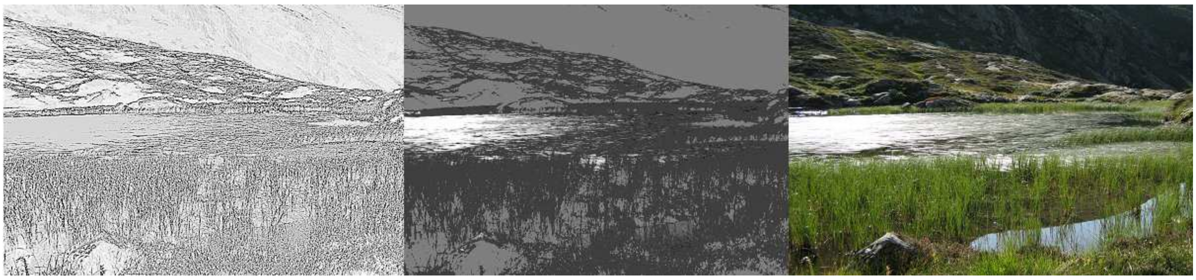
LUMA-GIS Thesis nr 36

Development of a web application based on MCDA and GIS for the decision support of river and floodplain rehabilitation projects



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Development of a web application based on MCDA and GIS for the decision support of river and floodplain rehabilitation projects

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Master Thesis, 30 Credits, in Geographical Information Sciences

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Abstract

Rivers have been modified significantly during the last 200 years in Switzerland. These modifications were done for protection purposes (protection against floods), construction of hydropower plants, gain of land or other human activities. These artificial transformations have reduced, sometimes drastically, the natural dynamic of the rivers, which has reduced biodiversity, and has also increased the risk of flood.

Nowadays, the rehabilitation of heavily affected rivers has become a task that all cantons have to tackle. However the choice of which measures are the best to apply is not simple for decision makers who have to take into account multiple factors, but who are also confronted with different stakeholders who do not necessarily all share the same point of view (scientists, farmers, inhabitants, policy makers, ...)

The present study has consisted of the development of a Web-GIS (geographic information systems) application to help decision makers in this task, by using the multicriteria decision analysis (MCDA) method and by automating all the needed computations. Beside the MCDA computation, the production of maps is also a central functionality. To ensure the reliability of the result, a sensitivity analysis tool was added, which uses the Monte Carlo simulation technique.

The application was developed using PHP, Javascript and Java, and by using open source libraries and softwares (for instance Geoserver, Geotools, MySQL,…). It was designed to let possible extensions be added easily, by using a modular approach to perform the different processes.

The web application enables a fast and easy computation and enables each user to set his own preferences (including the weights of the different factors). A score for each alternative is given as result, as well as maps. The ease of sharing data and results is also a great advantage in projects such as river restorations, where multiple stakeholders' desires must be taken into account.

Résumé

Les rivières suisses ont été fortement modifiées durant les 200 dernières années. Ces modifications ont été faites pour diverses raisons, protection contre les crues, construction de centrales hydro-électriques, gain de terrain ou autres activités humaines. Ces transformations artificielles ont parfois réduit de manière drastique la dynamique naturelle des rivières, ce qui a fortement affecté la biodiversité, mais a également fait accroître le danger lors de crues.

De nos jours la réhabilitation de rivières fortement modifiées est devenue une tâche à laquelle chaque canton doit s'atteler. Cependant le choix des mesures à prendre n'est pas aisé pour les décideurs, qui doivent prendre en compte de nombreux critères, mais sont également confrontés à divers groupes d'intérêt qui n'ont pas nécessairement le même point de vue (scientifiques, agriculteurs, habitants, politiciens, ...).

La présente étude a consisté dans le développement d'une application web - sig (système d'information géographique) dans le but d'aider les décideurs dans cette tâche, en utilisant une méthode d'analyse multicritères d'aide à la décision (MCDA) et en automatisant tous les calculs nécessaires. A côté de l'analyse multicritères, la production et visualisation de cartes est aussi une fonctionnalité centrale. Pour s'assurer de la fiabilité des résultats, un outil d'analyse de sensibilité, utilisant une méthode de simulation (Monte Carlo), a été ajoutée.

L'application a été développée en PHP, Java et Javascript, utilisant des outils open source (par exemple Geoserver, Geotools, MySQL, …) et laissant le champ ouvert à de possibles extensions par la modularisation des différents processus.

L'application web permet une analyse multicritère simple et rapide, et permet à chaque utilisateur d'utiliser ses propres préférences dans le calcul (en donnant les poids de son choix aux différents critères). Un score pour chaque alternative est donné comme résultat, ainsi que des cartes. La facilité d'échange de données et de résultats qu'offre une application web, est aussi un grand avantage dans un projet tel que la restauration d'une rivière, où de multiple groupes d'intérêts doivent être pris en compte.

Acknowledgments

I would like to thank Michael Doering (from Eawag) and Peter Burgherr (from PSI) who have enabled me to work on the very interessant subject which is river rehabilitation, and given me some key notion on this subject. Thank you also to David Tenenbaum, my thesis supervisor at Lund University, who has given me some precious advice for writing my thesis.

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Glossary

API	Application Programming Interface
ArcGIS	Geographic information software from ESRI company
csv	Comma Separated Values
Eawag	Swiss Federal Institute of Aquatic Science and Technology
GDAL/OGR	Geospatial Data Abstraction Library Library for raster and vector data translation and processing
GeoJSON	Format to encode spatial data, based on JSON (JavaScript Object

	Notation) syntax
Geoserver	Java-based application to publish spatial data (http://geoserver.org/about/)
GIS	Geographic Information System A Geographic Information System, is a system which is able to analyse, combine and display spatial information
ISO	International Organisation for Standardisation
MCDA	Multicriteria Decision Analysis
MVC	Model View Controller
OGC	Open Geospatial Consortium
PSI	Paul Scherrer Institut, Switzerland
REST	REpresentational State Transfer
Shapefile	Format for geospatial vector layers (developed by ESRI)
SLD	Style Layer Descriptor
VB	Visual Basic
WMS	Web Map Service
WPS	Web Processing Service
WSM	Weighted Sum Method

Introduction

Rivers have been modified significantly during the last 200 years in Switzerland. These modifications were done for protection purposes (protection against floods), construction of hydropower plants, gain of land or other human activities (Woolsey et al., 2005). However, man has modified streams in Switzerland since the Middle Ages, essentially to protect himself against floods (Visher, 2003). The result is, that few rivers were left in a natural or nearly natural state; about 39% (which makes about 15,000 km rivers or streams) have been heavily modified (canalised, culvert,...). Around 37% of rivers are still in a close to natural or natural state (Woolsey et al., 2005), but about 90% of the floodplains – which can be defined as "areas that are periodically inundated by the lateral overflow of rivers or lakes, and/or by direct precipitation or groundwater" (Bramlett, 2012) - have disappeared since 1850 (Müller-Wenk et al., 2003), in Switzerland, but also in all of the Western world (Europe and North America) (Tockner and Standford, 2002). These artificial transformations that have reduced, sometimes drastically, the natural dynamic of the rivers, have not only affected the biodiversity, but have increased the flood danger as well. Nowadays, however, the importance of restoring rivers to a more natural state has been well recognized. Restoring rivers is indeed not only beneficial for ecology and biodiversity, but also for human well-being; benefits, for instance, include a decrease of flood danger, the improvement of water quality and the improvement of the recreational attractiveness of the environment.

A river or floodplain restoration is, nevertheless, not easy to plan. What measures should you apply, what effects will those measures have, what are the priorities in such a rehabilitation (ecologic, economic, social), what are the different alternatives, is the project viable, etc.? – all these considerations come into play. River rehabilitation also "involves a wide range of stakeholders from the public and private sector including policy makers, practitioners, scientists and non-government organisations, as well as all citizens groups potentially impacted" (European Center of River Restoration, 2014). All these elements make the planning of a river rehabilitation a very difficult task. A large number of factors must be taken into account and evaluated.

Multicriteria Decision Analysis (MCDA) methods and Geographic Information Systems (GIS), can be useful tools to help in making such complex decisions. The key capability provided by GIS, of having a visual representation of the spatial data, is surely a great tool for analysis and communication (communication to the public at large, including inhabitants, authorities, etc.), but by itself it is perhaps not sufficient to enable making a decision when a lot of different factors must be taken into account. On another hand, the MCDA provides a way to base the decision on some more precise and objective elements that are more easily communicable, even if the subjectivity of the decision maker(s) will always be a factor.

However, the computation process of a MCDA and GIS analysis, can be time consuming if made by hand, and is difficult for a non GIS-specialist to manage. Combining both techniques in a single application that automates the computation can therefore be of non-negligible help for the decision maker. A web application will give, moreover, an easier way to share data and enable several stakeholders to work on a same project. The possibilities offered by the Web in general, and Web GIS in particular, are indeed growing very quickly in the past few years. The Web permits us to now work with large datasets and maps with a good level of reactivity and interactivity. In addition, a lot of very good open source software packages and libraries for GIS on the Web are available nowadays, which enables the sharing of spatial data in a not too expensive way, and thereby also enables the popular use of GIS.

Several studies have been made to develop Web GIS applications, in different fields of environmental research. For example, a recent study has developed a Web GIS application for water resources management (Delipetrev, 2013), using open source softwares. Another example is the development made by Hansen and Fuglsang (2014) for integrated coastal zones management (also using open source tools). In the field of river restoration, some Web GIS projects have been also developed (e.g. Wang Lianbo et al., 2010 or Mathiyalagan et al., 2005), but these applications are, however, centered on data sharing and visualisation and not on multicriteria analysis methods.

MCDA methods have also been used in many environmental projects. A study conducted by Huang et al. has reviewed over 300 papers between 2000 and 2009, which have used MCDA in environmental decision-making projects (Huang et al., 2011).

As example of the combination of GIS and MCDA, amongst others, was a project focused on high-speed rail track design (de Luca, 2012), which has demonstrated its usefulness in supporting decision makers in their final decision in projects in which different points of view can exist. Another is the study of Prévil et al. (2013) for the planning of a cycle path. Several studies on Decision Support System (DSS) for river rehabilitation have also been made, but these often used stand-alone software packages or extension of existing stand-alone GIS software packages. For example, consider the study of the flood vulnerability of a region of Turkey (Ozturk and Batuk, 2011), where the authors have developed an ArcGIS tool (in VB) combining GIS and MCDA.

Since January 2011, the modification of the law on water protection in Switzerland (LEaux), plans a renaturalisation of rivers and lakes. This law forces the cantons to plan and to take rehabilitation measures (BAFU, 2011; Confédération suisse, LEaux). The plan is to renaturalise about 4,000km (from the 15,000 km which are heavily modified) of river reaches.This is a huge undertaking which will take many years and several generations (80 years of work are planned) (OFEV, 2012).

In this context, the present study has tried to develop a tool to help and improve the implementation of such restoration projects. A Web application was implemented, combining MCDA and GIS. The computations required were automated in order to make the process easier and less time consuming for the user (decision maker, stakeholder). The latter can specify his own preferences and gets, as a result, the score for each possible alternative, as well as a visualisation of the spatial data that comes into account. The tool can combine spatial and non-spatial data, or use only one or the other. This enables the user to work on a project with a spatial extension, but also on a project that has no spatial component, and, in this latter case, the tool will use only a "classical" non-spatial MCDA. Moreover, to ensure the reliability of the result, a sensitivity analysis tool was added, which uses a Monte Carlo simulation technique.

The application was developed using PHP, Javascript and Java, by using open source libraries and/or softwares (for instance Geoserver, Geotools, MySQL,…), and was designed to let possible extensions be added easily, by using a modular approach to performing the different processes.

In addition to this application, a support tool for the generation of the indicators (which are the input data of the Web application) was developed. This tool extracts the indicators from some base layers and files (coming from field measurements and simulation models). It is, however, independent from the main application.

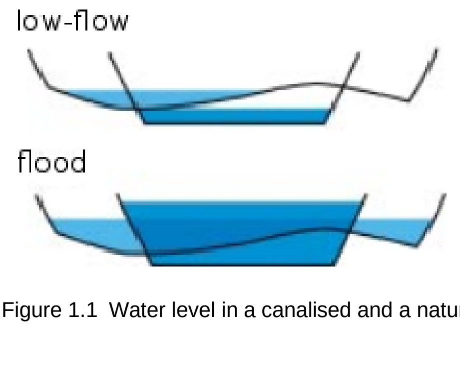
This work will take as a case study the rehabilitation of the Sandey floodplain, which is located in canton Bern (Switzerland). Many studies have been already made on this area at Eawag (see Blaurock, 2012): many datasets are available, including the results of simulations using several possible models. It is thus a good example to test the proposed approach.

1. River rehabilitation elements

Rivers and floodplains have, in their natural state, a natural dynamic - changes occur in space and time continually. This enables them to permanently have zones where water stagnates or flows more or less (lentic and semi-lentic waters), which creates a large variety of habitats and ecosystems (Tockner and Standford, 2002). These are therefore essential for biodiversity. Indeed, the number of animal and vegetation species that live in or nearby rivers, lakes or floodplains is considerable. In Switzerland, about 10% of the fauna live exclusively in floodplains, and more than 70% of them do so partially (regularly or occasionally) (Rust-Dubié et al. 2006). However the artificial modifications of rivers has a negative impact on these habitats and often simply destroys them. A canalised river, for example, is a very monotonous environment and no exchange between the river and the river bank occurs. There are a number of species that simply cannot live in these artificial environments, or are endangered because of the pressure of attempting to do so.

Beside being a center of biodiversity, floodplains can also reduce flood hazard, provide drinking-water, filter undesirable substances such as nitrogen, for example, which can lead to eutrophication problems (Ardö, 2009), or be used for energy production (Doering et al., 2013). Natural floodplains are also widely appreciated for their recreational aspects (walking, swimming, ...) (Eawag, 2013).

Paradoxally, a number of constructions which were made with a protective aim, are in fact increasing the danger. Floods are much more dangerous and destructive if the river is confined in a rigid construction. If the river has more regular, pervious banks, the surplus of water can be absorbed along the river and thus the danger is significantly reduced.



The figure alongside illustrates the water level in canalised and natural rivers, in low-flow and flood conditions.
From (Hunzinger, 2004)

Figure 1.1 Water level in a canalised and a natural river

In case of a sudden rise of water level (during a storm for example), the floodplain will attenuate the water energy by "absorbing" it laterally, and in this way, will reduce the water flow velocity. (Bramlett, 2012)

The aim of a river rehabilitation or restoration is to give back to the river natural conditions; that is, to restore its “original” or near original state. In this fashion, the environment can be improved in a number of different ways: Increase in biodiversity, reduction of damage caused by floods, improvement of the attractiveness of the environment for recreational activities, improvement of water quality, increase of land value, etc. Such a river will also be more resilient, which means that it can resist to significant damage caused by natural events (heavy rainfalls for example) and come back naturally to its “normal” state. (Woolsey et al., 2005)

A number of measures can be taken to restore a river. I will not go into a technical description of these measures, but the objectives of these measures are, most often, to improve the structural diversity of the river system:

Improving the flow regime	**Increasing structural diversity/lateral connectivity**	**Re-establishing continuity of flow**	**Improving bedload regime**
- Re-establishing a natural, dynamic flow regime - Increasing residual flow - Reducing hydropeaking	- Widening the river bed - Opening culverts - Structuring the river bed - Structuring the river bank	-Longitudinal connectivity	-Bedload rehabilitation

Table 1.1 Example of rehabilitation measures frequently applied. From (Woolsey et al., 2005)

To evaluate if these measures are efficient and to be able to compare them which each other, various indicators are used, such as: estimated water surface during flood periods, river width variability, variability of the water depth, etc. (Woolsey et al., 2005, Blaurock, 2012).

Woolsey describes several phases of a rehabilitation project. One phase is to define the objectives: improving biodiversity, enhancing economic value of the area, decreasing floods impact, etc. These objectives can be diverse and, often, contradictory. You can improve the area from an ecological point of view (more diversity in the river structure, more space for the river, etc.), but this can sometimes be incompatible with other objectives; economic objectives for example. Focusing on the ecological quality might run contrary to the interests of farmers which use this land for pastures or plantations, and will not be able to use it in those fashions anymore. In order to be well accepted by all, different stakeholders and interest groups should define these objectives together. Then, the possible measures that can be taken to realise these objectives should be selected, and also how each of these measures can be evaluated (i.e. the definition of relevant indicators).

As stated above, we have to deal with multiple points of views and interests, multiple possible measures, multiple indicators which can be used for evaluation, multiple persons which are involved in the decision (stakeholders) and/or involved because they live or work in the studied area. We have multiple variables, and the problem is to find the best possible solution: To identify measure(s) that can be taken to satisfy, to the greatest possible extent, all of the interests. Once all the needed data are gathered, one way to approach this sort of problem is to use multicriteria decision analysis methods to help in the evaluation of the measures. As the problem is often also spatially dependant, the integration of spatial data in this analysis is also certainly worthwhile. We will examine multicriteria decision analysis in more detail in the next chapter of this work.

2. Multicriteria decision analysis and spatial data

The aim of a multicriteria decision analysis is to help in decision-making in the case of a complex problem which is dependent on many factors (or criteria).

In a simple case where only one criterion must be taken into account, the decision is easy. Typically, a criterion can be the price. For example, I would like to rent an apartment. If the price is my unique criterion, it is very easy to make my decision and to choose to rent the apartment which is available at the lowest price. If other criteria are also important to me, such as living area, number of rooms, location, distance from the city, etc., the problem becomes more complicated (assuming that there are several available apartments to rent). As is often the case, we cannot have an optimal value for all criteria at the same time (that is, no ideal choice exists). Thus, I have to evaluate which criteria are most important to me. Is the price more important, or the surface area, or the number of rooms, etc.? Will I prefer a living area of 75m^2 with 2 rooms, or a living area of 60 m^2 with 3 rooms?

In everyday life, however, it is in general not very difficult to make such a decision (using our own subjectivity and intuition), and we usually do not use any mathematical methods to help us with this task. In other fields, like environmental projects, the consequences of decisions can be much more important, can involve many people and cost a lot. If many criteria (which can be in conflict with one another) should be taken into account, and we have several decision-makers and/or stakeholders with different opinions, the decision can become quite difficult to make.

In sustainable environmental projects, there are always many criteria to take into account, and several points of view (e.g. ecological, social or economic points of view) to consider. The problem is to find a compromise between these elements, and extract the « optimal » or most suitable alternative, « that is, the one showing the highest degree of desirability with respect to all the criteria » (Caterino,2009).

The purpose of a multicriteria analysis is precisely to find this optimal solution.

2.1. Components of a MCDA project [1]:

In a decision-making process, the three following elements must first be defined:

[1] Based essentially on Munier, N., 2011, Malczewski, J. 1999, Recchia et al., 2011

1) Objectives

The objectives define the aim of the project, the result we would like to obtain.

For example, in the case of a river restoration (our subject here), the main goal is to return the river to a natural condition. Objectives can then be to improve the biodiversity, to improve water quality, to reduce flood damages, etc.. These objectives are, however, often not compatible with each other, and therefore compromises are needed in decision-making.

2) Alternatives

The alternatives are the concrete measures or actions that can be taken to reach the objectives. The decision-making relates to the choice of an alternative.

3) Criteria

A criterion is a property of the system that can be measured or evaluated and which should give us an indication on how well an objective is reached for a given alternative. To be useful, the criterion should enable us to differentiate the different alternatives. Indeed, if a criterion has the same value (or almost the same value) for all the alternatives, it will not help us to differentiate the alternatives and thus not help for a decision. It is not a useful criterion.

One criterion in a restoration project, could be, for example, the variability of the river width, which is an indicator of the structural diversity of the river (which is needed for biodiversity). The problem here is to define a set of criteria which is complete enough to cover all the aspects of the problem (Malczewski, J. 1999), but not so large as to be unmanageable (data for all criteria must be available, which also implies resources available). The set of criteria will thus help us to evaluate the alternatives. The choice of the relevant criteria is, however, a difficult task that will influence the decision process. Woolsey et al.(2005) describe a few dozen indicators (or criteria) that could be used to evaluate river rehabilitation projects.

The criteria are not necessarily homogeneous in space. That is, the values can be spatially dependant. In this case, it is very useful to add a spatial component to the multicriteria analysis and to integrate some GIS functionalities to the decision process. In river rehabilitation, some factors are obviously spatially dependant. For instance, flood that occurs in inhabited zones has a different impact than a flood that occurs in unused areas. We have, therefore, integrated spatial capabilities into our application development.

The next step of a multicriteria analysis is to define how the criteria will be aggregated. That is, which MCDA method will be used to evaluate the alternatives. A number of methods exist that are described in the literature (for example, in Munier, 2011).

We will use, in the present work, the Weighted Sum Method (WSM)[2], which is based on the weighted average technique. This method offers the advantage of being very simple and therefore easily comprehensible and transparent to the decision maker or stakeholder. It also enables us to easily see the contribution of each criterion in the calculated score for an alternative. According to a study of Malczewski (2010) this method is also one of the most used in GIS-MCDA projects.

The criteria and alternatives should be defined by specialists in the field of river restoration. The decision makers have, indeed, the most often, not the needed knowledge for this. However, the decision makers will be able to choose the relative importance of each objective and criterion, by giving a weight to each one.

2.2. Weighted sum method

Lets say we have m alternatives, and n criteria

Alternatives: A_i for i= 1,…,m

Criteria: C_j for j=1,…,n

Each criterion has a value for each alternative (a performance value). For instance, the value of criterion j for alternative i will be noted a_{ij}. These values can be gathered in a table, the "decision matrix":

Decision matrix

	C1 (w1)	C2 (w2)	C3 (w3)	…	Cn (wn)
A1	a_{11}	a_{12}	a_{13}		a_{1n}
A2	a_{21}	a_{22}	a_{23}		a_{2n}
…					
Am	a_{m1}	a_{m2}	a_{m3}		a_{nm}

[2] See for example Ozturk & Batuk, 2011

Table 2.1 Decision matrix

Normalisation

In order to be used together and compared, these values should, however, be normalised first. Criteria are indeed not necessarily given in the same units and therefore cannot be directly compared without normalisation. The normalisation will transform the values of the criteria into dimensionless values; numbers between 0 and 1, where the higher the value, the more desirable that condition is.

Several methods of normalisation exist. The most commonly used normalisation methods (in MCDA) are (Rowley et al., 2012):

1. *proportion of max*: each value (a_{ij}) of the decision matrix (for a criterion C_j) is divided by the maximum value obtained for this criterion: $\widehat{a_{ij}} = a_{ij}/max(a_j)$

2. *min-max* : $\widehat{a_{ij}} = (a_{ij} - min(a_j))/(max(a_j) - min(a_j))$

3. *proportion of the sum* : $\widehat{a_{ij}} = a_{ij}/\sum_{j=1}^{n} a_j$

4. *fraction of the square root* : $\widehat{a_{ij}} = a_{ij}/(\sum_{i=1}^{n} {a_j}^2)^{1/2}$

In the present work, we have implemented the " *proportion of max* " and "*proportion of the sum*" methods, because the proportionality is kept between the criteria. The second method (min-max) does not conserve the proportionality. One problem is that the minimum value will always be set to 0, which means the score of the alternative for the lowest performance criterion will be strongly affected if the weight given to this criterion is high (Rowley et al.,2012).

These normalisation formulas are valid for criteria where a high score is better than a low score. It can however happen, that for some criteria a low score is preferable to a high score. These two types of criteria are named, respectively, "benefit type" and "cost type" criteria (Caterino et al., 2009). For a cost type criterion, we should reverse the formulas. Following the recommendation of Rowley et al. (2012) and Malczewski (1999), we have calculated the reversed normalised values by inverting the values (aij) of the decision matrix for the criterion j.

That is (for the two implemented methods (1) and (3)):

- *proportion of max* (reversed): $\widehat{a_{ij}} = (1/a_{ij})/max(1/a_j)$
- *proportion of the sum* (reversed): $\widehat{a_{ij}} = (1/a_{ij})/\sum_{j=1}^{n}(1/a_j)$

We can note that these reverse normalisation formulas also preserve proportionality.

Weights

We need to attribute a weight to each criterion (that is, estimate the relative importance of each criterion)

Weight: w_j for j=1,..,n where $\sum_{j=1}^{n} w_j = 1$

As it is often the case, the decision maker will attribute some weights to the criteria, depending on his or her own preferences. This is a critical part of the MCDA method, where the subjectivity of the decision maker comes into account. The problem is, however, not only that it is subjective, as subjectivity is part of a project such as a restoration river and different persons will have different ideas about the project (the inhabitants of the area would perhaps like to have a recreational area, farmers would like to preserve their pastures, some biologists are aiming at a great biodiversity,etc.). There is an intrinsic difficulty in the task of attempting to choose weights that are relevant. If I give a weight equal to 0.2 to a particular criterion, why not choose 0.17 or 0.25 instead? On what basis can I rationally make such a decision?

The problem is here to see if the criterion weight is very sensitive to a change. Does a small change affect the ranking of alternatives or not? If it does, perhaps should we eliminate this criterion from the analysis, in order to have a result that really corresponds to some choices, and not to chance.

Alternative score

We can now apply the WSM method, using the normalised values of the criteria. The score for the alternative A_i is obtained by calculating the weighted sum as follows:

$$scoreAi = \sum_{j=1}^{n} w_j \widehat{a_{ij}}$$ (Equation 2.1)

After calculating the scores for each alternative, we will be able to compare these latter according to their respective scores.

As we can observe in this formula, the WSM method is a compensatory method. That is, a low value for one criterion can be compensated for by the high value of another. That means an alternative can still be the best one according to this method, even if one of the criteria is not fulfilled at all. Wierzbick (2010) points out the problem of situations where a criterion cannot always be compensated for by any of other ones (in interdisciplinary applications for example).

2.3. Spatially dependent criteria [3]

The spatial criteria can be based on raster or vector layers. In our application, however, only vector layers are accepted as spatial criteria (a choice made because of the limited time available for this project).

The calculation will be made on the layer using the relevant attribute values. As with the "regular", non-spatial criteria, we will first normalise these values (in the same way as we would for a non-spatial criterion). The only difference is, that for a given alternative, the attribute can take on many possible values. We will thus take into account all these values to perform the normalisation computation.

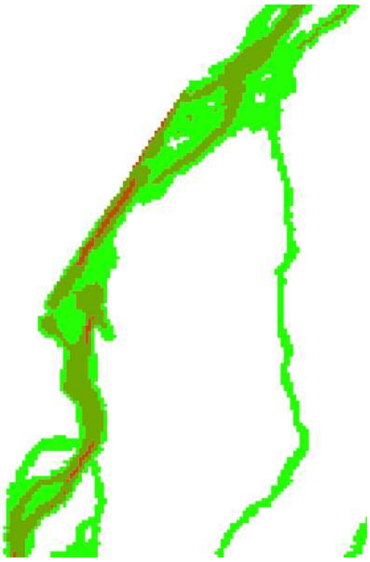


Figure 2.1 Vector layer criterion

Figure 2.1 shows an example of a criterion which is a polygon layer. Each colour represents a different value of the criterion (for one alternative).

Once the values are normalised, we calculate the weighted sum as follows:

Lets name the polygons Pk, the surface of each polygon Sk and the value of the attribute ak.

Where k = 1 to p (p =number of polygons in the layer)

S_{tot} = the total surface of all polygons.

To calculate the equivalent of the element $w_j\widehat{a_{ij}}$ of the formula (Equation 2.1), we have

[3] I have based this on Malczewski, J. (1999), although it discusses this topic about raster layers

summed the contribution of each polygon and normalised the value:

$$w_j(\widehat{\sum_{k=1}^{n} a_k S_k})_{ij}$$ (Equation 2.2)

For LINE geometries, the surface is replaced by the length of the line and the total surface by the total length.

For POINT geometries the surface will be replaced by just a counting of the number of points (the total surface corresponding to the total number of points).

What is interesting about spatial layers is also their support of visualisation on a map. We will thus also have a layer result. The result for an alternative is an overlay of the layers of each criterion for this alternative.

For example: two criteria c1(in red) and c2 (in blue) with their respective weighted values (Figure 2.2) and the resulting overlay values (Figure 2.3).

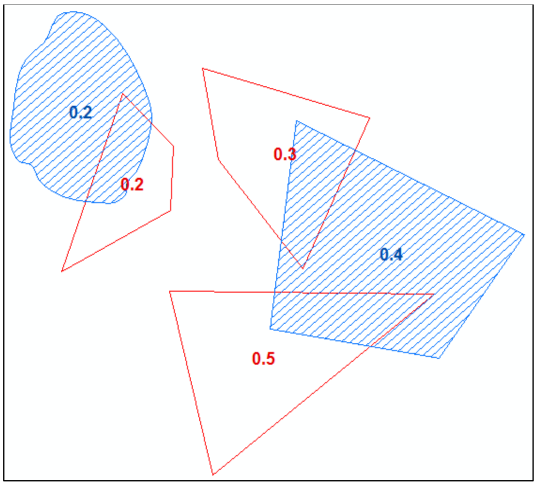


Figure 2.2 Two layer criteria

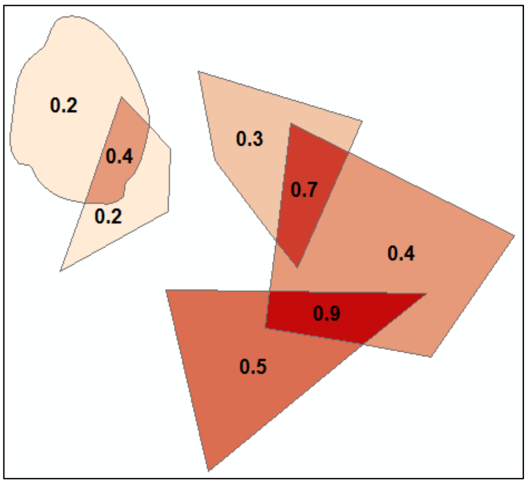


Figure 2.3 Combined layer criteria

2.4. Sensitivity analysis of the weights

The sensitivity analysis will consist of exploring "the sensitivity of the results of decision processes to simultaneous variation of [these] subjective parameters" (Bertsch et al., 2007) The subjective parameters here are the weights given to the objectives and criteria, and the result, the ranking of the alternatives.

Different approaches and methods for this sort of analysis exist and are described in the literature (e.g. Saltelli & al., 2004; Saltelli & al., 2008; Triantaphyllou, 1997; Butler et al., 1997; Chen, 2009). We will use the method developed by Butler et al. (1997), which consists of a Monte-Carlo simulation approach, varying all the weights simultaneously and randomly.

The weights, as well as the ranking of the alternatives, will be generated automatically by the sensitivity module (see section 3.3.1). Two models described by Butler et al. were implemented:

- Random weights: The weights are generated in a completely random way. No user input is given here.
- Rank order weights: The weights are still generated randomly, but the ranking order preference of the user is preserved. As Butler notes "(w)hile the exact magnitude of the weights may be called into question, the relative importance ranking of the attributes may be less controversial" (Butler et al.,1997).

The result are gathered in a csv[4] file, format which enables convenient further analysis (see section 5.2) .

3. Method and implementation

The application developed in this work has two distinct parts:

1. The development of a tool for an automatic extraction of the indicators from the data
2. The development of the spatial MCDA web application (the main application)

3.1. Extraction of the indicators

The process of extracting all the indicators from the available data is quite tedious if done by hand (in ArcGIS). Some Python scripts have already been created using the ArcGIS ModelBuilder (Blaurock, 2012), which is helpful, but a lot of operations still had to be performed manually, including changes in hardcoded scripts for each model, etc. It is thus not easy, and is a time consuming task to get all the indicators assembled manually. In order to make the process easier, we have therefore developed a Python tool (in ArcGIS) in

[4] csv: Comma separated values

which we only need to point to the input files, and then let the program compute and automatically extract all the indicators.

This tool was purposefully developed as an independent tool from the main application, as its purpose is the preparation of the indicator data. The main web application can thus stay independent of the choice of the indicators and of their computation.

As the previous work was already developed to function in the ArcGIS Desktop, the choice of developing a Python ArcGIS tool to perform the extraction was an obvious choice, and certainly the easiest way to automate the extraction of data.

3.1.1. Input data

Thanks to datasets developed for previous studies[5], we have access to the following data:

1. Simulation result (ascii file): see below for a description of this file
2. Study area (shapefile): defines the boundary of the study area
3. Habitat layer (shapefile): division of the study area into zones, depending on the type of habitat (forest, water, gravel,etc.)
4. Transect 10m layer (shapefile): river transect lines every 10 meters
5. Main channel length (number): the length of the main channel (within the study area)
6. Private plots layer (shapefile): those zones which are private plots.
7. Pasture layer (shapefile): those zones which are pasture lands

The simulation result file contains, for a given model, (at least) the following information:

- point coordinates : X,Y,Z
- depth of the water: depth
- water velocity (parallel and perpendicular to the flow direction): vel_x, vel_y

For a description of the simulation result and how it is obtained see Blaurock (2012) which explains it in detail.

Several simulations have been performed for different possible measures which can be taken to restore the river, and different flood event return periods (1 year, 30 years and 100

[5] See Blaurock, 2012

years). We call here a model the combination of a measure and a period.

We have an ascii file for each model: For example, the simulation file M1_HQ1_output.txt, is the simulation result obtained for the measure M1, with a one-year event recurrence flood value.

3.1.2. Create layers and indicators

From these input data, we can obtain the indicators (vector and number criteria).

The first step is the transformation of the simulation file into raster files, specifically a depth raster and a velocity raster.

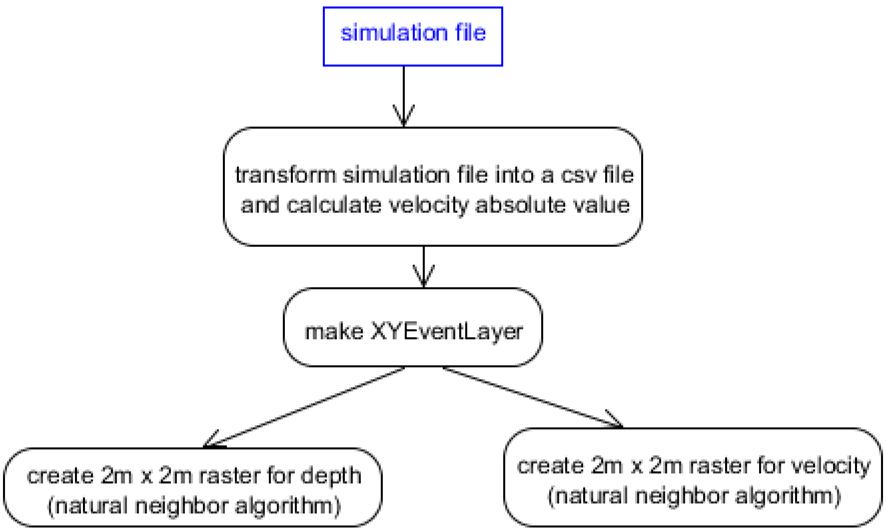


Figure 3.1 Indicators extraction – first step

The base document used for extracting the indicators is the following detailed process schema from the master thesis of M.Blaurock (Figure 3.2).

Anhang 4: Vereinfachte Übersicht zur Erhebung der Daten in ArcGIS: (a) Erhebung der ökologischen Indikatoren, (b) Ermittlung der betroffenen Flächen.
(Auf der DVD im Anhang12c im Ordner Zusatzmaterial befinden sich die mit Hilfe des Modelbuilders erstellten Werkzeuge in ArcGIS.)

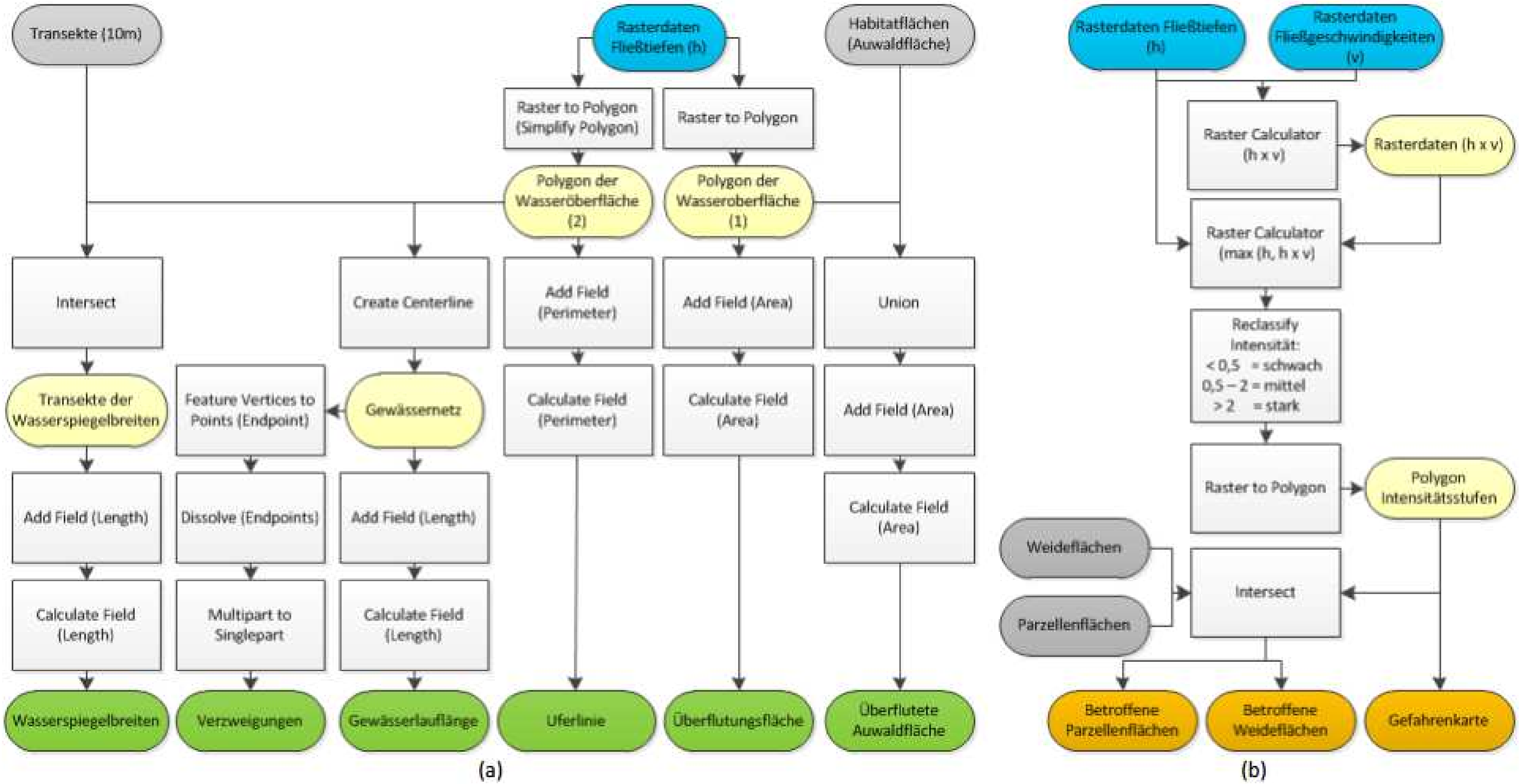


Figure 3.2 Indicators extraction process (Blaurock, 2012

The tool for the extraction is named “***Create layers and indicators***” (Figure 3.3):

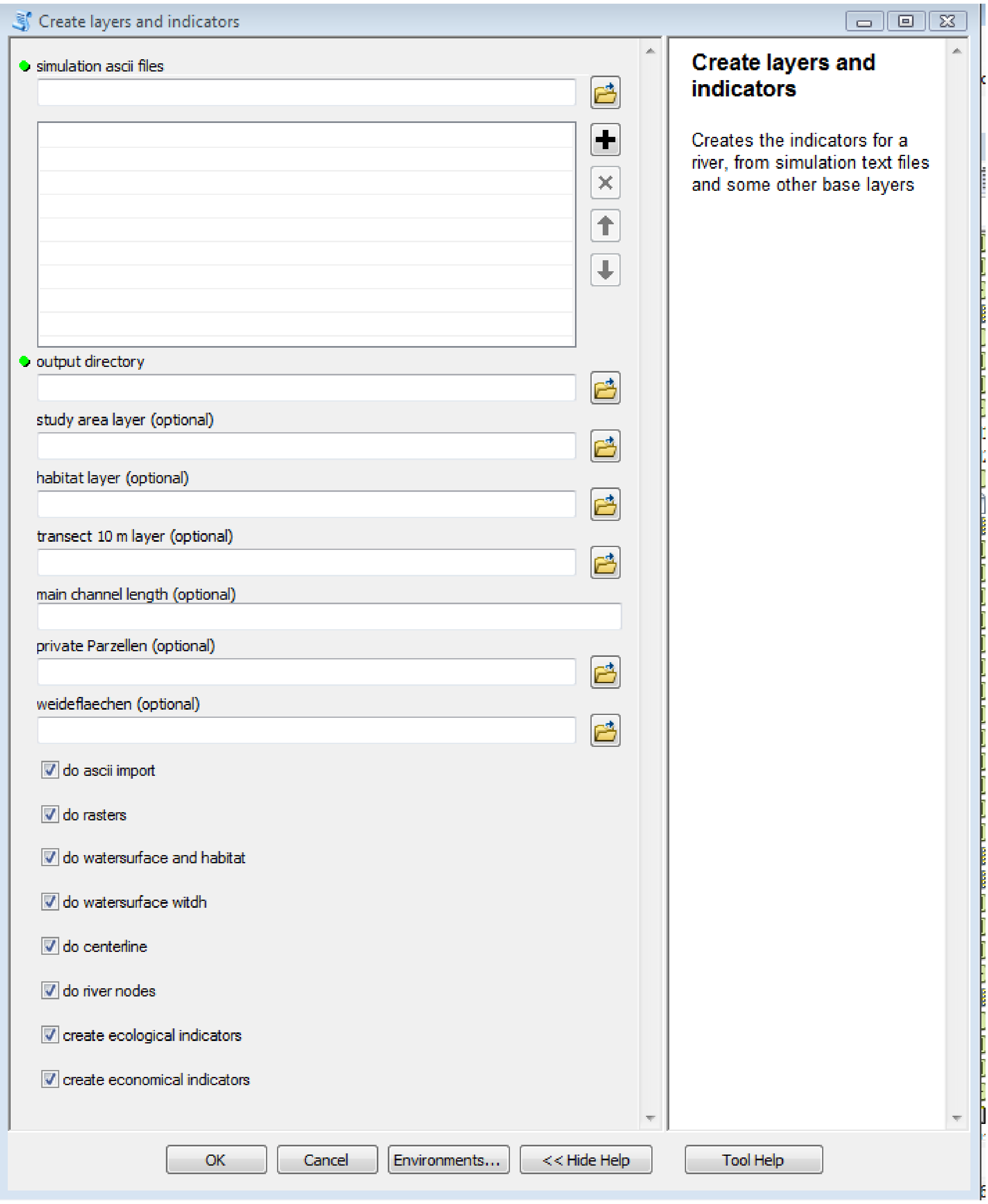


Figure 3.3 Indicators extraction tool interface

We can enter in this form one or more simulation files (the other data, that is, study area, habitat layer, etc., will remain the same for a defined study area). Each checkbox corresponds to a step in the process. We can uncheck some of them to make a partial process (note that the processes are listed in the order in which they should be done, so a step cannot be done before the previous ones are completed).

For each entered simulation file, a set of vector and raster files are created e.g. for the simulation file: M1_HQ1_output.txt, we obtain (Figure 3.4) :

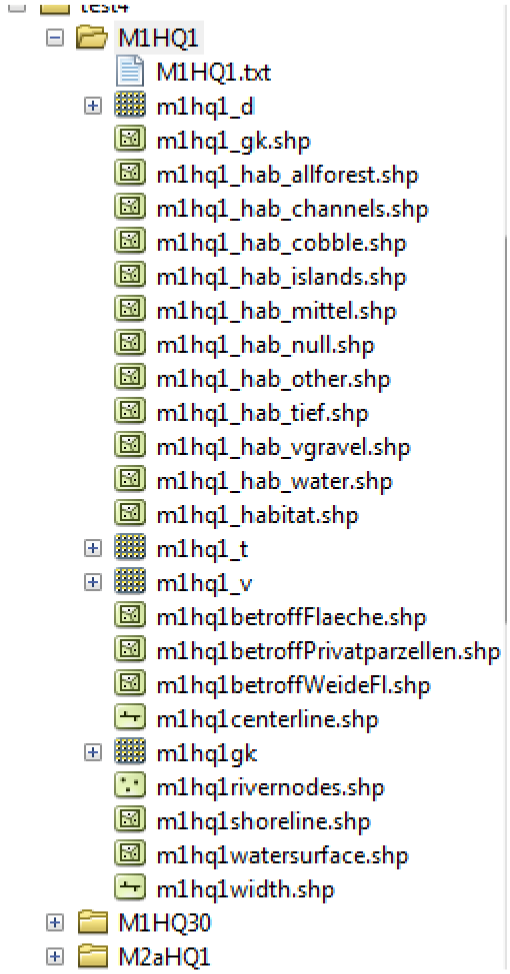


Figure 3.4 Created layers

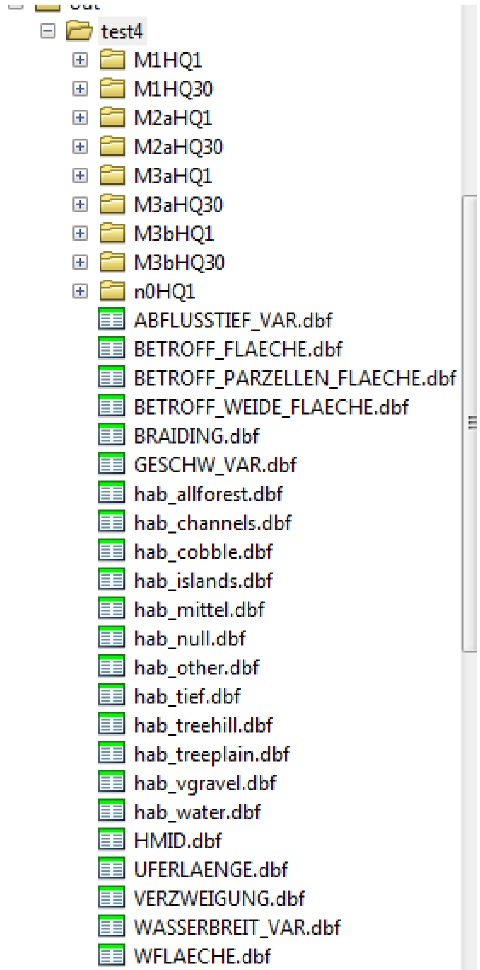


Figure 3.5 Created tables

For each non-spatial criterion, a dbf file is also created, which contains a three column table that contains a unique identifier, the model name and the value of the criterion (Figure 3.5 and 3.6). If some simulation files for different models are entered, these tables will contain the values of the criterion for each model (one line per criterion).

For example:

Table

VERZWEIGUNG

OID	MODEL	VALUE
0	M1HQ1	100
1	M1HQ30	228
2	M2aHQ1	176
3	M2aHQ3	308
5	M3aHQ1	132
6	M3aHQ3	272
7	M3bHQ1	132
8	M3bHQ3	220
4	n0HQ1	92

Figure 3.6 An example of a created table

To facilitate the use of the web application (the layers are uploaded in the web application in a zip format, see section 4.2.4), the shapefiles are automatically compressed as zip files and gathered in a particular directory (named *zip*). The dbf files are converted into csv files (in a directory named *csv*).

3.2. Web application

The development of the spatial MCDA web application is the central part of this work. I have tried to develop a tool which is flexible, easy to use, and which produces useful information for the evaluation of the alternatives for river restoration. The application should also be easily extensible, to support possible future developments.

A Web GIS tool has some advantages when compared to local software. The main advantage is that it can enable many users (more than one, which is normally the case with local software packages) to work on the **same project**, with the **same data**, and to eventually exchange and compare their results. Another advantage is that the application does not need to be installed on the user's computer, which can avoid some possible problems (different operating system, different configurations, different versions, etc). The web application also permits different user roles. The different roles are shown in Figure 3.7:

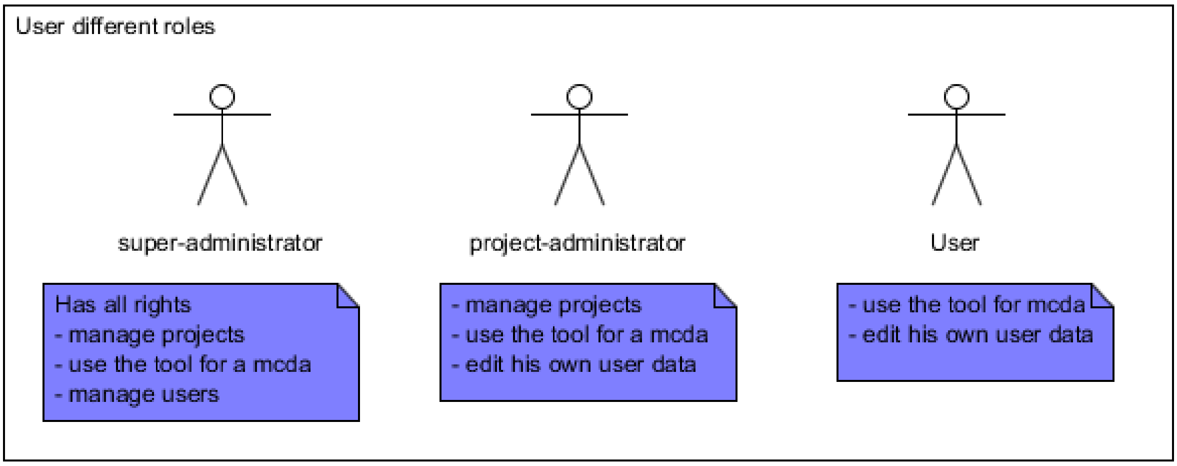


Figure 3.7 User roles

- The “regular” user (can be a decision maker or a stakeholder) will effectively use the system to perform a multicriteria analysis on an existing project with his own weighting preferences, and to analyse the result. The user does not need to be a GIS specialist (as the system will create and show the maps without the user needing experience with GIS)
- The user with a project administrator role, will additionally be able to create a project. That is, this sort of user can prepare and enter the data in the system, including the

alternatives, objectives and criteria, base layers, etc.

- The super-administrator has all the rights of a project administrator, and also the right to create/add new users.

On the other hand a Web tool introduces some difficulties in implementation, which are not present in a stand-alone application, for example in the storage and exchange of data. In the case of a local software package, the storage of data could simply be achieved by defining a working directory. But perhaps it might then stay there forever (presenting possible future problems with data compatibility, version of softwares, etc.).

The concept here is to use only open sources software and libraries to develop this Web application, for the following reasons:

- Many tools exist providing GIS capabilities, using open source software. A number of these tools are developed and used by a wide community which is very active. This helps to ensure their quality.
- Several GIS open source software packages follow the Open Geospatial Consortium (OGC)[6] standards (for example Geoserver, Geotools, etc.). These are open standards for geoinformation, specifying data format, methods for the exchange of data, web services, interoperability, etc. We will discuss the OGC further later in the text.
- Open source tools are generally free (sometimes with certain restrictions, depending on the type of the licence and of the usage you make of the tool).
- Open source is, by definition, “open”. You can, thus, look into the code if you want to see how a computation is made, and then modify and adapt it to your needs.
- It offers more flexibility in development approaches.
- Due to the utility of the interoperability of the data and services that follow OGC and ISO[7] standards, Web GIS open source tools have been used in many recent research projects.[8]

The Open Geospatial Consortium is, along with the International Organisation for

[6] http://www.opengeospatial.org

[7] ISO: International Organisation for Standardisation

[8] For example:

- GEOSS (Global Earth Observation System of Systems) at the University of Geneva, which regroups a set of open source gis softwares, too share and diffuse spatial data compliant with OGC and ISO standards.
- Delipetrev, 2013 ; Gkatzoflias,2012; Henning, 2014

Standardisation (ISO), the main organisation for defining geographic standards.

Founded in 1994, the ***OGC*** is an international consortium which includes more than 440 members: This includes companies (commercial or not), governments and universities. These members "collaborate in a consensus process encouraging development and implementation of open standards for geospatial content and services, geo data processing and sharing".[9]

Among the essential standards of OGC we can list:
- All the geo Web services: WMS (Web Map Service), WFS (Web Feature Service), WPS (Web Processing Service), etc., which enable us to easily distribute spatial data over the internet.
- Geography Markup language (GML): XML grammar that can be used to express geographical features. With the GML you can describe geographical objects and their attributes, projection systems, geometry, topology, etc. This language enables an easy exchange of data.
- Catalog Service for the Web (CSW): A standard which defines how to publish and search for geospatial data, via metadata.

The International Organisation for Standardisation (ISO) has developed international standards covering almost every field. Since its founding, in 1947, it has published more than 19500 standards.[10]

Among them are:
- GML 3.2.1: an OGC standard which is also an ISO standard (ISO 19136:2007)[11]
- ISO 19115: geographic information–Metadata, which defines the format of metadata[12].
- ISO 19128: this defines the behaviour of a Web Map Service (how to describe the service metadata, how to retrieve the map, how to query features shown on the map). This standard is the same as the OGC WMS standard.[13]
- ISO 6709:2008: this describes how a geographic point should be represented: longitude, latitude and altitude (optional)

[9] http://en.wikipedia.org/wiki/Open_Geospatial_Consortium, 2014

[10] http://www.iso.org/iso/home/about.htm, 2014

[11] http://www.opengeospatial.org/standards/gml

[12] e.g.The metadata of the european INSPIRE directive (Infrastructure for Spatial Information in the European Community) or the swiss standard for the metadata (GM03 model) are based on the ISO 19115 standard.

[13] http://www.opengeospatial.org/node/436

- ...

The **ISO/TC 211** is the ISO organisation that is responsible for standardization in the field of digital geographic information. A list of all published standards is available on the ISO website.[14]

Although the OGC and the ISO TC211 are two distinct organisations, they collaborate and some OGC standards have been approved and integrated into ISO/TC211 (for example the GML and WMS standards).

3.3. Implementation of the application

Presented below are use cases diagrams, which illustrates the program's functionalities.

[14] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=54904&published=on&includesc=true, May 2014

The creation and editing of a project is shown in Figure 3.8:

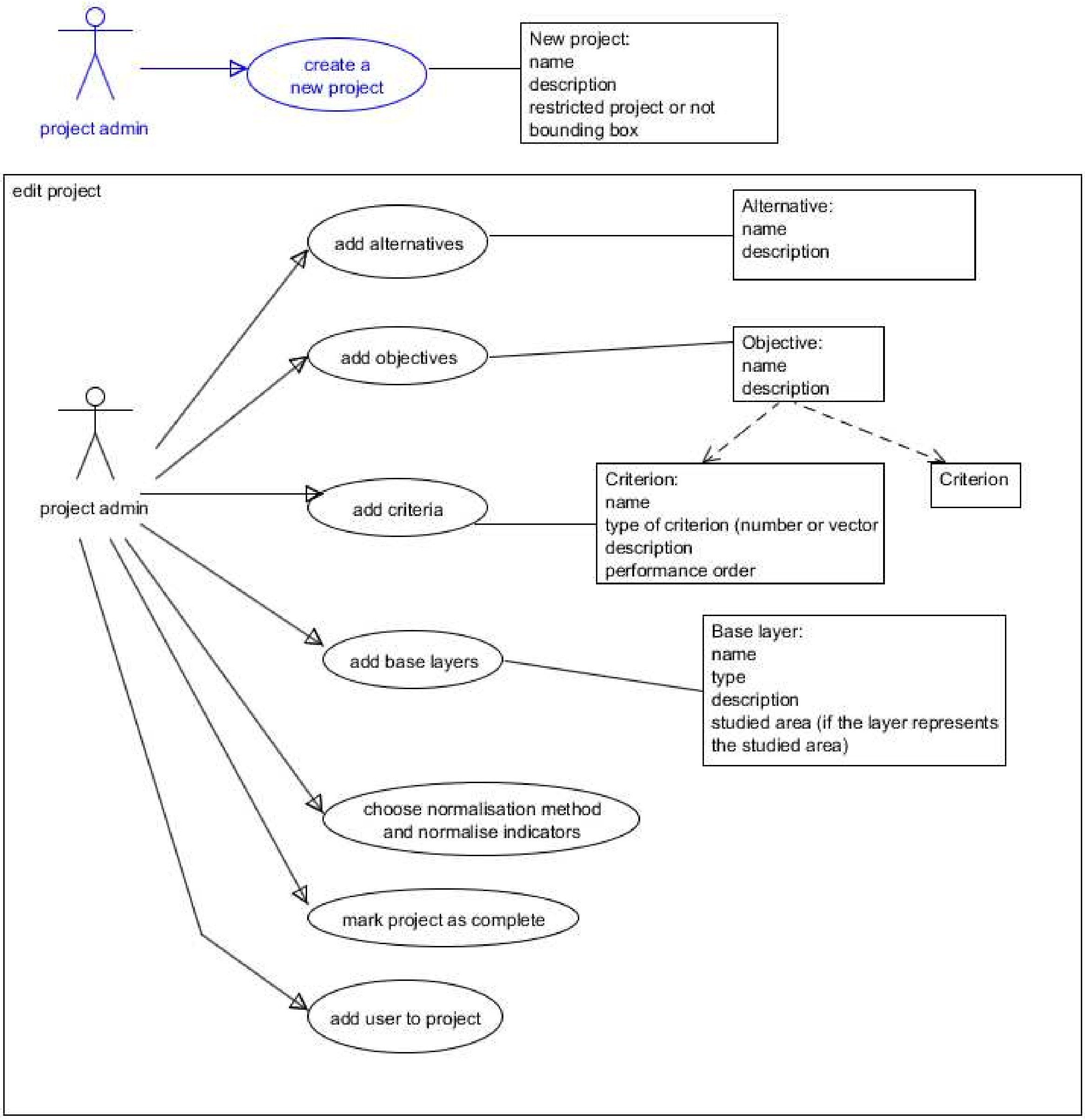


Figure 3.8 Use case: creation of a project

The project is created and defined with its alternatives, objectives, criteria, base layers, definition of methods, normalisation of the criteria[15]. In the end, the project administrator should mark the project as "complete" to enable other users (and himself as well) to perform some analyses.

[15] A detailed description of the application will be provided in chapter 4 "Description of the application"

Multicriteria analysis

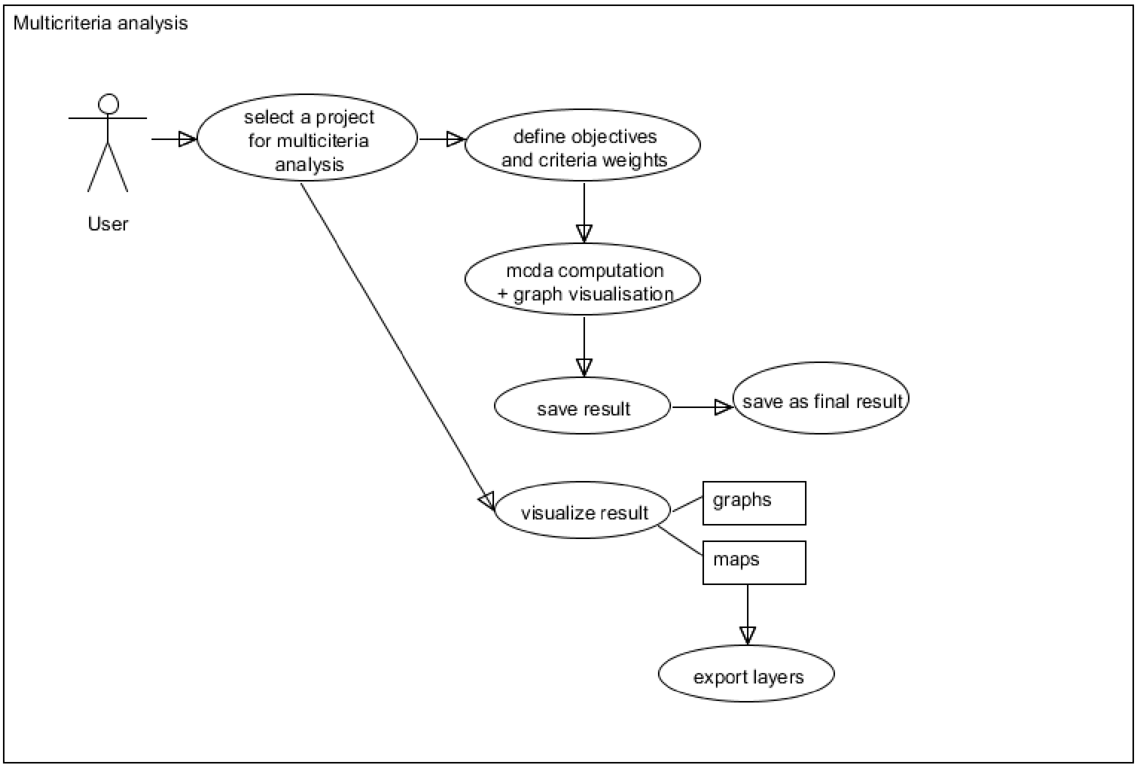


Figure 3.9 Use case: Multicriteria analysis

This is the central purpose and key function of the application: Making a multicriteria analysis and displaying the obtained results in order to help the user with decision-making. The user can export (download) the criteria layers with the weighted values - in a shapefile or GeoJSON format - to perform some further analyses on them.

3.3.1. Components of the application

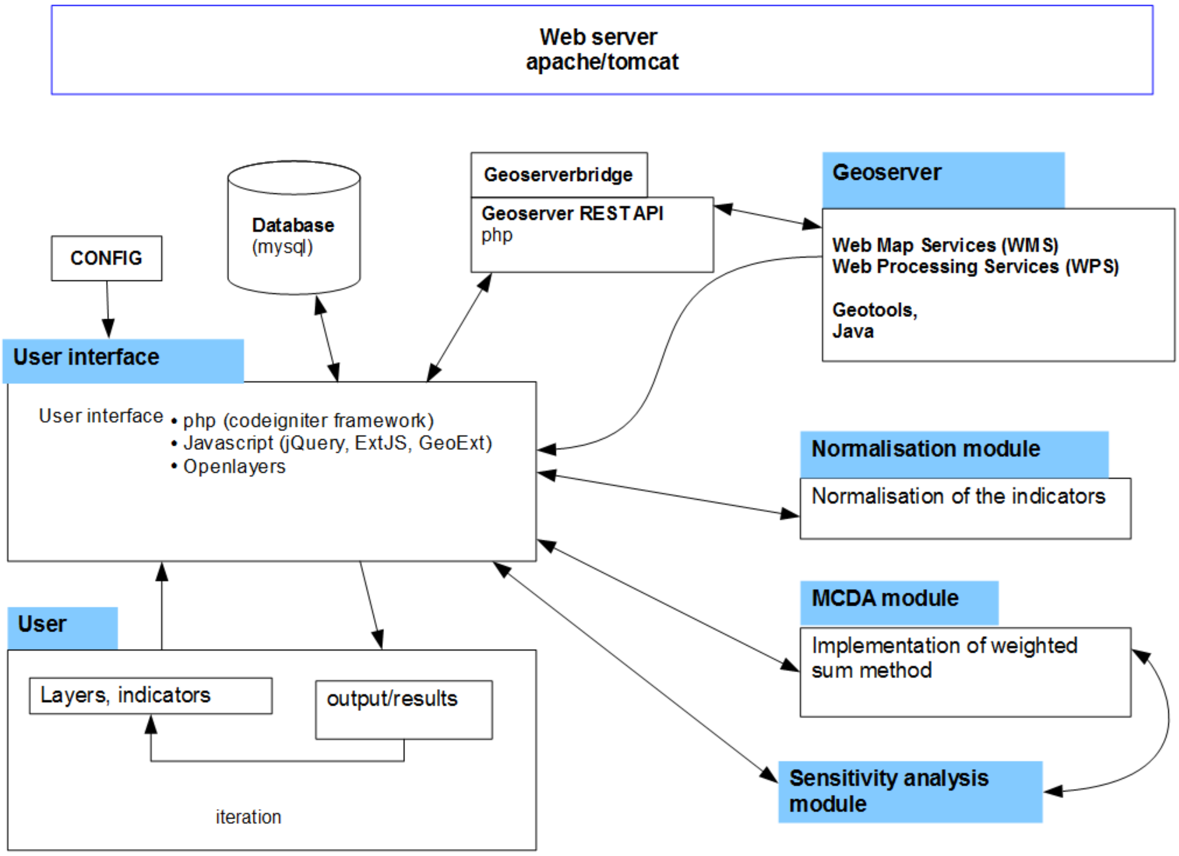


Figure 3.10 Application architecture

In order to create an application which can be easily extended, the different tasks have been developed in separate modules.

a) Config: We have here the files containing all the needed configurations: Access to the database, the base url of the application, access to the Geoserver application instance, the definition of the directories for project base layers and criteria layers and for results (images and other files) are all stored here.

b) User interface:

This is the user interface of the application. All inputs and outputs from and to the user will go through this element.

This element is developed in PHP using the MVC (Model View Controller) framework *CodeIgniter*[16]. A Model View Controller framework enables us to organise the code into

[16] CodeIgniter framework http://ellislab.com/codeigniter/user-guide/index.html, version 2.1.4

three parts:

- The View: The code for the layout of the page (this is what the user sees)
- The Controller: The code which contains the logic of the application
- The Model: The code which controls the access to the database

A lot of good php frameworks exist, and several use the MVC design. The choice of the php framework is not necessarily the only possible choice here; I have chosen this one because I already have experience developing a few web applications with it.

Javascript, and the libraries JQuery, ExtJS, GeoExt and Openlayers have been also used in this module:

- *Openlayers*[17] is an open source API (Application Programming Interface), which enables to make dynamic web maps. It enables a multitude of mapping capabilities. For example, several useful and standard controls for maps are available (such as zoom, pan, etc) and enable a dynamic interaction with the user. In the present application, this library is used to display Web Map Service (WMS) and GeoJSON[18] layers in the final map.
- *ExtJS*[19] and *JQuery*[20] are Javascript libraries used to make dynamic elements on a web page.
- GeoExt[21] is an extension of ExtJS, which includes the spatial functionalities of Openlayers .

c) MCDA and Normalisation modules:

These two modules are developed as php libraries that can be loaded by the main application controllers. The normalisation module is used for the number criteria only. For the spatial criteria, a WPS (Web Processing Service) is used (see next section).

d) Geoserver / geoserver-bridge:

Geoserver is a java-based application to publish spatial data[22]. It follows OGC standards, which ensures a good interoperability with other applications. The integration of a system of

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[17] http://openlayers.org/, version 2.13. This API is under freeBSD licence.

[18] GeoJSON is a format to encode spatial data, based on JSON (JavaScript Object Notation) syntax

[19] http://docs.sencha.com/extjs/3.4.0/ , version 3.4 . Library under GNU GPL license v3 licence.

[20] https://jquery.org/ . JQuery is under MIT license

[21] http://geoext.org/ (under BSD license, http://en.wikipedia.org/wiki/BSD_licenses)

[22] http://geoserver.org/about/

tiles generation and caching (geowebcache) can accelerate the response to requests to the server and enable smooth navigation on the map.

GeoServer implements, among others, the WMS standard. WMS is a web service that provides a map (or a layer). The formats it can handle can be quite diverse: georeferenced images (e.g. png, jpeg), KML[23], and others.

In our application, access to GeoServer is made possible through the GeoServer REST API[24], which enables us to programmatically access the server functionalities via http requests: We can publish some spatial data, define some parameters such as the projection or the style of the layer, and transform or make some computations on spatial data. This is done in the *geoserver-bridge* module (developed as a php library). The layers are thus published through the geoserver-bridge module to GeoServer and then retrieved as a WMS (using Openlayers) and displayed on the map.

We have also used the WPS extension of GeoServer, to make some calculations and transformations of the spatial data. This extension already has quite a lot of functions already implemented, such as intersection, buffering, etc., but we can also develop some custom WPS processes (in Java) and deploy them in GeoServer. This is a very powerful capability of this WPS extension, which enables us to use the infrastructure of GeoServer to publish our own services.

Several custom WPS processes have been here developed for the treatment of the layers (with Java and the library Geotools, which is an open source library providing functionalities to work with geospatial data[25]):

- AddAttributes: Adds the attributes *normValue* (the normalised value), *weightVal* (the weighted value) and *geomextent* (area or length), to each vector criterion.
- Normalise: Normalises the vector criteria values (using the selected normalisation method).
- AddCriteriaLayers: This WPS calculates the weighted value of a list of raster layers (GeoTiff files[26]) and then adds them together to obtain the resulting overlay layer.
- GetArea: Calculates the total area of a polygon layer.

[23] KML: Keyhole Markup Language

[24] http://docs.geoserver.org/2.0.0/user/extensions/rest/index.html

[25] http://www.geotools.org/

[26] GeoTiff is a format for georeferenced images

An example of WPS implementation is shown in Appendix B.

Some existing WPS have also been used to transform the raster layers back to vector layers (see Figure 3.13b) and to get the bounding box of a vector layer (to get the extent of the study area).

For the display of the layers, we have styled the layers using SLD (Style Layer descriptor) files. SLD is also an OGC standard[27]. It is XML[28] based, and is used to define the styles of the layers (vector or raster).

e) Sensitivity module:

This module is also a php library. As already mentioned in section 2.4, this module creates some random values for the weights and computes, for each set of values, the score and rank of each alternative, using the MCDA method (weighted sum method). The result is then written in a csv file, which can be saved.

Example:

```
obj_O1;parzellen;parzellen_mult;weide;weide_mult;verzweigung;verzweigung_mult;obj_o2;Braiding;
Braiding_mult;geschw;geschw_mult;score_M1;score_M2;score_M3;rank_M1;rank_M2;rank_M3
44;23;10.12;31;13.64;46;20.24;56;3;1.68;97;54.32;737.57303780345;2894.4512522213;758.8179530324;1;3;2
57;25;14.25;2;1.14;73;41.61;43;98;42.14;2;0.86;476.93629409266;834.34945009741;327.87369810118;2;3;1
59;10;5.9;8;4.72;82;48.38;41;29;11.89;71;29.11;329.65512264674;1107.7923778558;310.05286395416;2;3;1
...
```

The csv file lists the objectives and criteria weights, followed by the scores and ranks of the alternatives.

f) Database:

The database is a central part of the application, where all information on the projects and results are kept.

[27] http://www.opengeospatial.org/standards/sld

[28] XML: Extensible Markup Language

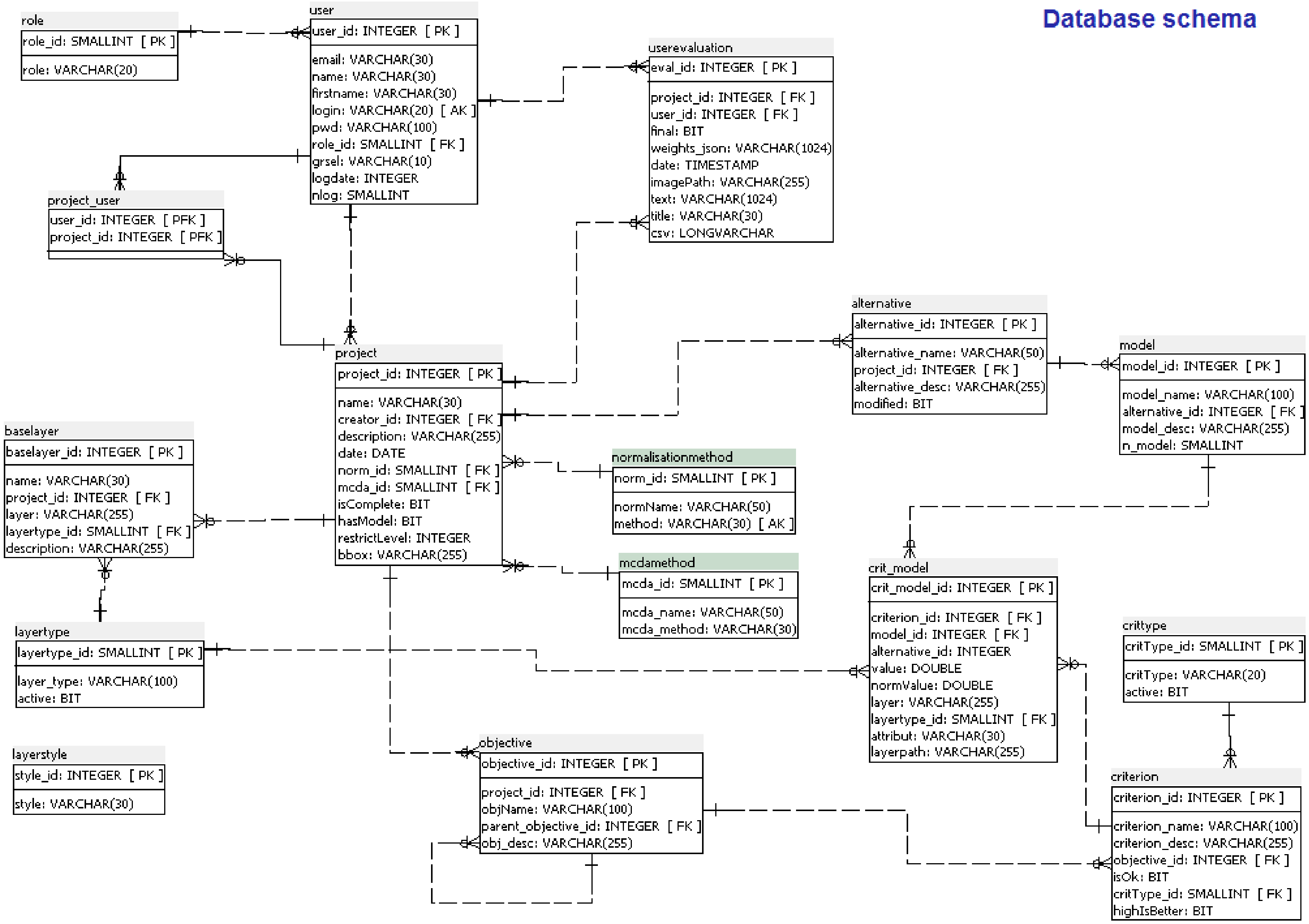


Figure 3.11 Database schema

3.3.2. Process description

The two main processes are : 1) The process for the definition of the criteria of a project, 2) The multicriteria analysis computation

Figure 3.12 Definition of the criteria - sequence diagram

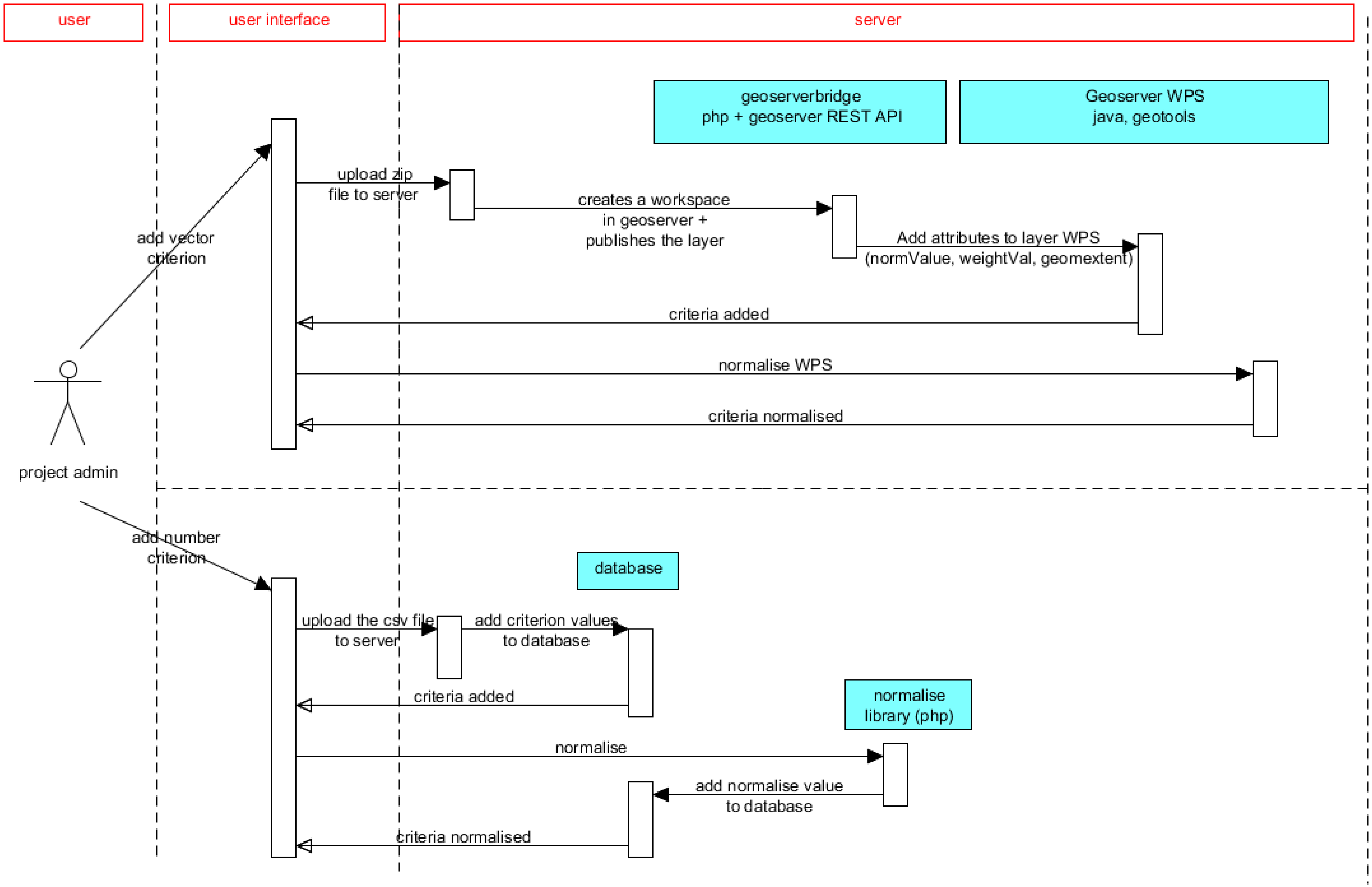
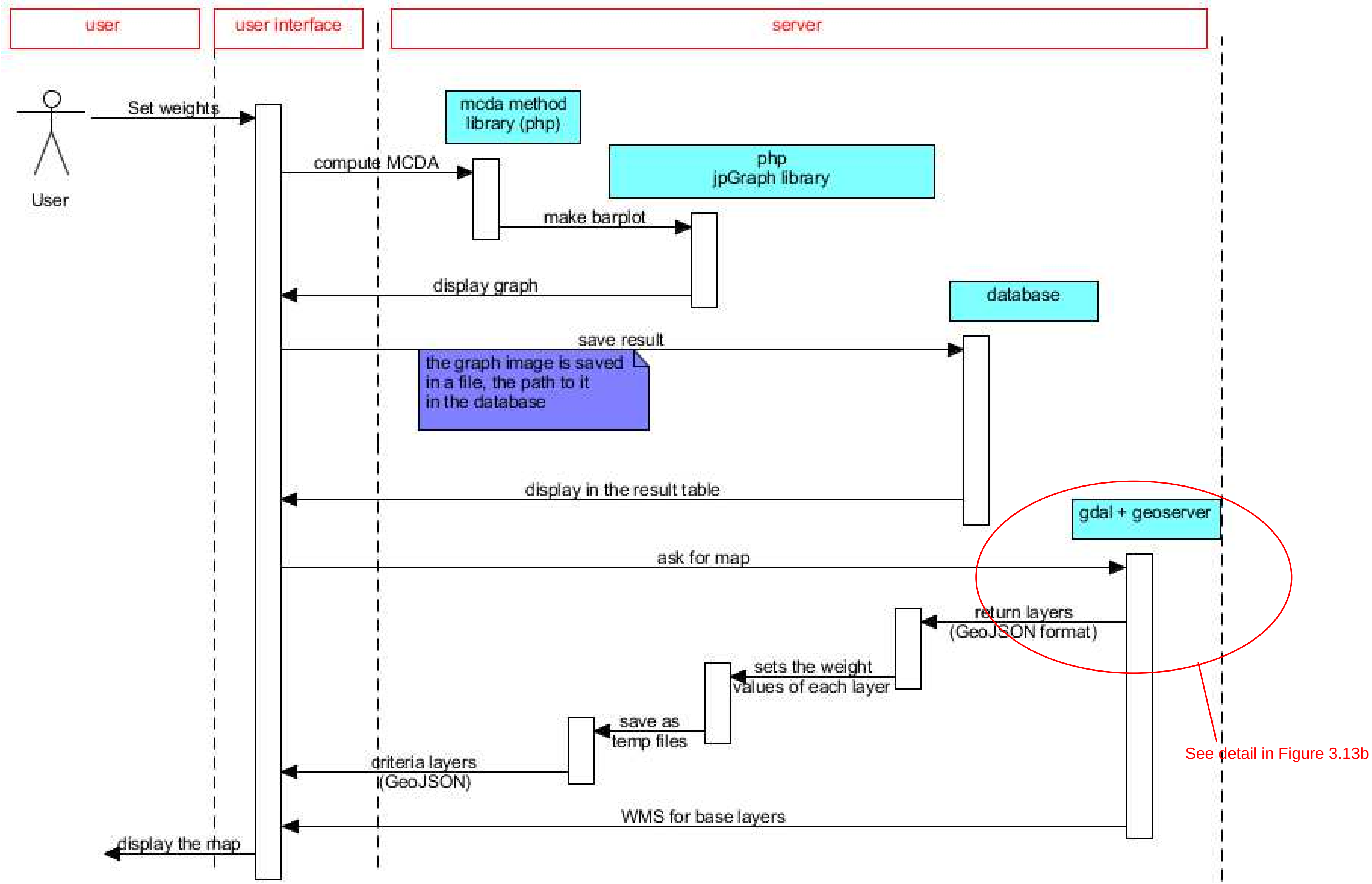


Figure 3.13 The multicriteria analysis computation process – sequence diagram



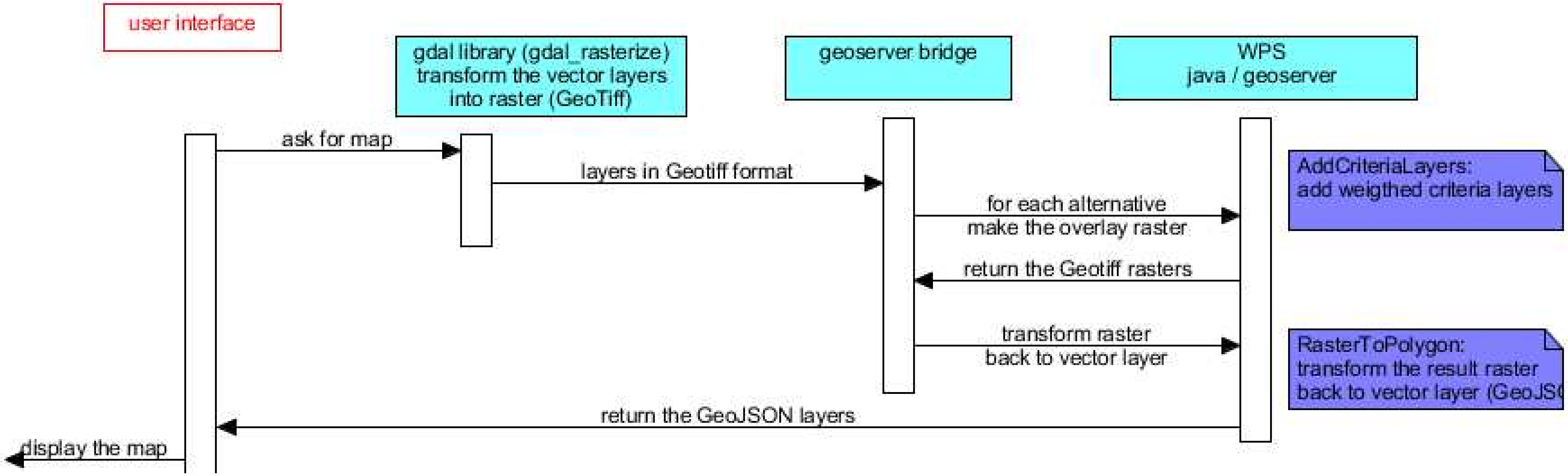


Figure 3.13b Layers transformation

4. Description of the application

I will describe here, in detail, the application functionalities.

4.1. Login

There are three user roles:

- superadmin: This role can see all projects (as a project user) and make a multicriteria analysis (MCDA) on them, can create and edit his own projects, can manage users (user creation, modification)
- projectadmin: This role can create and edit projects (editing only for his own projects), can modify his own user data, and can see and make a multicriteria analysis in projects where he is a project user.
- user: This role can make a MCDA in an existing project, for which he is a project user, and can modify his own user data.

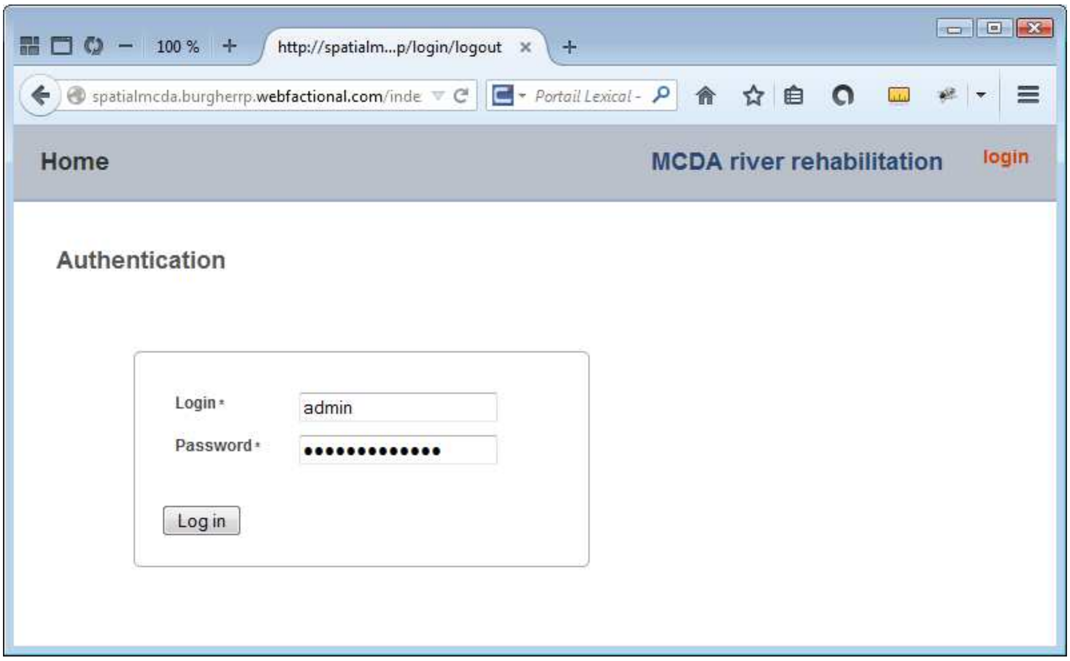


Figure 4.1 Login page

After 4 unsuccessful attempts, the ability to login is blocked for several minutes for this user (in order to prevent an automatic program to try to log in over and over, rapidly).

4.2. Projects management

Once the user is logged in, the list of projects for which he has rights is displayed.

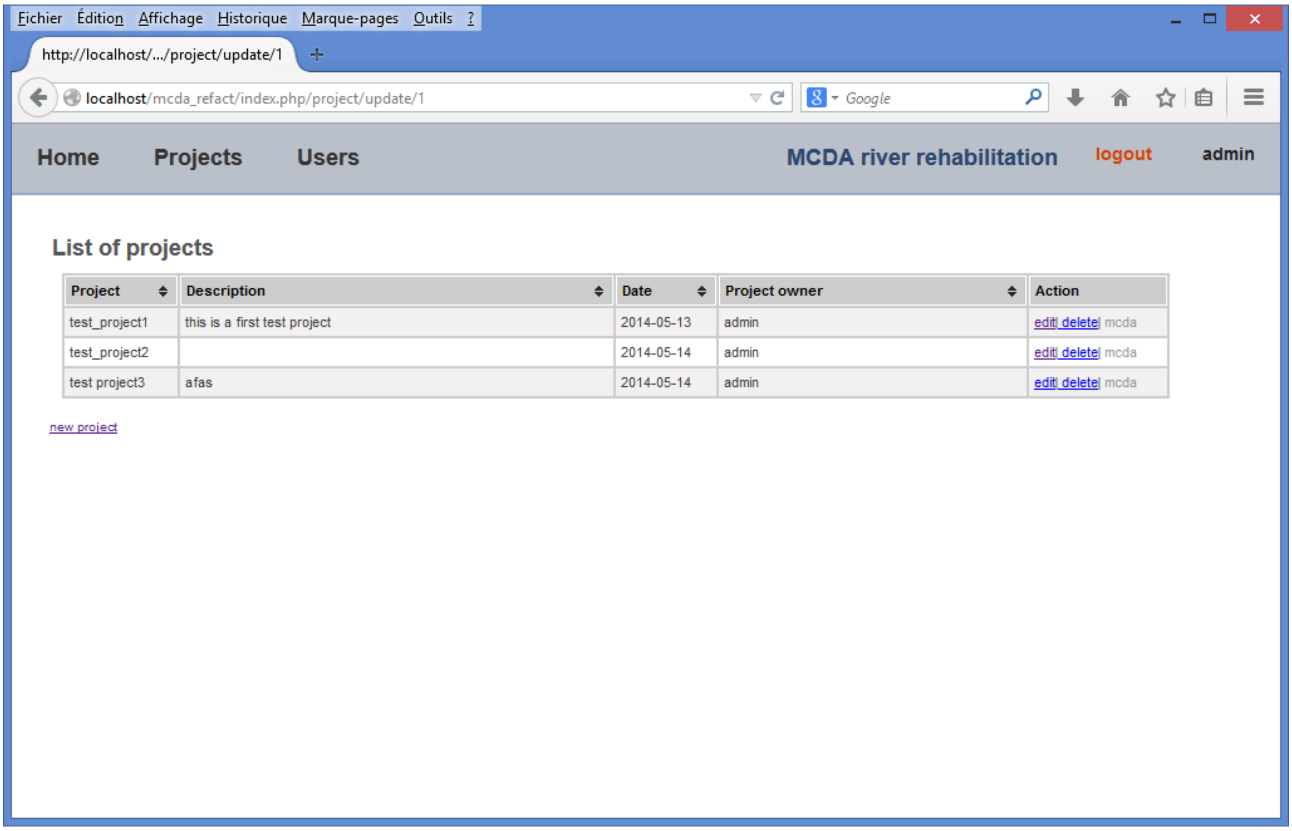


Figure 4.2 List of projects

A list of actions available for the displayed projects is shown:

- *edit*: Edit and modify the project properties
- *delete*: Delete a project
- *mcda*: Perform a multicriteria analysis on the project. This functionality is enabled only if the project has been completely set up (that is, all its alternatives, objectives, and criteria have been entered and the criteria values have been normalised)
- *new project:* Create a new project

4.2.1. Creation of a new project

Add general information

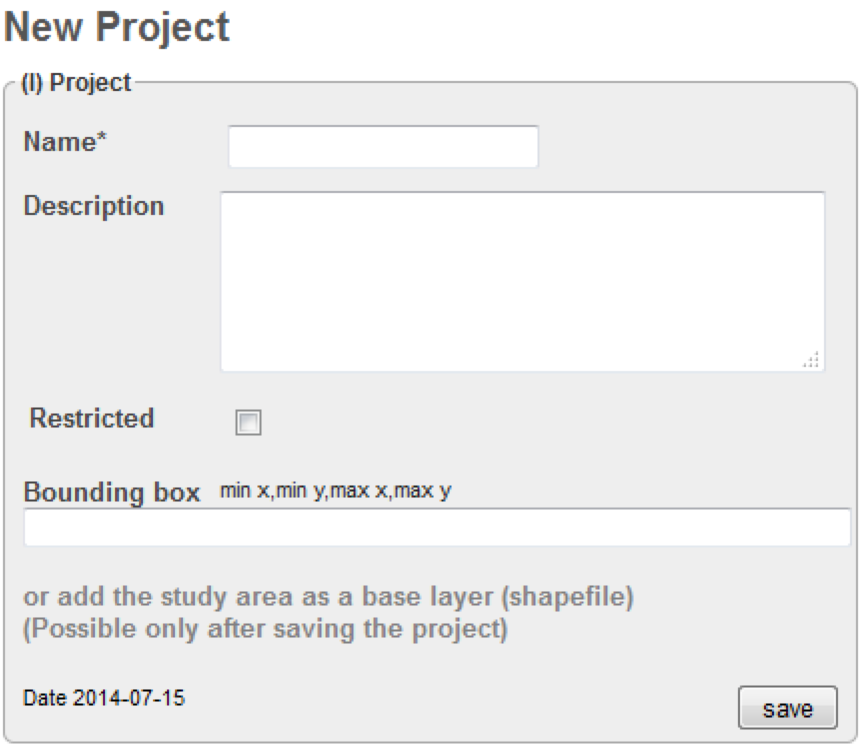


Figure 4.3 New project

- Name: Name of the project (mandatory field)
- Description: A description of the project (optional)
- Restricted: If the checkbox is checked, the project is restricted, which means there is no visibility for a project user of the saved results of other project users (we will describe this screen in more detail below). Only the project owner will be able to see the saved results of the other users.
- Bounding box (bbox): The min x, min y, max x and max y bounding coordinates of the study area. This field is obligatory, only in the case where some layers (criteria or base layers) are uploaded. This ensures a proper display on the final map.

The bounding box can either be directly specified by its min and max coordinates, or by uploading a base layer, which corresponds to the study area. The bounding box will then be automatically calculated from this layer in the program, by a web processing service (WPS). This can be done only once the project is saved.

Add project properties

Choose the project on the project list and click on *edit*. This will open the project editing screen.

This screen contains all the necessary properties of the project: Alternatives, objectives and criteria, methods, base layers, and project users are listed.

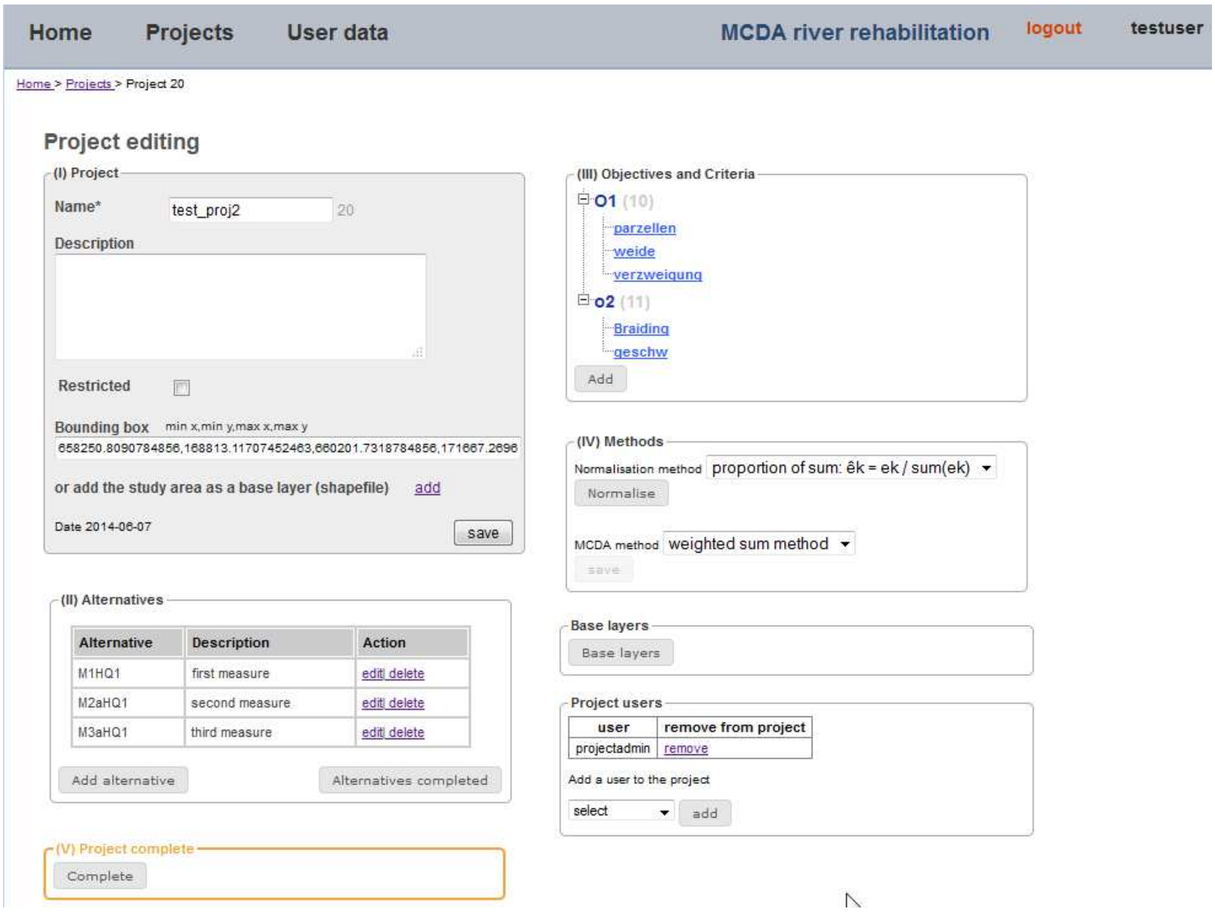


Figure 4.4 Project editing

4.2.2. Project

(I) Project: General information about the project (already added in the project creation step, but this information can be modified and updated here)

4.2.3. Alternatives

(II) Alternatives: This panel enables us to manage (add/edit/delete) the alternatives for the project. For the record, these are the alternatives that we have for the revitalisation project. Or, in other words, the possible measures we can take. The multicriteria analysis will help the user to make a choice, by ranking them from the worst to the best, based on the values of the other parameters (criteria and weights).

Figure 4.5 Add an alternative

4.2.4. Objectives and criteria

(III) Objectives and Criteria: Objectives and, above all criteria, should normally be added after all the alternatives have been added.

1. Button *Add:* To **add a new objective**

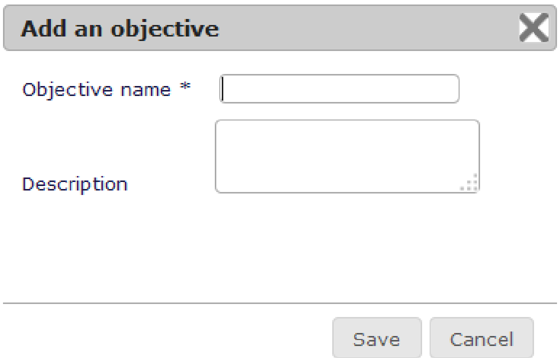


Figure 4.6 Add an objective

2. Right click on the objective to obtain a context menu with the *Edit, Add criterion* and *Delete* options (Figure 4.7a)
3. Click on ***Add criterion*** to add a new criterion to the objective (Figure 4.7a)

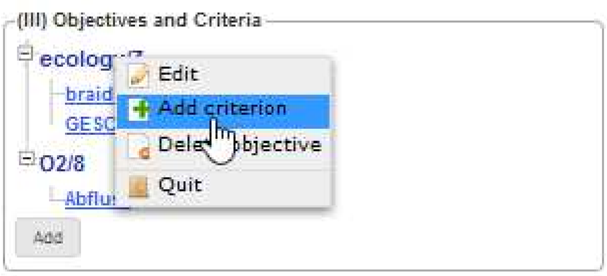


Figure 4.7a Add a criterion

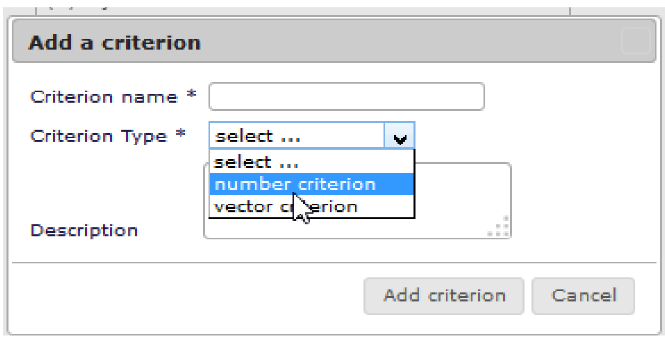


Figure 4.7b Add a criterion

Two types of criteria are available: Number criteria and vector criteria (Figure 4.7b).

- A number criterion has a numeric value for each alternative. We will enter these values in the system by the means of a csv file (see next screen description).
- A vector criterion is a vector layer (a shapefile). One layer per alternative will have to be uploaded (see, again, the next screen).

For the moment only number and vector criteria can be used, but raster criterion and/or other vector layer formats (other than shapefiles) could be added to the system in the future.

***Edit a criterion**:* Click on the criterion. This will open the criterion editing window, in which we can complete the criterion information.

Number criterion:

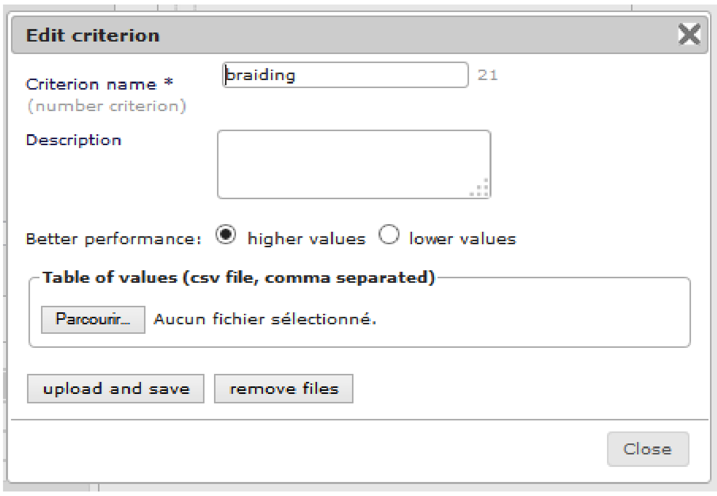


Figure 4.8 Number criterion editing

Better performance: This indicates whether the lowest or the highest values are the best for this criterion. This is important in the case where we have some criteria that are “better” when values are high, and some which are better when values are low. We should, in this case, make a reverse normalisation for the latter case (when low is better), in order to be able to take into account all the criteria properly in further analysis. If we do not do so, the computation will be erroneous, and no useful result will be given by the multicriteria analysis computation.

Table of values:

Upload of a csv file that contains the value of each alternative.

Example:

```
MODEL,VALUE
M1,2.1
M2a,3.8
```

The first line is just the attribute names (which can be whatever we want them to be).
The first column gives the name of the alternative, the second gives the value of the criterion for this alternative (we have here, for example, a value = 2.1 for the alternative M1, and a value=3.8 for the alternative M2a).

The system will automatically fill the database with these values and assign to each alternative the given criterion value. If an alternative is missing, an error message will be shown.

Vector criterion:

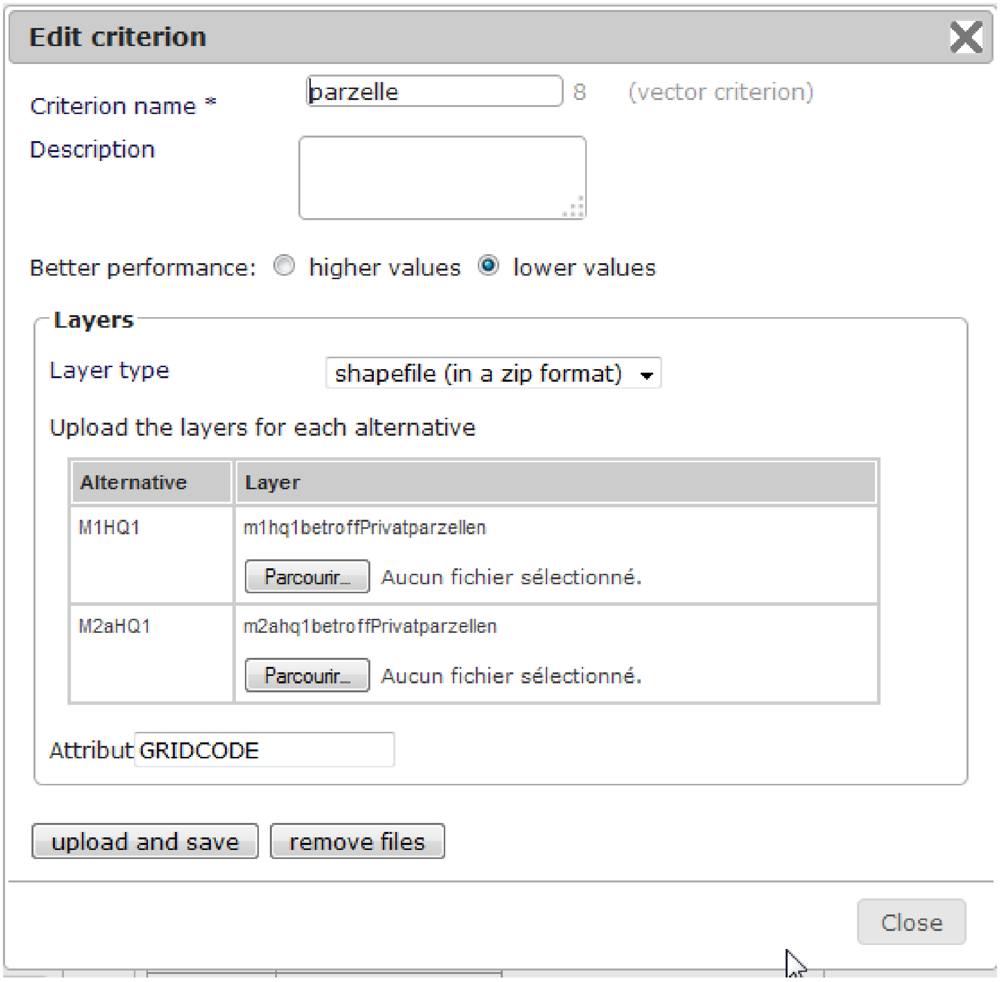


Figure 4.9 Vector criterion editing

Better performance: The same as for number criteria

Layer type: Shapefile which should be uploaded in a zip file. The name should not contain any special characters (see base layers, section 4.2.6)

Upload layers: One layer for each alternative has to be uploaded.

Attribute: The name of the attribute which contains the criterion value.

Delete a criterion: Right click on the criterion, *Delete Criterion* link (see Figure 4.10)

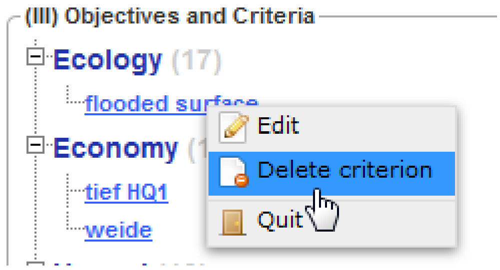


Figure 4.10 Delete a criterion

4.2.5. Methods

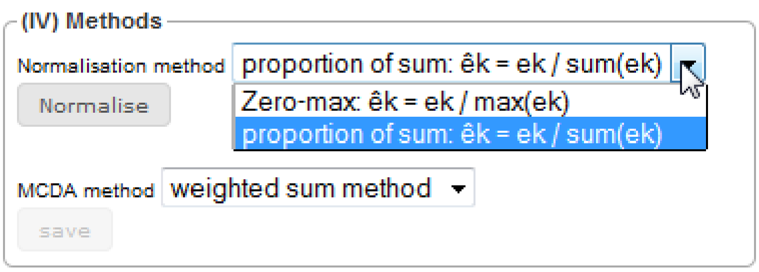


Figure 4.11 Methods

Here we can choose the particular normalisation method we want to use.
Two methods were implemented:

- êk = ek / max(ek) (division by the maximum value)
- êk = ek / sum(ek) (division by the sum of the values)

The architecture of the application, in which the normalisation methods are written in a separate module, should enable an easy implementation of other methods.

The button "*Normalise*" will normalise the values of the criteria, using the chosen method. For number criteria, the normalised values are saved in the database, while for vector layers the normalised values are saved directly in the layers (in an added attribute "normValue").

MCDA method:

Only the weighted sum method was implemented, but we leave the option open to implement other methods.

4.2.6. Base layers

We can add some base layers to the project. These layers are not used in the computation of the MCDA, but they can enable a better interpretation of the final result by providing some context.

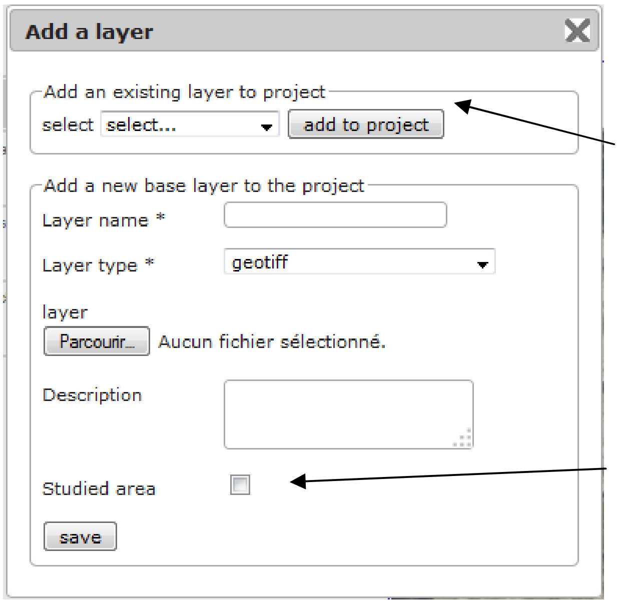


Figure 4.12 Add base layer

Base layers can be shapefiles or GeoTIFFs.

If the size of the base layer is too big (more than 10Mb), it can be loaded by ftp on the server and then published by Geoserver. This layer can then be selected later as a base layer in the MCDA application.

If this box is checked, the extent of the layer will be considered to be the study area and the bounding box (the geographical extent of the project) will be calculated and updated.

All layers (vector and geotiff) should be uploaded in a zip format.
To avoid possible problems, the layer names should contain only alphanumeric characters or underscores: a-z, A-Z, 0-9, and _ only (no accentuated or other special characters). In order to be displayed correctly, a GeoTIFF layer should have a colormap, or be a RGB composite and have a projection defined (CH1903_LV03). In the application the projection is defined in the config file.

Example of base layers: aerial image, studied area, ...

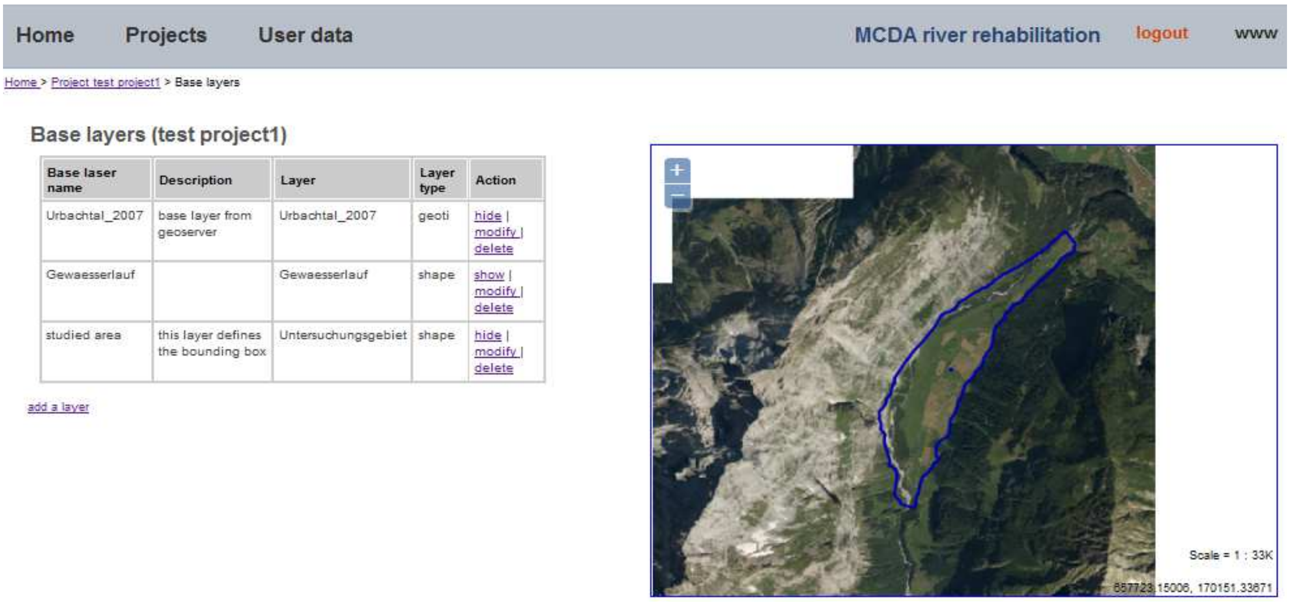


Figure 4.13 Base layers screen

Modify the layer style:

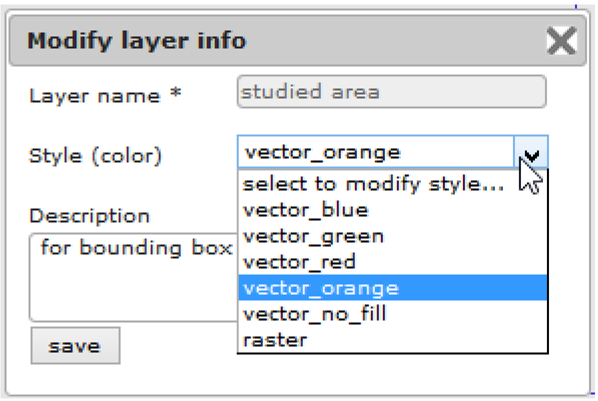


Figure 4.14 Change layer style

The style of vector layers can be modified, by selecting a style option in the dropdown box. These styles correspond to SLD (style layer description) files which are present in Geoserver. They change only the colour of the vector objects (polygons, lines or points).

The “vector_no_fill” style, draws only the outlines of the polygons.

These styles do not apply to raster (geotiff) layers, and the “raster” style is present only to provide an appropriate symbolisation for the raster in the case it was changed and its style is lost.

4.2.7. Add user to project

In order to enable other users to participate in the project (that is, enable them to make some multicriteria analyses), the project

Figure 4.15 Add a user to the project

owner should add them to the project.

A project user will see the project in his list of projects, but only the “mcda” link will be available to him (see Figure 4.2). That means he cannot edit the project and modify it, but can only make an analysis in it.

4.2.8. Complete project

Figure 4.16 Project complete

Once all the project settings are set, we can click on the “*Complete*” button. Modifications will then not be possible anymore (unless we re-open the project).

The link “mcda” on the project list (Figure 4.2) will then be enabled for all project users and multicriteria analyses can therefore be made.

4.3. Multicriteria analysis

On the project list (Figure 4.2), we have a *mcda* link for each project. If the link is not enabled, this means the project is not ready yet.

This link brings us to the following page:

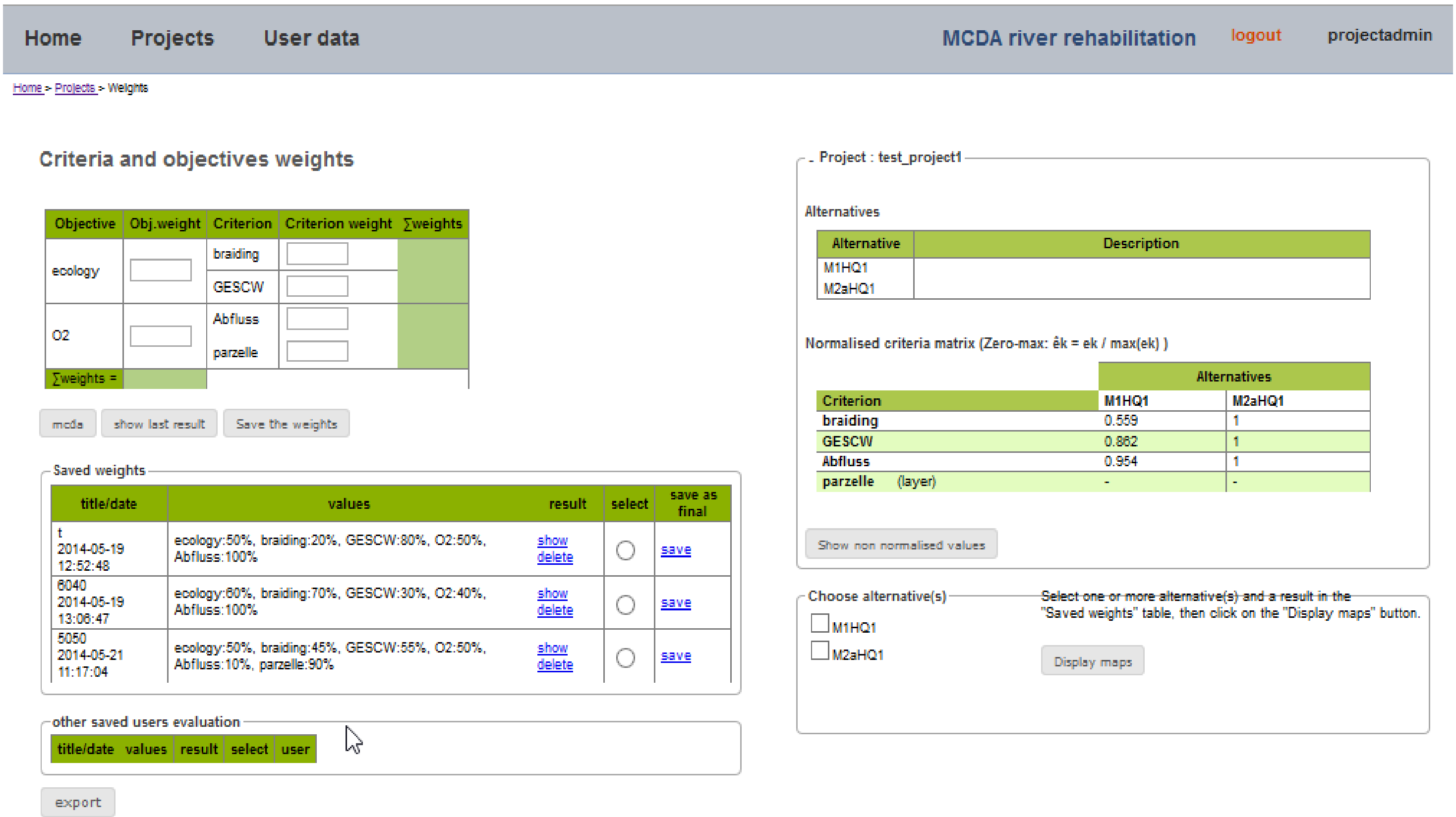
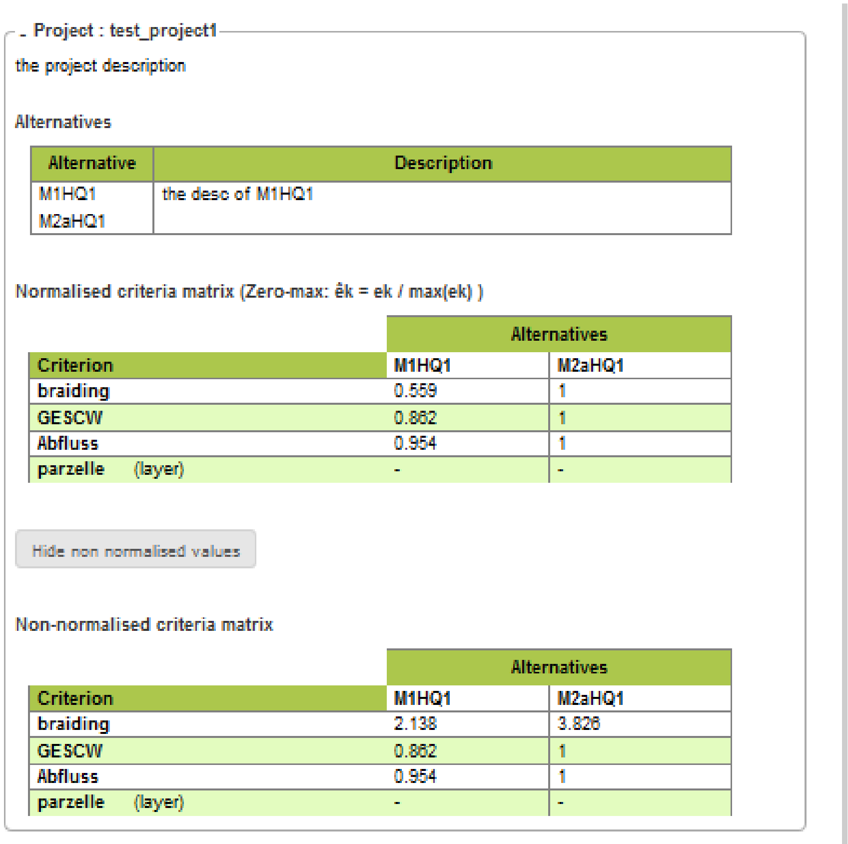


Figure 4.17 mcda screen

4.3.1. Project properties summary

The right part of the screen, gives a summary of the project properties:



Project : test_project1

the project description

Alternatives

Alternative	Description
M1HQ1	the desc of M1HQ1
M2aHQ1	

Normalised criteria matrix (Zero-max: êk = ek / max(ek))

	Alternatives	
Criterion	M1HQ1	M2aHQ1
braiding	0.559	1
GESCW	0.862	1
Abfluss	0.954	1
parzelle (layer)	-	-

Hide non normalised values

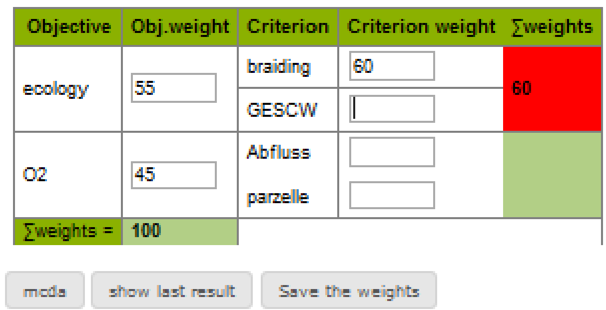
Non-normalised criteria matrix

	Alternatives	
Criterion	M1HQ1	M2aHQ1
braiding	2.138	3.826
GESCW	0.862	1
Abfluss	0.954	1
parzelle (layer)	-	-

Figure 4.18 Project properties

4.3.2. Weighting and computation

On the left part of the page, we can set the weights (in %) for each objectives and criteria.



Objective	Obj.weight	Criterion	Criterion weight	∑weights
ecology	55	braiding	60	60
		GESCW		
O2	45	Abfluss		
		parzelle		
∑weights =	100			

mcda | show last result | Save the weights

Figure 4.19 Weighting

The system will ensure that the sums of the weights are correct (sum of objectives weights = 100, sum of criteria weights for each objective = 100).

The "mcda" button, will launch the computation and make a bar plot graph representing the score of each alternative, e.g.

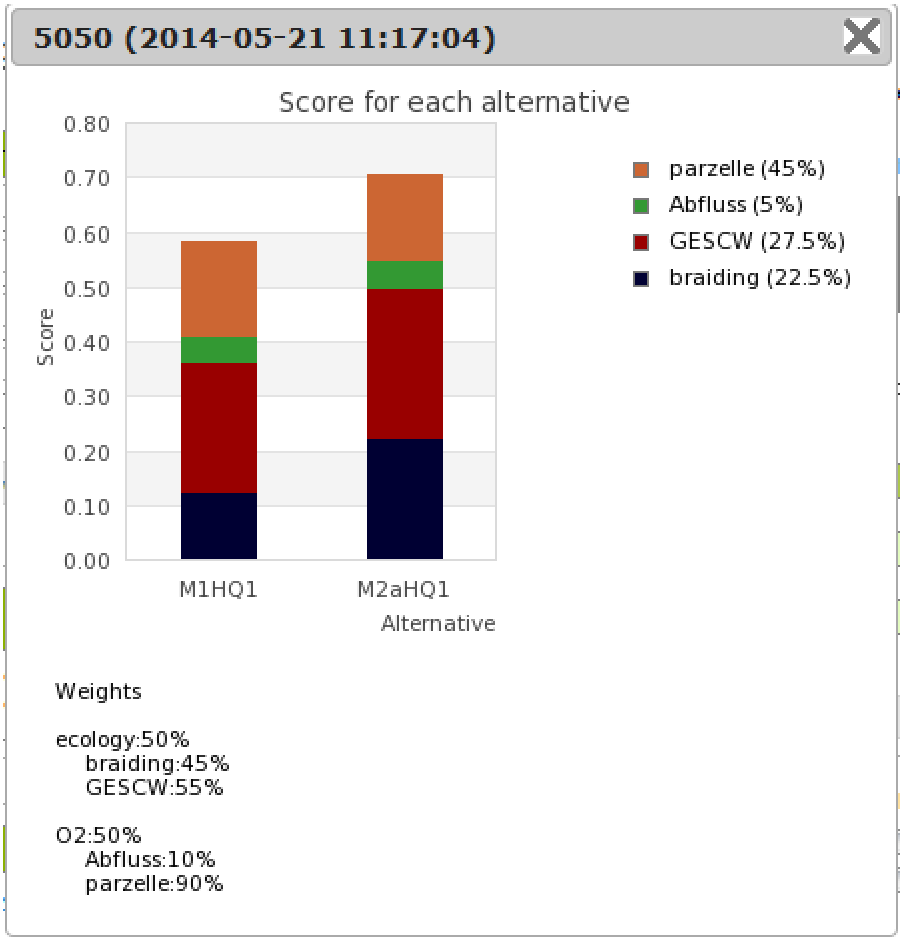
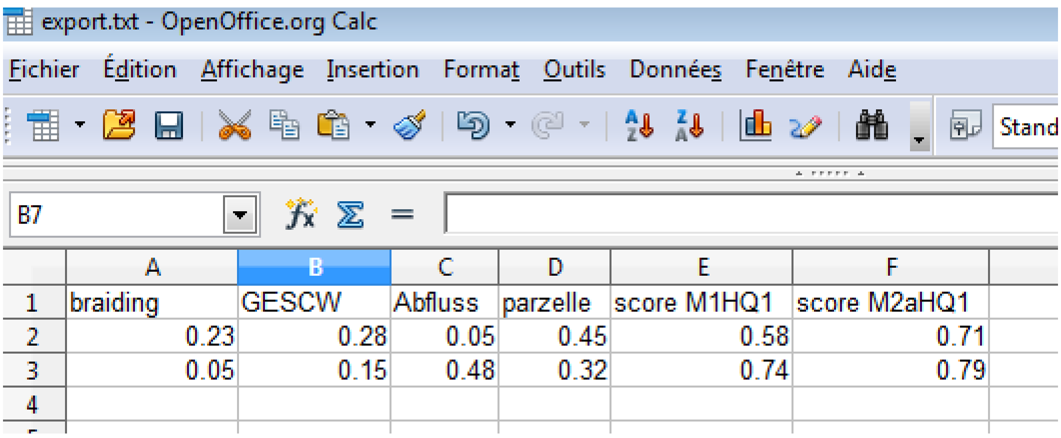


Figure 4.20 Alternatives scores

This result can be saved by clicking on the “ Save the weights” button (Figure 4.19). All saved results will be displayed in the “Saved weights” table. If the result is saved as final, the other project users will also see the result (in the table underneath) unless the project is restricted (see Figure 4.3). In that case only the project owner will see results of other users.

The ***export*** button (see Figure 4.17) enables us to export all results in a csv file, for further analysis.



	A	B	C	D	E	F
1	braiding	GESCW	Abfluss	parzelle	score M1HQ1	score M2aHQ1
2	0.23	0.28	0.05	0.45	0.58	0.71
3	0.05	0.15	0.48	0.32	0.74	0.79
4						

Figure 4.21 Export csv file

In this example, the first four columns are the criteria weights, while the last two (starting with "score...") are the results obtained for each alternative.

Finally the user can choose his alternative(s) and preferred weights result, and display a final map.

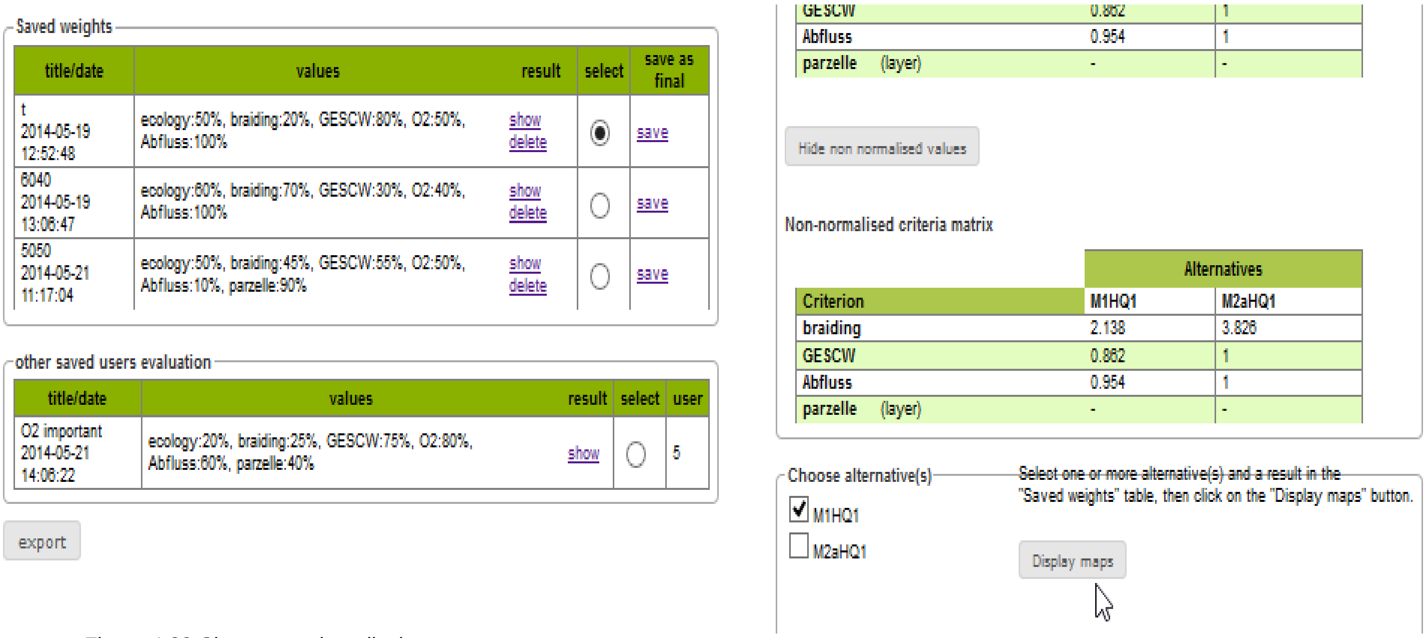


Figure 4.22 Choose result to display

Final map, where we have a result layer (here for example @M2, for the alternative M2)

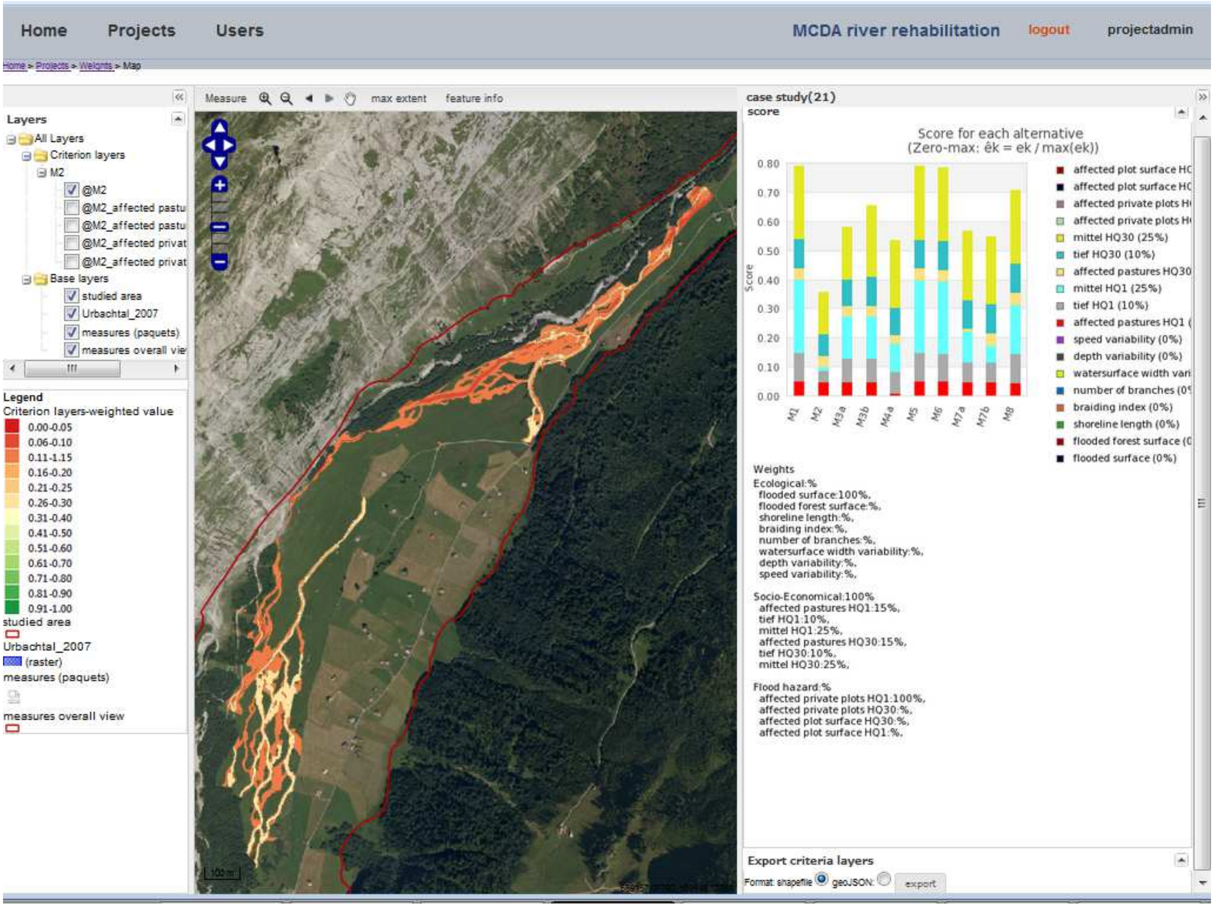


Figure 4.23 Final map

We can get feature information for the criteria layers, by activating the “feature info” tool:

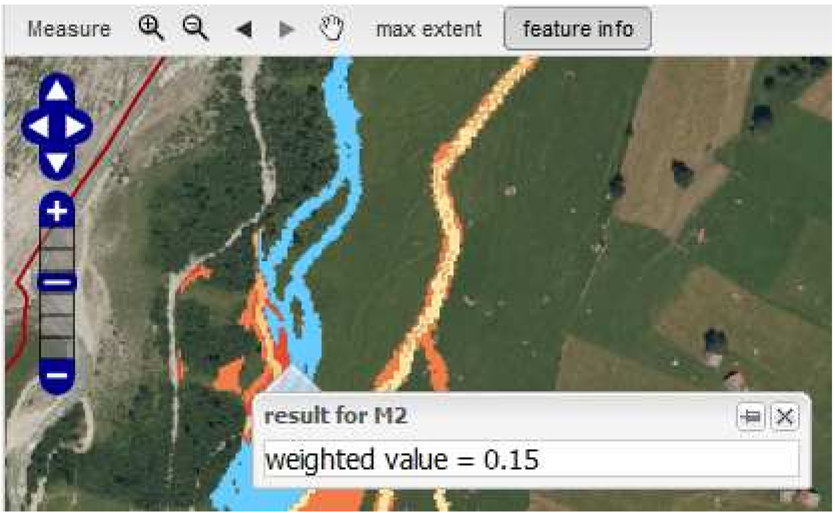


Figure 4.24 Feature info

At the bottom right of Figure 4.23 there is an export button, which enables the user to export the criteria layers (in shapefile or GeoJSON format).

5. Case study: the Sandey floodplain

The Sandey floodplain in Canton Bern (in Urbach valley), Switzerland, is a floodplain of national importance. The federal regulations on alluvial zones of national importance stipulate that alluvial zones which are not altered should be preserved and that the other ones should be rehabilitated if possible, in particular by restoring the natural dynamic of the river. If a rehabilitation is not possible, a revalorisation of the zone should be made (by the creation of artificial biotopes) (Lachat et al., 2001).

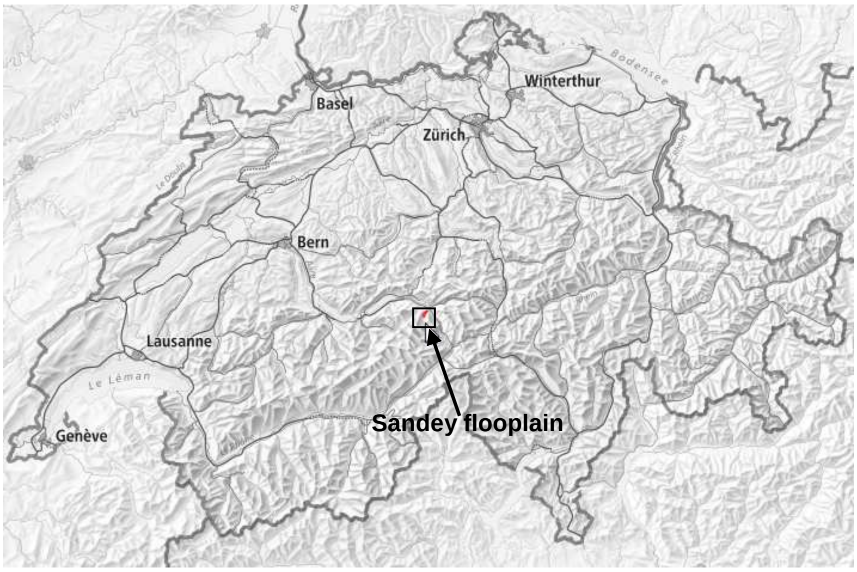


Figure 5.1 Case study: Sandey floodplain
© swisstopo

The floodplain is about 4 km long and 125 hectares in area, and is up to 600 m wide.The river (Urbach) is affected by a hydroelectric power plant (6 km upstream of the flood plain) which diverts 30% of the river water. Moreover, the floodplain is also affected by several longitudinal levees which were built in the 1990's for flood protection (Doering et al., 2013, Doering, 2012).

In this chapter we will use the developed application to analyse the possible measures which can be taken to restore the floodplain. As I am not a specialist in river restoration, this part of my manuscript will not be developed in too much detail. The aim of this chapter is to show the use of the application in a real case, to see what results can be obtained from it and what benefit it can bring.

I have followed the work of Blaurock (2012), who has defined in detail the possible measures and indicators, and has already made a multicriteria analysis of this site.

The used objectives and criteria:

Objective	Obj.weight	Criterion	Criterion weight	∑weights
Ecological		flooded surface	25	100
		flooded forest surface	20	
		shoreline length	10	
		braiding index	10	
		number of branching points	10	
		watersurface width variability	5	
		depth variability	10	
		speed variability	10	
Socio-Economical		affected pastures HQ1	15	100
		low HQ1	10	
		medium HQ1	25	
		affected pastures HQ30	15	
		low HQ30	10	
		medium HQ30	25	
Flood hazard		affected private plots HQ1	25	100
		affected private plots HQ30	25	
		affected plot surface HQ30	25	
		affected plot surface HQ1	25	
∑weights =				

Figure 5.2 Case study, criteria weights

Here is a short description of the objectives and criteria:

Ecological

The objective is here to enhance the structural diversity of the river and thus to attempt to restore a natural state of the floodplain.

- Flooded surface: the annual mean area of the flooded surface
- Flooded forest surface: the annual mean area of the surface of the forest which is flooded
- Shoreline length = (total shoreline length) / (main channel length)
  where the main channel length was established to be 3961 m
- Braiding index = (length of all channels) / (main channel length)
- Number of branching points: points where two or more branches meet.
- Water surface width variability:

$$VC_b = \frac{\sigma_b}{\mu_b} \times 100\% \quad \sigma_b = standard\ deviation\ of\ the\ water\ surface$$
$$\mu_b = mean\ value\ of\ the\ water\ surface$$

- Depth variability:

$$VC_h = \frac{\sigma_h}{\mu_h} \times 100\% \quad \sigma_h = standard\ deviation\ of\ the\ water\ depth$$
$$\mu_h = mean\ value\ of\ the\ water\ depth$$

- Speed variability

$$VC_v = \frac{\sigma_v}{\mu_v} \times 100\% \quad \sigma_v = standard\ deviation\ of\ the\ water\ flow\ speed$$
$$\mu_v = mean\ value\ of\ the\ water\ flow\ speed$$

Socio-Economical

In this objective, the impact on pastures should be minimized.

- affected pastures (HQ1/HQ30): pastures which are flooded (layer). The layer is composed of polygons, whose attribute values depend on the dangerousness of the flood (velocity x depth)
- low (HQ1/HQ30): area of zones of low quality of grass (for cattle grazing) which are flooded
- medium (HQ1/HQ30): area of zones of medium quality of grass (for cattle grazing) which are flooded

where HQ1 refers to a 1-year flood event and HQ30 to a 30-year flood event.

Flood hazard

The impact on private plots (and therefore possible habitations) should be minimized.

- affected private plots HQ1/HQ30: privates plots which are flooded (layer). The layer is composed of polygons, whose attribute values depend on the dangerousness of the flood (velocity x depth)
- affected plot surface HQ1/HQ30: the area of private plots which are flooded.

The weights of the criteria will be set as in Figure 5.2. in the scenarios which are described further on in section 6.1.

The criteria have been previously extracted using the Python tool described in section 3.1. As result of this extraction, we obtain each of the number criteria in a csv file format (in a directory named "csv"), and each of the layer criteria in a compressed shapefile (in the directory "zip").

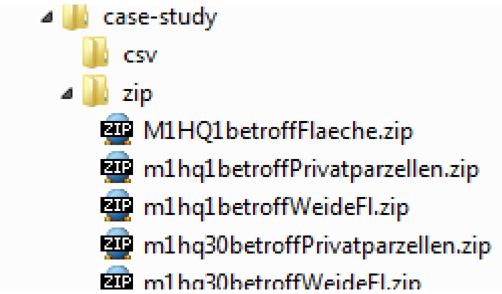


Figure 5.2b Result of the indicators extraction

The possible alternatives (or measures M1, M2, …, M8) are also described in detail in Blaurock (2012, p.12). They essentially consist in opening ways or (re-)connecting disconnected channels of the river.

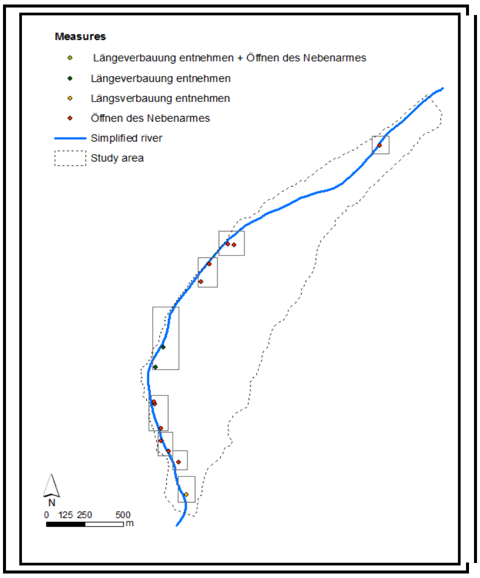


Figure 5.3 Possible measures

5.1. Result

As in Blaurock (2012) we have set the objectives' weights as follows:

1) Ecological : 100%
2) Economical: 100%
3) Flood hazard: 100%

We thus have three scenarios in which one of the objective is always maximised (100%).

We have used the *proportion of max* (zero-max) normalisation method (see section 2.2). The ecological criteria were set with "the higher values are the best" logic, while the economical and hazard criteria were set using the "lower values are the best" logic.

In the following graphs, the higher the score, the better the alternative ranks.

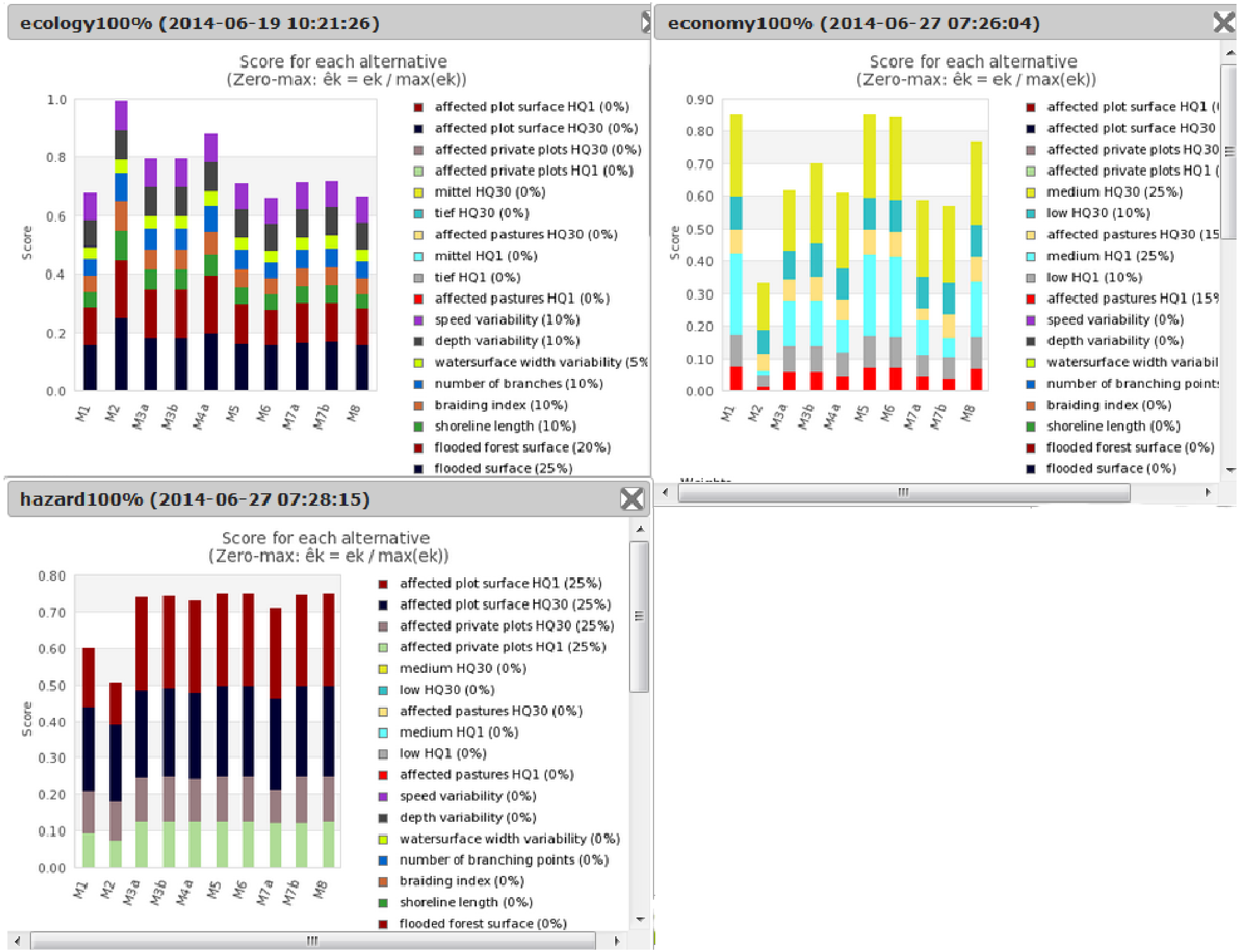


Figure 5.4 Results for three max scenarios

We observe that although the measure M2 is the best for the first objective (ecology), it is the worst one for the two last objectives (economy and hazard), as the flooded area is bigger than with other measures (see Figure 5.5).

With the "economy100%" evaluation (Figure 5.4), we can display, for example, the maps for M1 and M2 alternatives (best and worst alternatives), and observe the difference in the flooded pasture zones.

M1 M2

Figure 5.5 Result map example

Mixed scenario

I have also tried to make an evaluation that gives some different weights to the three objectives (a "mixed" scenario). I have chosen to give 25% to the ecological objective, 25% to the economical one, and 50% to the flood hazard (assuming that reducing the hazard is the most desired objective) and kept the criteria weights the same as before:

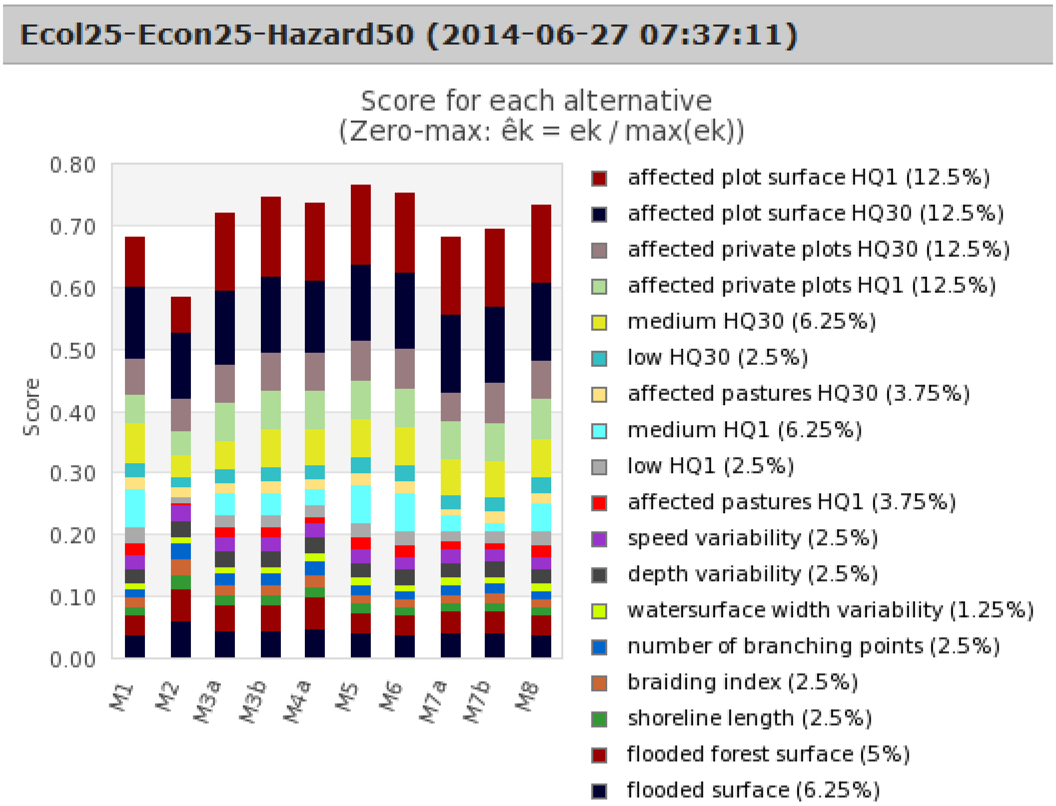


Figure 5.6 Result for mixed scenario

Again, according to the MCDA results, the M2 alternative is the worst one. As written above, I will not analyse the result in detail, but comparing this graph with the ones obtained previously, we can note that, for example, the M3b or M5 measures give a quite good result for each objective separately, as well as in the latter evaluation.

5.2. Sensitivity analysis

Using the sensitivity module, 5000 random weights (preserving rank order of the previous evaluations, Figures 5.4 and 5.6) were generated, as well as the score and ranking order of the ten alternatives. Importing these csv files in the software R[29], we can then create boxplots for each of the four evaluations.

[29] http://www.r-project.org/, software and programming language for statistical computation

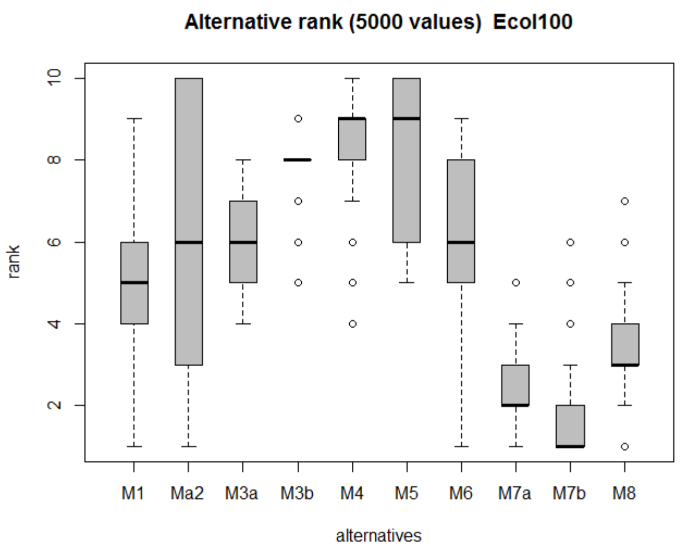


Figure 5.7 Boxplot Ecology 100%

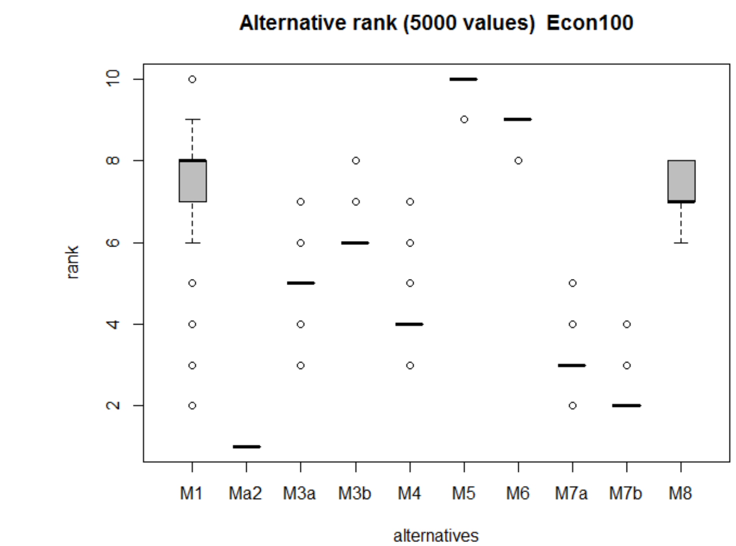


Figure 5.8 Boxplot Economy 100%

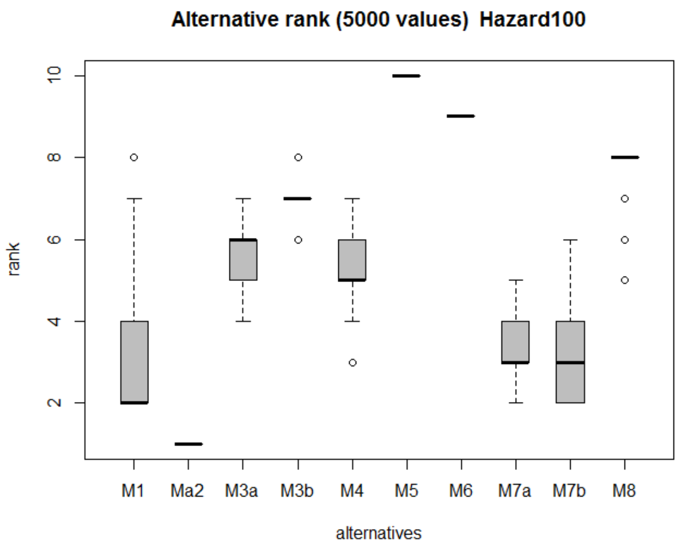


Figure 5.9 Boxplot Hazard 100%

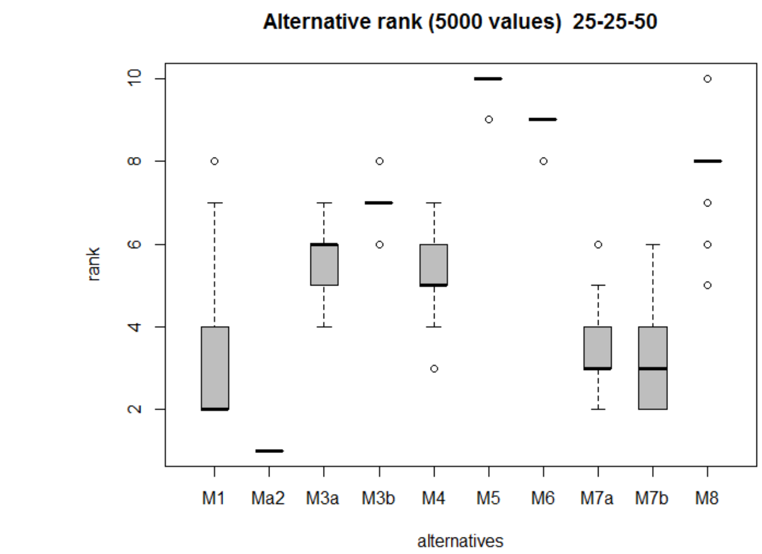


Figure 5.10 Boxplot Mixed scenario

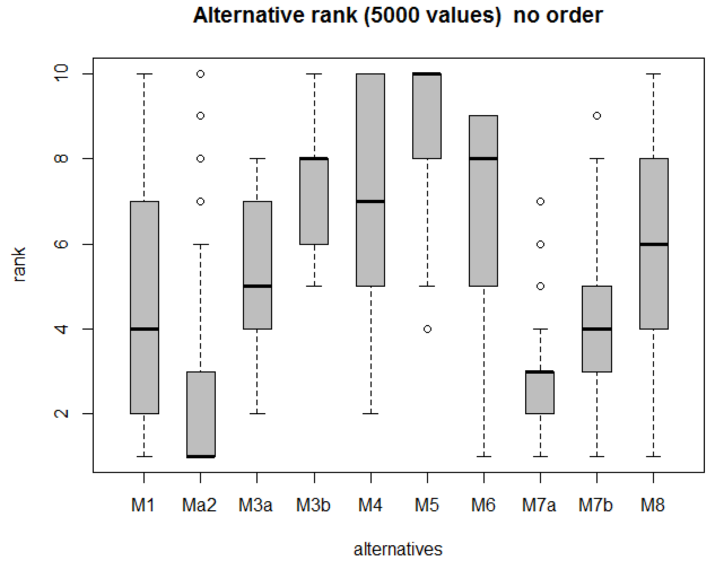


Figure 5.11 Boxplot Mixed scenario (random values with no order)

Where

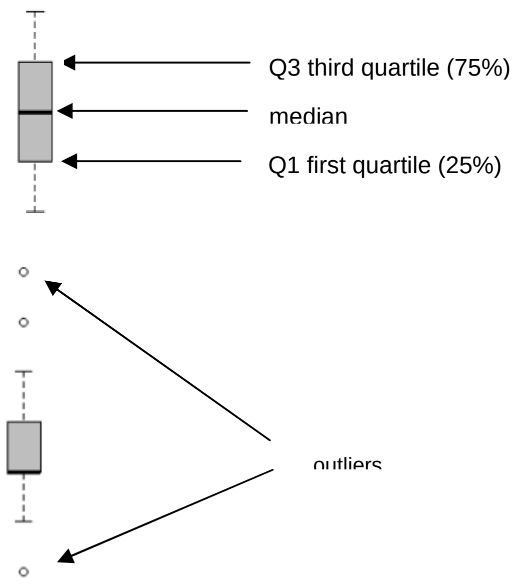


Figure 5.12 Guide to reading boxplots

The interquartile range is defined as IQR = Q3 – Q1 (with a probabiliy of 50 % of being in the interquartile range).

The outliers are values which are < Q1 - 1.5(IQR) or >Q3 + 1.5(IQR) [30]

We note that as the rank order of the weights are the same for the hazard evaluation and for

[30] http://en.wikipedia.org/wiki/Interquartile_range

the "mixed" solution, we obtain the same graphs in Figures 5.9 and 5.10.

From Figures 5.7 to 5.11, we can observe that the alternative M2 is always the last ranked in an evaluation where hazard or economy objectives are preferred to the ecology objective (also in the mixed evaluation, Figure 5.10).

Figure 5.11 gives the result of a set of totally random weights (with no preferred order). Here too, the M2 alternative is badly ranked. Only outliers reach better ranking positions. This alternative will certainly not be chose. M5 is well ranked in all graphs, which could indicate that this could be a good alternative.

Coming back to our evaluation in Figure 5.6, we can compare it to Figure 5.14 (where the random values have kept the same order than the latter evaluation):

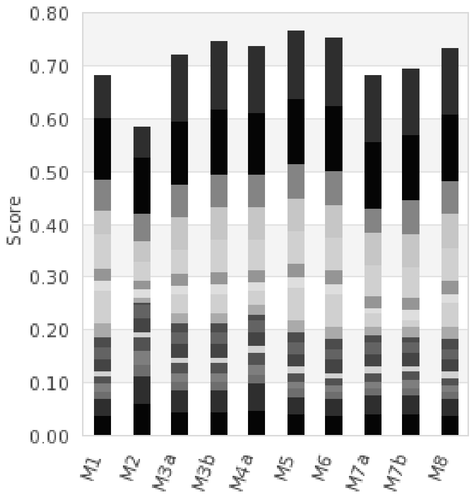


Figure 5.13 Mixed scenario result

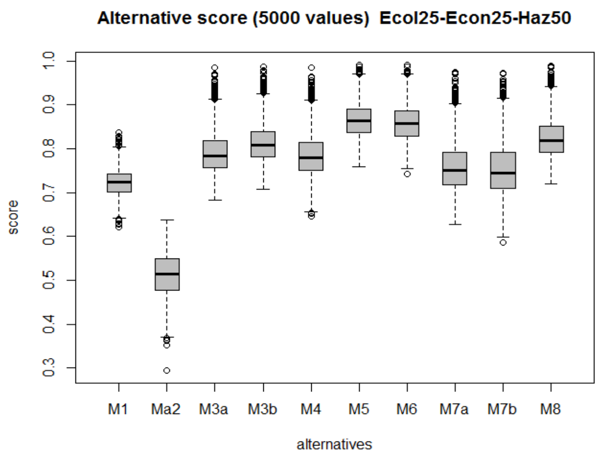


Figure 5.14 Mixed scenario boxplot scores

We observe that the scores obtained in our evaluation and in the statistical results, are quite similar, above all in the ranking of the alternatives (M2a is worst, M5 and M6 are the best). Furthermore, Figure 5.10 shows us that the ranking of the alternatives M2a, M3b, M5, M6 and M8 is not particularly sensitive to changes in the weights. This indicates that the results obtained by our evaluation are not too sensitive to the weights, and that it is, thus, reliable.

6. Discussion

The provided case study has demonstrated that the computation of a MCDA can be very easily made using the developed application. The automated computation enables us to compare different weightings for different objectives, and to visualize the result, showing the contribution of each criterion, as well as the resulting maps. The fact that the computations are automated enables us to easily make a Monte Carlo simulation, by generating a large quantity of random (or rank order random) weights, and then to obtain the ranking result of the alternatives. We can, thus, observe the statistical tendencies found in the ranking of the alternatives. We find that some alternatives are always last, while others are always well ranked. We also observe that some alternatives are somewhat insensitive to weighting changes (Figure 5.10).

The automatic extraction of the indicators is also a great help in the preparation of the project. Automation can also avoid some errors which can be easily made during a tedious and laborious work.

As a GIS-user could be frustrated by the limited provided ways of displaying the maps on the web page, the export of the criteria layers enables him to work on these layers (weighted layers) further, on his own computer, with the GIS software of his choice.

The usability of the application could, however, be improved. In particular, the process of the creation of the project could be more straightforward. For example, the current method for the addition of the layers of a criterion is not very practical and user friendly: You have to select each file by browsing to it, and you cannot change only one of the layers (all layers of a criterion have to be uploaded at the same time, which is a bit tedious if you have made a mistake). A drag and drop solution could be a better solution here. It would also be practical to be able to make a copy of a project (with its alternatives, criteria and base layers). We could then, for example, choose another normalisation method, or modify some of the criteria or objectives, without modifying the initial project or being forced to create and re-enter all the details of an essentially identical project, again.

Some other possible characteristics and capabilities of the application can also be imagined:

- the possibility of adding sub-objectives could be interesting (the database already has this possibility implemented).
- implementation of other normalisation methods (for example the min-max method described in section 2.2).

- the possibility of making an iterative process. That is, if you have chosen different possibilities of combination of measures, we can imagine that the tool could make the MCDA computation again with these combinations as alternatives.
- the integration of R functions in PHP, in order to directly generate some statistical results from the application (e.g. the boxplots of section 5.2).
- pdf creation with all relevant information (maps, graphs, …) .

Some application testing with "real" users still needs to be performed, and would be useful to help to identify any malfunctions or missing, but desired functions which would help in the decision making process.

From a technical point of view, the use of open source tools has proven to be efficient and has offered a wide range of possibilities. Several remarks can be made:

- we have chosen to use vector layers and to work with them directly. This works all right with layers that do not have a very large number of features, but could cause performance problems with very large files. Importing the data into a spatial database is then probably more efficient (Giuliani et al., 2013). However, we have not encountered this type of problem in our testing and with our case study (see Chapter 5).
- the transformation of vector layers to rasters is a relatively long process. The process is done before the layers are displayed (Figure 3.13). However, the transformation could have probably been done just after the normalisation process (Figure 3.12) and thus could be done just once (during the project definition), instead of each time the user displays the result maps.

7. Conclusion

The developed tool can provide a useful support for the difficult choice of what measures are to be taken for a river rehabilitation.

The Web application enables the user to work with the tool without any installation. In addition to facilitating the use of the application, this ensures that all users have the same version of the application. A user can be added to a project (by the project administrator) and then directly make a MCDA calculation with his own chosen weights. This process is very easy and fast, especially when compared to the time-consuming process of computation by hand. The ease of sharing data and results within the application is also a great advantage in a project such as river restoration, where multiple stakeholders and their varying perspectives must be taken into account.

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9. Appendices

9.1. Appendix A: used softwares, libraries and programming language version

- Apache Tomcat 7.0.53
- ArcGIS 10.2
- Codeigniter 2.1.4
- ExtJS 3.4.1
- GDAL/OGR 1.10.1
- GeoExt 1.1
- GeoServer 2.5
- GeoTools 11.0
- Java 1.6.0_30 (OpenJDK)
- JpGraph 3.5.0b1
- JQuery 2.0.3
- MySQL 5.5.32
- Openlayers 2.13
- PHP 5.5.7
- Python 2.7
- R 3.1.10
- R studio 0.98.953

9.2. Appendix B: example of custom WPS

The WPS were implemented in Java, using the Geotools library.

Two essential components are needed:

- The main class which implements the GeoServerProcess interface (see Figure 8.1)
- An XML file (*applicationContext.xml*) which enables GeoServer to load the WPS when it is started (see Figure 8.2)

In the "*execute"* function of the main class, any process can than be called. In the following example (Figure 8.1), we call the *"calculate"* function which was implemented in the

MakeGeotiff class (Figure 8.3)

Example: WPS for weighting and adding the raster layers

Figure 8.1 WPS example: Addcriterialayers class

```java
package org.geoserver.mcda.addcriterialayers;

import org.geoserver.wps.gs.GeoServerProcess;

/**
 * This process multiplies the criteria rasters (of one alternative) by the corresponding
 * weights and then adds them into a result raster file.
 *
 * @author alexia chang-wailing
 * @version june 2014
 */
@DescribeProcess(title = "addcriterialayers", description = "raster process (weight and add)")

public class Addcriterialayers implements  GeoServerProcess {

    @DescribeResult(name = "result", description = "'ok' or error message ")
    public String execute(
            @DescribeParameter(name = "criteria", description = "geotiff paths") String criteria,
            @DescribeParameter(name = "criteriaWeights", description = "weights of the criteria") String weights,
            @DescribeParameter(name = "alternative", description = "alternative name") String alternativeName) {

        try {
            return MakeGeotiff.calculate(alternativeName, criteria, weights);

        } catch (Exception e) {
            e.printStackTrace();
            return e.getMessage();
        }


    }
}
```

Figure 8.2 WPS example: applicationContext.xml

```xml
<?xml version="1.0" encoding="UTF-8"?>
  <!DOCTYPE beans PUBLIC "-//SPRING//DTD BEAN//EN" "http://www.springframework.org/dtd/spring-beans.dtd">
  <beans>
    <bean id="Addcriterialayers" class="org.geoserver.mcda.addcriterialayers.Addcriterialayers"/>
  </beans>
```

Figure 8.3 WPS example: extract of the process class

```java
import org.geotools.gce.geotiff.GeoTiffReader;
import org.geotools.gce.geotiff.GeoTiffWriter;
import org.geotools.referencing.CRS;
import org.opengis.parameter.ParameterValueGroup;


/**
 * This class makes some processes on the geotiff files
 *
 * @author alexia chang-wailing
 * @version june 2014
 */
public class MakeGeotiff {


    /**
     * First multiply each criteria by the corresponding weight, then add all the criteria together
     * to obtain a result Geotiff
     *
     * @param resultPath the path  of the result file (Geotiff)
     * @param scriteria the list of criteria separated by a ;  (c1;c2;...)
     *        A criteria is given by a Geotiff file. c1 is the path to the file for the criteria1
     * @param sweights  the list of weights (duble) separated by a ;  (w1;w2; ...)
     * @throws Exception
     */
    public static String calculate(String resultPath, String scriteria,String sweights) throws Exce

        String[] criteriafiles = scriteria.split(";");
        String[] weights = sweights.split(";");

        if (criteriafiles.length != weights.length){
            throw new Exception("arguments not valid");
        }


        //this list will contain the coverages after the multiplication by the weight
        List<GridCoverage2D> coverages = new ArrayList<GridCoverage2D>();

        Hints hints = new Hints();

        // dont't use the EPSG-Factory because of wrong behaviour
        hints.put(Hints.CRS_AUTHORITY_FACTORY, CRS.getAuthorityFactory(true));
```

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