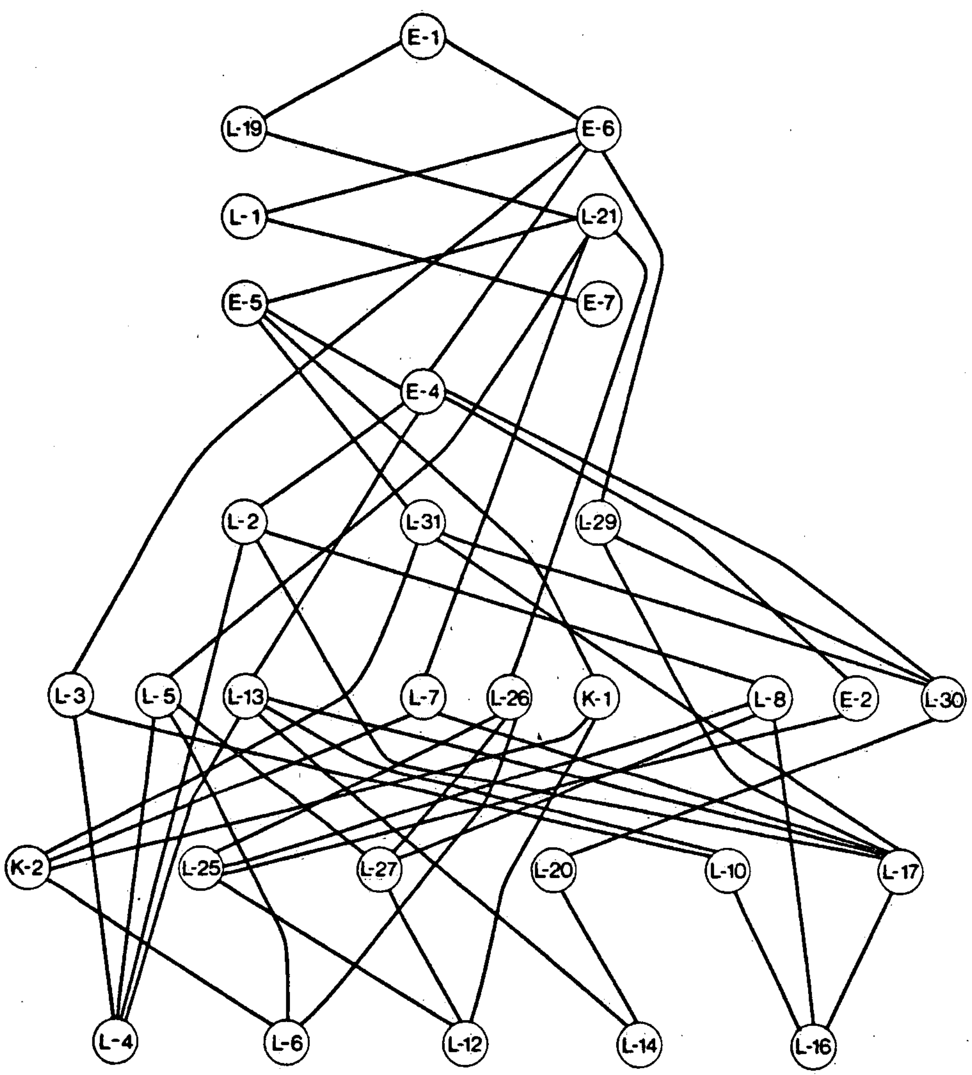
K-3
E-3
L-4
L-29



E-1
L-19
E-6
L-1
L-21
E-5
E-7
E-4
L-2
L-31
L-29
L-3
L-5
L-13
L-7
L-26
K-1
L-8
E-2
L-30
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L-10
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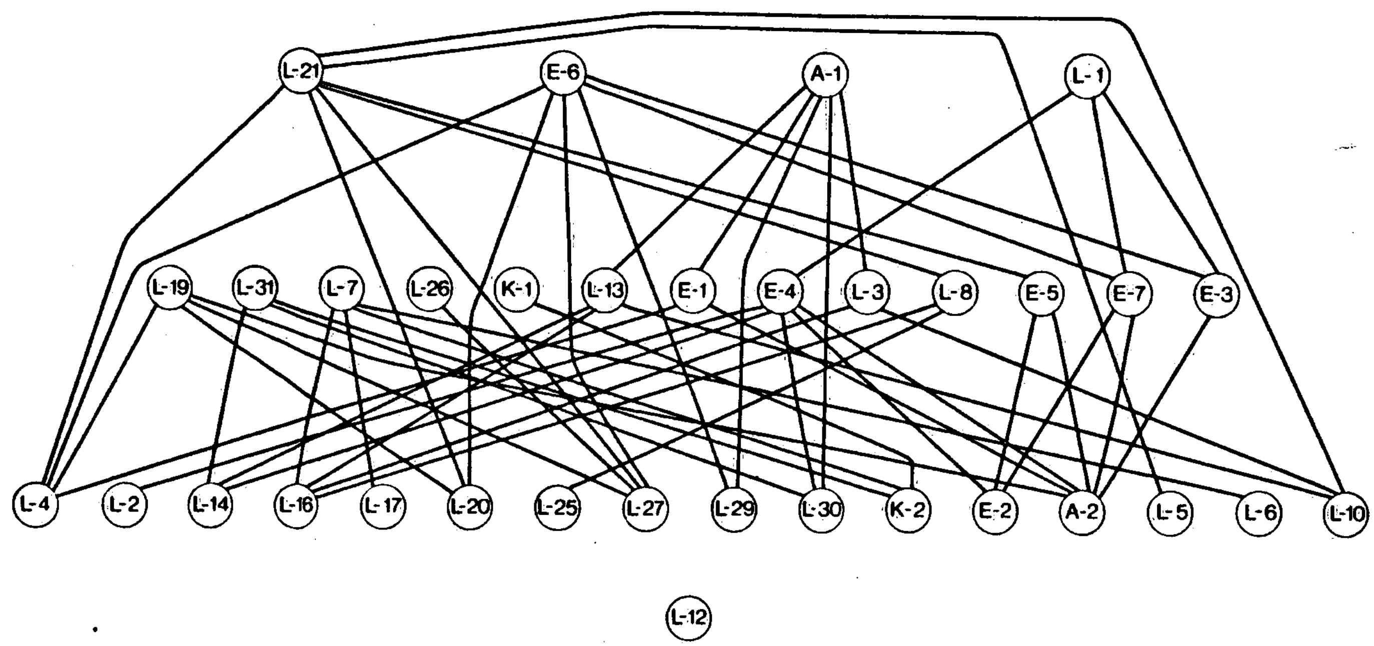
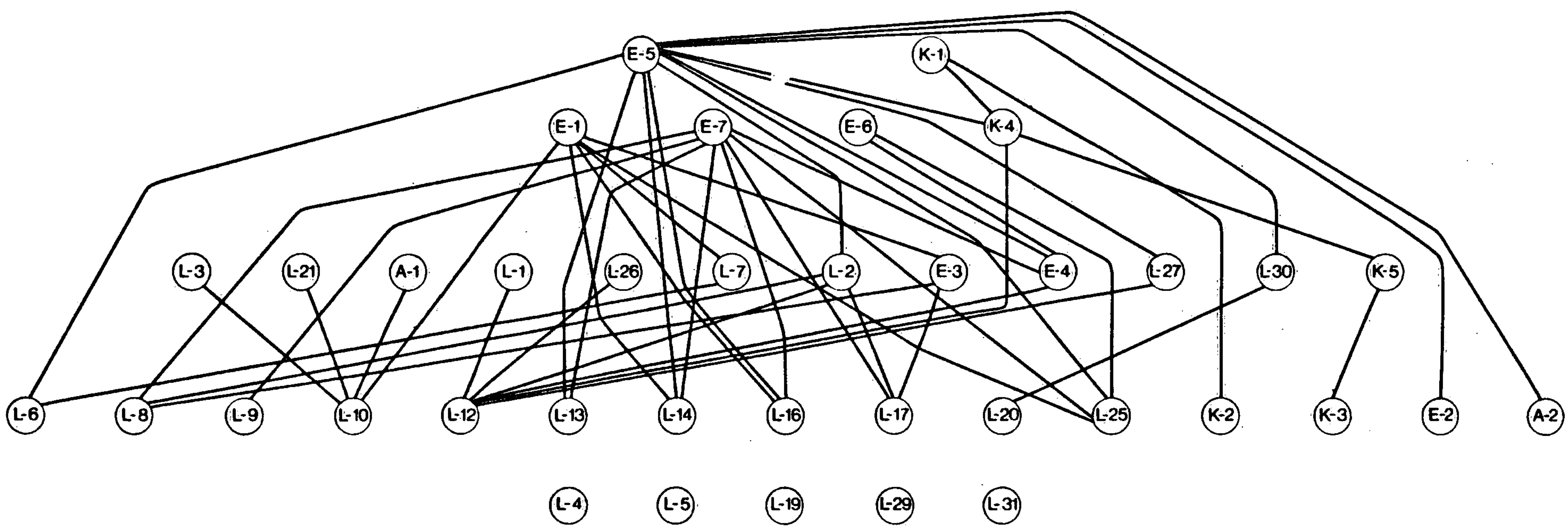
L-6
L-12
L-14
L-16


L-21
E-6
A-1
L-1
L-19
L-31
L-7
L-26
K-1
L-13
E-1
E-4
L-3
L-8
E-5
E-7
E-3
L-4
L-2
L-14
L-16
L-17
L-20
L-25
L-27
L-29
L-30
K-2
E-2
A-2
L-5
L-6
L-10
L-12



E-5
K-1
E-1
E-7
E-6
K-4
L-3
L-21
A-1
L-1
L-26
L-7
L-2
E-3
E-4
L-27
L-30
K-5
L-6
L-8
L-9
L-10
L-12
L-13
L-14
L-16
L-17
L-20
L-25
K-2
K-3
E-2
A-2
L-4
L-5
L-19
L-29
L-31

TABLE 1 Waste Sites Criterio and description of Designations

Assessment Criteria Number		Waste Site Assessment Criterion	Designation Category and Score ( )		
A. Geologic Information					
A1	1	Surficial sediment type	clay (1)	till (2)	silt (3) sand (5)
A2	2	Depth of overburden on site	30-45 m (1)	15-30 m (2)	0-15 m (3)
A3	3	Stratigraphic uniformity	1 soil type (1)	2 soil types (2)	3 soil types (3)
A4	4	Site soil data	detailed (1)	intermediate (2)	sparse (3)
A5	5	Degree of soils testing	detailed (1)	intermediate (2)	sparse (3)
B. Hydrologic Information					
B1	6	Site proximity to major surface water receptor	< 8 km (1)	5-8 km (3)	0-5 km (5)
B2	7	Site proximity to minor surface water receptor	< 2 km (1)	1-2 km (3)	0-1 km (5)
B3	8	Availability of hydrologic data	detailed (1)	intermediate (2)	sparse (3)
B4	9	Potential for flooding of site	none (1)	partial (2)	complete (3)
C. Hydrogeologic Information					
C1	10	Extent of hydrogeologic investigations	detailed (1)	intermediate (3)	sparse (5)
C2	11	Shallow ground water flow studies	detailed (1)	intermediate (3)	sparse (5)
C3	12	Deep ground water flow studies	detailed (1)	intermediate (2)	sparse (3)
C4	13	Relationship of stored waste to ground water flow system	none (1)	partial recharge (2)	leachate interaction (3)
C5	14	Potential for off-site leachate migration	low (1)	moderate (2)	high (3)
D. Geochemical Information					
D1	15	Extent of site geochemical investigations	detailed (1)	intermediate (3)	sparse (5)
D2	16	Details of natural ground water quality characterization	detailed (1)	intermediate (2)	sparse (3)
D3	17	Leachate characterization	detailed (1)	intermediate (2)	sparse (3)
D4	18	Soil attenuation characteristics	high (1)	moderate (2)	low (3)

TABLE 1 Waste Sites Criterio and description of Designations continued

Assessment Criteria Number		Waste Site Assessment Criterion	Designation Category and Score ( )		
E. On-Site Monitoring					
E1	19	Adequacy of surface water monitoring	good (1)	adequate (3)	poor (5)
E2	20	Adequacy of ground water monitoring	good (1)	adequate (3)	poor (5)
E3	21	Details of site ground water quality monitoring	detailed (1)	intermediate (2)	sparse (3)
E4	22	Results of monitoring for evidence of leachage migration	negative (1)	intermediate (2)	positive (3)
F. Waste Characterization and Containment					
F1	23	Details of waste types	detailed (1)	intermediate (3)	sparse (5)
F2	24	Volume of waste disposed	<500 tonnes/yr (1)	500-5000 tonnes/yr (3)	>5000 tonnes/yr (5)
F3	25	Degree of engineered waste containment	high (1)	intermediate (3)	low (5)
F4	26	Estimated effectiveness of long-term waste containment	good (1)	fair (2)	poor (3)
F5	27	Details of waste site decommissioning plans	detailed (1)	intermediate (2)	sparse (3)
F6	28	Compatibility of waste type with containment system for long-term effective containment	good (1)	fair (2)	poor (3)
G. Health and Safety					
G1	29	Potential for immediate effect to health and safety of local population	low (1)	medium (3)	high (5)
G2	30	Potential for long-term effect to health and safety of local population given a similar future demographic make-up	low (1)d (1)	medium (3)	high (5)

TABLE 1 Waste Sites Criterio and description of Designations

Assessment Criteria Number		Waste Site Assessment Criterion	Designation Category and Score ( )		
A.		**Geologic Information**			
A1	1	Surficial sediment type	clay (1)	till (2)	silt (3) sand (5)
A2	2	Depth of overburden on site	30-45 m (1)	15-30 m (2)	0-15 m (3)
A3	3	Stratigraphic uniformity	1 soil type (1)	2 soil types (2)	3 soil types (3)
A4	4	Site soil data	detailed (1)	intermediate (2)	sparse (3)
A5	5	Degree of soils testing	detailed (1)	intermediate (2)	sparse (3)
B.		**Hydrologic Information**			
B1	6	Site proximity to major surface water receptor	< 8 km (1)	5-8 km (3)	0-5 km (5)
B2	7	Site proximity to minor surface water receptor	< 2 km (1)	1-2 km (3)	0-1 km (5)
B3	8	Availability of hydrologic data	detailed (1)	intermediate (2)	sparse (3)
B4	9	Potential for flooding of site	none (1)	partial (2)	complete (3)
C.		**Hydrogeologic Information**			
C1	10	Extent of hydrogeologic investigations	detailed (1)	intermediate (3)	sparse (5)
C2	11	Shallow ground water flow studies	detailed (1)	intermediate (3)	sparse (5)
C3	12	Deep ground water flow studies	detailed (1)	intermediate (2)	sparse (3)
C4	13	Relationship of stored waste to ground water flow system	none (1)	partial recharge (2)	leachate interaction (3)
C5	14	Potential for off-site leachate migration	low (1)	moderate (2)	high (3)
D.		**Geochemical Information**			
D1	15	Extent of site geochemical investigations	detailed (1)	intermediate (3)	sparse (5)
D2	16	Details of natural ground water quality characterization	detailed (1)	intermediate (2)	sparse (3)
D3	17	Leachate characterization	detailed (1)	intermediate (2)	sparse (3)
D4	18	Soil attenuation characteristics	high (1)	moderate (2)	low (3)

TABLE 2 Waste Disposal Sites Evaluation and Grading

GTC Site #	Site	A	B	C	D	E	F	G	GTC Score
		1 2 3 4 5	1 2 3 4	1 2 3 4 5	1 2 3 4	1 2 3 4	1 2 3 4 5 6	1 2	
L-1		1 1 2 2 3	5 5 3 1	5 5 3 3 3	5 3 3 3	5 5 3 3	3 5 3 3 2 2	5 5	100
L-2		5 1 2 3 2	5 5 3 1	5 5 3 3 2	5 3 2 3	5 5 3 3	1 5 3 2 2 2	1 3	93
L-3		5 1 2 2 2	5 5 3 1	3 3 3 3 3	3 2 2 3	3 5 2 3	5 5 2 3 2 3	5 5	94
L-4		5 2 1 2 2	1 5 1 2	1 1 3 2 2	3 2 3 2	1 1 1 2	3 3 1 2 3 2	1 1	61
L-5		1 2 2 3 3	1 5 3 2	5 5 3 2 2	5 3 3 3	3 5 3 3	1 3 5 2 3 3	1 1	86
L-6		2 2 1 2 3	1 5 3 1	5 5 3 2 3	5 3 3 2	5 5 3 3	1 1 5 1 3 1	1 1	81
L-7		2 2 1 3 3	1 5 3 2	5 5 3 2 3	5 3 3 2	5 5 3 3	5 1 5 3 3 3	1 3	93
L-8		2 1 2 2 2	5 5 1 1	3 3 3 2 1	5 3 3 2	3 5 3 3	5 5 3 1 2 2	1 3	82
L-9		2 1 1 1 1	5 3 2 1	3 5 3 2 2	3 2 2 3	5 5 3 3	1 5 3 2 2 2	1 3	79
L-10		2 1 2 1 1	1 1 1 1	1 1 1 3 1	1 1 1 1	1 1 1 1	5 5 1 1 1 1	3 3	46
L-11		DISPOSAL WELL ----							
L-12		1 1 2 3 3	3 1 3 1	5 5 3 2 2	5 3 3 3	5 5 3 3	3 3 3 1 3 1	1 1	81
L-13		1 2 2 2 2	5 3 3 1	5 5 3 2 3	5 3 2 3	5 5 2 2	5 5 3 2 3 2	3 3	92
L-14		2 1 2 2 2	5 5 2 1	3 3 3 3 2	3 3 2 1	5 5 2 1	3 1 3 2 2 2	3 1	75
L-15		DISPOSAL WELL - NEVER USED ----							
L-16		2 2 2 2 2	5 5 2 1	1 1 3 2 1	3 2 2 2	3 1 1 1	5 1 1 1 1 1	1 3	60
L-17		2 1 2 3 3	3 3 3 1	5 5 3 2 2	5 3 3 1	5 5 3 2	3 1 3 2 3 1	1 3	81
L-18		DISPOSAL WELL - IN USE ----							
L-19		2 1 1 3 3	1 5 3 1	3 3 3 2 2	3 2 3 3	3 3 3 3	3 5 5 3 3 3	5 3	86
L-20		5 1 2 2 2	5 3 2 1	5 5 3 2 2	5 3 3 3	3 3 3 1	1 1 3 3 3 2	3 1	81
L-21		5 2 3 3 2	5 1 3 3	3 3 3 3 1	3 2 2 3	3 5 3 3	5 5 5 3 3 3	3 3	92
L-22		DEEP WELL - CLOSED IN 1981 ----							
L-23		DEEP WELL - CLOSED IN 1981 ----							
L-24		DEEP WELL - CLOSED In 1983 ----							
L-25		2 2 1 3 2	5 1 3 1	5 5 3 2 2	5 3 3 2	1 3 3 3	5 5 3 1 2 1	1 1	79
L-26		5 1 2 3 2	5 3 3 3	3 3 3 3 3	5 3 3 3	5 3 3 3	3 5 5 1 3 3	1 1	92
L-27		5 1 2 3 3	3 5 3 1	5 5 3 2 3	5 3 3 3	3 3 3 3	3 3 3 1 3 2	1 1	87
L-28		DISPOSAL WELL - NEVER USED ----							
L-29		2 1 3 3 3	5 3 3 1	5 5 3 1 3	5 3 2 2	3 5 2 3	1 1 3 3 3 3	3 5	88
L-30		5 1 2 2 2	5 3 3 1	1 1 3 3 2	3 2 2 3	5 1 2 2	3 1 3 3 2 2	3 1	72
L-31		5 3 3 2 3	5 1 3 3	5 5 3 3 2	5 3 3 3	5 5 3 3	3 1 5 3 2 2	3 3	98

TABLE 2 Waste Disposal Sites Evaluation and Grading continued

GTC Site #	Site	A					B				C					D				E				F						G		GTC Score
		1	2	3	4	5	1	2	3	4	1	2	3	4	5	1	2	3	4	1	2	3	4	1	2	3	4	5	6	1	2	
K-1		5	3	2	3	3	5	5	3	1	5	5	3	3	2	5	3	3	3	5	5	3	3	3	3	5	3	1	1	1	1	96
K-2		1	3	2	3	3	5	5	3	1	5	5	3	3	2	5	3	3	3	5	5	3	3	3	1	5	3	1	1	1	1	90
K-3		1	2	2	3	3	1	5	3	1	5	5	3	3	2	5	3	3	3	5	5	3	3	3	3	5	3	1	1	1	1	87
K-4		2	2	2	3	3	5	5	3	1	5	5	3	3	2	5	3	3	3	5	5	3	3	3	3	5	3	1	1	1	1	91
K-5		2	2	2	3	3	1	5	3	1	5	5	3	3	2	5	3	3	3	5	5	3	3	3	3	5	3	1	1	1	1	88
E-1		2	3	2	2	2	5	5	3	2	1	3	1	3	3	1	1	2	2	3	3	2	3	3	5	5	3	3	3	5	5	83
E-2		2	2	3	2	2	1	3	3	1	1	3	3	3	3	5	2	2	2	3	5	3	3	3	5	3	3	1	1	1	1	75
E-3		2	1	2	2	2	5	5	3	1	3	3	3	2	2	3	2	2	2	3	3	3	3	3	5	3	3	2	2	5	5	92
E-4		2	1	2	3	3	5	1	3	1	5	5	3	3	3	5	3	3	3	5	5	3	3	3	5	3	3	2	2	3	3	94
E-5		5	2	3	3	3	5	5	3	1	5	5	3	3	3	5	2	3	3	3	5	3	3	3	5	5	3	2	2	3	3	102
E-6		5	2	3	2	2	5	1	2	3	3	3	3	3	3	3	2	2	3	3	5	3	3	3	5	3	3	3	3	5	5	94
E-7		2	2	2	3	3	5	5	3	3	5	5	3	3	3	5	3	3	3	3	5	3	3	3	5	3	3	2	2	3	5	101
A-1		5	1	3	2	2	5	1	2	2	3	3	3	3	3	3	2	2	2	5	5	2	3	5	5	5	3	3	3	5	5	101
A-2		5	1	3	1	2	1	5	3	1	1	1	2	3	3	1	1	2	3	3	1	2	3	3	5	3	2	2	2	1	3	68

TABLE 3 **Vector Distance Components. Example data to show development of Hasse Diagram**

	Factors					
Sites	1	2	3	4	5	6
1	380	94	0.1	1,900	.03	.119
6	3	5.3	0.1	1,300	.01	.098
23	540	280	0.4	2,600	.06	.105
24	2,690	2,420	0.1	6,300	10	.286
28	11,500	2,320	39.8	27,800	3.33	.192
34	24,800	2,600	55.7	35,000	10	.667