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Multi-criteria evaluation of wastewater treatment technologies in constructed wetlands

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Abstract: Segmenting constructed wetland for natural wastewater treatment can be considered as multi-criteria decision-making problem because there are conflicts between criteria while assessing alternative orderings of treatment technologies among segments. Criteria such as: size of wetland area, possible economic effects, technical effectiveness, hydraulic conductivity of soil, and plant coverage and growing conditions, are by nature qualitative, quantitative and 'grey'. Alternatives' performance across criteria is difficult to measure because of incommensurate units and inter-dependence between criteria. In this paper the results obtained with different decision-making tools are presented for the problem of selecting best ordering of treatment technologies in wetland segmentation. Methods used are: analytic hierarchy process (AHP), simple additive weighting (SAW), simple product weighting (SPW), technique for order preference by similarity to ideal solution (TOPSIS) and compromise programming (CP). Horizontal flows, vertical flows and shallow gravel ditches are evaluated across criteria in different orderings considering differences in effects that their ordering produce during purification of incoming wastewaters. A decision-making problem is hierarchically structured and the AHP-based pair wise comparisons are used to derive the weights of criteria and local weights of orderings regarding each criterion. With the decision matrix created in this way, the weighting and distance methods are used along with the AHP to declare the best ordering of technologies by segments. The results obtained for a typical wetland in Serbia are presented to illustrate an approach and the results of sensitivity analysis are discussed, indicating advantages and possible drawbacks of combining or parallel using the results from more multi-criteria methods.

Key words: Wetland segmentation, wastewater treatment technologies, AHP, TOPSIS, CP

1. INTRODUCTION

Real life problems in water resources management are commonly observed in atmosphere of abundance of impacts and multiplicity of choices. Making decisions is a complex procedure, especially in cases when multiple contrasted or extremely conflict criteria must be used to evaluate different alternative solutions to the problem in hand. As a process, decision making requires deep understanding of the problem and assumes competency and responsibility of human(s) for the final decision and its consequences in either individual or group context. To validate possible solutions and choose an optimal one (in multi-criteria sense) means that the decision maker's preferences about alternatives will be elicited in some way, e.g. by direct rating or face-to-face comparison of alternatives versus each criterion, preceded by the same procedure applied to criteria versus the goal.

Eliciting decision maker's preferences can be achieved in different ways. In most cases, it depends on the selected multi-criteria decision-making (MCDM) methodology. There is a plenty of approaches, methodologies and tools that can support the whole process, within both individual and group decision-making frameworks in water management. In all cases, a key issue is: (a) how to provide consistent procedure in deriving solution; (b) why to use specific scientifically proven decision-making model to attain and that outcomes (consequences of decision made) will be monitored and additionally evaluated with assumed criticism. trustful decisions; and (c) to be aware that audit trial will eventually follow.

Based on earlier research and published papers (e.g., Suvocarev and Srdjevic, 2007; Srdjevic et al., 2008, 2013), in this paper we describe how various multi-criteria decision-making methods are used to select best segmentation of one constructed wetland in Serbia. Created decision-making framework included selection of methodology for decision-making, enabling judgment process in which five experts from academia, engineering and management evaluated six alternative segmentations against six selected criteria. In Chapter 2 methodological approach is briefly described. Chapter 3 contains the main results and discussion, and Chapter 4 concludes the paper.

2. METHODOLOGICAL APPROACH

2.1 Decision-making problems and multi-criteria solving methods

In certain phase of the decision-making process the decision matrix is commonly created. For instance, for given set of n alternatives ($A_1, A_2, ..., A_n$), and set of m criteria ($C_1, C_2, ..., C_m$), this matrix is of dimension nxm with rows corresponding to alternatives and columns to criteria, Eq. (1). Entries of the matrix (r_{ij}) represent scores (ratings) of alternatives with respect to criteria. Values $(w_1,w_2,...,w_m)$ written above the matrix are the importance weights of criteria defined by the decision maker (DM), or derived in another way; they usually (but not necessarily) sum up to 1.

$$R = \begin{array}{c c} & \begin{array}{ccccc} (w_1 & w_2 & . & . & w_m) \\ C_1 & C_2 & . & . & C_m \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ . \\ . \\ A_n \end{array} & \begin{bmatrix} r_{11} & r_{12} & . & . & r_{1m} \\ r_{21} & r_{22} & . & . & r_{2m} \\ . & & & & . \\ . & & & & . \\ r_{n1} & r_{n2} & . & . & r_{nm} \end{bmatrix} \end{array} \tag{1}$$

Decision problems can be divided into the two categories: selection and allocation. The first one is characterised by preferential ordering of alternatives, e.g. ranking of candidate development plans for given catchment or selecting the best supplier of irrigation equipment. Allocation of resources on the other hand means that exact values are needed to determine how certain commodity or any measurable resource can be divided. For instance, allocation problem is how to divide available agricultural land for application of different cropping schemes, or how to allocate reservoir storage to water uses such as flood protection, urban supply, irrigation, hydroelectric power generation, navigation, fishing and other outdoor activities. The solution of the problem that belongs to the selection category is of ordinal type, which means that ordering of alternatives commonly does not provide any additional information to the user, e.g. how big is the difference between any two ranked alternatives. If allocation problem is solved, the output information is the set of weights of alternatives (usually normalized to sum to 1). This is cardinal information which implies ordinal information after alternatives are ranked in ascending or descending order.

Different multi-criteria decision methods (MCDM) do not yield the same best outcome (see, for instance, Tavana and Hatami-Marbini, 2011). Majority of well-established MCDM methods generates ordinal information, i.e. ranking of alternatives. Only few known methods produce cardinal information (weights) of alternatives. In our research we used five MCDM methods: analytic hierarchy process (AHP), simple additive weighting (SAW), simple product weighting (SPW), TOPSIS and compromise programming (CP); only the first one computes weights and remaining four produce ranks.

The first method, the AHP, served as a base in this research. The method relies on structured decision problem represented by the hierarchy with goal on the top, criteria at level bellow and alternatives at the third, bottom, level. The roadmap of the method consists of three main steps. Decision maker firstly performs pair wise comparisons of criteria versus goal, and then alternatives versus criteria by using certain ratio scale (e.g. Saaty, 1980; Ma et al., 1999). A set of comparison matrices is the result of this step. The method then applies selected mathematical procedure (matrix calculus or optimization) and prioritize decision elements and compute local weights of criteria vs. goal, and alternatives vs. criteria. The final step is the synthesis of local weights and obtaining the global weights of alternatives with respect to the goal. In turn, AHP 'controls' consistency of the decision maker while making pair wise comparisons and indicates if there are violations in preferential judgements and computed local and final weights.

The next two methods SAW and SPW are simple and they are based on additive and geometrical aggregation of alternatives' ratings with respect to criteria, assuming that normalization or scalarization of the decision problem is performed to make data consistent. Although the methods are simple and intuitively correct, they are nevertheless good decision making methods, in that their results are usually very close to more sophisticated methods. To apply these two methods, weights of criteria must be known.

The methods TOPSIS and CP belong to a class of similarity-to-ideal-solution methods. For their application, it is required that decision matrix with alternatives ratings exist and that weights of criteria are known. Both methods are well described in pertinent literature (e.g., Hwang and Yoon, 1981; Zeleny, 1982).

2.2 Methodology

The solving methodology is organized in four steps:

2.2.1 Step #1: Problem formulation and its hierarchy

The overall goal is set as to identify the best option for constructed wetland segmentation assuming that the constructed wetland will have three segments, and that the internal ordering of the possible three wastewater natural treatment technologies will anticipate preferences from a group of decision makers coming from academia, engineering and water management.

By reaching full consensus, five decision makers (DMs) specified six evaluation criteria and six technologically justified options for wetland segmentation. They created hierarchy with three levels in top down direction goal-criteria-alternatives. DMs also decided to work in a best will to reach agreement in each judgment they will make while performing AHP pair wise comparisons. For comparisons of decision elements, it was decided to use well known 9-point rating scale presented in Table 1.

Table 1. Saaty's scale for pair wise comparisons in AHP

Judgment term	Numeric value of judgment*
Absolute preference (element *i* over element *j*)	9
Very strong preference (*i* over *j*)	7
Strong preference (*i* over *j*)	5
Weak preference (*i* over *j*)	3
Indifference of *i* and *j*	1
Weak preference (*j* over *i*)	1/3
Strong preference (*j* over *i*)	1/5
Very strong preference (*j* over *i*)	1/7
Absolute preference (*j* over *i*)	1/9

* *Intermediate numerical values are used in both scales to model hesitations between two adjacent judgments*

The decision elements are contained in the set of six criteria and the set of six alternatives. In the decision-making process five experts took place.

Criteria set (6). AREA – size of wetland area needed; (2) COST – cost of constructing the wetland; (3) EFFECT – effectiveness of the wetland segmentation alternative; (4) COND – hydraulic conductivity of soil; (5) COVER – planned/available plant coverage; and (6) LOAD –

amount of collected water in the future. Criterions are given in Fig. 1 as second level of the hierarchy and they were mutually compared in pairs versus stated goal.

Alternatives (6). Alternatives are defined based on the idea that both horizontal and vertical water flows should be present for a better purifying effect, especially in the secondary segment where the main purification process takes place. To achieve better purification, solutions that combine vertical flows and flows in shallow gravel ditches are also considered as alternatives. Alternative abbreviations in the bottom level of the hierarchy shown in Fig. 1 are given according to the combination of segmentation flows. For example, H-T-V means that the primary purification is within a segment with horizontal groundwater flow (H), the secondary is within a segment with shallow gravel ditches (T), and the tertiary occurs in the final segment where vertical water flow (V) is dominant.

Decision Makers (5). The group of five decision makers (DMs) participated in assessing mutual importance of criteria against goal, and then alternatives against each criterion. DMs are all with specific experience gained during planning and implementation of several constructed wetlands in Serbia, mainly for purification of wastewaters in small rural municipalities in the Vojvodina Province. Three DMs came from academia, one is experienced professional and one is a consultant.

2.2.2 Step #2: Judgment elicitation (pair wise comparisons)

Based on pair wise comparisons of decision elements in pairs with respect to adjacent elements in upper hierarchical level, a set of 7 matrices is created for further computation within the AHP methodology, Table 2. Note that all judgments are elicited in a consensus manner differently from several other cases presented in earlier papers (e.g., Suvocarev and Srdjevic, 2007).

2.2.3 Step #3: Prioritization by eigenvector method

Local weights of criteria and alternatives are obtained after prioritization process took place. The eigenvector method proposed in (Saaty, 1980) is used to compute all local vectors containing weights of decision element.

2.2.4 Step #4: Application of other multi-criteria methods to check the AHP results

The AHP prioritization in the previous step enabled creation of standard decision matrix for direct use of another four multi-criteria methods: SAW, SPW, TOPSI and CP. Differently from AHP, these methods use decision matrix given by Eq.1 with known weights of criteria. The AHP prioritization at the top two levels (goal-criteria) produces these weights, while prioritizations at the second and third level (criteria-alternatives) produce local weights of alternatives for each criterion which can be understood as ratings of alternatives for criteria (Cf. Eq.1).

3. RESULTS AND DISCUSSION

Recall that the hierarchy of the decision making came out from a real-life application of AHP in supporting the segmentation of a specific wetland for water purification under the sanitation plan developed for a small rural area in the Vojvodina Province of Serbia (Srdjevic et al., 2008). Results presented hereafter are obtained by the original software DECIDE, developed by the authors.

Based on results of prioritization performed with the eigenvector method (applied on matrices in Table 2), the criteria weights and local weights of alternatives with respect to criteria are summarized in Table 3.

Table 2. Pairwise comparisons of crteria and alternatives

	AREA	COST	EFFECT	COND	COVER	LOAD
AREA	1	2	1/5	2	2	1/5
COST		1	1/7	1/2	1/4	1/5
EFFECT			1	5	7	2
COND				1	1/2	1/2
COVER					1	1/2
LOAD						1

AREA

	A_1	A_2	A_3	A_4	A_5	A_6
A_1	1	2	1/3	1/4	5	3
A_2		1	1/2	1/4	3	4
A_3			1	1/4	7	5
A4				1	8	9
A_5					1	1/3
A_6						1

COST

	A_1	A_2	A_3	A_4	A_5	A_6
A_1	1	3	1/5	1/7	7	2
A_2		1	1/5	1/6	4	1/2
A_3			1	1/3	8	7
A_4				1	9	8
A_5					1	1/5
A_6						1

EFFECT

	A_1	A_2	A_3	A_4	A_5	A_6
A_1	1	1/2	3	5	1/7	1/2
A_2		1	5	6	1/3	2
A_3			1	2	1/8	1/4
A_4				1	1/9	1/5
A_5					1	6
A_6						1

COND

	A_1	A_2	A_3	A_4	A_5	A_6
A_1	1	1/4	1/3	1/2	3	3
A_2		1	6	1/3	3	5
A_3			1	1/3	4	2
A_4				1	7	5
A_5					1	2
A_6						1

COVER

	A_1	A_2	A_3	A_4	A_5	A_6
A_1	1	3	1/2	1/3	1)2	1/3
A_2		1	1/5	!/2	1/2	1/5
A_3			1	3	2	1/2
A_4				1	1	3
A_5					1	2
A_6						1

LOAD

	A_1	A_2	A_3	A_4	A_5	A_6
A_1	1	1/2	3	2	2	3
A_2		1	5	1	3	5
A_3			1	1/5	1	3
A_4				1	7	5
A_5					1	4
A_6						1

Table 3. Weights of criteria and local weights of alternatives versus criteria

		AREA	COST	EFFECT	COND	COVER	LOAD
		0.105	0.042	0.439	0.073	0.101	0.241
		CR_{CRIT}=0.066					
A_1	H-T-V	0.130	0.103	0.097	0.103	0.088	0.224
A_2	H-T-T	0.107	0.053	0.193	0.299	0.054	0.285
A_3	H-V-V	0.219	0.284	0.043	0.135	0.262	0.073
A_4	H-V-H	0.465	0.471	0.030	0.364	0.213	0.287
A_5	T-T-T	0.031	0.023	0.505	0.054	0.177	0.089
A_6	V-T-V	0.048	0.067	0.132	0.045	0.206	0.042
*CR_{ALTER}		*0.062*	*0.095*	*0.043*	*0.128*	*0.144*	*0.088*

** CR values represent inconsistency of decision makers.*
Suggested tolerant values are 0.100

Structure of Table 3 completely corresponds to the decision matrix represented by Eq. 1. Local weights of alternatives in columns under criteria are local weights of alternatives derived by AHP from comparison matrices in Table 2.

Note that consistency coefficients (CRs) computed in AHP for the group of decision makers was acceptable in 5 of 7 cases (comparison matrices in Table 2). What is especially important, criteria weights are derived in very consistent way (CR is equal to 0.066, well below tolerant value 0.100). Consistency of decision making at upmost level of the hierarchy is essential because derived weights of criteria drive the rest of AHP synthesis.

Referring to CR values in Table 3, one may see that in two cases (for criteria COND and

COVER), consistency values CR are slightly higher (0.128 and 0.144, respectively). This may be considered as acceptable as well because it simply may happen. Finally, the overall consistency of a hierarchy reached the value HCR = 0.070 which is very good.

The global weights and ranking of alternative segmentations of constructed wetland presented in Table 4 show that the best segmentation is to use shallow gravel ditches in all three segments (T-T-T). The second-best solution(H-V-H) is to use horizontal groundwater flow in border segments and vertical water flow in medium in in-between segment. The third top ranked solution is (H-T-T), that is horizontal groundwater flow in the first segment, and shallow gravel ditches in the remaining two, etc.

Table 4. Final AHP weights and ranking of alternatives

Alternative	A1	A2	A3	A4	A5	A6
Order of segments	H-T-V	H-T-T	H-V-V	H-V-H	T-T-T	V-T-V
Weight	0.131	0.194	0.108	0.199	0.269	0.100
Rank	(4)	(3)	(5)	(2)	(1)	(6)

The decision matrix represented by Table 2 is directly used to prioritize alternatives by methods SAW, SPW, TOPSIS and CP (p=2). The rankings are presented in Table 5, and Borda Count method from Social Choice Theory is applied to identify best alternative across all methods. Obviously, the best option is segmentation T-T-T (A5). This alternative significantly outperforms the others. The second-best option is segmentation H-T-T (A2), and the third-best is H-T-V (A1).

Table 5. Ranking of alternatives derived by different MCDM methods

Methods / Alternatives	A1	A2	A3	A4	A5	A6
AHP	4	3	5	2	1	6
SAW	3	2	4	5	1	6
SPW	3	2	6	4	1	5
TOPSIS	3	2	4	5	1	6
CP	3	2	6	4	1	5
Sum of ranks (Borda Count)	16	11	25	20	5	28
Final ranking	**(3)**	**(2)**	**(5)**	**(4)**	**(1)**	**(6)**

Note that the second-best alternative H-V-H (A4) identified by the AHP is ranked at the forth place if other MCDM are used for cross-checking the results of AHP. This once more suggests that different MCDM methods may produce different final results and that analyst should be aware of the importance which method to use, or how to combine the results from different methods even if the judgment process in the group is performed in unique way.

4. CONCLUSIONS

Constructed wetlands are sometimes useful to locate near small cities or villages to enable natural wastewater treatment, once solid wastes are removed and just waste water is transferred from urbanized area into the wetland area. Segmenting the wetland usually means that three to four consecutive fields are constructed with different purification technologies applied. The purpose of wetland will be fulfilled if its segments will efficiently purify waste water, i.e. preserve that water discharged from the field into recipient (usually canal or river) is of acceptable quality.

During the planning phase, i.e. before construction takes place, segmenting the wetland field and application of available technologies in segments, more options of combining technologies in segments should be assessed and select the one which best satisfies standards related to water quality, but also assure that most of objectives are satisfied. To enable this, segmenting wetland is good to treat as the multi-criteria decision-making problem because there are conflicts between criteria while assessing alternative orderings of treatment technologies among segments.

In several installations of constructed wetlands in Serbia experts, project engineers and managers concluded that for any particular wetland there could be many contrasted and/or conflicted criteria to be respected in order to achieve community or management goals related to handling of urban wastewaters. This paper presents results of one completed application of multi-criteria decision making methodology to evaluate 6 possible segmentations of three commonly used natural purification technologies. For three segments and six criteria, five decision-makers participated in evaluating six alternative combinations of technologies. They used well known analytic hierarchy method (AHP) as a decision-making tool and in completely consensual manner prioritized alternative segmentations. In addition, four other multi-criteria methods are used to assess the results of AHP, i.e. the weighting methods SAW and SPW, and distance methods TOPSIS and CP. All methods identified the same segmentation as the best option for constructing the wetland in hand. It was also concluded that at lower ranking positions the ordering of alternatives may differ from method to method and that analysts must be aware how to combine methods or share their results. The results obtained for typical wetland in Serbia indicate that aside of advantages of different methods, there are possible drawbacks of their combining or parallel using their results, especially in cases if analysis should continue by using several top ranked alternatives. Major drawback in combining multi-criteria methods can be reordering of alternatives and selection of the wrong one. This can happen in reality if methodological approach is not carefully selected and sensitivity analyses are not undertaken.

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