

Full Integration of the multiple criteria decision making method KEMIRA-sort into a Geographical Information System for spatial management

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Abstract. Geographic Information Systems (GIS) are tools dedicated to the processing and representation of spatial data and are therefore very useful, among others, for land use management. However, they are limited when it comes to taking into account and aggregating heterogeneous and conflicting information. Multiple criteria decision making (MCDM) methods are able to take into account the heterogeneous and conflicting nature of the data to facilitate their aggregation and to make them useful for decision making. In order to enhance the capacity of GIS for resource management in a given region, we propose a methodology for the full integration of the MCDM method KEMIRA Sort into an open source GIS and to show its effectiveness by applying it for the management of degraded landscapes (soil and vegetation) of a region in Burkina Faso.

Keywords: GIS, MCDM, KEMIRA-sort, Python, QGIS.

1 Introduction

In this paper, we are interested in the problem of the management of territorial resources (*e.g.* soil, water, vegetation) or territorial propagation of a phenomena (*e.g.* a disease). To tackle these problems the literature proposes methodologies combining Geographic Information System (GIS) and/or Multiple Criteria Decision Making (MCDM) methods [1, 2, 3]. In these works from the literature, limitations of both GIS tools and MCDM methods are highlighted. Among the limitations common to the application of GIS-CDMA models to real life cases, we can mention the large number of parameters to be considered due to the use of the MCDM method, but also the difficulty to avoid the compensation between heterogeneous criteria¹.

Considering the aspect of reducing the number of parameters to be considered in the use of a CDMA method, and in relation to the problem of multiple criteria choicing[4] in the field of

¹Two criteria are said to be heterogeneous if a weak performance of an alternative on one of the criteria cannot be compensated by a strong performance of that alternative on the other criterion

human resources management, a new method called KEmeny Median Indicator Ranks Accordance (KEMIRA) has been proposed in[5]. This KEMIRA method also allows to respect the heterogeneous character of the criteria. Recently an extension of the KEMIRA method for multiple criteria sorting problems[4], called KEMIRA-sort, has been proposed in[6]. The present paper aims at proposing a model for the full integration of this KEMIRA-sort method in the open source GIS QGIS in order to address the above mentioned limitations relative to the conjoint use of GIS and MCDM methods.

The rest of the drafting plan for the article is as follows. Section 2 briefly presents the mathematical formulation of the KEMIRA-sort method while in the third section we briefly presents the GIS. Section 4 deals with the integration process and the implementation of KEMIRA-sort method into the GIS. Section 5 is dedicated to the application of the proposed GIS-MCDM model to a case study. Finally, we conclude by providing some perspectives for future research.

2 Mathematical formulation of KEMIRA-sort model

In this section we present briefly the mathematical formulation of the MCDM methode KEMIRA-Sort. For more detail about KEMIRA-Sort we refer the reader to [6, 7] on which is based this section2. We assume that the set of alternative is $X = \{x^1, x^2, \dots, x^P\}$. For $k \in \{1, \dots, P\}$, alternative x^k is a real-valued vector of dimension Q . Each component of this vector represents the performance of alternative x^k on a specific criterion. The Q criteria are partitioned into S groups indexed by $\{1, \dots, S\}$ and the elements of each group are indexed in turn by $\{1, \dots, n_i\}$ where n_i is the size of group i . We have of course $\sum_{i=1}^S n_i = Q$ because the S groups form a partition of the Q criteria. Each criterion is thus indexed by a pair of natural numbers (i, j) , the first one for the group, and the second one for the criterion within the group. The performance of alternative x^k on criterion (i, j) is thus denoted by $X_{i,j}^k$. To each criterion (i, j) , we associate a weight $w_{i,j}$.

Our objective is to compute the weight $w_{i,j}$ of each criterion (i, j) and to assign each alternative x^j to one of the M predefined ordered categories $C_1 \prec C_2 \prec \dots \prec C_M$, C_1 being the worst category and C_M the best by formulating and solving an optimization problem.

2.1 Criteria priority and increasing functions

we assume that the Decision Maker (DM) is able to provide a ranking of criteria in each group. Therefore, without loss of generality, we suppose that in each group the criteria are ranked in the decreasing order so that the relations (1) and the corresponding restrictions on the criteria weights (2) hold:

$$\begin{aligned}
 (1, 1) \succcurlyeq (1, 2) \succcurlyeq \dots \succcurlyeq (1, n_1), \\
 (2, 1) \succcurlyeq (2, 2) \succcurlyeq \dots \succcurlyeq (2, n_2), \\
 \vdots \\
 (S, 1) \succcurlyeq (S, 2) \succcurlyeq \dots \succcurlyeq (S, n_S);
 \end{aligned} \tag{1}$$

$$\begin{aligned}
w_{1,1} &\geq w_{1,2} \geq \dots \geq w_{1,n_1}, \\
w_{2,1} &\geq w_{2,2} \geq \dots \geq w_{2,n_2}, \\
&\vdots \\
w_{S,1} &\geq w_{S,2} \geq \dots \geq w_{S,n_S}.
\end{aligned} \tag{2}$$

So, having the performance $X_{i,j}^k$, $k \in \{1, 2, \dots, P\}$, $i \in \{1, 2, \dots, S\}$, $j \in \{1, 2, \dots, n_i\}$, of alternatives w.r.t. the Q criteria, we normalize them and obtain the relation (3):

$$x_{i,j}^k = \frac{X_{i,j}^k - \min_i X_{i,j}^k}{\max_i X_{i,j}^k - \min_i X_{i,j}^k}. \tag{3}$$

In each group we assume that the weights are normalized and we verify

$$\sum_{j=1}^{n_i} w_{i,j} = 1, \quad \forall i \in \{1, 2, \dots, S\}. \tag{4}$$

We also assume that all criteria are to be maximized; the bigger values of variables $x_{i,j}^k$ represent better satisfaction w.r.t. the considered criterion. Then, for an alternative x^k and for each group i , we compute the weighted average of the performance, denoted by W_i :

$$W_i(x^k) = \sum_{j=1}^{n_i} w_{i,j} \times x_{i,j}^k, \tag{5}$$

where weights ($w_{i,j}$) satisfy requirements (2) and (4).

2.2 Process of assignment to categories

For each increasing function W_i we introduce $M - 1$ thresholds

$$0 < \alpha_i^1 < \alpha_i^2 \dots < \alpha_i^{M-1} < 1, \tag{6}$$

since we have M predefined ordered categories $C_1 \prec C_2 \prec \dots \prec C_M$. Thus, for an alternative x^k , the assignment process is stated as follows :

$$\begin{aligned}
\text{Step1 :} & \quad \text{if } \exists i \in \{1, 2, \dots, S\}, W_i(x^k) \leq \alpha_i^1 \text{ then } x^k \in C_1. \\
\text{Step2 :} & \quad \text{if } \exists i \in \{1, 2, \dots, S\}, W_i(x^k) \leq \alpha_i^2 \text{ and not}(x^k \in C_1) \\
& \quad \text{then } x^k \in C_2. \\
\text{Step3 :} & \quad \text{if } \exists i \in \{1, 2, \dots, S\}, W_i(x^k) \leq \alpha_i^3 \text{ and not}(x^k \in C_1) \\
& \quad \text{and not}(x^k \in C_2) \text{ then } x^k \in C_3. \\
& \quad \vdots \\
\text{StepM :} & \quad \text{if } x^k \text{ does not satisfy Step1 to StepM-1, then } x^k \in C_M.
\end{aligned} \tag{7}$$

The idea behind the assignment rule (7) is to limit the compensation between poor performance on a given group of criteria and good performance on the other groups of criteria due to the different

nature of the criteria groups. For this reason, poor performance on a single group of criteria logically decides the assignment.

In practice the thresholds α_i^l are the performance levels, set by the DM, that any alternative must meet. So the DM must express his preference on these thresholds in terms of percentage of the best performance respectively in each group of criteria. Formally, for each group i and for each category C_l the DM is asked to set a number p strictly between 0 and 100 such that:

$$\begin{aligned} \alpha_i^l &= p\% \times \max_{k=1}^P W_i(x^k), \\ 0 &< \alpha_i^1 < \alpha_i^2 \dots < \alpha_i^{M-1} < 1. \end{aligned} \quad (8)$$

2.3 Objective function

The objective function is defined as follows:

- We set f_{opt} the function to be optimized. $|C_l|$ denotes the number of elements in the set C_l . The index l can be considered as the rank of the category C_l .
- We can define the objective function f_{opt} to be maximized by the formula:

$$f_{opt} = \sum_{l=1}^M l \times |C_l|. \quad (9)$$

with this definition of the objective function f_{opt} , the higher its value is, the better the alternatives are globally assigned to their best categories.

In what follows we suppose that the DM is able to set the value of α_i^l with the constraints:

$$0 < \beta_i \leq \alpha_i^1 < \alpha_i^2 \dots < \alpha_i^{M-1} < \gamma_i < 1, \quad (10)$$

$$\beta_i = \min_{k=1}^P (W_i(x^k) : W_i(x^k) > 0), \quad (11)$$

$$\gamma_i = \max_{k=1}^P (W_i(x^k) : W_i(x^k) > 0). \quad (12)$$

2.4 Algorithm for the assignment problem

Here, we recall the KEMIRA sort assignment algorithm with some comments as presented in [6]:

1. Fixed algorithm parameters:

$$10^{-3} \leq \varepsilon \leq 10^{-1}, \max_{iter} \text{ the maximum number of iteration.}$$

$$\text{Thresholds: } 0 < \beta_i \leq \alpha_i^1 < \alpha_i^2 \dots < \alpha_i^{M-1} < \gamma_i < 1$$

2. The initial vector of weights satisfying conditions (2) and (4) is chosen:

$$w^0 = (w_{1,1}^0, w_{1,2}^0, \dots, w_{1,n_1}^0; w_{2,1}^0, w_{2,2}^0, \dots, w_{2,n_2}^0; \dots; w_{S,1}^0, w_{S,2}^0, \dots, w_{S,n_S}^0);$$

3. Run the condition (7) of the assignment process;
4. Compute the value of the objective function f_{opt}^0 as showed in relation (9);
5. Randomly selected direction vector Δw

$$\Delta w = (\Delta_{1,1}, \Delta_{1,2}, \dots, \Delta_{1,n_1}; \Delta_{2,1}, \Delta_{2,2}, \dots, \Delta_{2,n_2}; \dots; \Delta_{S,1}, \Delta_{S,2}, \dots, \Delta_{S,n_S});$$

6. The vector $w^1 = w^0 + \varepsilon \times \Delta w$ is calculated. If it does not satisfy restrictions (2) and (4), the corrections proposed by [5] are carried out:
 - (i) if $w_{i,j}^1 < 0$, change: $w_{i,j}^1 = 0$;
 - (ii) if $w_{i,j}^1 < w_{i,j+1}^1$ change: $w_{i,j}^1 = w_{i,j+1}^1$;
 - (iii) if $t_i = \sum_{l=1}^{n_i} w_{i,l}^1 \neq 1$ change: $w_{i,l}^1 = \frac{w_{i,l}^1}{t_i}$;
 - (iv) the number of iterations $iter$ is calculated.
7. If $iter > \max_{iter}$ stop the algorithm.

Else

- (a) Run the condition (7) of the assignment process with the current weights vector w^1 satisfying conditions (2);
- (b) Compute the value of the current objective function f_{opt}^1 as showed in relation (9):
 - (α) If $f_{opt}^1 > f_{opt}^0$
 - change: $f_{opt}^0 = f_{opt}^1$; $w^0 = w^1$;
 - go to the point 5 of the algorithm.
 - (β) Else, go to point 2 of the algorithm.

The following comments can be highlighted on this algorithm:

- Considering point 7 of the algorithm, when the condition in (α) is satisfied, there is a possibility to get a better solution in the selected direction Δw .
- If not, in order to avoid local minimum which could prevent from going toward better solution, a new direction of solution searching is initiated as stated in condition (β) by generating randomly a new w^0 .
- The space of feasible weights to explore is infinite. Thus, in order to give the algorithm enough chance to find a best set of weight, solution for our optimization problem, a considerable number of feasible sets of weight must be explored. Here, we use a random generation of directions to initialize the exploration procedure, and direction changes occur as necessary to avoid local optima. In this context, a heuristic can be useful if it allows to quickly explore a large feasible sets of weight while avoiding local optima. This concern will be investigated in our future work.

3 Brief presentation of GIS

3.1 Description and structure of a GIS

GIS is a very powerful information technology especially adapted to geographic data. In general, GIS consists of three modules as showed in **Figure 1** :

- A module managing the data which acts as a Database Management System (DBMS), including functionalities allowing, among other things, the access, the interrogation, the update of the data.
- A module specialized in the treatment of the spatial character of the information and consisting of functions allowing, among other things, the display of data in the form of a map, the superimposition of maps, the analysis of surfaces, the calculation of distances, perimeters and surfaces.
- A last module allowing to visualize the geographical data.

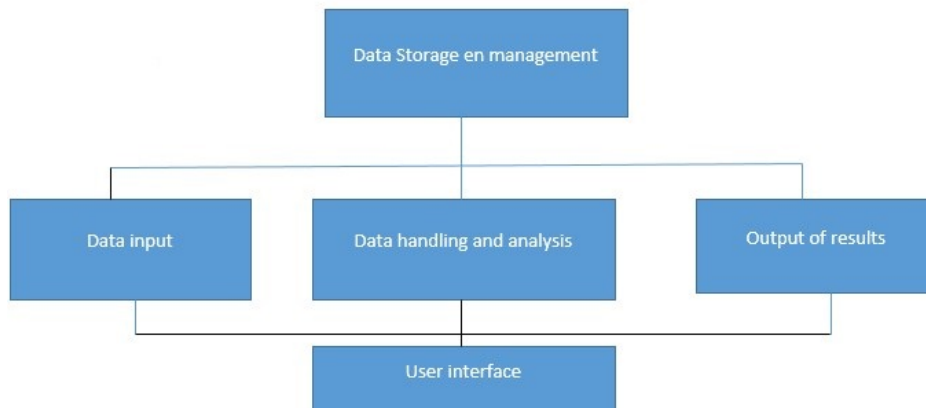


Fig. 1. Structure of a GIS according to Malczewski[2]

Also, a GIS is a set of subsystems that includes the components necessary for:

- the acquisition of input data (data from maps, census data, field data, etc.);
- the storage, representation and management of databases;
- the manipulation and analysis of data;

- the display and generation of products (reports, statistical maps, etc.);
- the dialogue with the user.

3.2 Presentation of the GIS used

An open source GIS, QGIS 3.14.0, is used in this paper. We have fully integrated the MCDM method KEMIRA-sort into the QGIS 3.14.0 kernel using the python language. Hence The MCDM method KEMIRA-sort appears as a plugin which can be used as a tool like any other GIS tools. The capabilities of QGIS are thus reinforced by a decision support module.

4 Integration of KEMIRA-sort into a GIS

4.1 Integration process

As showed in **Figure 2**, for implementation of KEMIRA-sort in a GIS, we have adapted the approach used in[1] when integrating MCDM method ELECTRE tri[8] in QGIS. The main difference between our approach and that of[1] is that, KEMIRA-sort does not use a complementary inference module because KEMIRA-sort method allows to determine the weights of criteria.

Let's make some comment in **Figure 2**:

- Step 1: Definition of the problem In the process of building our decision map, our first step was to define the decision support problem. For our case related to a spatial decision problem, we first delimited the study area and defined the criteria that have an impact on the decision we want to suggest. This first phase consists in creating criteria layers that will spatially represent in the GIS the different criteria involved in the decision process. vector maps are used to represent these criteria layers, called criteria maps.
- Step 2: Construction of the multicriteria map. The second step is the construction of our multi-criteria map, having all the spatial entities evaluated on each of the homogeneous groups of criteria. To obtain this multicriteria map we had to use an overlay tool of QGIS. The spatial entities that constitute the multicriteria map, are evaluated on all the groups of homogeneous criteria, each criterion having a weight assigned by the decision maker, for the resolution of the decision problem. Concerning the spatial definition of alternatives, the interested reader can consult[9].
- Step 3: Definition of the KEMIRA Sort model parameters. Then we define the KEMIRA-sort model: the parameters to be entered in order to define the model are: the evaluation matrix, the number of groups of criteria, the performance thresholds defined by the decision maker representing the level to meet by each alternative in each group of criteria and finally the number of categories of assignment.
- Step 4: Generation of the decision map. Once the KEMIRA Sort model is defined, the next step in our approach is to generate the decision map for decision support purposes[10]. We generate this map from the data of the multicriteria map and the parameters of the KEMIRA Sort model. In

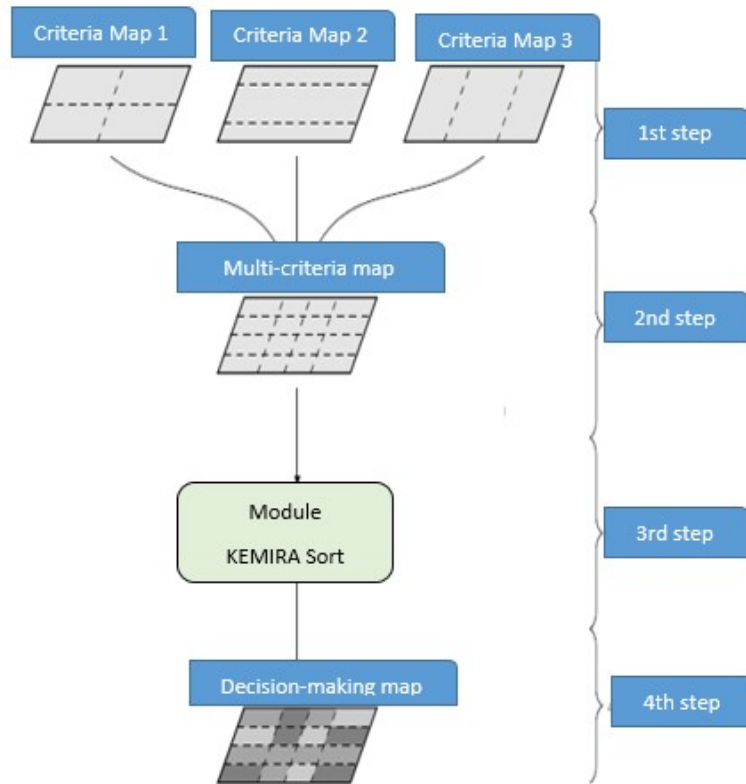


Fig. 2. building a decision map in a GIS (adapted from[1])

the final decision map, for all spatial units (representing alternatives or actions) in the multi-criteria map, each is assigned to a predefined category in the KEMIRA TRI model. Depending on the category to which it is assigned, each spatial unit is attributed a corresponding color.

Step 5: Validation of the decision map. Finally, the decision maker checks the assignments of the actions on the whole decision map and can possibly revise the model parameters such as the performance thresholds of certain group of criteria, if some assignments seem erroneous.

4.2 Implementation in QGIS

The implementation of the KEMIRA-sort method in Quantum GIS consists in developing a plugin for the KEMIRA-sort method in the GIS. Plugins are an excellent way to extend the functionality of QGIS and to automate map processing. The QGIS plugin created in this work allows, through Python functions :

- to retrieve attributes² of one or more open layers in a QGIS
- to sort and display, w.r.t. its performance, each of the spatial units in one of the predefined categories according to algorithm of section 2.4.

5 Application to a landscape degradation problem

5.1 Description of the case study

Here we consider a case study reported in [11]. In this case study the objective was to guide the choices of strategies and measures to be applied in the Loulouka watershed in Burkina Faso to promote sustainable land use. The region under study, i.e., the Loulouka watershed has been partitioned into 227 spatial units which have constituted the alternatives or actions (*i.e.* the set of alternative is $X = \{x^1, x^2, \dots, x^{227}\}$). Four predefined categories expressing different increasing levels of response to the risk of degradation have been defined:

- not adequate
- weakly adequate
- moderately adequate
- adequate

The level of response to the risk of landscape degradation w.r.t. each spatial unit was determined using an ELECTRE TRI model in its optimistic version based on 11 criteria. This criteria derived from five principles (groups) allowing to consider that degradation is limited in the framework of sustainable development and management:

- Group 1: ERO: Soil erosion is limited: $S_1 = \{(1, 1), (1, 2), (1, 3), (1, 4)\}$;
- Group 2: BIO: Loss of biodiversity is limited: $S_2 = \{(2, 1), (2, 2)\}$;
- Group 3: FER: Soil fertility is maintained: $S_3 = \{(3, 1), (3, 2)\}$;
- Group 4: PRO: Good agricultural productivity is promoted : $S_4 = \{(4, 1), (4, 2)\}$.

To help the decision-maker in taking remediation action against landscape degradation (soils and vegetation), a decision map giving for each spatial unit its level of response to the risk, i.e. its assignment category, was constructed (see **Figure 3**). In order to obtain this map, it was necessary to pass the data from the GIS ArcView3.2a to the multi-criteria analysis tool allowing to execute ELECTRE TRI method and vice versa. In this process the GIS and the ELECTRE TRI method interact indirectly. In our model it is precisely this kind of processing that we want to avoid by implementing directly KEMIRA Sort method into the kernel of the GIS QGIS.

²This attributes are the performance of spatial units or alternatives

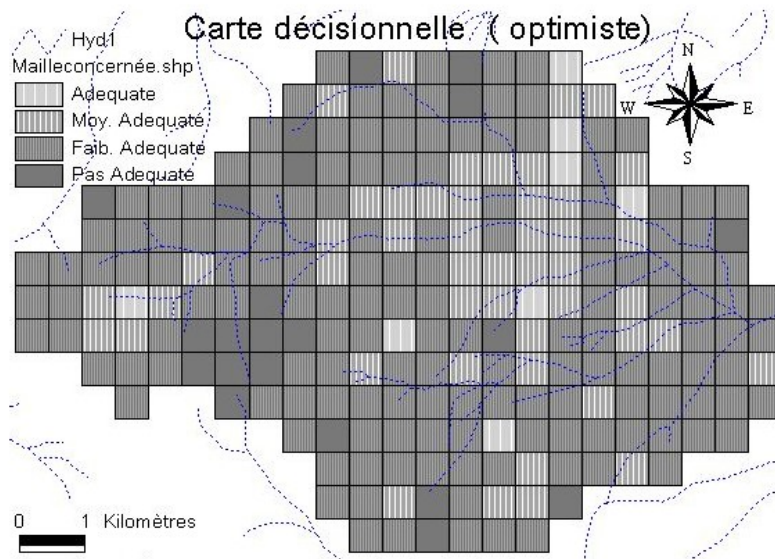


Fig. 3. ELECTRE Tri decision map[11]

5.2 Application of KEMIRA Sort to the case study

The application of our approach was done in three steps: firstly the integration of the eleven (11) criteria in QGIS in the form of csv (Comma-Separated Values) files, secondly the importation in the QGIS of the study area partitioned in 227 spatial units of five (25) hectares each in the form of shp (Shape) files and finally the writing of the python program of the KEMIRA Sort model in the QGIS kernel. The implementation was done in the most modular way possible under Python code and continues to be improved in this sense. Below we sketch some steps of the python program of the KEMIRA Sort plugin in QGIS:

- Building a function that will retrieve the evaluation matrix A (each line represents an action and each column represents a criterion: the evaluation of an action on a criterion is placed at the row-column intersection) in the layer containing the 227 spatial units in QGIS; this layer has in its attribute table the decision maker's evaluation of the 227 actions on the 11 criteria; is the performance matrix according to the decision maker's preferences; this matrix is not normalized.
- Build a function that retrieves the attribute table of a layer on QGIS as a performance matrix. This matrix is called as an argument in a python function that will normalize the say-called matrix. This normalized matrix returned by the previous function is then grouped w.r.t. different criteria groups according to the KEMIRA-sort method.

- Implementing the KEMIRA-sort algorithm is the QGIS Idle for python script.
- Implementing a function that adds the sets of actions per categories returned by the KEMIRA-sort method to the attribute table of the selected layer. The layer is labeled in "Batch" execution mode allowing the same processing tool to be run automatically on the input file.

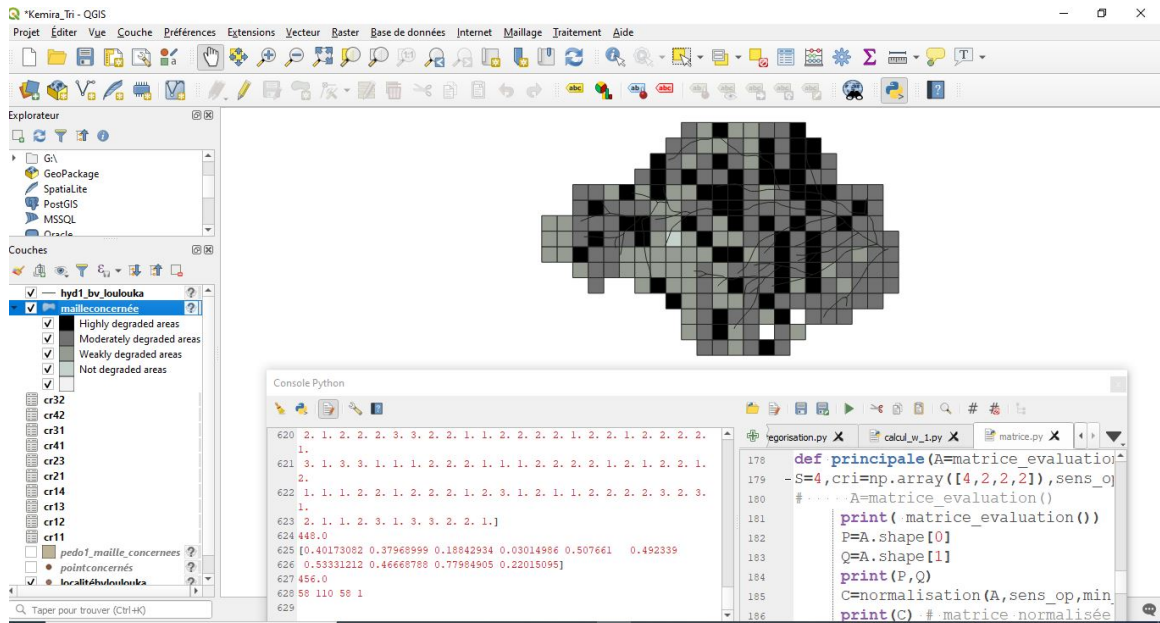


Fig. 4. KEMIRA Sort decision map

5.3 Result and Discussion

In other to run KEMIRA-sort algorithm, and make some comparison with result obtained from application of the ELECTRI-TRI model done by[11], the other parameter have been set as follows:

- The threshold level: $\alpha_i^1 = 0.5 \forall i \in \{1, 2, 3\}$; $\alpha_i^2 = 60 \forall i \in \{1, 2, 3\}$; $\alpha_i^3 = 97 \forall i \in \{1, 2, 3\}$
- $\max_{iter} = 100$
- $\varepsilon = 0.01$

The decision map generated by acting on KEMIRIA plugin in QGIS is showed in **Figure 4**). Such a map will serve as the basis for the remediation strategy for the degradation. Thus, one can see the actual extent of degradation and address the priority areas in terms of urgent land use needs in order to effectively combat degradation. Below we highlight some comparisons between the decision

maps stemming respectively from ELECTRE TRI model and from KEMIRA sort model based on **Table 1**.

Table 1: Comparison of ELECTRE Tri and KEMIRA-sort methods

ELECTRE TRI assignment[11]				
	C_1	C_2	C_3	C_4
TOTAL	22	152	47	8
%	10	66	21	3
KEMIRA-sort assignment				
	C_1	C_2	C_3	C_4
TOTAL	58	110	58	1
%	25.55	48	25.55	0.44

Note that in the context of the case study, it has been approved that spatial units belonging to the first two categories C_1 and C_2 are considered to be degraded and the spatial units belonging to the categories C_3 and C_4 are considered to be non degraded. The **Table 1** shows that:

- In [11] using ELECTRE TRI method, the assignment of the 227 spatial units in the 4 categories of response to the risk of degradation gives: 76% degraded and 24% non-degraded (with $C_1 = 22$ actions, $C_2= 152$ actions, $C_3= 47$ actions, $C_4 = 8$ actions).
- With KEMIRA-sort method, the assignment of the 227 spatial units in the 4 categories gives 74% degraded and 26% non-degraded (with $C_1 = 58$ actions, $C_2= 110$ actions, $C_3= 58$ actions, $C_4 = 1$ action)
- Considering overall the degraded and non-degraded character of spatial units, the two models give approximately the same results whereas there is some difference when considering the two categories constituting respectively the degraded and non degraded.

6 conclusion and perspectives

We have proposed a complete integration of the KEMIRA-sort MCDM method into an open source QGIS. This integration is visible in the QGIS GIS as a plugin implemented under the python language. The plugin is implemented in the GIS in the most integrated way possible. The KEMIRA-sort plugin appears to the user in a similar way to any other GIS functionality. The chosen GIS QGIS is an open source so that the plugin is accessible to as many people as possible. The source code of the plugin is also an open source so that anyone can reuse it for other applications or improve it. Applied to a land-use planning problem, the proposed GIS-MCDM tool has made it possible to obtain a decision map on which each spatial unit is assigned in one of the predefined category representing increasing level of response to the risk of degradation. Such a decisional map will allow territorial authorities to better orient their planning policies.

As perspectives, we intend to apply empirically our new GIS-KEMIRA-sort approach to other case study and compare the result with those stemming from other integrating GIS-sorting methods (*e.g.* ELECTRE TRI, MR-SORT[12]). In a second time, we intend to use the tools GIS-KEMIRA-Sort thus conceived in the determination of the zones at risk of propagation of diseases like the malaria or the Covid-19.

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