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Application of Partial Order to Bridge Engineering, Stream Channel Assessment, and Infrastructure Management

By G.P. Patil[1] and Jessica T. Newlin[2]

[1]Center for Statistical Ecology and Environmental Statistics
Department of Statistics
The Pennsylvania State University, University Park, PA 16802

[2]Civil and Environmental Engineering Department
Becknell University, Lewisburg, PA 17837

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Department of Statistics
The Pennsylvania State University
University Park, PA 16802

G. P. Patil
Distinguished Professor and Director
Tel: (814)865-9442 Fax: (814)865-1278
Email: gpp@stat.psu.edu
http: //www.stat.psu.edu/~gpp
http://www.stat.psu.edu/hotspots
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Ganapati P. Patil
Penn State University, Center for Statistical Ecology and Environmental Statistics, University Park, PA 16802, gpp@stat.psu.edu

Jessica T. Newlin
Bucknell University, Civil and Environmental Engineering Department, Lewisburg, PA 17837, jessica.newlin@bucknell.edu

Abstract

Many environmental systems and infrastructure systems are monitored using a set of indicators or index values. The values of different indicators often convey a different comparative message and there is no unique way to rank the study sites while taking all of the indicator information into account. Properties of these partially-ordered sets can still be very beneficial to a manager of environmental or infrastructure systems. The advantages of analyses of large data sets gathered through monitoring are demonstrated using a data set comprised of stream channel stability assessments at bridge crossing sites. These analyses lead to information that can be used by a manager for decision-making and prioritization purposes.

Keywords: partial order, prioritization, management, stream channel assessment, bridges, ranking, multiple indicators

1. Introduction

Managers are often faced with large databases of information from which they need to make decisions regarding where their resource allocations are to be best used. Managers of natural resources, infrastructure systems, and other environmental systems all face the daunting task of extracting the information that is most useful to them from these large datasets. Of most interest to a manager are the ability to prioritize sites based on condition or need for mitigation, an evaluation of the performance of existing indicators, and an idea of the best mitigation practices to improve the worst problems. This paper presents a summary of tools that managers can use with large databases of information. These tools are based on the properties of partially-ordered sets.

2. Description of Data and Management Questions Used for Demonstration

The data that is used for demonstration purposes in this paper represents stream channel stability assessment at bridge crossing sites. Instability in a stream channel can result in the undermining of the bridge foundation and can lead to structural failure. Instability also can cause more frequent flood overtopping of the structure, which leads to an increased public safety hazard. While channel stability can increase the risk of failure of a bridge structure, these problems often can be dealt with using instream mitigation measures to stabilize the channel with little or no reconstruction of the bridge structure itself.

There are different levels of risk associated with varying levels of channel instability. Therefore, it would be beneficial to rank the level of instability in a stream channel near a bridge crossing for the purpose of prioritizing stream channel mitigation efforts and funds. Stream channel mitigation measures have been developed to make an unstable channel more stable near a bridge crossing, and those channels posing the highest risk to bridge failure should have a higher priority for mitigation.

The state of channel stability near bridges can be described by a stream stability assessment method (Johnson 2005, 2006). This method is based on a rapid assessment method (Johnson et al. 1999) and is intended for use by bridge inspectors. Bridge inspectors are responsible for evaluating the structural integrity of bridge on a biennial basis and following major flood events. The stream stability assessment method was developed for use in any physiographic region in the United States and was tested in 13 physiographic regions for a range of sites with varying stream type and stream order (Johnson 2005, 2006).

The stream stability assessment method was applied to 49 bridge crossings in 13 physiographic regions and subregions in the United States (Johnson 2005). The method is comprised of 13 individual indicators of stream channel stability. These indicators are summarized in Table 1. For each indicator, a value between 1 and 12 is assigned in the following manner; (1-3) Excellent, (4-6) Good, (7-9) Fair, and (10-12) Poor. The stream stability assessment method as described by Johnson (2005, 2006) uses the sum of the 13 indicator values or a total score to assign an overall condition to the bridge crossing site.

The total score is then given a classification of Excellent, Good, Fair, or Poor based on threshold values of the total score and the stream channel type.

There is a natural hierarchy to the 13 indicators where they can be grouped into four categories representing a particular feature of the bridge crossing site. These categories are watershed and regional features, local channel features, bank stability features, and channel alignment features. The category that a particular indicator belongs in is listed in Table 1. Each category is represented by a different number of individual indicators. Therefore, the total score (sum of all 13 indicator values) can be viewed as a weighted score with respect to the four feature categories. The data is then analyzed as a 13-indicator data set and as a 4-category data set. The 13-indicator data set is a 49 by 13 matrix of scores for each of the individual indicators, and the 4-category data set is a 49 by 4 matrix of normalized composite scores for each of the feature categories.

3. Partially-ordered Sets

The values of different indicators often convey a different comparative message and there is no unique way to rank the study sites while taking all of the indicator information into account. For example, site A may be considered better than site B with respect to the watershed and floodplain activities indicator, but site B is considered superior to site A with respect to channel alignment. The different comparative messages of an indicator set complicates a manager's ability to prioritize sites based on the indicator scores. Often, this problem is circumvented by developing a single value or total score. While a total score sum is useful in ranking study sites, the way in which indicator values are summed (equal or unequal weight) involves some degree of judgment (Patil and Taillie 2004).

To visualize the comparability between all of the sites considering all of the available indicators for each site, a Hasse diagram is constructed. A Hasse diagram is a graphical representation of a partially-ordered set (Patil and Taillie 2004, Bruggemann and Carsen 2006). Figure 1 is the Hasse diagram for the 49 stream stability study sites considering all 13 indicators individually, labeled by overall stream condition as determined from the total score according to Johnson (2005). Figure 2 is the Hasse diagram for the 49 study sites considering the 4-category data set. The Hasse diagram consists of three parts: circles, levels, and lines. Each circle is an object or study site and the lines between them describe the comparability between sites. For two sites that are comparable, all of the indicator scores for the better site are less than all of the indicator scores for the worse site. If two sites are not comparable, the indicator scores are not consistently better or worse for one site or the other. If there are no lines going into or coming from a site, it cannot be compared to the other sites. For example in Figure 1, site 14 is better than site 15, and site 1 cannot be compared to site 14. Generally, the decrease in the number of indicators from 13 individual indicators to 4 category indices resulted in an increase in comparability between study sites with 133 comparabilities in the 13-indicator data set and 460 comparabilities in the 4-category data set.

The levels of the Hasse diagram are referred to as ‘maximality’ levels. The sites that are located on the top level in the diagram do not have any sites that can be considered superior to them. This is maximality level 1. Removing the objects in the top maximality level, the objects of the remaining poset determine maximality level 2. This procedure is repeated until all of the levels are established. The 13-indicator data set results in three maximality levels (Figure 1), and the 4-category data set results in seven maximality levels (Figure 2). More comparabilities create more maximality levels in the Hasse diagram.

4. Conversion of Database to Rank Matrix

This investigation requires converting the indicator values to ranks, with the best site relative to an indicator given a rank of 1. If several sites are tied, the sites are assigned a rank that is an average of the tied ranks. After converting all indicator values to ranks, statistics can be computed on the set of rank values for each study site (Myers et al. 2006). The difference between the minimum and maximum ranks for a site is referred to as the rank range for that site. If a site is equal or superior to another in its best rank and also is better in its worst rank, then there is superiority in a limited sense (Myers et al. 2006). Additionally, sites with a narrower rank range reflect consistency with respect to the indicators. A consistent site can be identified as being in similar overall condition regardless of the indicator or index that is used. Therefore, sites can be sequenced according to the rank ranges. See Myers et al. (2006) for the rank range run sequencing algorithm. Figure 3 is the rank range run sequence for the 13-indicator data set, and Figure 4 is the rank range run sequence for the 4-category data set. The most consistent sites with respect to the indicators or indices are assigned a consistency level of one. Less consistent sites are given higher consistency levels.

End-member elimination involves removing the maximum and minimum ranks separately and recalculating the rank range for a particular site (Myers et al. 2006). Knowledge of the indicators that result in the largest change in the rank range through end-member elimination can identify how a stream channel at a bridge crossing could be maintained or restored. If removing the minimum rank results in the largest change in the rank range, the end-member elimination effect (EEE) is given a negative value and maintenance of the stream channel with respect to the indicator with the lowest rank becomes important. If this aspect of the stream channel is not maintained, the overall rank and state of the stream channel stability could deteriorate. If removing the maximum rank results in the largest change in the rank range, the EEE is given a positive value and restoration of the stream channel with respect to the indicator with the highest rank has the potential to improve the state of the stream channel stability. Figures 5 and 6 are a graphical representation of the end-member elimination effect for the 49 bridge crossing study sites for the 13-indicator data set and the 4-category data set, respectively. The x-axis in these figures is the rank range run sequence number. For the more consistent sites (i.e. those with a lower rank range run sequence), the end-member elimination effect tends to be smaller than the sites with less consistency with respect to the indicators or indices.

By combining the maximality level as demonstrated by the Hasse diagram and the consistency level as determined by rank range run analysis, reference sites can be identified. In stream restoration, a reference reach that is in good condition often is used a template to restore a reach that is not in acceptable condition (FISRWG 1998, Rosgen

1998). The maximality level identifies sites that are ranked as being in the best overall condition, while the consistency level identifies the sites where one indicator or index score is not conveying a substantially different message about the overall condition of the site. Figure 7 shows the combination of the maximality level and consistency level information for the 49 bridge crossing sites with the 13-indicator data set. Of the most consistent sites (consistency level one), there are seven sites that also have a maximality level of one according to the Hasse diagram. These seven sites can be used as a reference for managers that have restoration of other sites as a main goal. Field managers will need to determine which of these seven sites should be used a reference reach for restoration of a site of interest. This will depend on the overall context of each of the sites. Environmental and infrastructure systems behave differently depending on surroundings and circumstances. For example, the streams at the bridge crossings sites are identified according to a stream classification system developed by Montgomery and Buffington (1997). For restoration purposes, the manager should use a reference reach that is a similar stream type and in a similar environment as the site that needs restored.

5. Prioritization Methods

The stream stability assessment data for the 49 sites can be viewed in various ways for the purposes of prioritizing the sites based on the relative stability of the stream channels that a bridge is crossing. The stream stability assessment method (Johnson 2005, 2006) combines all of the 13 indicator values into a total score that can be viewed as a single index. Based on the value of this index the sites can be ranked in order of increasing channel instability. This method of prioritizing the sites assumes that the 13 indicators are weighted equally in importance, each indicator is independent of all others, and that there is a linear relationship between channel stability and the 13 indicators (Johnson 2005). Recall that the total score computed as a sum of the 13 indicators can be seen as a weighted index with respect to the 4 categories because each category is composed of a different number of indicators. To obtain a total score that weights the feature categories equally, the category index values are summed. The sites can then be prioritized according to the total score of the 4 category indices.

Instead of summing all of the indicator scores into a single total score of the 13 indicators or into a sum of the 4 category indices, properties of partially-ordered sets are used to compare study sites. A collection of rankings can be determined that are compatible with the comparabilities illustrated in the Hasse diagram for a partially-ordered set. This collection is referred to as linear extensions. A linear extension is a total order that is extracted from the partial order of the data matrix. Partially-ordered set (poset) prioritization uses the cumulative rank-frequency distribution that is developed considering all of the possible ranks (linear extensions) given the individual indicator values (Patil and Taillie 2004). The cumulative rank frequency method treats each linear extension as an equally possible ranking. A simple Hasse diagram representing a partially-ordered set is shown in Figure 8a as the first step in the poset prioritization process. The second step (Figure 8b) is a graphical representation of all of the possible total order rankings of the objects based on the comparabilities in the Hasse diagram. The third step (Figure 8c) shows the cumulative rank frequency for the objects based on the linear extensions. It is evident that the curves in Figure 8c are stacked one above the other, which gives a total order of the objects: A>B>C>D>E.

The number of linear extensions grows dramatically as the number of objects or the number of dimensions in the data matrix increases. For cases with large data sets, the rank frequencies can be estimated using discrete Markov chain Monte Carlo (MCMC) methods to make the problem more computationally feasible (Patil and Taillie 2004). The MCMC methods were applied to the demonstration bridge crossing data sets (49 sites by 13 indicators matrix and 49 sites by 4 categories matrix).

The rankings based on the total score were compared to the rankings determined from poset prioritization with the 13-indicator data set and the 4-category data set (see Table 2). Figure 9 compares the ranking based on the total score with the ranking using poset prioritization for the 13-indicator data set. For the sites with higher ranks, the total score ranking is consistently greater than the poset prioritization ranking. However, the correlation between the two rankings is 0.92. The results were similar when comparing the total score ranking and the poset prioritization ranking for the 4-category data set (Figure 9), which have a correlation of 0.99. The correlation between all of the rankings is above 0.90 for all comparisons. The lowest correlated rankings were the results of the poset prioritization with the 13-indicator data set and the poset prioritization with the 4-category data set with a value of 0.91.

6. Influential Indicators

Several methods were used to help identify which of the 13 indicators were most influential in determining the condition of a stream channel at a bridge crossing site. Sensitivity analysis can be applied to Hasse diagrams by computing a W-matrix (Voigt et al. 2004). The W-matrix method identifies the difference in comparabilities between Hasse diagrams with indicators removed (Voigt et al. 2004). The first row of the W-matrix indicates the difference in comparabilities between the full Hasse diagram and each of the Hasse diagrams with the particular indicator removed. The indicator that causes the most changes to the comparabilities between sites is considered the most influential. In the 13-indicator model, the removal of the channel alignment indicator, gives a Hasse Diagram with a difference of 85 comparabilities from the Hasse Diagram that includes all the indicators. This is greater than the difference between the Hasse diagram of any other indicator removed and the Hasse diagram with no indicator removed, so channel alignment is considered the most influential indicator using the W-matrix method. The W-matrix method also was applied to the 4-index data set. The removal of the category that contains the channel alignment indicator, results in the largest change in comparabilities. Therefore, channel alignment can be considered the most influential indicator according to the W-matrix method. Table 3 summarizes the three most influential indicators for the 13-indicator and 4-category data sets as determined by the W-matrix method.

It also is noticed that the order of influential indicators did not seem to change when the sums of the columns of the W-matrix were computed. The sum of each column represents the sum of the number of comparabilities between the Hasse diagram with the indicator representing that column removed, and each row’s Hasse diagram with that indicator removed. The idea is to get a characteristic of the change in comparabilities with all the Hasse diagrams with indicators removed, as opposed to simply the change in comparabilities from the model without any indicators removed. The order of the most influential indicators were also very consistent for all the rows in the matrix, which justifies using just the first row of the W-matrix to determine which indicators are influential and which are not.

The influence of specific indicators as determined from changes in the Hasse Diagram was not as expected in all cases. For example, the overall most influential indicators were expected to be watershed/floodplain activities and channel alignment (Johnson, personal commun.). Watershed and floodplain activities are not included in the list of the three most influential indicators as determined from the W-matrix method. However, channel alignment is considered very influential when considering both the 13-indicator data set and the 4-category data set. Because the effects of watershed and floodplain activities can be manifested as other channel characteristics, it is possible that there are several channel indicators acting as surrogates for the watershed/floodplain activities indicator. This could be a reason for the decreased influence of the watershed/floodplain activities indicator. The five surrogate indicators are entrenchment or channel confinement, bar development, average bank slope angle, bank cutting, and mass wasting or bank failure. However, the ranking of sites based on the five surrogates as compared to the ranking based on watershed and floodplain activities is somewhat poorly correlated (0.5).

The influence as given by the W-matrix method appears to be related to the correlation between indicators. Indicators that are not highly correlated with other indicators appear to be more influential according to the W-matrix. For example, the most influential indicator, channel alignment, is not correlated with any of the other indicators (Tables 4 and 5).

The influential indicator as determined with the W-matrix is one that is important in determining the comparabilities between sites. Another method of attempting to determine the most influential indicators examines the sensitivity in the overall poset prioritization ranking of sites with each indicator removed one by one. The poset prioritization ranking with an indicator removed is compared to the poset ranking with all indicators included. The indicator whose removal produces a ranking that is the least correlated with the ranking using all indicators is considered to be the most influential. Again, channel alignment was the most influential indicator (see Table 3).

The results of an end-member elimination analysis can be used to identify the indicators that are most influential in terms of determining the end-member elimination effect. The channel alignment indicator was the indicator that was most often responsible for causing the largest change in rank range for the 13-indicator data set. Channel alignment also was the feature category that was most often responsible for causing the largest change in the rank range for the 4-category data set.

Influential indicators can be useful to field managers in several ways. The manager of a particular group of sites may find it useful to concentrate on the maintenance of the most influential indicators for those sites. For example, a bridge crossing site can have a good ranking overall but the overall ranking is being strongly influenced by channel alignment. The field manager would be alerted to closely monitor the channel alignment in this case. If the alignment were to change for the worse, the risk of the degraded stream channel causing failure of the bridge structure greatly increases. Influential indicators also can be used by field managers to determine the type of restoration or maintenance activity that is most appropriate for the sites in the worst condition. In the bridge crossing case study, if bank protection is the indicator that is responsible for end-member elimination effect (EEE), the manager knows that existing bank protection needs to be maintained or bank protection needs to be installed at that site. Preliminary knowledge of the restoration or maintenance action is beneficial for cost estimation and optimization of management resources.

7. Conclusion

Several tools were introduced that can aid a manager or engineer in stream channel restoration decision-making at bridge crossing sites. While these tools do not point to a single definitive answer for a manager, they do give more insight into where and how restoration efforts should be guided. The tools provide ways of simplification for a matrix of sites and 13 indicator scores that can provide a clearer picture for restoration decision-making.

The same methods can be applicable to management situations where similar problems need to be confronted. With limited resources, it is important for a manager to have systematic tools for gleaning essential information from large databases. While a set of numerous indicators is useful for assessing the overall condition of a site, it is often the case that a sudden change to one of those indicators could cause a catastrophic situation. Summing of indicator scores into a single value will mask this situation. Without examining the properties of partially-ordered sets such as prioritization and influential indicators, a manager may not be aware of an imminent problem.

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Table 1. Summary of stream stability assessment method (Johnson, 2005; 2006).

Indicator	Description	Feature Category
1. Watershed and Floodplain Activity	Surrounding land use; forested, grazing, urbanization, logging, etc.	Watershed or Regional
2. Flow Habit	Perennial, intermittent, ephemeral streams, flooding behavior, stream order	Watershed or Regional
3. Channel Pattern	Straight, engineered, meandering, braided	Watershed or Regional
4. Entrenchment or Channel Confinement	Connectivity of floodplain with channel, evidence of infrastructure undercutting	Watershed or Regional
5. Bed Material	Sediment size, packed or loose, fraction of sand	Local Channel
6. Bar Development	Narrow or wide, vegetated or newly deposited, grain size of deposited sediment	Local Channel
7. Obstructions	Bedrock outcrops, amour layer, LWD, grade control structures, revetment, vanes	Local Channel
8. Bank Soil Texture	Clay, silt, loam, sand; cohesive or noncohesive	Bank Stability
9. Average Bank Slope Angle	Bank slope for unconsolidated and consolidated materials	Bank Stability
10. Bank Protection	Vegetative (riparian zone width), engineered revetment	Bank Stability
11. Bank Cutting	Percentage of raw banks, undercutting	Bank Stability
12. Mass Wasting or Bank Failure	Scalloping of banks, slumping, tension cracks	Bank Stability
13. Bridge-Channel Alignment	Upstream distance to bridge from meander impact point, bridge alignment with channel flow direction	Alignment

Table 2. Summary of ranking using several methods.

Stream ID	13-Indicator Total Score	4-Category Total Score	POSET 13	POSET 4
1	15.5	11	18	12.5
2	26	20	24	16
3	27.5	31	39	33
4	7	4	17	4
5	10	14	12	17
6	41	32	28.5	34.5
7	42.5	42	40	45
14	39	34	31	39
15	49	49	49	49
16	35	28.5	19	24
17	48	44	45	43
18	38	28.5	36	27
19	40	41	42	41
20	34	33	38	32
21	29	36	35	31
22	42.5	43	46	42
23	44.5	45	43	44
24	32	25	28.5	26
25	23.5	27	20.5	28
26	12.5	8	7	1
27	30.5	35	33.5	34.5
28	25	19	32	22
29	17	12	20.5	11
30	36.5	37	33.5	39
31	8	10	14	10
32	22	22	30	19
33	27.5	24	27	25
34	33	39	44	36
35	15.5	16	10.5	15
36	46	47	47	48
37	20.5	15	13	14
38	19	30	22.5	30
39	18	13	9	12.5
40	36.5	40	37	39
41	30.5	38	25.5	37
42	4	6	6	8
43	44.5	46	41	46
44	47	48	48	47
45	23.5	17	25.5	21
48	1	2.5	3	6
49	5	7	4	7
50	11	18	10.5	18
51	20.5	23	15	23
52	2	2.5	2	5
53	6	9	5	9
54	14	26	16	29
55	9	5	8	2
56	12.5	21	22.5	20
57	3	1	1	3

Table 3. Influential indicators as determined by several methods using the 13-indicator and the 4-category data sets.

Data Set		**13-Indicator Data Set**			**4-Category Index Data Set**	
Method		**W-Matrix**	**POSET Prioritization**	**EEE**	**W-Matrix**	**EEE**
Order of Influence	**1**	Channel Alignment	Channel Alignment	Channel Alignment	Channel Alignment	Channel Alignment
	2	Bank Soil Texture	Flow Habit	Bank Soil Texture	Local Channel Characteristics	Local Channel
	3	Obstructions	Bank Protection	Bank Protection	Watershed/ Regional Characteristics	*

* Watershed/Regional Characteristics and Bank Characteristics are tied for 3rd.

Table 4. Correlation between 13 indicator scores.

Correlation Table (13 Indicator Scores)													
	Watershed and Floodplain Characteristics	Flow Habit	Channel Pattern	Entrenchment	Bed Material	Bar Development	Obstructions	Bank Soil	Bank Slope	Bank Protection	Bank Cutting	Mass Wasting	Channel Alignment
Watershed and Floodplain Characteristics	1												
Flow Habit	0.596	1											
Channel Pattern	0.533	0.641	1										
Entrenchment	0.374	0.280	0.218	1									
Bed Material	0.530	0.572	0.493	0.401	1								
Bar Development	0.474	0.286	0.341	0.554	0.589	1							
Obstructions	0.192	-0.158	0.219	0.467	0.190	0.399	1						
Bank Soil	0.473	0.551	0.598	0.204	0.551	0.165	0.174	1					
Bank Slope	0.470	0.261	0.231	0.804	0.372	0.553	0.421	0.148	1				
Bank Protection	0.426	0.378	0.374	0.570	0.363	0.429	0.245	0.234	0.702	1			
Bank Cutting	0.486	0.207	0.263	0.574	0.328	0.488	0.454	0.152	0.729	0.570	1		
Mass Wasting	0.385	0.198	0.328	0.705	0.397	0.610	0.505	0.274	0.795	0.722	0.703	1	
Channel Alignment	-0.062	-0.009	0.026	-0.035	-0.119	0.165	0.051	-0.134	0.169	0.079	0.277	0.132	1

Table 5. Correlation between 4 category indices.

	Watershed and Regional Indicators	Local Channel Indicators	Bank Stability Indicators	Channel Alignment
Watershed and Regional Indicators	1			
Local Channel Indicators	0.649	1		
Bank Stability Indicators	0.729	0.675	1	
Channel Alignment	-0.031	0.025	0.130	1

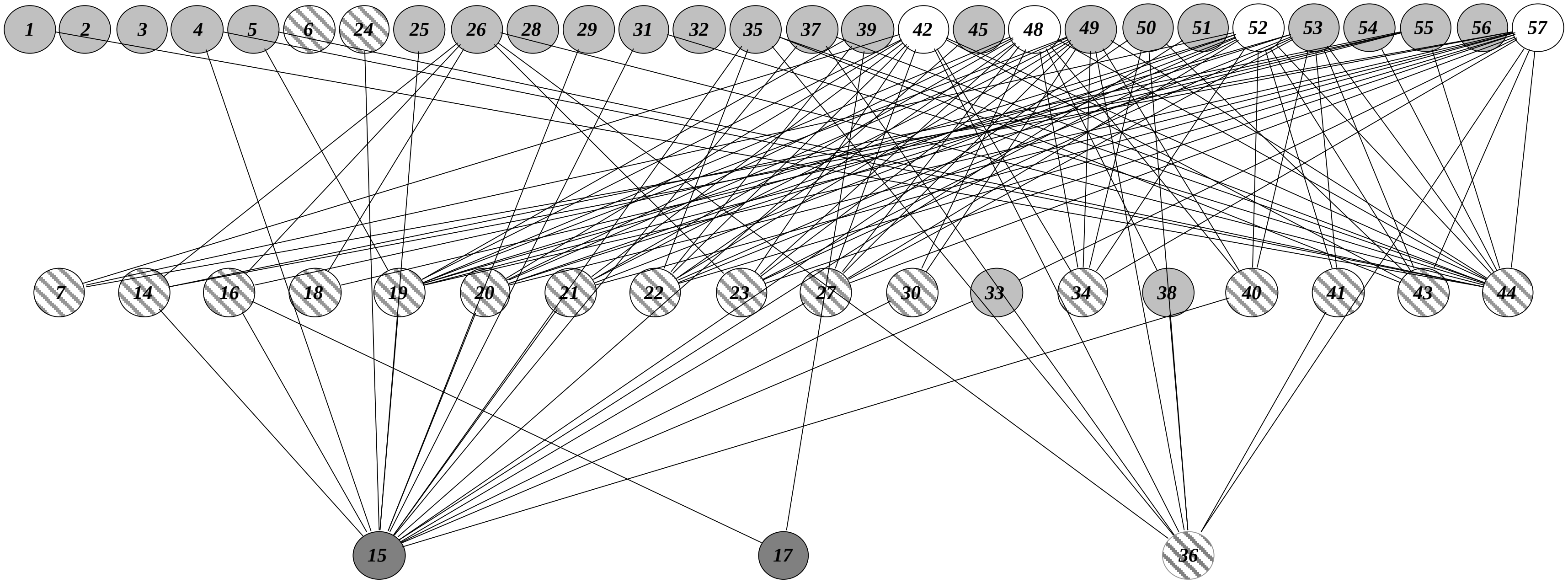

Figure 1. Hasse Diagram for 49 sites with 13 indicators. The fill patterns represent the stream condition assigned based on the total score of summing all 13 indicators. (■ – *Poor*, ▨ – *Fair*, ▒ – *Good*, □ – *Excellent*.)

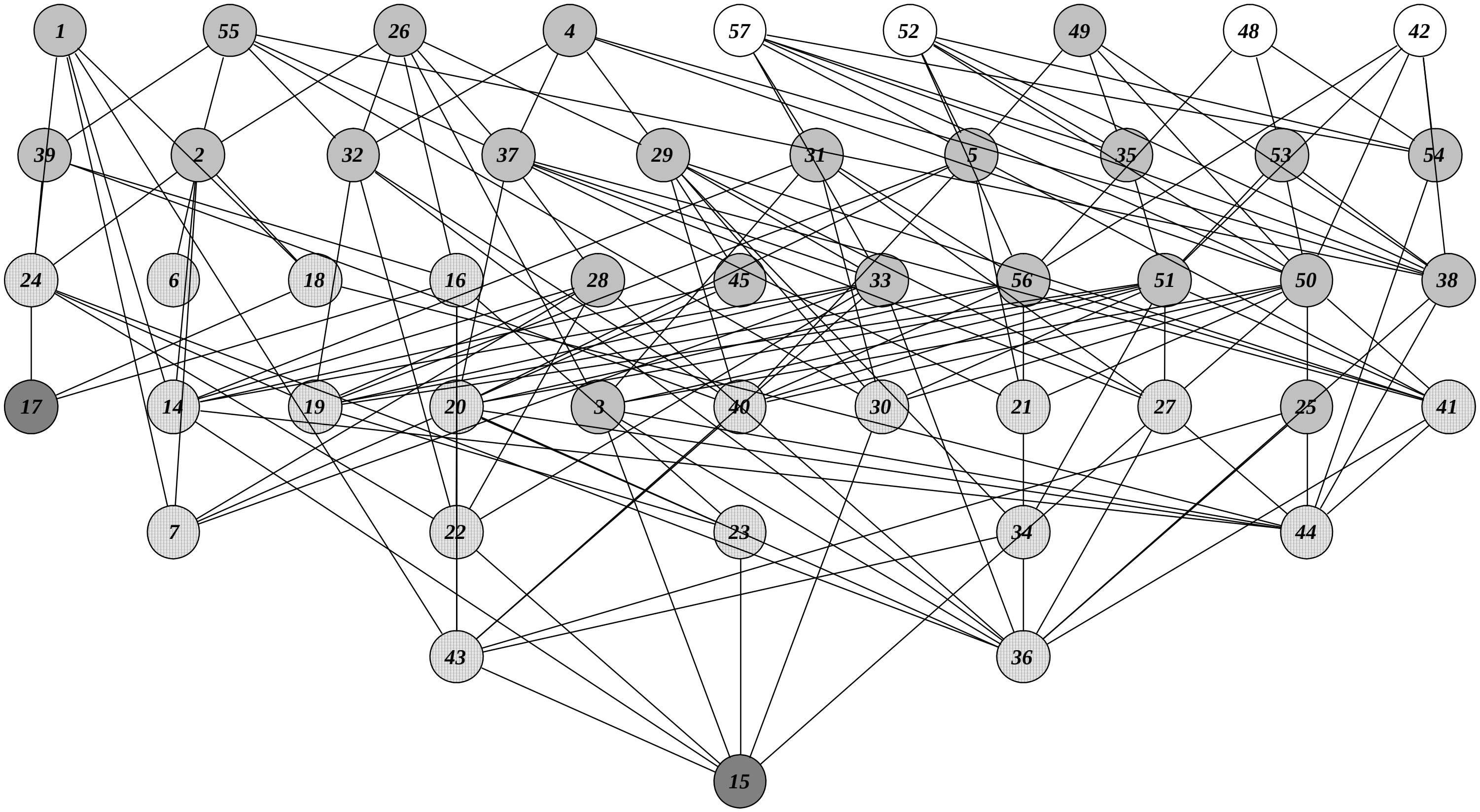

Figure 2. Hasse Diagram for 49 sites with 4 indices. The fill patterns represent the stream condition assigned to the sites based on the total score of summing all 13 indicators. (■ – *Poor*, ▦ – *Fair*, ▒ – *Good*, □ – *Excellent)*

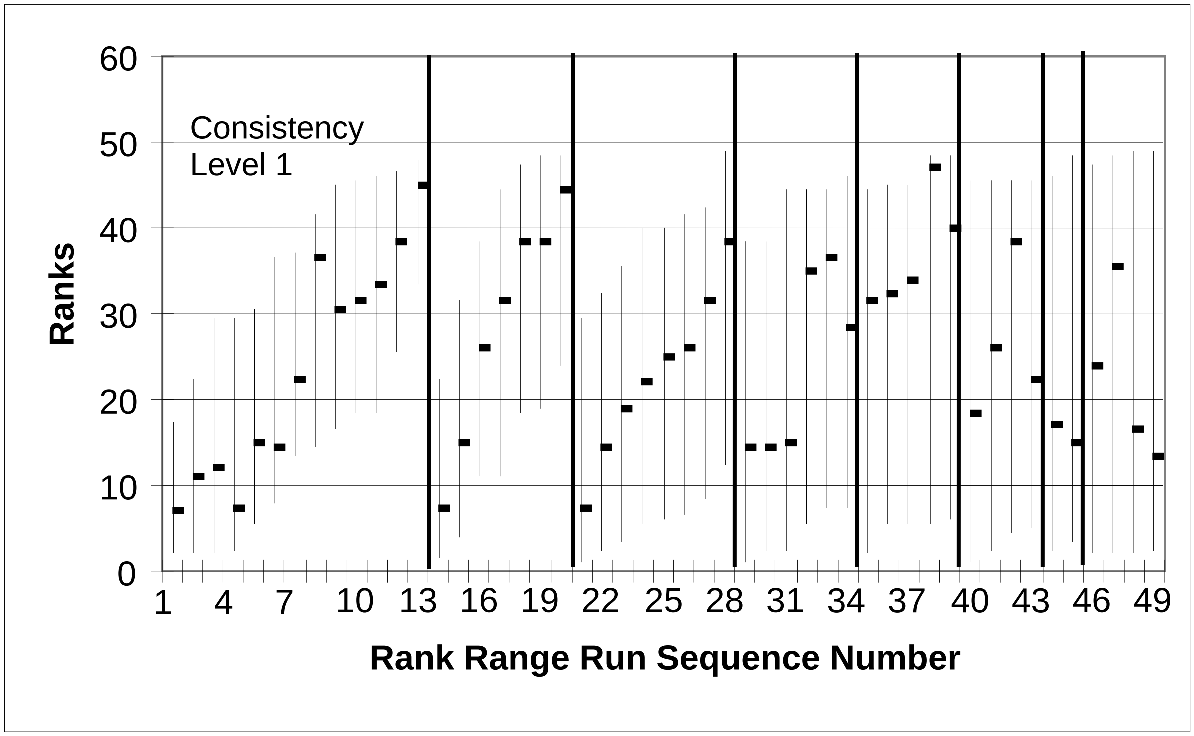

Figure 3. Rank range run sequence for the 13-indicator data set. The bottom of each vertical line represents the minimum rank and the top of the line is the maximum rank for the indicators.

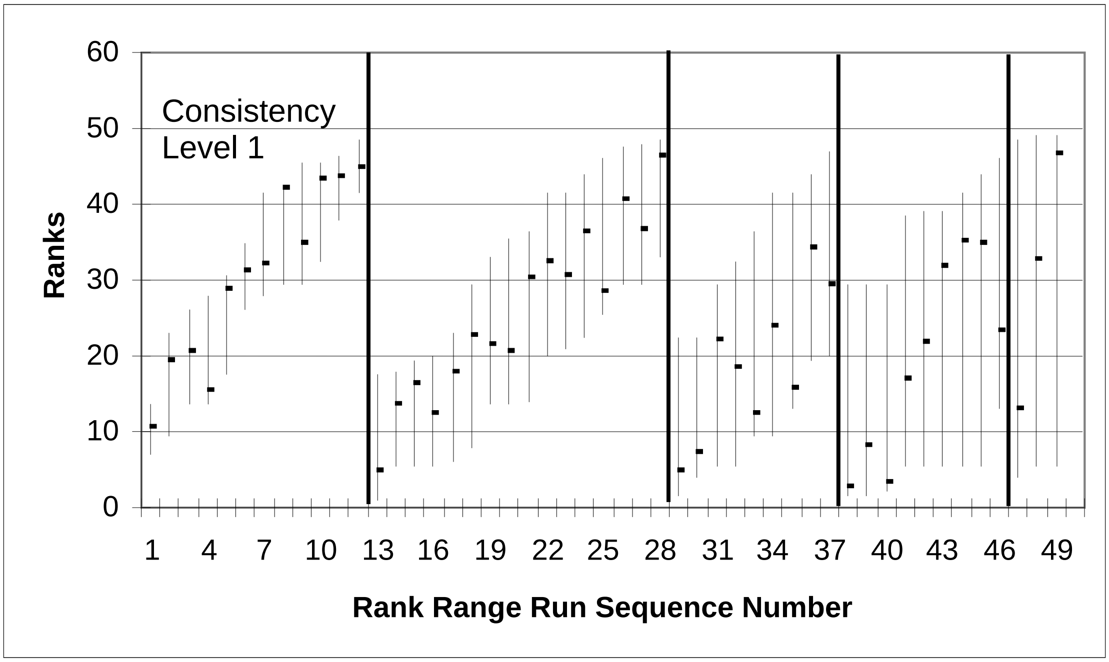

Figure 4. Rank range run sequence for the 4-category data set. The bottom of each vertical line represents the minimum rank and the top of the line is the maximum rank for the indicators.

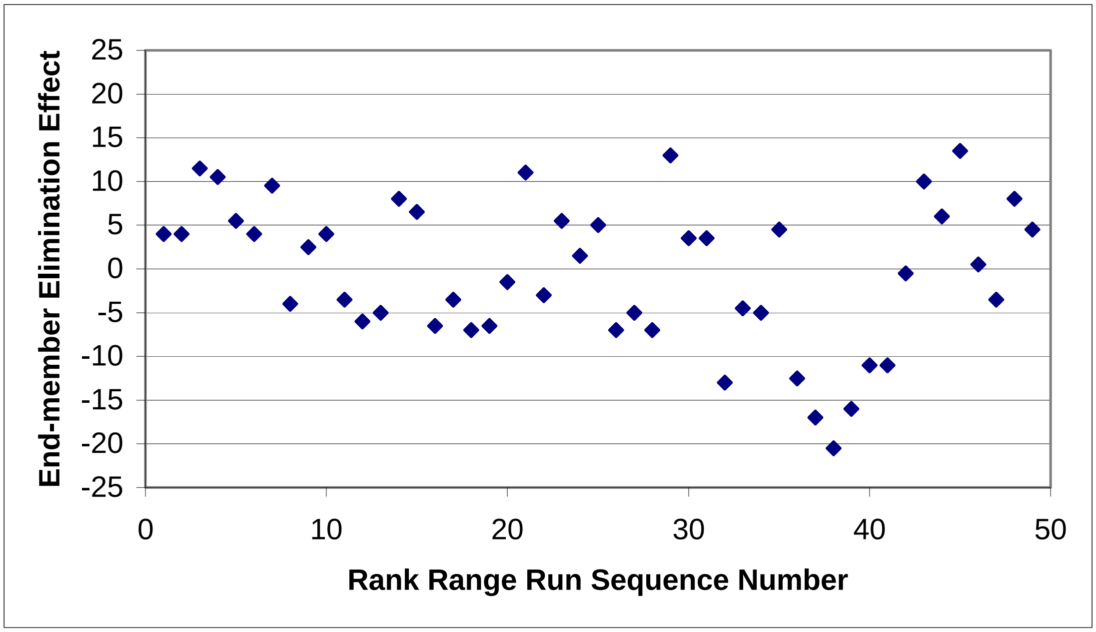

Figure 5. End-member elimination effect for the 13-indicator data set.

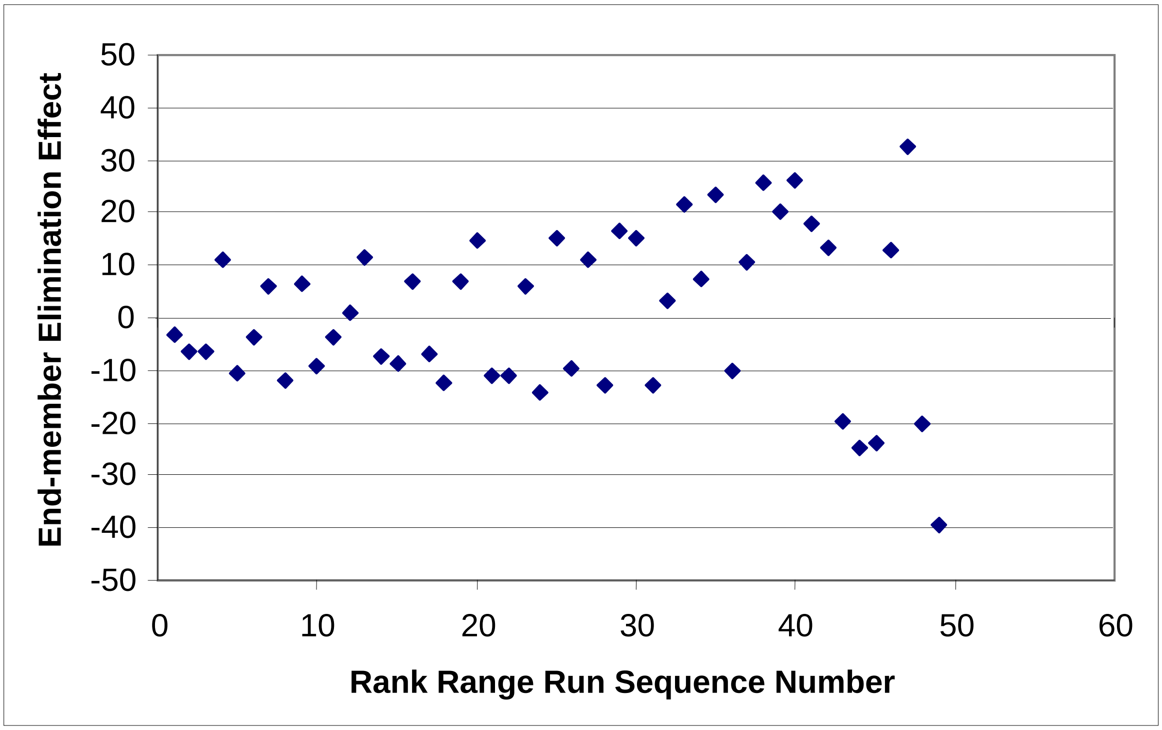

Figure 6. End-member elimination effect for the 4-category data set.

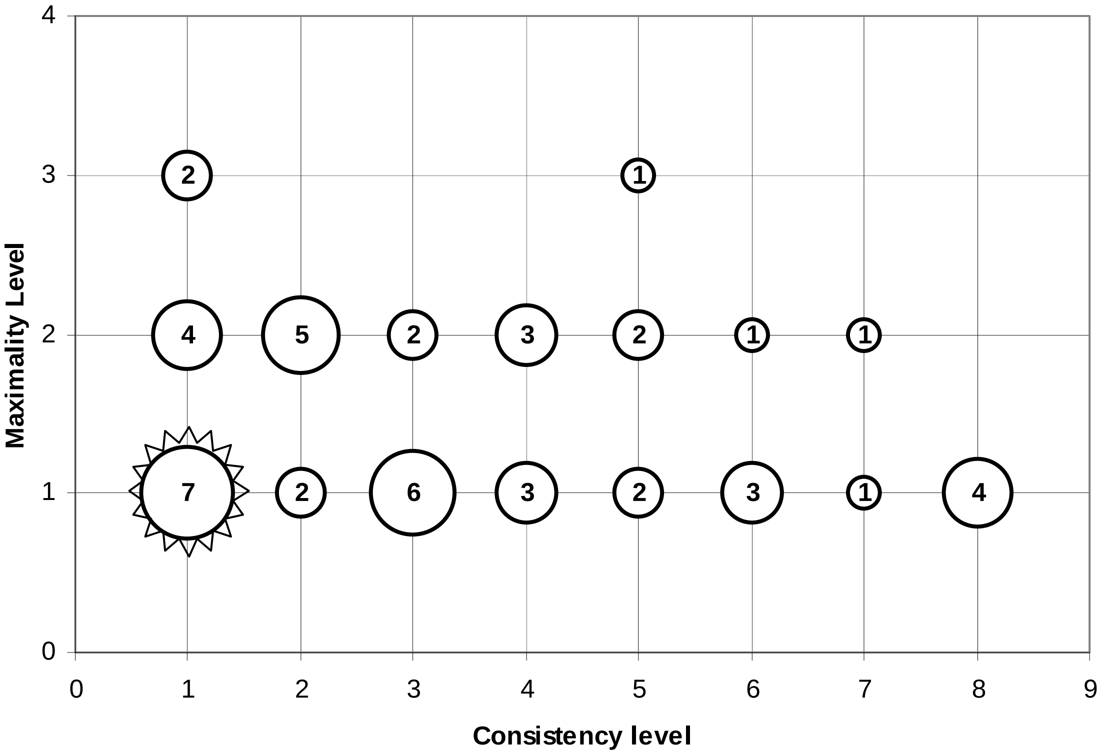

Figure 7. Sites grouped by maximality level and consistency level. The number inside the circle represents the number of sites that have that particular combination of maximality level and consistency level.

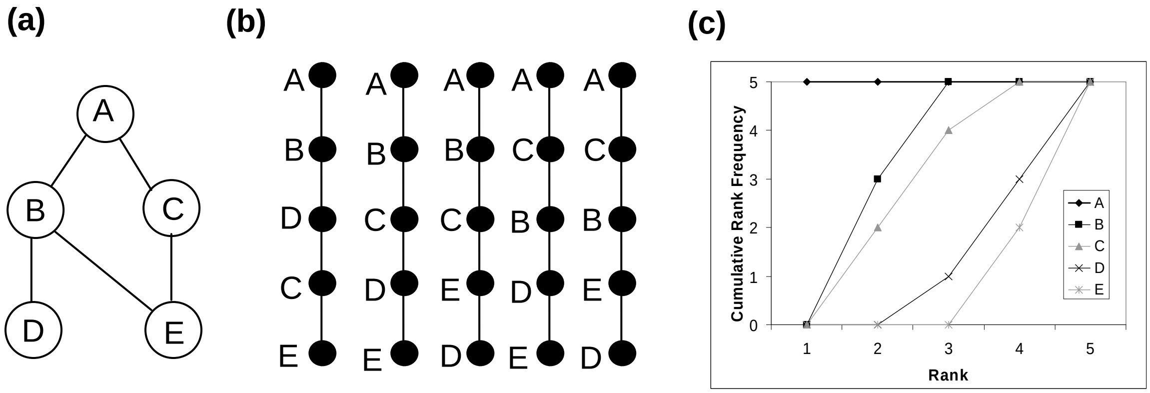

Figure 8. Poset prioritization steps. (a) Hasse diagram, (b) linear extensions, (c) cumulative rank frequency plot.

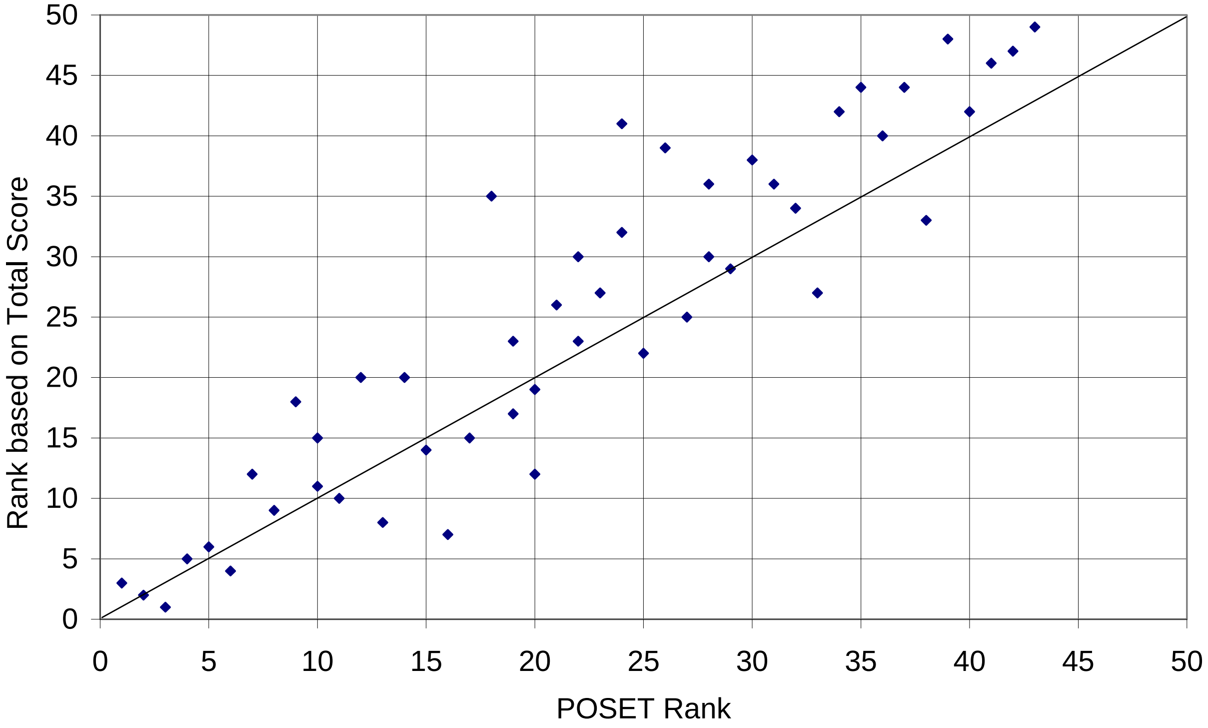

Figure 9. Comparison of the rank of a site based on total score and based on poset prioritization for the 13 indicator data set.