Massimo BARBIERI (*), Jaime BONACHEA (**), Alessandro CORSINI (*)
& Cecilia GIUSTI (*)

GIS-BASED METHOD FOR GEOMORPHOLOGICAL IMPACT ASSESSMENT ON A RAILWAY TRACK IN PROVINCE OF MODENA (ITALY)

ABSTRACT: BARBIERI M., BONACHEA J., CORSINI A. & GIUSTI C., *Gis-based method for Geomorphological Impact Assessment on railway track in Province of Modena (Italy)*. (IT ISSN 0391-9838, 2002).

The paper illustrates a method for the assessment of geomorphological impacts and risks related to the construction of an high speed railway track. The method has been applied in the study area of Castelfranco Emilia Municipality (Province of Modena, northern Italy) as part of the activities of the EC-project GETS. The method fits into general Multi-Criteria Analysis procedures and it is based on the use of GIS to store, elaborate and manage maps making up the basic components of impact and risk matrices. Three possible tracks of the railway and geomorphological components falling into the assets, resources and processes categories, have been considered in the analysis. In the end, a number of impact and risk maps has been generated and combined in order to estimate impacts and risks for each alternative and to provide decision makers with cartographic tools to evaluate the best possible alternative track from the geomorphological standpoint.

KEY WORDS: Geomorphological Impact Assessment, Multi-Criteria Analysis, GIS, Railway track, Castelfranco Emilia (Italy).

RIASSUNTO: BARBIERI M., BONACHEA J., CORSINI A. & GIUSTI C., *Un Metodo basato su tecniche GIS per la Valutazione dell'Impatto Geomorfologico di un tracciato ferroviario in Provincia di Modena*. (IT ISSN 0391-9838, 2002).

L'articolo illustra un metodo per la valutazione degli impatti e dei rischi geomorfologici legati alla costruzione di un tracciato ferroviario per un treno ad alta velocità. La metodologia è stata applicata all'area di studio del Comune di Castelfranco Emilia (Provincia di Modena, Nord Italia), in quanto parte del progetto europeo GETS. Il metodo si basa su procedure di Analisi Multi-Criteriale e si avvale di tecniche GIS per l'immagazzinamento, l'elaborazione e la gestione delle carte, componenti base per le matrici dell'impatto e del rischio. Nell'analisi sono stati considerati i tre possibili tracciati della ferrovia e come componente geomorfologica i beni, le risorse e i processi. Sono state prodotte e incrociate una serie di carte di impatto e di rischio per stimare gli impatti e i rischi geomorfologici di ogni alternativa e per fornire ai decisori uno strumento cartografico per la valutazione del miglior tracciato.

TERMINI CHIAVE: Valutazione d'Impatto Geomorfologico, Analisi Multi-Criteriale GIS, Tracciato ferroviario, Castelfranco Emilia (Emilia Romagna).

INTRODUCTION

A method for the assessment of geomorphological impact and risk related to the construction of an high speed railway track (TAV, Tracciato Alta Velocità) in a flood plain area has been developed as part of the activities of GETS project (Geomorphology and Environmental Impacts Assessment to Transportation Systems) financed by the EC Programme TMR (Training and Mobility of Researchers). This method has been applied to an area located in the Municipality of Castelfranco Emilia (Province of Modena, Northern Italy), where such a type of transportation system will soon be constructed. In particular, the method has been conceived for the analysis and the quantitative assessment of possible geomorphological impacts and risks related to each of the three alternative paths of the railway that were proposed to the decision makers by the constructing company (herein referred to as TAV1, TAV2 and TAV3). The method provides such an assessment in the form of overall impact and risk maps that can be used for immediate visualisation as well as precise estimation of the consequences of any alternative track of the project.

The study area of Castelfranco Emilia is located in the southern central part of the Po river alluvial plain, in the

Apennine fluvial system domain (fig. 1). Two rivers, flowing northward, cross the Castelfanco Emilia territory: the Panaro river, along the western boundary, and the Samoggia rive, along the eastern one. The morphological characteristics of the area are principally related to the connected evolution of the Panaro and Samoggia rivers and to abandoned fluvial forms (Castaldini, 1989) and to the progressive decrease in texture of the alluvial deposits which takes place from south to north (downstream). In particular the decrease of texture and slope plain is the cause of the presence, near Castelfranco Emilia, of natural water springs termed «risorgive» and of the change in the fluvial pattern of the Panaro river from a braided pattern to a meandering one (Castiglioni & *alii*, 1997).

METHOD OVERVIEW

The method has its scientific roots on studies carried out in a previous EC-project called «Geomorphology and Environmental Impact Assessment», funded in the framework of the «Human Capital and Mobility» Programme (Panizza & Fabbri, 1996). The basic principle put forward in that project is that a mutual influence between engineering projects and geomorphology exists, resulting, on the one hand, on an impact of the project on the geomorphological components of the construction site and of surrounding areas and, on the one other hand, on a risk for the project itself related to natural processes (Panizza, 1992; Cavallin & *alii*, 1994; Marchetti & *alii* eds., 1995; Panizza, 1996). Ultimately, this network of mutual interrelationships between geomorphological components and the alternatives for a certain project can be framed into general Multi-Criteria Analysis approaches (Beinat & Nijkam, 1998), with impact and risk matrixes being structured using maps as basic elements.

The adopted procedure is schematised in fig. 2. It is divided into two main parts, an impacts branch (to the left, in fig. 2) and a risks branch (to the right, in fig. 2) and, altogether, comprises four basic work-steps (named A, B, C, D in fig. 2).

Work step A regards the creation of a cartographic database within a GIS. This database has to include thematic maps representing all of the three different proposed railway tracks, as well as other thematic maps, and related attribute tables, representing the various geomorphological components to account for (Barbieri & *alii*, 2000).

Work step B is about the generation of a set of maps displaying impacts and risks for each given alternative track. In the impacts branch of fig. 2, the following operations need to be performed:

– transformation of the qualitative thematic maps (representing classes of geomorphological components), into «values maps» reflecting the quality, fragility or rarity of each of the classes represented in the parent thematic maps. The values assigned to each class, ranging from a
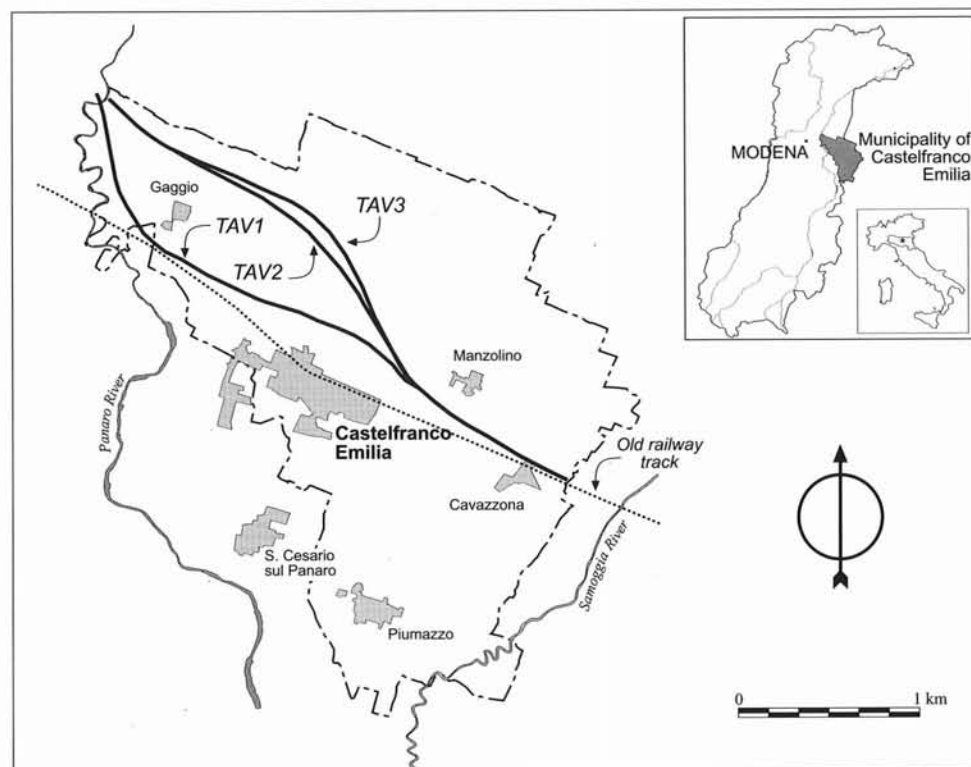

FIG. 1 - Localisation of the study area and of the three akternative paths of the high speed railway track (TAV1, TAV2, TAV3).
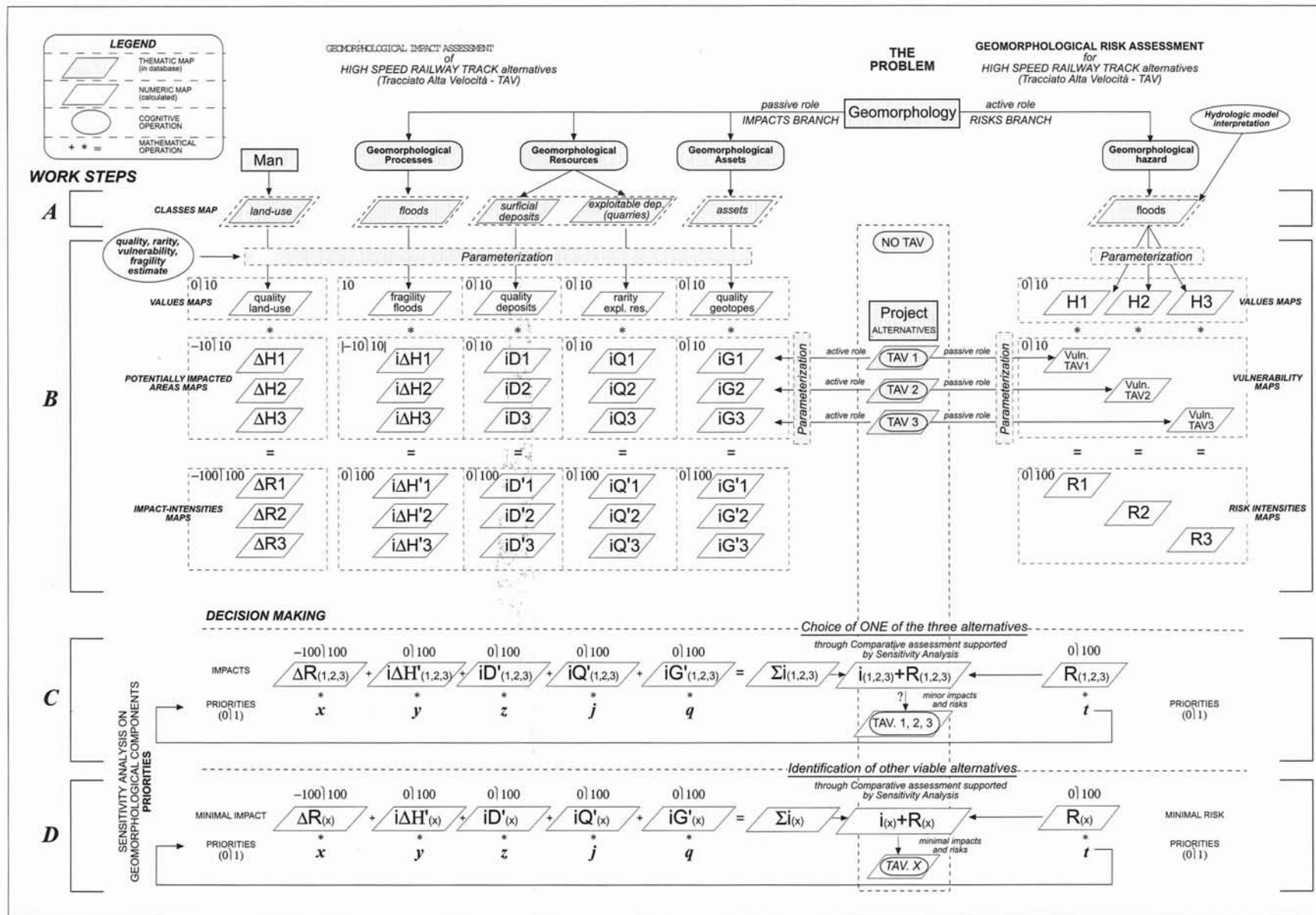
FIG. 2 - General scheme of the conceptual and operative framework of the method.

minimum of 0 (no quality or rarity or fragility) to a maximum of 10 (top quality or rarity or fragility), can be defined by means of the Delphi method (Balkey, 1969);

– transformation of the railway alternatives track maps into «potentially impacted areas maps». These maps represent areas of value ranging from 0 to 10, in relation to the level of potential impact due to the railway;

– one-by one cross multiplication of geomorphological components parametric maps and potentially impacted areas map. This results in «impact intensities maps» that quantify, in a range from 0 to 100, the actual impacts related to each geomorphic component and alternative.

In the risks branch of fig. 2, which is dedicated to the assessment of flood risk suffered by each of the three alternatives, the following operations need to be performed:

– transformation of qualitative maps of classes representing flood hazard (defined using the outputs of a flood propagation model, Cf. Bertens & *alii*, 2000, on the basis of the computed height of the water wave) into «values maps» representing zones with hazard levels ranging from 0 to 10 (min-max hazard).

– transformation of the railway alternative tracks into «maps of vulnerability» to floods, by setting vulnerability values according to the different constructional characteristics of the railway. In practice, if the railway track runs on an embankment, the vulnerability has been considered high (value = 10) whereas if it runs on a viaduct the vulnerability has been considered low (value = 5);

– one-by-one cross multiplication of flood hazard values maps and project vulnerability values maps to create a «flood risk map» which quantifies, in a range from 0 to 100, actual levels of flood risk for the structure associated to each alternative.

Work step C focuses on the identification of a railway track, within the set of given alternatives, that is preferable from the geomorphological standpoint. This is achieved by means of a Multi-Criteria Procedure of comparative assessment centred on the definition of priorities within the environmental components suffering impacts and the risk suffered by the structure. In practice, the following operations need to be performed:

– identification of priorities for the different environmental components which suffer impacts and for the risk suffered by the structure (weight can be defined by means of the Delphi method or can be set subjectively to reflect decision makers preferences on respect to any geomorphological component);

– comparison of the overall weighted sum of impacts and of the risk associated to each alternative with various combinations of priorities (in other terms, a Sensitivity Analysis has to be carried out on priorities);

– identification of the best alternative, from the geomorphological standpoint, for each combination of priorities. This can be carried out by computing the overall levels of impacts and risk in terms of combined impacted areas and impact levels.

Work step D is about the identification of an hypothetical optimal railway track which would result in littlest overall geomorphological impacts and risk. This can be done by considering contextually the spatial location of all vulnerable elements in the area, the distribution of naturally hazardous zones and other factors which might condition the feasibility of the project such as, for example, land use, land slope, income and outcome point of the track in the area (that might be predefined accordingly to what has been decided for neighbourhood areas).

The following paragraphs will give details on the work steps introduced and will outlook on the results achieved with the application of the method to the Castelfranco Emilia case study.

WORK-STEP A: CREATION OF THE CARTOGRAPHIC DATABASE

The creation of the GIS cartographic database has to be structured functionally to further analysis and has to include thematic maps representing the various geomorphological components (each with its range of qualitative classes) as well as thematic maps representing all the different proposed tracks for the planned railway.

The contents and the development of the GIS database that has been created for Castelfranco Emilia area is explained in Barbieri & *alii*, 2000. It is composed by several maps and includes environmental information and data concerning human activity. From this database the following thematic maps have been extracted: geomorphological assets, superficial lithology, quarry activities, flood process and land use (fig. 3a, 4a, 5a, 6a). They are grouped in the categories of assets, resources and processes according to the nomenclature of Rivas & *alii* (1997).

WORK STEP B: ASSESSMENT OF IMPACTS AND RISKS

Impact on Geomorphological Assets

The quality and fragility of the Geomorphological Assets in respect to a certain type of engineering project depends upon several factors (Panizza & *alii*, 1995; Bertacchini & *alii*, 1999). Assets can be damaged to various extent by a structure such as a railway. For instance, they can be destroyed if the structure is constructed directly on the site, the process generating the assets can be interrupted, the landscape quality decreased if the embankment of the railway is visible from the site.

For the purpose of the impact analysis, the assets classes maps has been transformed into a values map by scoring asset classes according to their quality by means of the Delphi method (fig. 3b). Quality has been here intended as the relative asset rarity in the study area. On the one other hand, it has been assumed that potentially impacted
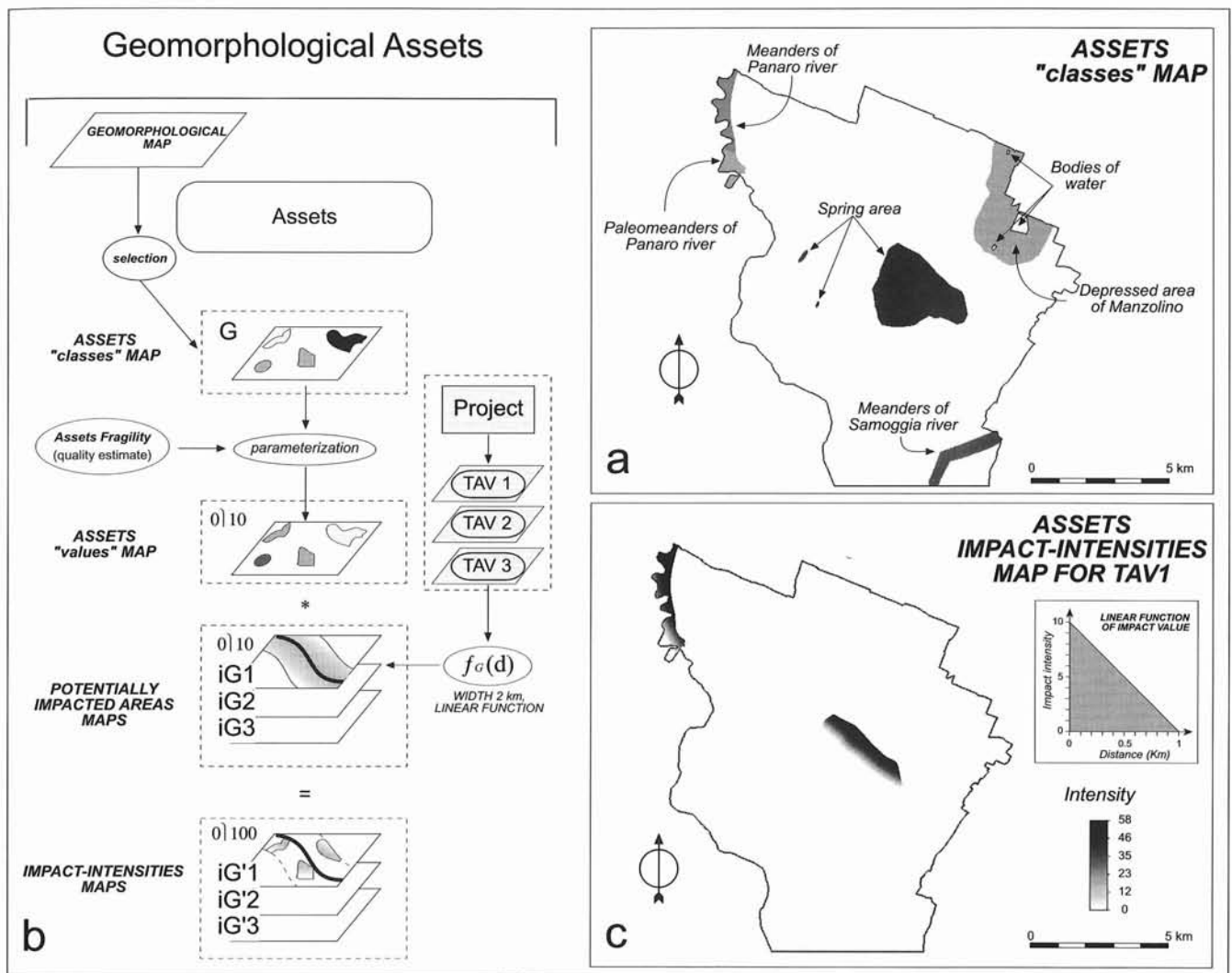
FIG. 3 - Method for the assessment of impacts of an high speed railway track on assets.

areas are only these in the surroundings of the railway track, with level of potential impact becoming progressively lower for points located further away from the track. On account of that, a set of potentially impacted areas maps has been drawn by creating a 2 km wide buffer around the track and by setting levels of potential impact to decrease linearly from a maximum of 10 at the track to a 0 at the edge of the buffer.

The «impact intensities maps» on assets has then been calculated on a range of 0 to 100 by multiplying, pixel by pixel, the assets values map and the map of potential impact. As can it can be seen in fig. 3c, the assets more affected are the natural springs area and the meanders area of Panaro river. Alternative track n° 1 (TAV1) has an impact higher than the other two tracks, especially in the areas of meanders and paleomeanders of the Panaro river.

Impact on geomorphological resources

Geomorphological resources have been divided in two broad categories. One is represented by superficial deposits which, eventually, could be excavated in quarries in the future. The other is that of actual exploitable deposits, which are already planned to be excavated in the next years. The way of analysing the impact of the railway construction on the one and on the other case has been substantially different.

In the first case, the importance of the superficial deposits is related to their quality as a potential resource or reserve for raw materials (fig. 4b). By evaluating this factor for each class of deposits, and assessing values to each class by means of the Delphi method, a 0-10 quality values map for superficial deposit has been created. The level of potential impact is related to the loss of the resource related

Geomorphological Resources

Surficial deposits

DEPOSITS "classes" MAP — D

Deposits quality (as a resource for raw material) → *parameterization*

Project
TAV 1
TAV 2
TAV 3

DEPOSITS "values" MAP — 0| 10

POTENTIALLY IMPACTED AREAS MAPS — 0| 10 — iD1 iD2 iD3

$f_D(d)$
(WIDTH 200m; 0-1 FUNCTION)

IMPACT-INTENSITIES MAPS — 0| 100 — iD'1 iD'2 iD'3

a — DEPOSITS "classes" MAP

Mainly gravel
Mainly sand
Mainly silt
Mainly clay

0   5 km

c — DEPOSITS IMPACT-INTENSITIES MAP FOR TAV1

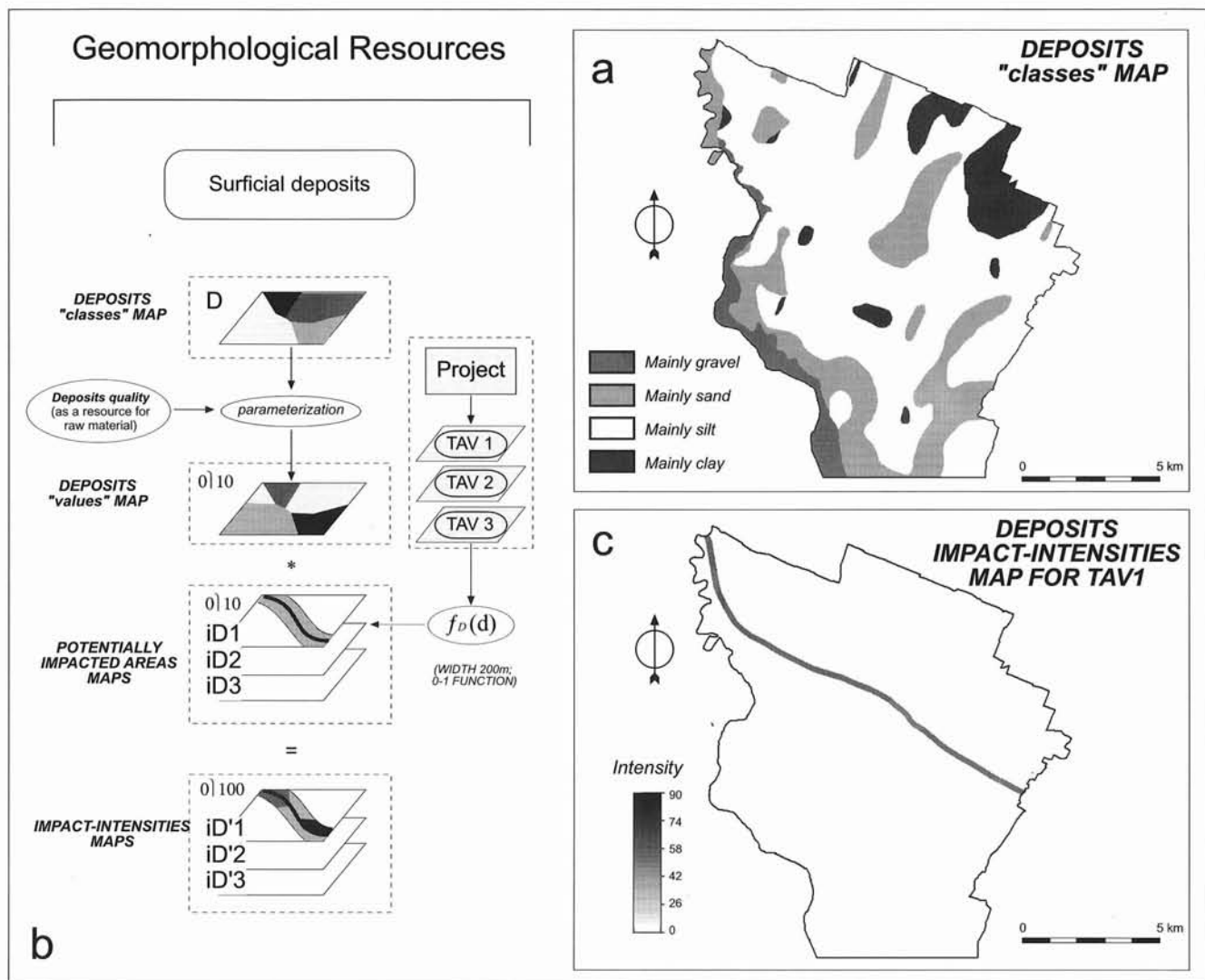Intensity
90
74
58
42
26
0

0   5 km

b

FIG. 4 - Method for the assessment of impacts of an high speed railway track on surficial deposits.

to mere space occupation of the structure. A set of potentially impacted areas maps has been created by drawing a 200 m wide buffer around the track, representing the area occupied by the structures, and by assigning a maximum value of 10 as impact level into the buffer and null 0 value of potential impact out of the buffer. The impact intensities maps on superficial deposits have been subsequently calculated, on a range of 0 to 100, by multiplying, pixel by pixel, the deposits quality values map and the maps of potential impact represented by the buffer. As it is possible to appreciate from fig. 4c, where the lithology crossed by the buffers of the three alternatives is made up of silt the impact is low, while it is higher when sand bands are crossed. In the end, only a little difference exists within the impact levels obtained from the three alternatives, but TAV1 has a total impact level slightly higher than the others.

In the second case, regarding quarries, the importance of deposits falling within a specific quarry resort has been set proportional to the relative rarity of the extractable material in relation to the overall development plans regulating quarry activity in the study area (fig. 5b). To give an example, if quarry N has 100 cubic metres of gravel allowed for extraction and the local regulations allows a total of 500 cubic metres of gravel to be extracted in the whole study area, then the rarity of the gravel of that quarry can be scored a value of 2. Theoretically, if all the extractable gravel is located in the same quarry, its rarity scores 10. This reasoning, and the collection of data on quarries and regulations for the study area of Castelfranco Emilia, has permitted a parameterisation of all quarry sites to be done and a rarity values map for quarry resources to be drawn.

Furthermore, the potentially impacted areas maps for quarries is obtained attributing values to quarry sites as a function of the % of volume extracted form the quarry for the project itself: In other terms, it is the % of the resources existing in quarry N which is used for the project that measures the impact. For instance, if quarry N has 100 cubic metres allowed for extraction and the project utilises 80 cubic metres, then the usage is 80% of the total and the impact level scores «8». Again, if all the quarry material would be used, maximum impact level would score 10. The value adopted in practice during the analysis have been somehow arbitrary, since not all the information was made available by the documentation collected, which only indicated which quarries would be involved in the project (fig. 5c). The overall quantities of gravel and sand needed for construction of each alternative have been eval-uated by considering the length of the three alternatives and its constructional characteristics (on embankment and on viaduct). This has permitted the following estimates of total indispensable material for each alternative to be made: 830,652 m³ for TAV1, 840,640 m³ for TAV2 and 823,740 m³ for TAV3. These quantities have been equally distributed over the quarries involved and the potential impact has been calculated following the procedure illustrated. The impact intensities maps on quarries have then been calculated on a range of 0 to 100 by multiplying, pixel by pixel, the quarry rarity values map and the maps of potential impact. The impact maps obtained for the case study of Castelfranco Emilia have indicated that the first alternative (TAV1) is the one that requires more quantity of material and it is therefore the one with the larger impact on quarries.
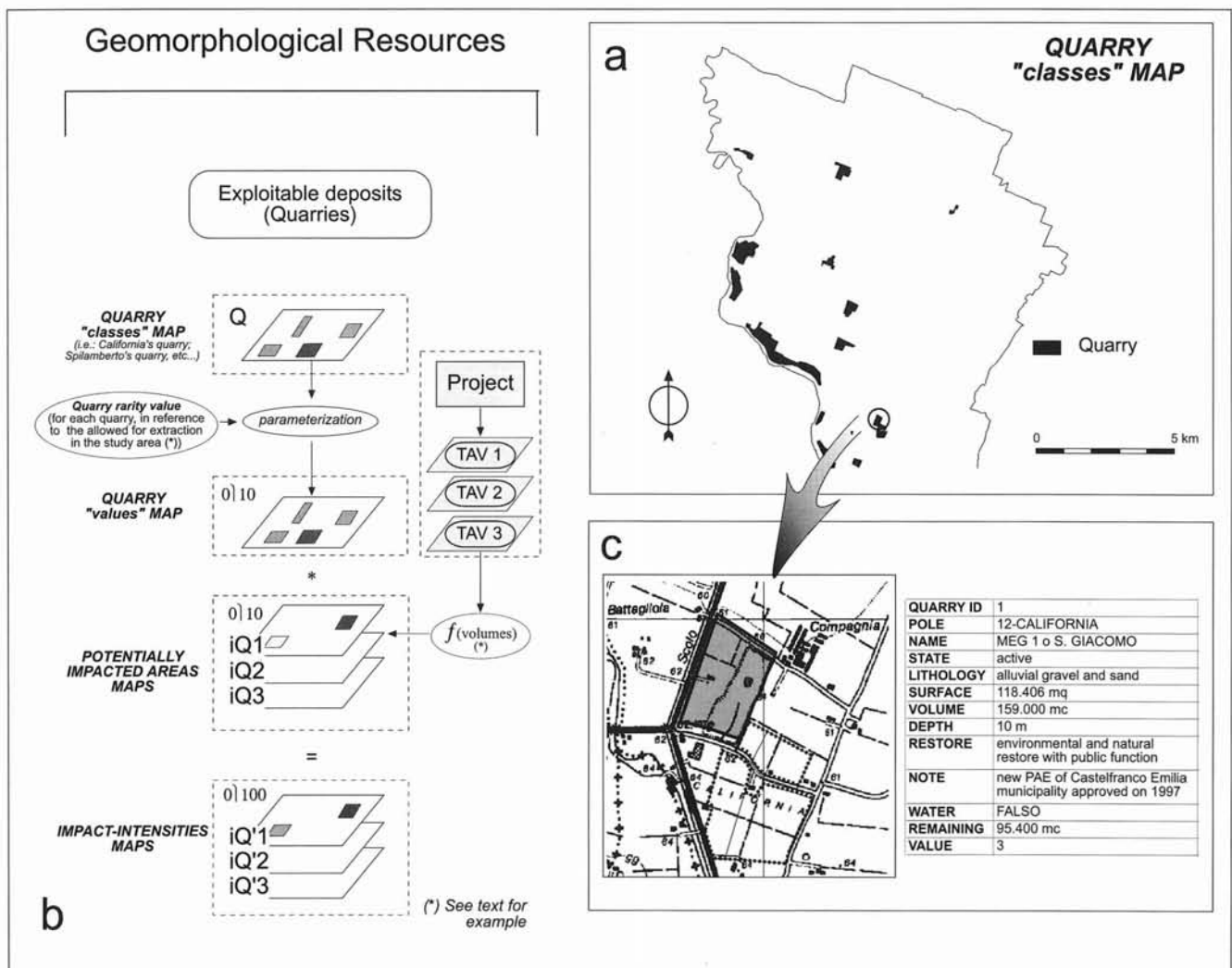

FIG. 5 - Method for the assessment of impacts of an high speed railway track on exploitable deposits (quarries).

Impact on geomorphological processes

The most significant geomorphological process affecting the study area of Castelfranco Emilia is flooding, as witnessed by the several flood occurred during the 20th century (Moratti & Pellegrini, 1977; Castaldini & Pellegrini, 1989). A dynamic modelling of flood events has been developed with the PC-Raster Dynamic Modelling Package (Van Deursen & Wesseling, 1997) in order to simulate scenarios of a flood, with and without the presence of the three alternatives of the railway track (Bertens & *alii*, 2000) (fig. 6a).

The following process, in terms of naturalness, has a quality value that can be assumed as being the same all over the study area. Hence, flooding process «quality» can be ranked a maximum value of 10 in the whole of the study area and a process quality values map can readily be derived. A structure such as a railway track can influence flood process by diverting, slowing or accelerating a flood wave. A flood simulation model, based on several input parameters (slope, lithology, precipitation, land use, etc.), has been developed and calibrated for the study area (Bertens & *alii*, 2000). The outcomes of the model are flood scenarios expressed in terms of the height of the water wave, with or without any of the alternative tracks of the railway (fig. 6a). Flood parameters can, in turn, be interpreted in terms of flood hazard zonation (with hazard levels ranked from 0 to 10) at the moment of maximum intensity of the water wave (fig. 6b). By subtracting the «natural» flood hazard level values (simulated by the model in no-railway conditions, H0) to the hazard level values obtained in presence of any of the railway alternative tracks (H1, H2, H3), it has been possible to compute the potential impact level on floods caused by the railway structure alternatives. This operation has resulted in a set of potentially impacted areas maps for floods that display pixels with values ranging from a theoretical −10 (in areas naturally flooded that become shielded to floods if the structure is built) to 10 (in areas resulting flooded only in presence of the structure). It should be noticed that in terms of impact on the flood process itself, it makes no real difference between a value −10 and a value 10: both express a drastic change, or impact, on natural conditions. So, in this case, a set of potentially impacted areas maps has been calculated using the absolute value of the difference H(i)-H0. Therefore, once again, impact values have been obtained in a range from 0 to 10. Afterwards, it has been possible to calculate a set of overall impact intensities maps on flood process by multiplying the former map for the theoretical 10 importance value associated to the process in the whole of the study area.

In our case study, the simulation carried out with the flood model hasn't highlighted large modifications of the flood hazard due to the railway tracks. A certain backward shift of hazard levels boundaries has been recorded for distal areas, meaning that certain sites downstream will no longer, or less severely, be flooded once the railway is constructed. However, this changes regard only a few pixels of 25 x 25 m size and, therefore, no substantial impact on flood processes is generated by any of the alternatives considered (fig. 6d)

A different procedure has been adopted for the assessment of indirect impact on land use due to flood process modification (fig. 6c). In this case, a land use quality values map has been obtained by scoring land use classes from 0 to 10 with the Delphi method accordingly to the socioeconomic quality of the land use. The set of potentially impacted areas maps adopted has been the one directly derived by the difference between flood hazard values with and without the railway structure, with the −10 to +10 values range. The negative values of these latter maps make sense in the perspective of their relation to land use: areas scoring negative values are sites made safer by the structure, thus the impact is bringing a benefit to land use; areas scoring positive values are sites made hazardous by the structure, with negative consequences for land use. The set of indirect impact intensities maps on land use due to change of flooding, with a variability range from −100 to +100, has been obtained by multiplying these latter maps for the land use quality values map. Obviously, being the modifications of the flood process caused by the three alternatives quite little and limited in space to a few pixels, the impacts on the land use has resulted to be very little (fig. 6d)

Flood risk for the railway structure

The flood hazard scenarios obtained from the flood simulation model run with or without any of the railway alternative track have also been used to evaluate the potential flood risk for the structure itself. As previously reported, flood hazard maps with hazard levels ranked from 0 to 10 have been generated for any possible alternative track of the railway (H1, H2, H3) and for natural conditions (H0). At the same time, the vulnerability to floods of the different tracks, defined on the basis of the constructional characteristics of the track itself, has been represented in a set of «track vulnerability maps». In high vulnerability value (= 10) has been assigned for tracts built on embankment and a low vulnerability value (= 5) has been assigned for tracts built viaduct. The flood risk for the railway structure alternatives has then been calculated on a scale 0 to100 by multiplying, for each possible track option, the hazard and the vulnerability maps. This part of the procedure has, at present, been only partially applied to the case study of Castelfraco Emilia.

WORK STEP C: IDENTIFICATION OF A GEOMORPHOLOGICALLY PREFERABLE RAILWAY TRACK

Once the impact branch matrix has been completed by all the impacts intensities maps, and the risk branch has been completed by risk maps for the railway structure, it has been possible to undertake a comparative assessment of impacts and risks related to each proposed alternative railway track. In practice, all of the impact levels map on
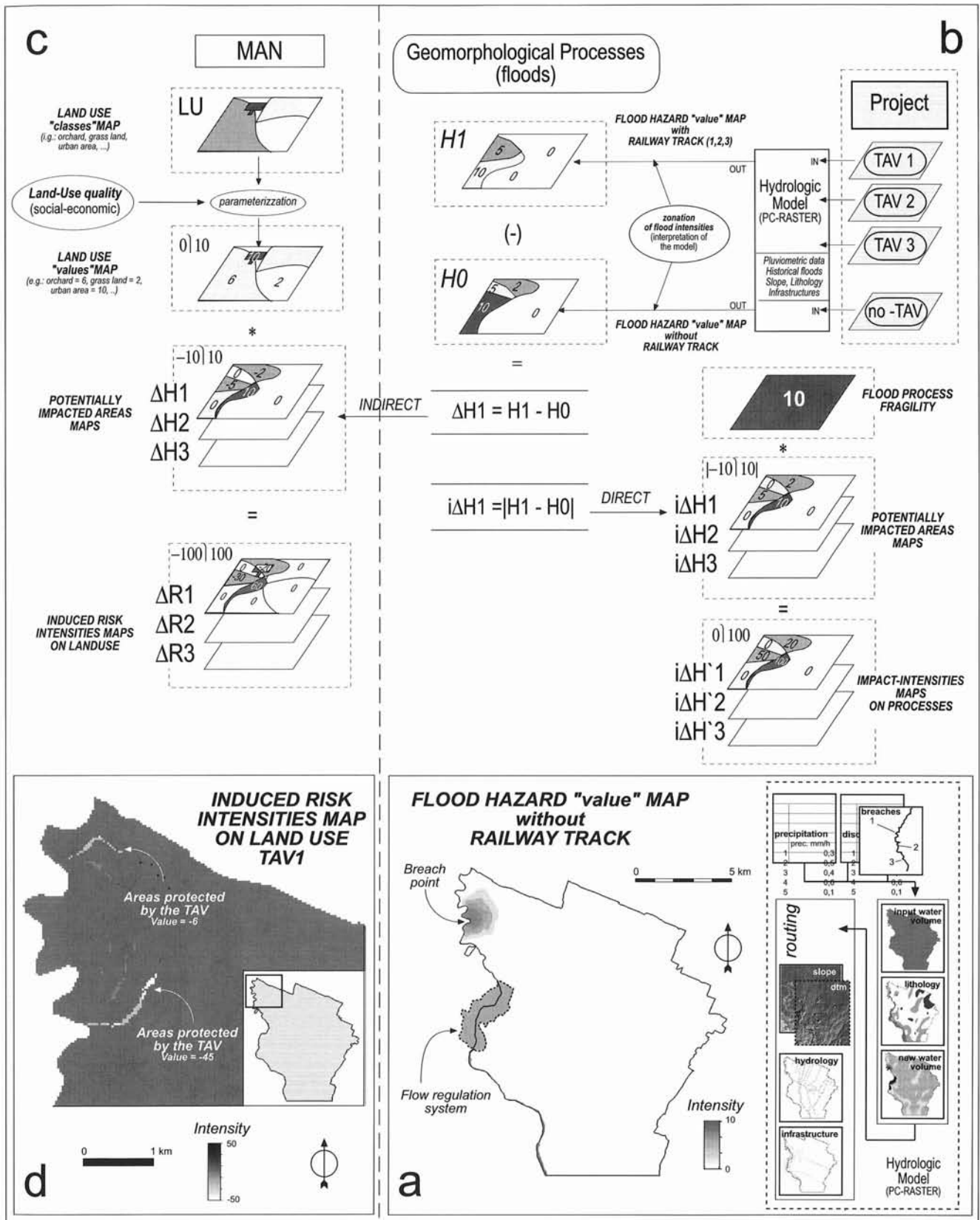
FIG. 6 - Method for the assessment of impacts of an high speed railway track on: a) geomorphological processes; b) on land use as indirect consequences of flood processes modification.

geomorphic components referring to a certain track alternative, can be crossed in order to generate a set of so called «unique conditions area». At the same time, each of these maps can be attributed with a priority value. These priority values can be assessed by means of Delphi method, or, alternatively, can be set subjectively and be used as a gateway for decision makers to explore the consequence of the project on different perspectives. In this latter case, they can also represent the relative importance given by the person carrying out the analysis to each environmental component. Therefore, each alternative has resulted in a variable number of «unique conditions areas» (Chung & Fabbri, 1999) characterised by an overall impact value which is in turn given by the weighted summation of impact level values of the single maps, and also by an overall extent expressed as pixels number. By multiplying these two quantities, the total impact level for each set of unique condition areas can be calculated. The attribution of this value to each polygon making up a certain set of unique condition areas has permitted maps of the overall impact associated to each alternative track to be generated.

Moreover, a set of overall impacts maps has been generated by performing Sensitivity Analysis on the priorities. The Sensitivity Analysis is a procedure trough which it is possible to create a series of final impact maps by modifying the relative importance (priority) of the single impacts. This permits the influence of each parameters on the total impact to be evaluated (Napolitano & Fabbri, 1996). Moreover, it permits the geomorphological features more impacted by the three alternatives of the high-speed railway track to be identify, on a function of the different choices of priority. In other words, this analysis enables the decision makers to choose the best alternative according by the relative importance he decides to attribute to the single geomorphological components suffering impact. In practice, for the Castelfranco Emilia case study an equal priority of 1 was assigned to first to all the impact maps. Afterwards, a priority of 0 was cyclically given to each of the impact maps, so to test for the importance of each single map in the final impact evaluation, (fig. 7).

WORK STEP D: IDENTIFICATION OF A GEOMORPHOLOGICALLY OPTIMAL RAILWAY TRACK

Applying a somehow reverse procedure to the one of work step C, it is also possible to use the database to trace out and identify, from a geomorphic perspective, an optimal track for the railway, hence, an alternative with littlest impact on geomorphological components and littlest risk for the structure. This assessment has been only partially attempted for the case study of Castelfranco Emilia, so the procedure is herein only briefly described. On the one hand, it is necessary to set priorities to the values maps representing the geomorphological components considered and, contextually, to cross these maps in order to define unique condition areas to which an overall geomorphic quality value can be assigned. On the one other hand, conditioning factors such as the point of income and outcome of the railway from the study area, slope angle and land use must also be accounted for. This is done, in practice, by crossing all of the maps representing the conditioning factors and generating a patchwork of unique condition areas. Moreover, it is also necessary to consider flood hazard for the structure, since it is preferable for the railway to run on areas with null or low flood hazard. The combination of the three resulting unique condition sets, can permit to generate a map in which sub-areas are characterised by a value expressing the favourability of that site for the railway construction. Applying interconnectivity test functions to this map, it is then possible to trace out a track for the railway which is potentially the most favourable one from the geomorphic perspective. Obviously, this is a relative assessment, since a change in priorities will change the favourability value of each sub-area and, as a consequence, the optimal track path. Finally, each option designed throughout this work step can be tested with the overall impact assessment procedure described previously.

CONCLUSIONS

With the Sensitivity Analysis performed on the Castelfranco Emilia impact maps database, it was made clear that the geomorphological assets resulted to be the most influential elements on the total impact (fig. 10). Therefore, if low to very low priority is given to geomorphological assets, the overall geonmorphological impact decreases substantially. In the end, it has been calculated that, even with different priorities combinations, the first alternative (TAV1) produces the strongest impact on geomorphological assets as well as on the superficial lithology and on quarry activities. On the contrary, the second alternative (TAV2) is the one that results in the littlest impact on the geomorphological elements considered. However, the differences between the TAV2 and the TAV3 are very little. The impact on flood processes and consequently on land use has influenced in a minimum way the total impact related to all the three alternatives.

It can be concluded that the methodology presented in this paper has permitted the analysis of impacts caused by the TAV on geomorphological features, which are typical of a plain area, to be defined numerically. Also, the method can permit the flood risk suffered by the structure to be assessed. Also this specific procedure for Environmental Impact Assessment is quite simple and enables the generation of map sets that can be of strong support to decision makers.
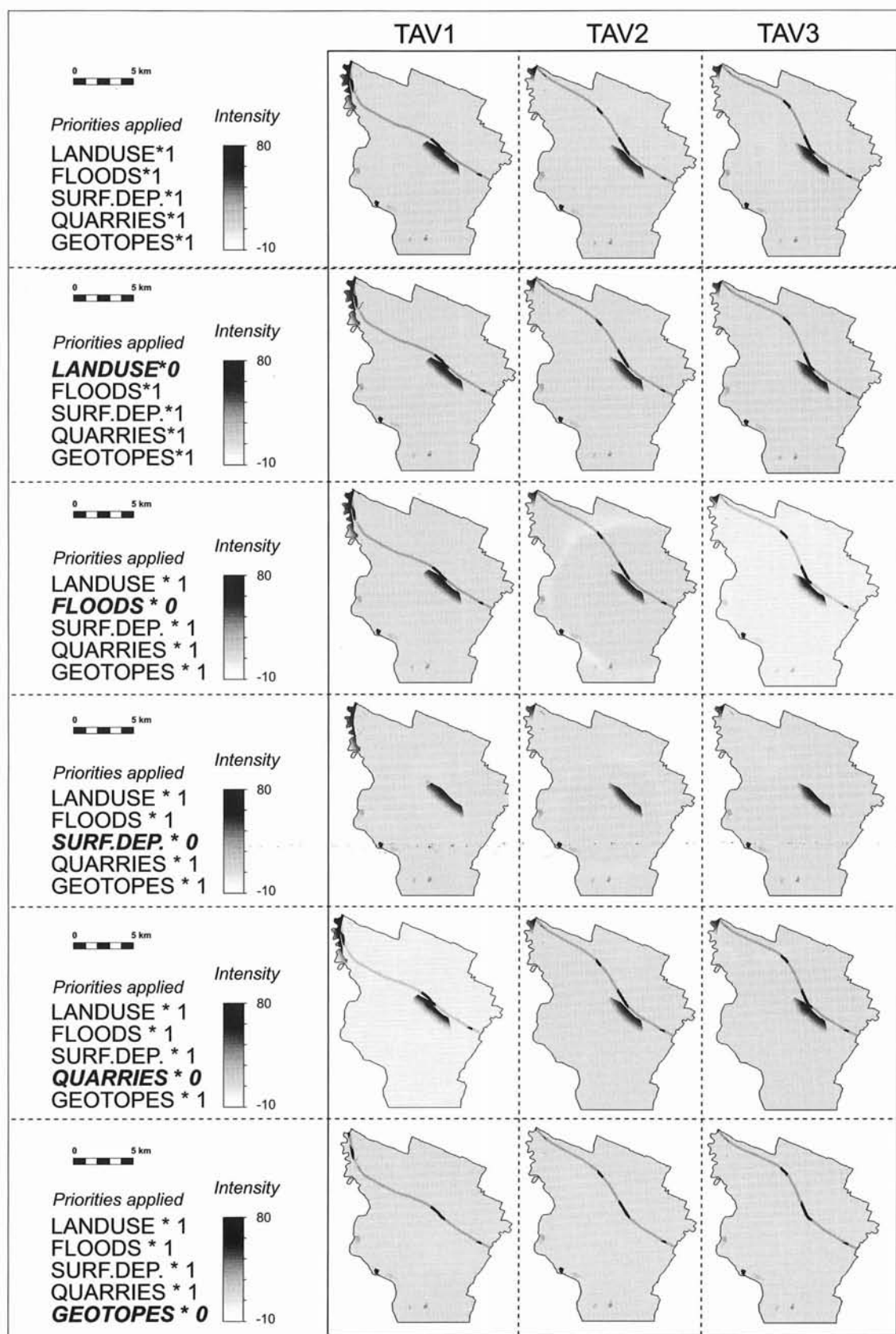
FIG. 7 - Overall impacts maps obtained with Sensitivity Analysis.

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