FUZZY DECISION ANALYSIS FOR INTEGRATED ENVIRONMENTAL VULNERABILITY ASSESSMENT OF THE MID-ATLANTIC REGION

Liem T. Tran and C. Gregory Knight

Center for Integrated Regional Assessment, The Pennsylvania State University, University Park, PA 16802.

1. INTRODUCTION

One of the most important issues of a regional ecological vulnerability assessment is integrating information from different sorts of risk to produce an index representing the overall integrity of a particular ecosystem and to prioritize a set of ecosystems in the region in terms of vulnerability risk. A good framework to carry out this task should be suitable in handling extensive and diverse information and be intelligible to the ecologist and the decision-maker. However, research on methods to integrate individual indicators of stressors and receptors into a vulnerability risk assessment is not an easy proposition due to several reasons:

- Past studies have focused mainly on the effects of single stressors on single ecological processes or receptors. As a result, our knowledge about cumulative and synergistic effects of multiple stressors on multiple receptors is relatively small.

- Calculation of risk for integrated assessment must be synthesized across all sources of stress as well as resources to reveal the overall environmental condition and quality of life (Wickham *et al.*, 1997).

- Assessment has to deal with uncertainty coming from different sources: error and/or randomness (with known or unknown probability) of measured data and model parameters, imprecision or vagueness in knowledge (*e.g.*, vague relationships between stressors and receptors), and ambiguity (*e.g.*, different meanings of risk from different disciplines).

- Assessment is a decision-making problem in the context of multiple objectives, multiple criteria, and multiple stakeholders, which introduce a great deal of complexity.

This poster reflects part of a larger study whose overarching goal is *to develop a comprehensive fuzzy decision analysis model for ecological vulnerability assessment*. The study aims to investigate the fuzzy set theory and decision analysis approaches toward ecological assessment, in general, and integrating ecological indicators, in particular; to determine where specific techniques are valid; and to examine ways to combine appropriate techniques of fuzzy set theory and decision analysis for integrating ecological indicators.

The method presented in this poster is a combination of a fuzzy ranking method and the Analytic Hierarchy Process (AHP). The method is capable of providing an integrated ecological index and ranking of ecosystems in terms of environmental conditions and cumulative impacts across a large region.

ABSTRACT

A fuzzy decision analysis method for integrating ecological indicators is developed. This is a combination of a fuzzy ranking method and the Analytic Hierarchy Process (AHP). The method is capable of providing an integrated ecological index ranking ecosystems in terms of environmental conditions and suggesting cumulative impacts across a large region. Using data on land-cover, population, roads, streams, air pollution, and topography of the Mid-Atlantic region, we are able to point out areas which are in relatively poor condition and/or vulnerable to future deterioration. Some spatial patterns can be revealed from results of this work. For example, watersheds located near urban centers (e.g., Philadelphia, Washington D.C.) have relative high impact index scores. A buffer zone between areas of good and bad conditions is not seen very clearly, suggesting that any future environmental policy applied to the region should be developed in a very careful manner to avoid further environmental degradation. The method offers an easy and comprehensive way to combine the strengths of fuzzy set theory and the AHP for ecological assessment. Furthermore, the suggested method can serve as a building block for the evaluation of environmental policies.

Keyword: *vulnerability assessment, fuzzy decision analysis, ecological indicators.*

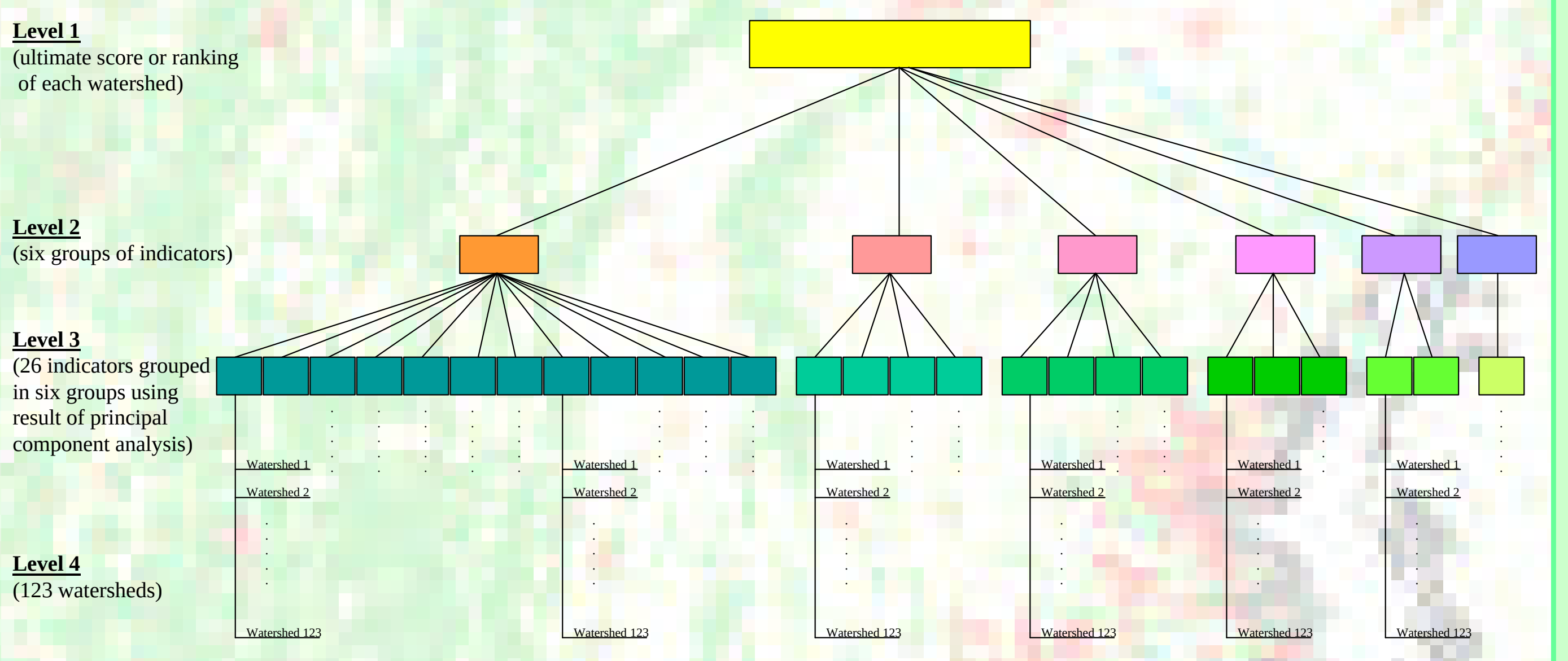

Figure 2. The four-level hierarchy used in the fuzzy decision analysis model for integrated environmental vulnerability assessment of the mid-Atlantic region

2. MATERIALS & METHODS

2.1. Data

- Landscape units: 123 watersheds in Mid-Atlantic region, using the USGS map of 8-digit hydrologic accounting units, are used in the analysis (Fig. 1).

- Data: 26 out of 33 landscape indicators provided in the Landscape Atlas of the Mid-Atlantic region (EPA, 1997) are used in the analysis. They include UINDEX, STRD, STNO3L, STPL, PSOIL, FOR %, FORFRAG, INT7, INT65, INT600, INTALL, FORDIF, POPDENS, EDGE7, EDGE65, EDGE600, RIPFOR, RIPCROP, CROPSL, AGSL, NO3DEP, SO4DEP, OZAVG, POPCHG, RDDENS, DAMS.

2.2. Methods

a. Fuzzy Ranking Methods in the Context of Ecological Indicators and Reference Points

- Fuzzy set is a suitable and powerful means to represent simultaneously the ecological indicators' values (*e.g.*, mean, median, mode) and their variation or uncertainty (e.g., standard deviation, minimum, maximum).

- Once fuzzy number are used to represent the ecological indicators, fuzzy ranking is used to reveal the distance from a ecological entity to a reference point, or the relative ranking of different ecosystems with respect to a particular indicator.

- Tran and Duckstein (in review) recently suggested a fuzzy ranking method based on a new fuzzy distance measure that overcomes several problems inherent to existing fuzzy ranking methods and is suitable in representing ecological indicators.

b. The Analytic Hierarchy Process (AHP)

- AHP (Saaty, 1980), which is a concordance analysis, is considered the most widely used MCDM method. One of the reasons for AHP's popularity is that it derives (presents) preference information from (to) the decision-makers in a manner that they find easy to understand.

- AHP is a systematic procedure to construct and represent the elements of a problem in a hierarchy format. The basic rationale of AHP is organized by the breaking down the problem into smaller constituent parts at different levels. Decision-makers are guided through a series of pairwise comparison judgments to reveal the relative impact, or priority of the elements (*e.g.*, criteria, alternatives) in the hierarchy. These judgments in turn are transformed to ratio-scale numbers representing relative weights of the elements at a certain level of the hierarchy, as well as globally.

- The hierarchy in AHP is often constructed from the top (goals from the management standpoint, *e.g.*, environmentally-sound development), through intermediate levels (criteria on which subsequent levels depend, *e.g.*, physical, chemical, biological, and socioeconomic criteria) to the lowest level (usually a set of alternatives, possible actions). AHP allows the combination of group judgments by taking the geometric mean of single judgments.

c. The Fuzzy Decision Analysis Method

The idea of the method presented in this poster is to compare the values of the ecological indicators with some reference points, such as the ideal and undesirable ecological states (condition) via the use of an appropriate fuzzy ranking method. Next with AHP, a relative ranking of different ecological entities will be derived, helping the identification and prioritization of the most vulnerable ecosystems. This combination of fuzzy ranking and AHP will make the process much simpler in calculation (less pairwise comparison than the original AHP) and easier to understand in concept (e.g., the concepts of ideal/undesirable references are familiar to ecologists and decision-makers). Step-by-step procedure is as follows:

- Multivariate analysis: using principal component analysis (varimax rotation with Kaiser normalization) to group the indicators into six subgroups (group 1: UINDEX, STRD, STNO3L, STPL, PSOIL, FOR %, FORFRAG, INT7, INT65, INT600, INTALL, FORDIF; group 2: POPDENS, EDGE7, EDGE65, EDGE600; group 3: RIPFOR, RIPCROP, CROPSL, AGSL; group 4: NO3DEP, SO4DEP, OZAVG; group 5: POPCHG, RDDENS; and group 6: DAMS).

- AHP: constructing a four-level hierarchy (Fig. 2). The lowest level (the fourth level) is for 123 watersheds. The next level (the third level) contains six groups of indicators associated with six principal components. The second level is for cumulative scores of six groups of indicators. The highest level is for the ultimate score of each watershed.

- Weights assigned for six groups at the second level are based on the % of variance explained by each principal component.

- Weights at level three (within each subgroup) are equally assigned.

- Normalize the indicators' values to have them all on the same scale 0-1.

- Reference points: using the minimum (0) and maximum (1) values of each indicator as reference points.

- Fuzzy ranking: applying the Tran and Duckstein's fuzzy distance to measure the distance with respect to a particular indicator from a watershed to the reference points. These distance values are used as the watersheds' scores for different indicators used at the lowest level of the hierarchy.

- Scores at the third level are computed by using two different methods: the L_1 norm (full compensation) and L_2 (sum of squared scores).

- Scores at the second level are weighted sum of scores at the third level (equal weights in this analysis).

- Scores at the highest level are weighted sum of scores at the second level.

3. RESULTS & DISCUSSION

3.1 Results

- The ultimate scores for 123 watersheds and their rankings, derived from two different methods (so-called AHP-L_1 and AHP-L_2), are provided in Table 1. Using their rankings, watersheds are grouped into seven groups ranked from 1 (good condition) to 7 (bad condition) (Figs. 4 and 5). From those information we are able to tell which watershed as a whole is in good or bad condition and which are in need of the most protection.

- Results of the AHP- L_1 are very similar to those from the cluster analysis in the Landscape Atlas of the Mid-Atlantic region (Fig. 3). Note that the AHP- L_1 uses more variables and reveals more specific details than the cluster analysis (e.g., contribution of different indicators to the ultimate score of a watershed).

- Results from AHP-L_1 and AHP-L_2 are different, of course, but not contradictory each other, as a result of more weight being put for indicators closer to reference points in AHP-L_2 than in AHP-L_1. From the decision-making viewpoint, the AHP-L_2 is more conservative (low scores in a few of indicators will make the watershed be ranked low).

- Some spatial patterns can be revealed from results of this work. For example, watersheds located near urban centers (e.g., Philadelphia, Washington D.C.) have relative high impact index scores. A buffer zone between areas of good and bad conditions is not seen very clearly, suggesting that any future environmental policy applied to the region should be developed in a very careful manner to avoid further environmental degradation.

3.2. Discussion

- Fuzzy set with appropriate fuzzy distance measure and fuzzy ranking method provide a powerful and suitable way to represent ecological indicators. This feature is not only important for the integration of ecological indicators but also crucial for environmental-policy evaluation in later phases.

- The use of multivariate statistical analysis in clustering the indicators in the AHP's hierarchy allows the model to deal with codependence among the indicators efficiently.

- The AHP provides a productive framework in dealing with complexity (by means of a structured hierarchy) and in moving from ecological assessment to environmental-policy evaluation.

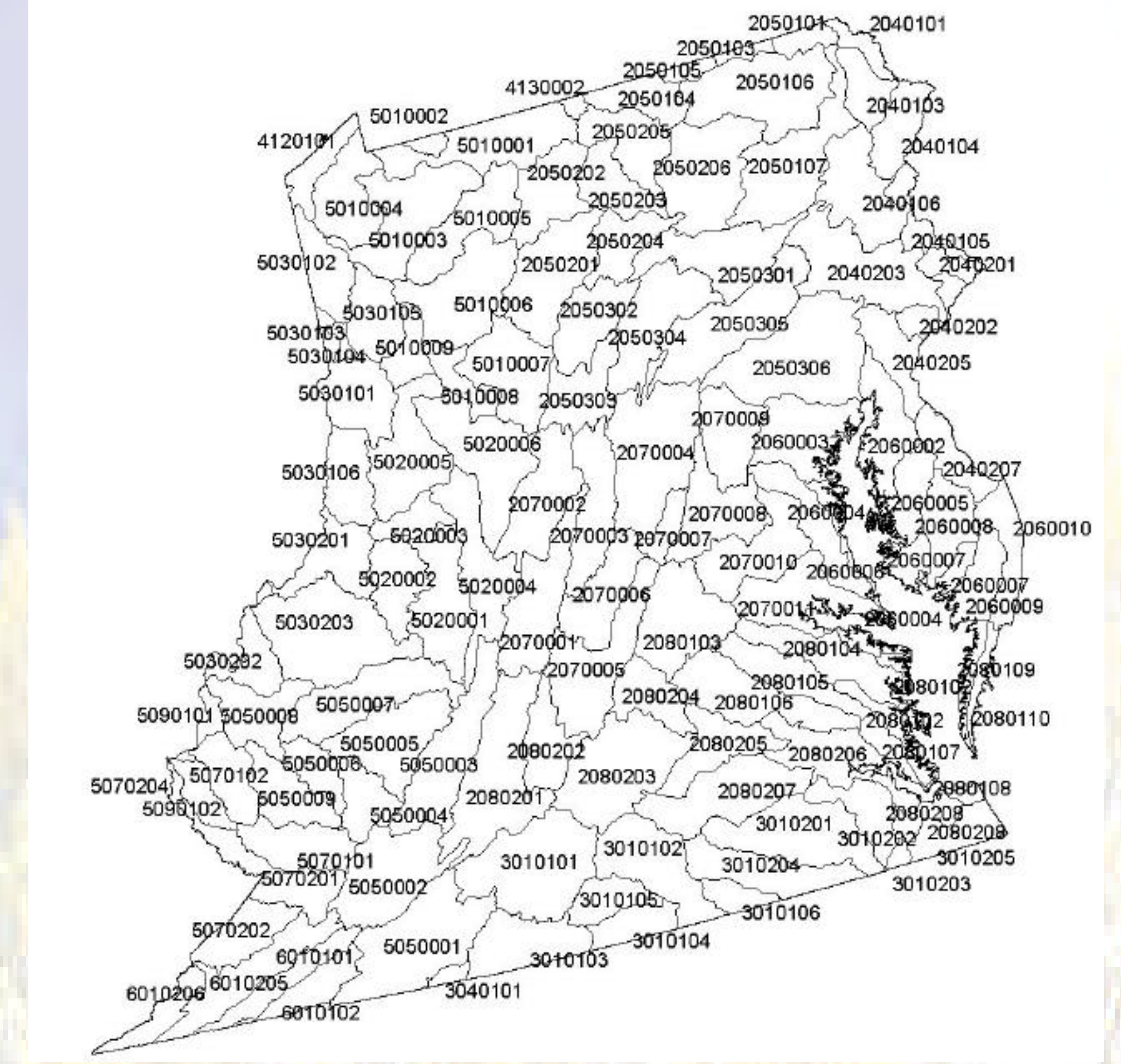

Figure 1. Watershed boundaries within the mid-Atlantic region. The numbers are USGS hydrologic unit codes (HUCs). See Table 1 for watershed names. Source: USGS, Hydrological Unit Code Boundaries (HUC250), 1:250,000 scale.

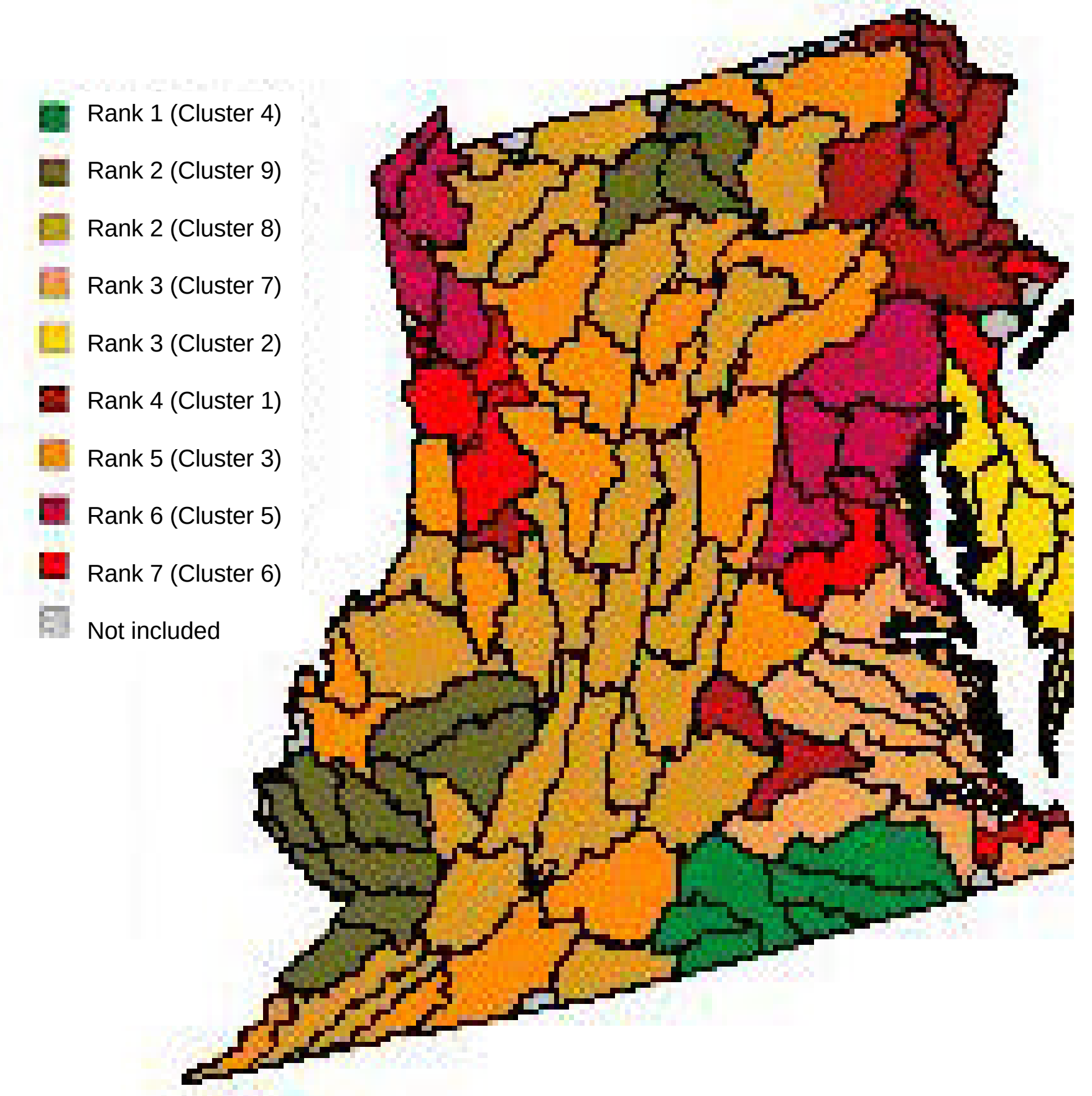

Figure 3. Results of the cluster analysis based on indicator values. Source: EPA, An Ecological Assessment of the United States Mid-Atlantic Region, A Landscape Atlas.

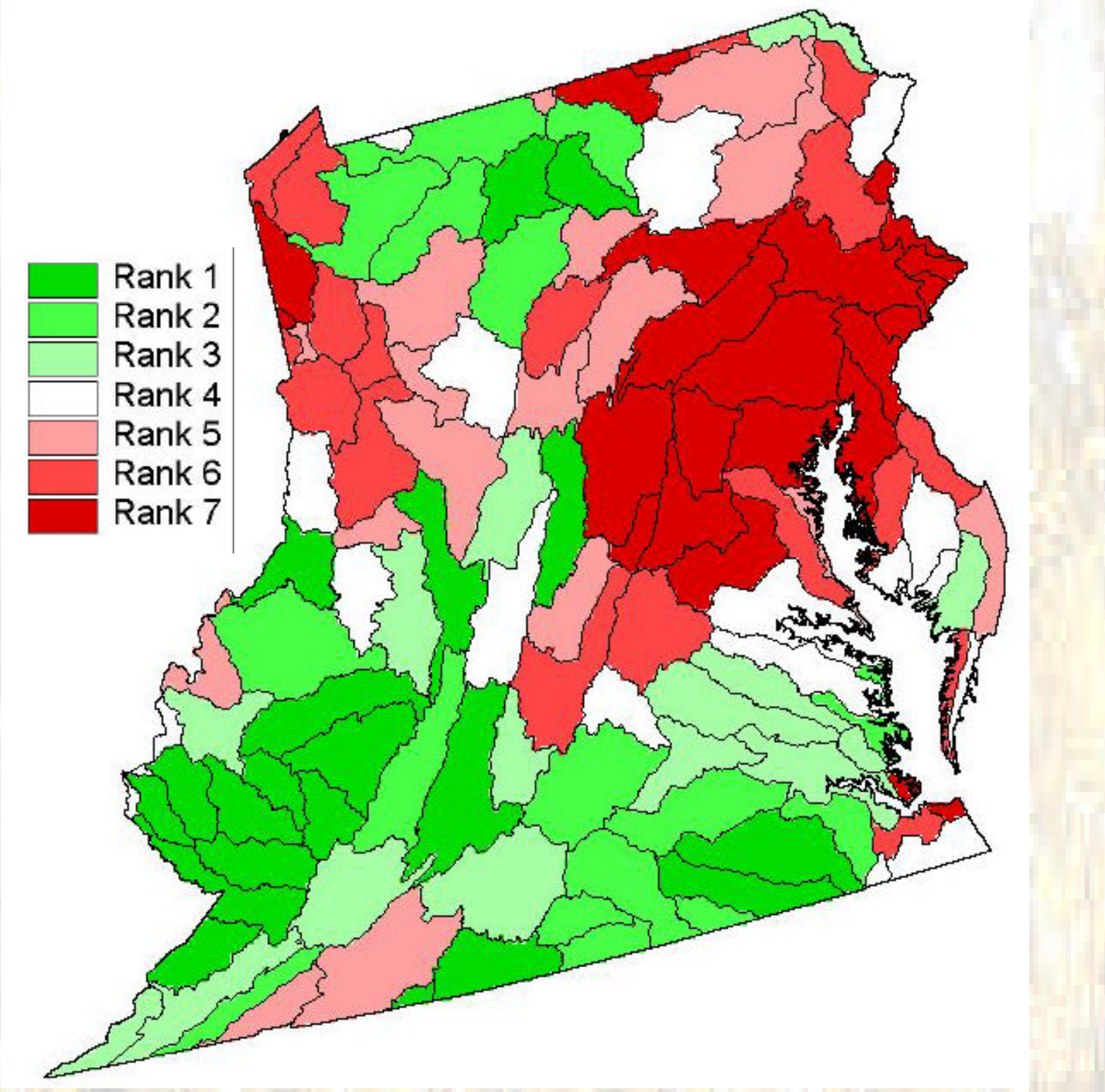

Figure 4. Results of the AHP-L1 model. Using their rankings shown in Table 1, watersheds are grouped into seven groups ranked from 1 (good condition) to 7 (bad condition).

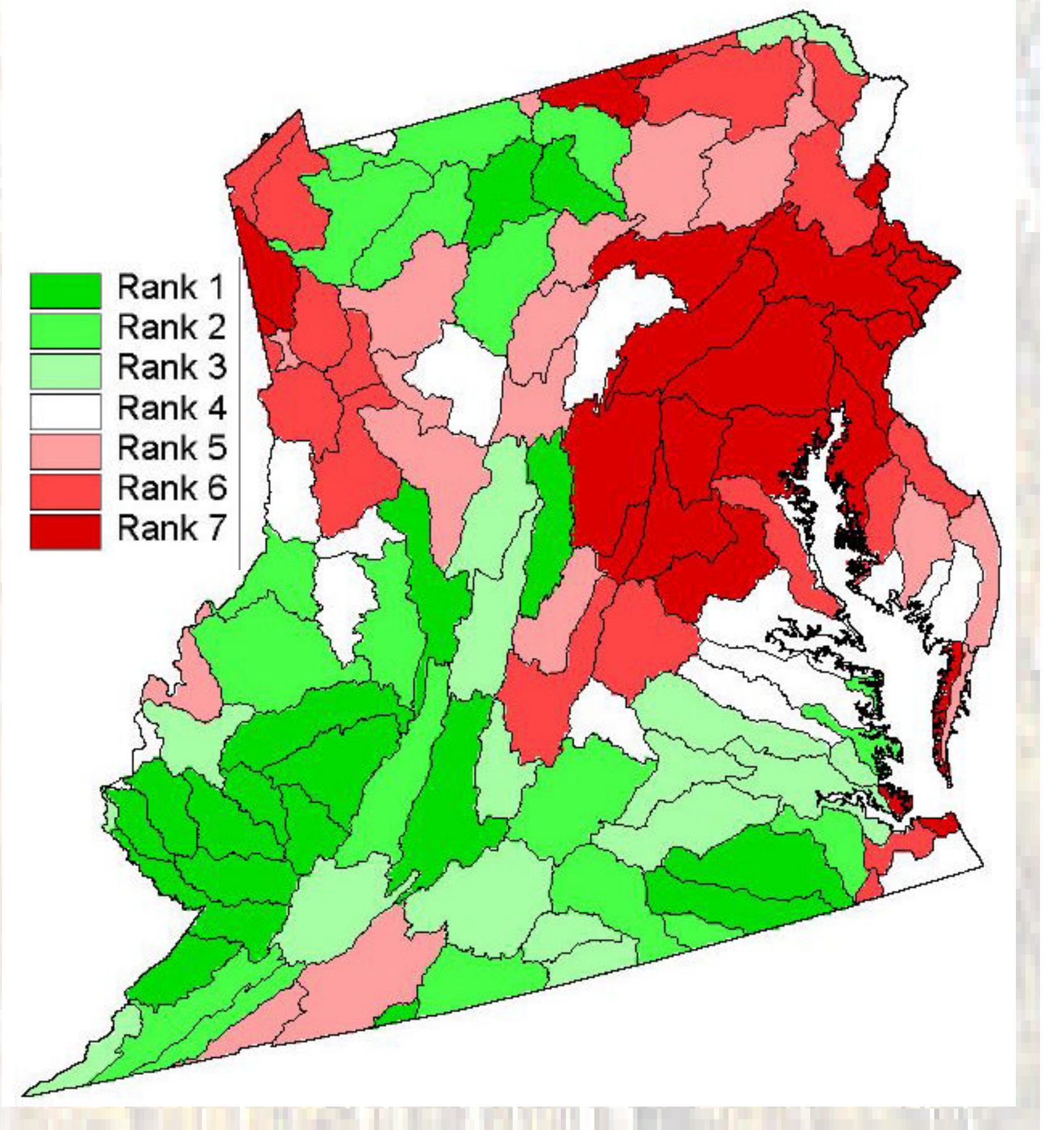

Figure 5. Results of the AHP-L2 model. Using their rankings shown in Tabl 1, watersheds are grouped into seven groups ranked from 1 (good condition) 7 (bad condition)..

Table 1. Results of the AHP-L1 and AHP-L1 models: relative cumulative impact score and rankings of 123 watershed in the mid-Atlantic region.

HUC	Watershed names	Relative scores		Ranking	
		AHP - L1	AHP - L2	AHP - L1	AHP - L2
2040101	Upper Delaware	0.266	0.247	39	42
2040103	Lackawaxen	0.469	0.451	89	88
2040104	Middle Delaware-Mongaup-Brodhead	0.395	0.349	63	60
2040105	Middle Delaware-Musconetcong	0.695	0.649	114	112
2040106	Lehigh	0.517	0.468	99	95
2040201	Crosswicks-Neshaminy	0.881	0.845	120	120
2040202	Lower Delaware	1.000	1.000	123	123
2040203	Schuylkill	0.829	0.780	119	119
2040205	Brandywine-Christina	0.718	0.680	116	115
2040207	Broadkill-Smyrna	0.492	0.485	96	96
2050101	Upper Susquehanna	0.292	0.286	49	52
2050103	Owego-Wappasening	0.469	0.461	88	92
2050104	Tioga	0.599	0.584	107	107
2050105	Chemung	0.699	0.693	115	116
2050106	Upper Susquehanna-Tunkhannock	0.463	0.456	86	90
2050107	Upper Susquehanna-Lackawanna	0.433	0.418	79	81
2050201	Upper West Branch Susquehanna	0.223	0.200	30	28
2050202	Sinnemahoning	0.088	0.056	7	8
2050203	Middle West Branch Susquehanna	0.123	0.093	11	10
2050204	Bald Eagle	0.432	0.404	78	78
2050205	Pine	0.205	0.178	21	25
2050206	Lower West Branch Susquehanna	0.404	0.389	66	70
2050301	Lower Susquehanna-Penns	0.567	0.550	104	104
2050302	Upper Juniata	0.478	0.439	92	85
2050303	Raystown	0.448	0.402	84	75
2050304	Lower Juniata	0.416	0.384	76	68
2050305	Lower Susquehanna-Swatara	0.671	0.649	113	113
2050306	Lower Susquehanna	0.968	0.943	122	122
2060002	Upper Chesapeake Bay	0.592	0.581	106	106
2060003	Gunpowder-Patapsco	0.816	0.775	118	118
2060004	Severn	0.410	0.370	70	64
2060005	Choptank	0.509	0.530	97	102
2060006	Patuxent	0.558	0.518	102	100
2060007	Blackwater-Wicomico	0.309	0.288	55	53
2060008	Nanticoke	0.408	0.409	69	79
2060009	Pocomoke	0.294	0.289	50	54
2060010	Chincoteague	0.435	0.426	81	82
2070001	South Branch Potomac	0.329	0.285	57	51
2070002	North Branch Potomac	0.278	0.231	45	36
2070003	Cacapon-Town	0.188	0.147	18	18
2070004	Conococheague-Opequon	0.636	0.602	111	109
2070005	South Fork Shenandoah	0.515	0.495	98	97
2070006	North Fork Shenandoah	0.415	0.402	75	74
2070007	Shenandoah	0.621	0.618	108	110
2070008	Middle Potomac-Catoctin	0.750	0.720	117	117
2070009	Monocacy	0.959	0.939	121	121
2070010	Middle Potomac-Anacostia-Occoquan	0.627	0.591	110	108
2070011	Lower Potomac	0.314	0.293	56	55
2080102	Great Wicomico-Piankatank	0.218	0.210	28	33
2080103	Rapidan-Upper Rappahannock	0.489	0.515	95	99
2080104	Lower Rappahannock	0.357	0.361	58	63
2080105	Mattaponi	0.297	0.311	51	57
2080106	Pamunkey	0.270	0.269	41	46
2080107	York	0.299	0.280	52	50
2080108	Lynnhaven-Poquoson	0.646	0.646	112	111
2080109	Western Lower Delmarva	0.562	0.559	103	105
2080110	Eastern Lower Delmarva	0.408	0.398	68	71
2080201	Upper James	0.168	0.134	17	16
2080202	Maury	0.292	0.258	48	43
2080203	Middle James-Buffalo	0.224	0.205	31	31
2080204	Rivanna	0.365	0.357	61	61
2080205	Middle James-Willis	0.287	0.272	47	47
2080206	Lower James	0.267	0.241	40	40
2080207	Appomattox	0.240	0.232	34	37
2080208	Hampton Roads	0.549	0.524	101	101
3010101	Upper Roanoke	0.276	0.269	43	45
3010102	Middle Roanoke	0.206	0.203	22	29
3010103	Upper Dan	0.159	0.157	15	19
3010104	Lower Dan	0.235	0.242	33	41
3010105	Banister	0.248	0.267	36	44
3010106	Roanoke Rapids	0.208	0.197	24	27
3010201	Nottoway	0.136	0.112	13	13
3010202	Blackwater	0.209	0.192	25	26
3010203	Chowan	0.405	0.458	67	91
3010204	Meherrin	0.148	0.127	14	14
3010205	Albemarle	0.309	0.301	54	56
3040101	Upper Yadkin	0.081	0.094	5	11
4120101	Chautauqua-Conneaut	0.474	0.444	91	86
4130002	Upper Genesee	0.410	0.403	71	77
5010001	Upper Allegheny	0.218	0.177	29	23
5010002	Conewango	0.371	0.361	62	62
5010003	Middle Allegheny-Tionesta	0.206	0.165	23	21
5010004	French	0.480	0.455	93	89
5010005	Clarion	0.210	0.178	27	24
5010006	Middle Allegheny-Redbank	0.411	0.400	73	73
5010007	Conemaugh	0.357	0.335	59	58
5010008	Kiskiminetas	0.456	0.429	85	83
5010009	Lower Allegheny	0.473	0.464	90	93
5020001	Tygart Valley	0.252	0.203	38	30
5020002	West Fork	0.401	0.380	65	67
5020003	Upper Monongahela	0.413	0.377	74	66
5020004	Cheat	0.189	0.144	19	17
5020005	Lower Monongahela	0.526	0.496	100	98
5020006	Youghiogheny	0.436	0.399	83	72
5030101	Upper Ohio	0.468	0.449	87	87
5030102	Shenango	0.571	0.550	105	103
5030103	Mahoning	0.623	0.666	109	114
5030104	Beaver	0.433	0.413	80	80
5030105	Connoquenessing	0.485	0.468	94	94
5030106	Upper Ohio-Wheeling	0.360	0.342	60	59
5030201	Little Muskingum-Middle Island	0.189	0.161	20	20
5030202	Upper Ohio-Shade	0.420	0.388	77	69
5030203	Little Kanawha	0.209	0.171	26	22
5050001	Upper New	0.410	0.402	72	76
5050002	Middle New	0.278	0.273	44	49
5050003	Greenbrier	0.240	0.206	35	32
5050004	Lower New	0.132	0.107	12	12
5050005	Gauley	0.096	0.045	10	6
5050006	Upper Kanawha	0.086	0.053	6	7
5050007	Elk	0.093	0.042	8	5
5050008	Lower Kanawha	0.287	0.241	46	39
5050009	Coal	0.036	0.000	4	1
5070101	Upper Guyandotte	0.020	0.014	2	3
5070102	Lower Guyandotte	0.166	0.133	16	15
5070201	Tug	0.021	0.019	3	4
5070202	Upper Levisa	0.000	0.002	1	2
5070204	Big Sandy	0.305	0.273	53	48
5090101	Raccoon-Symmes	0.400	0.372	64	65
5090102	Twelvepole	0.095	0.062	9	9
6010101	North Fork Holston	0.233	0.218	32	34
6010102	South Fork Holston	0.436	0.439	82	84
6010205	Upper Clinch	0.251	0.225	37	35
6010206	Powell	0.272	0.233	42	38

4. CONCLUSIONS

In terms of scientific contribution, the developed method offers a creative and comprehensive way to combine fuzzy set theory and decision analysis techniques for ecological assessment. In tangible terms, a fuzzy decision analysis model for integrating ecological indicators will be developed. This model can serve as the building block for the evaluation of environmental policies. Given the strong focus of the EPA's Regional Vulnerability Assessment program on an approach to comprehensive regional-scale relative risk assessment, it is expected that this model will be useful to EPA and a wide array of environmental scientists and decision-makers.

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