

RECONCILING PRECISION AND SCALE IN MONITORING URBAN LAND COVER CHANGES WITH SATELLITE IMAGERY

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ABSTRACT:

Ever increasing advances in the resolution of satellite imagery are matched by commensurate increases in the expectations of the precision of the results emanating from the interpretation of such imagery. This is particularly apparent in the case of urban planning applications of remote sensing techniques to the monitoring of land use changes at a local territorial scale. Clearly it is unreasonable to expect that remote sensing techniques will ever replace the precision of monitoring changes in patterns of land use activity on a site by site manual basis. Nevertheless urban planners and public decision makers alike share the implicit hope that enhanced resolutions in satellite imagery will lead to ever more accurate descriptions of land use dynamics.

The methodological dilemma of having to reconcile precision and scale of remote sensing applications addressing urban land cover changes was faced by researchers in a recent study aimed at monitoring urban change in and around the metropolitan area of Barcelona, in Spain. The study formed part of the *CNES* and *Spot Image* jointly sponsored *SPOT5 Application and Validation Programme (SAVP)* (2002-2004) and drew upon the comparison of 1995 Spot 3 (20m resolution) and 2002 Spot 5 (2.5 m resolution) satellite images. The supervised classification methodology led to the identification of some eight land cover classes. In terms of comparing the resulting change in urban development, the said 'change' was found to be overly exaggerated. Given that the 2002 images were of a considerably higher resolution than those of 1995 led to distort or over-exaggerate the magnitude of change experienced between 1995 and 2002. Uses clearly not identified by virtue of the 20m x 20m pixel size of the 1995 20m image were in turn detected by the smaller 2.5m x 2.5m pixels of the 2002 image. Had the 1995 images been of a similar or closer resolution, then the degree of change observed would have been more credible. This was particularly relevant in fringe areas demonstrating disperse urban development and where urban development is in the process of consolidation.

This 'limitation' does not undermine the benefits from incorporating remote sensing and satellite image analysis in urban planning. Nevertheless it is suggested that in order to achieve more accurate results, overcoming this distortion effect requires baseline imagery to be of a much closer resolution to the later imagery used for comparative purposes. Indeed it is anticipated that this limitation is something of the past, in the sense that as of this point in time, the increases in the resolution will be increasingly smaller, thereby reducing the distortion effect when comparing areas over time. Therefore it is hoped that urban planners and public decision makers with very local territorial interests, as opposed to those with more regional or strategic territorial interests, will not have to compromise the issue of scale and precision, and will be able to place more weight on the reliability of results coming out of monitoring exercises of this nature.

1. INTRODUCTION

1.1 Metropolitan urban agglomerations

According to the METREX Network, throughout Europe, the metropolitan regions are all facing similar problems of economic change, social cohesion, urban sprawl, traffic congestion, city centre vitality and viability, and environmental damage and pollution. At the same time these areas and regions offer opportunities for renewal and regeneration, high quality urban life, and economic competitiveness. (METREX, 1999) While it is clearly recognised that these problems and opportunities arise at a general level within Europe, in spatial terms it is more difficult to ascertain with exactitude the spatial extent to which such problems and opportunities are found.

Traditionally the physical delimitation of urban areas and agglomerations has been characterised by two clearly

differentiated approaches. On the one hand a delimitation based upon physical or morphological criteria, where the continuous built-up area, or the density of contiguous ambits, comprises the basic mechanisms for the delimitation. On the other hand studies based upon functional or economic criteria, where the emphasis is placed upon the existing relations and flows throughout the urbanised territory where the relation between place of residence and place of work is fundamental.

Having said that, the lack of homogeneous criteria for the definition and delimitation of 'metropolitan urban regions' does nothing to add to the ease of studying individual cases or making comparisons at the European level. In the case of European Commission funded research project under the INTERREG IIC

initiative, aimed at reaching an understanding of the territorial and functional characteristics of the metropolitan system of South Western Europe, a common methodology was agreed between the three partner countries of Spain, Portugal and France, in order to allow a cross-border comparison of the respective metropolitan urban regions under consideration (Barcelona, Bilbao, Madrid, Málaga, Seville, Saragossa and Valencia in Spain; Lisbon and Oporto in Portugal; and Bordeaux, Montpellier and Toulouse in France). These metropolitan urban regions were defined taking a functional approach, consisting of adding to the central city of each area the adjoining municipalities where the level of commuting between place of residence/place of work was superior to a certain threshold, following the methodology based upon that used by the Bureau of Census in the United States, for the states of New England, for the definition of statistical metropolitan areas (Office of Management and Budget, 1990).

In the case of Barcelona, this methodology led to the delimitation of a metropolitan urban region of some 4,592 km² with a population of more than 4,5 million persons (CPSV, 2001). This contrasts strongly with two more administrative definitions used locally: the Metropolitan Region of Barcelona (RMB) and the Metropolitan Area of Barcelona (MAB).

The RMB, recognised for some aspects of regional planning, refers to an area of 3,236 km² incorporating some seven counties and a total of 164 municipalities. The MAB, under the jurisdiction of the *Mancomunitat de Municipis* (MMAMB) is a voluntary association of some 31 municipalities, comprising cities and smaller towns and villages within the immediate environs of Barcelona extending over an area of 495 km². Although extending over approximately one tenth of the area of the metropolitan urban region, as defined under the INTERREG-IIC research project, the MAB contained some 62.5% of the metropolitan urban region's population, giving some indication of the compact form of urban development at the core of this wider metropolitan area.

	Area (km ²)	Population (2001)	Population density (inhabitants per km ²)
Barcelona City Council	98	1,503,884	15,322
Metropolitan Area of Barcelona (MMAMB)	495	2,833,349	5,724
Metropolitan Region of Barcelona (RMB)	3,236	4,390,390	1,357
Functional metropolitan area of Barcelona (CPSV)	4,592	4,537,468	988

Table 1: Basic characteristics of the different administrative and spatial areas of Barcelona's metropolitan urban region.

1.2 Urban sprawl

In recent years Barcelona's metropolitan area has witnessed significant growth in peripheral urban development, or urban sprawl, with progressively increased land consumption, matched by a decrease in population at the core. Regardless of

the nuances between the different administrative and planning areas, it is clear that Barcelona and its surrounding area represent a metropolitan urban region of an international scale, experiencing those same problems and opportunities identified by the METREX network and referred to earlier, including that of "urban sprawl".

As Wilson et. al (2003) rightly indicate, no such universally accepted definition of urban sprawl exists and indeed the phenomenon it seeks to describe, i.e. the land-consumptive pattern of urban development, can be interpreted both positively and negatively. The authors develop an urban "growth", rather than "sprawl" model, to quantify the amount of land converted to urban uses, leaving it open to subjective interpretation whether or not it constitutes "sprawl". They wisely suggest that "the challenge is to quantify and categorise urban growth in a way that is useful and meaningful to land use decision-makers at the municipal, regional and state levels". (p. 276)

The invitation extended to the Universitat Politècnica de Catalunya and the MMAMB from the CNES and SPOT Image to participate in the Spot 5 Application and Validation Programme (SAVP) in 2003 provided the ideal opportunity to engage in research taking a physical or morphological approach to examine a number of key urban development issues both within the confines and beyond the edge of Barcelona's metropolitan area. The joint UPC/MMAMB research proposal therefore sought to assess the extent to which the satellite data could aid in the quantification and analysis of this pattern of apparent outward encroachment of urban development into the surrounding countryside of the metropolitan area or 'peri-urbanisation'.

Although recognising that Barcelona's functional metropolitan urban region is considerably more expansive, for the purposes of this study, the metropolitan area was taken as that defined by the 31 local authorities belonging to the MMAMB. In view of the urban planning services and responsibilities, the MMAMB represented an ideal end user for the results emanating from a study of this nature.

This paper presents the results of this comparative research project under the SAVP programme and at the same time highlights the inherent limitations in the accuracy of these results stemming directly from the differences in resolution of the two satellites image data sets.

2. METHODOLOGY

2.1 Background

It is irrefutable that Earth observation is a modern science, which studies the Earth's changing environment, through "remote sensing" tools such as satellite imagery and aerial photography (EEA, 2002). A report published by NASA in 2001 highlighted the fact that the advances in satellite-based land surface mapping are contributing to the creation of considerably more detailed urban maps, offering planners a much deeper understanding of the dynamics of urban growth, as well as associated matters relating to territorial management (NASA, 2001).

Within the European context, the most recent comparable study of this nature is that of the MURBANDY/MOLAND project (Monitoring Urban Dynamics / Monitoring Land Use Changes) which has used “remote sensing”, the results of which have been published by the European Environment Agency (EEA, 2002). This project drew together a network of European partners and sought to measure and assess urban dynamics, through the creation of a land use data base, for a range of European cities and urban regions, including Bilbao. These data bases combine environmental, social and economic information, in order to reach a better understanding of the characteristics and dynamics of urban growth and the changes related to land use, such as transport and energy infrastructure, and the changes in agriculture and natural areas. The results show the spatial evolution of a group of urban areas, with the objective of proposing a methodology for strategic monitoring of the environmental impact of urban development.

It is relevant to highlight the fact that the Report of this project suggests that “urban growth and sprawl is a pertinent topic for analysis and assessment today. The environmental impacts of urban sprawl and the extent of urban problems have been growing in complexity and relevance, generating strong imbalances between the city and its hinterland. The need to address this complexity in assessing and monitoring urban planning and management processes and practices is strongly felt” (EEA, 2002, p.7).

The MOLAND methodology, a more advanced version than MURBANDY, has created the data bases for four periods, for the 1950s, the 1960s, the 1980s and the 1990s, through the interpretation of satellite images, principally IRS images, but in some cases IKONOS and SPOT images (Lavallo et. alt., 2002). It is important to note that the nomenclature adopted for the “remote sensing” was a more extensive version of the CORINE legend. One of the fundamental differences between Murbandy/Moland and Corine, apart from the greater precision with the level of detail, is that with Murbandy/Moland it is possible to make the distinction between different land uses. By contrast, Corine is more limited related to the distinction between different land classifications. This methodology has enabled the evaluation of “urban sprawl” for the 25 case studies, understood as the percentage increase in the urbanised surface area during the period under review.

2.2 Data

Participation in the Spot 5 Application and Validation Programme provided the researchers with access to the following images::

- Spot 5 (2002) THR, black and white, 2.5 m resolution, Processing level 1A
- Spot 5 (2002) THR CNA C1-3, natural colours, 2.5 m resolution, Processing level 1A
- Spot 5 (2002) THX FC C1-3, false colours, 2.5 m resolution, Processing level 1A
- Spot 3 (1995) Infrared, 20m resolution, Processing level 1A

The 60km x 60km SPOT Scene extended over a land area of some 2,700 km², taking into consideration the significant component of the sea.

2.3 Method

The three 2,5 metre resolution images were orthorectified simultaneously, with the aid of a 2.5 metre Orthophoto, in TIFF format, for the entire study area. This saved time and also contributed to the subsequent classification process.

The researchers elaborated a supervised classification methodology, drawing upon the four images (with 2.5 m and 20 m resolutions) in order to maximise the number of distinguishable land cover classes for the study area. This methodology employed **maximum and minimum likelihood**, **binary encoding** and **parallel piped methods**, prior to **scattergram processes** and the merging of all the data, drawing upon a **subtraction process** to arrive at the final classified image.

The images were classified without being broken down into smaller units. Rather once the initial classification had taken place, errors were searched for and where these occurred, the sections containing them were removed from the overall image, reclassified as single units and then reinserted in the master image in a mosaic form.

The methodology made use of **ER Mapper** and **ENVI** software applications.

This classification process led to the identification of some eight land cover classes:

- forestry
- agriculture
- irrigated fields
- dry land
- residential
- industrial (A and B)
- streets and roads
- shallow and deep waters

which was considerably more than was at first envisaged through the three bands (RGB) of the 2002 true colour Spot image.

3. RESULTS

3.1 Quantification of urban sprawl

In order to quantify the magnitude of the change in urban development experienced over the 1995-2002 study period, and measure what could legitimately be termed ‘urban sprawl’, it was decided to focus attention on the land which had been ‘artificialised’ for urban land uses, i.e. undergone some form of urbanisation. This meant focusing on the following land cover classes:

- residential
- industrial (A and B)
- streets and roads

It should be emphasised that these first results relate to the entire area contained within the respective Spot scenes for 1995 and 2002 (i.e. the 3.600 km²), and not to any territorial area with fixed limits for administrative purposes. That is to say neither the 495 km² of the Metropolitan Area of Barcelona, as used by the MMAMB, nor the 3,236 km² of the Metropolitan Region of Barcelona.

Land cover class	1995	2003
Urbanised	219.33 km ² (8.15%)	397.09 km ² (15.24 %)
Non-urbanised	2,472.81 km ² (91.85%)	2,209.08 km ² (84.76%)
TOTAL	2,692.14 km ² (25.21%)	2,606.17 km ² (27.60%)

Table 2: Changes in urbanised and non-urbanised shares of the overall study area of the Spot scenes between - 1995 and 2002

While both images covered a surface area of 3.600 km², the total land areas obtained through the supervised classifications, excluding the shallow and deep water categories amounted to 2,692km² in 1995 and 2,606 km² for 2002. In 1995, the artificial or urbanised land cover accounted for 8.15% (219 km²) of the entire study area. In 2002, the artificial or urbanised categories represented 15.24% (397 km²) of the overall study area. This increase in the artificialised or urbanised component was matched by a concomitant decrease in the non-urbanised land cover, from 91.85% in 1995 to 84.76% in 2002.

As can be seen from Table 3, over the study period there was an apparent change in the overall proportion of residential land cover from 3.75% in 1995 to 5.27% in 2002. Industrial land cover accounted for a smaller proportion, increasing from 2.61% in 1995 to 4.18% in 2002. Finally streets and roads indicated a significant increase over the study period, from 1.78% of the overall study area in 1995 to 5.79% in 2002. While a significant degree of new road building has indeed taken place over the study period in the environs of Barcelona, it is considered that this degree of change is exaggerated. The figures may indeed reflect upgrading to existing roads, but in any event need to be treated with a certain degree of care.

Land cover category	1995	2002
Residential	101 km ² (3.75%)	137 km ² (5.27 %)
Industrial (A and B)	70.30 km ² (2.61 %)	108.87 km ² (4.18 %)
Streets and roads	48 km ² (1.78 %)	151 km ² (5.79 %)

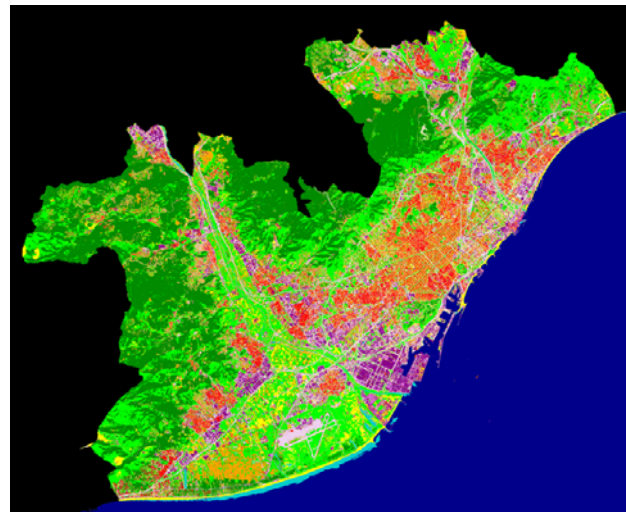
Table 3: Changes denoted in the individual urban land cover classes between 1995 and 2002 for the overall Spot scenes

Turning attention upon the dynamics within the 495 km² of the Metropolitan Area of Barcelona, i.e. the territorial area coming under the jurisdiction of the Mancomunitat de Municipis de l'Àrea Metropolitana de Barcelona (MMAMB), some difficulties were encountered in correctly superimposing the boundaries of the MAB over the respective images. Furthermore the assessment of the areas pertaining to the land cover classes in 1995 and 2002 was made from the two images in raster format, by assessing the sum of the pixels belonging to the different categories, rather than vector format which would have enabled the derivation of areas from polygons. This was because of the sheer weight of the 2002 image and difficulties in converting the entire image to vector format. As a consequence, the conversion of the actual boundaries to raster format led to their 'widening', thereby introducing an element of uncertainty as to the exact land areas, pertaining to the different land cover categories, within the overall area of the 31

municipalities of the Metropolitan Area of Barcelona. Having said that, the total land area obtained by way of the supervised classification for the 1995 image was 473.704 km², compared with 521.79 km² from the 2002 image. Therefore it is considered that these figures provide a reasonable fit to the MAB study area and in turn a reasonable approximation to the change experienced over the study period, taking into account the constraints imposed by a remote sensing exercise of this nature.

By definition the territory coming under the jurisdiction of the MMAMB is of a far greater urban nature, embracing the principal municipalities adjoining the City of Barcelona, than the remainder of the wider study area. (See Figure 1) This is clearly reflected in Table 4, where according to the supervised classification, the urbanised land cover category accounted for almost 25% of the MAB in 1995 and over 32% in 2002. However looking in more detail at the individual components of the urbanised category one sees greater change experienced in the industrial, and streets and roads categories than in the residential category.

Figure 1: Classification resulting from the 2002 Spot 5 image



(2.5 metre resolution) for the territorial limits of the MMAMB
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Land cover category	1995	2003
Urbanised	117.2 km ² (24.74%)	167.598 km ² (32.12%)
<i>Residential</i>	<i>53.466 km²</i> <i>(11.10%)</i>	<i>56.492 km²</i> <i>(10.69%)</i>
<i>Industrial</i>	<i>38.573 km²</i> <i>(8.01 %)</i>	<i>46.904 km²</i> <i>(8.87%)</i>
<i>Streets and roads</i>	<i>25.161km²</i> <i>(5.23%)</i>	<i>64.192 km²</i> <i>(12.14%)</i>
Non-urbanised	356.504 km ² (75.26%)	354.19 km ² (67.88%)
Total	473.704 km ² (100 %)	521.79 km ² (100 %)

Table 4: Changes denoted in the urban land cover classes between 1995 and 2002 for the 495km² of the Metropolitan Area of Barcelona, coming under the jurisdiction of the MMAMB.

With regard to interpreting these specific results for the residential category, what should be mentioned is that in the wider metropolitan area of Barcelona, beyond the immediate built up limits of the city, a substantial amount of the urban area is in the form of “garden city” type development. This forms a marked contrast with the compact form of urban development found within the built-up area of Barcelona. If one were analysing this more diffuse nature of urban development on a site by site basis, such private gardens would be interpreted as artificialised land, linked to the principal adjoining residential use. However through remote sensing, such gardens would automatically be classified as non-urbanised categories. For this reason and taking into consideration the enhanced precision facilitated by the 2.5 m resolution images of the Spot 5 series, it is considered that the 2002 image of the study area will have under-estimated the degree of more disperse and diffuse residential development beyond the immediate limits of the built-up areas of the Metropolitan Area of Barcelona.

4. DISCUSSION AND CONCLUSIONS

4.1 Monitoring urban sprawl

The morphological approximation to the delimitation of urban and/or metropolitan systems through the interpretation and analysis of satellite images, particularly incorporating a dynamic approach by comparing two points in time, would appear to offer a clear advantage over more functional approaches. By simply superimposing the earlier and later of two images, professionals working in the realm of urban and regional planning are provided with a wealth of information. This enables them to determine at a glance the areas where development pressures have been most strongly experienced.

4.2 Methodological limitations

Having said that the principal limitation encountered with this study related to the different resolutions of the two sets of satellite images. This may seem a curious observation to make, within the context of a study programme, the very objectives of which were to highlight the added value resulting from the higher resolution (2.5 m) of the Spot5 images over previous images in the Spot series. Nevertheless taking into consideration the specific objectives of the research exercise carried out by the UPC and the MMAMB, to ascertain the degree to which the enhanced resolution could assist in monitoring urban sprawl, these differences highlighted some very real limitations. However this can be seen as a positive conclusion, indicating that it is probably from this point in time onwards, that the monitoring of urban sprawl and other planning and development issues, it is stressed of a local nature, will be more usefully served by high resolution satellite imagery.

While the research compared the same study area over time, the fact that the 2002 images were of a considerably higher resolution, led to distort or over-exaggerate the magnitude of change experienced between 1995 and 2002. Uses clearly not identified, by virtue of the 20m x 20m pixel size of the 1995 image were in turn detected by the smaller 2.5m x 2.5m pixels of the 2002 images. Clearly this limitation is introduced in any dynamic remote sensing exercise which compares images of different resolutions, as illustrated by Figure 2. As a consequence the quantification of the degree of ‘change’ over

the intervening period appeared to be of a magnitude somewhat removed from the reality. Had the 1995 images been of a similar or closer resolution, then the degree of change observed would have been more credible. However in view of the resolution differences, not all of the new urban development detected by the SPOT 5 image can be considered as genuinely new urban development. This is of particular relevance in fringe area, in areas demonstrating disperse urban development and where urban development is in the process of consolidation.

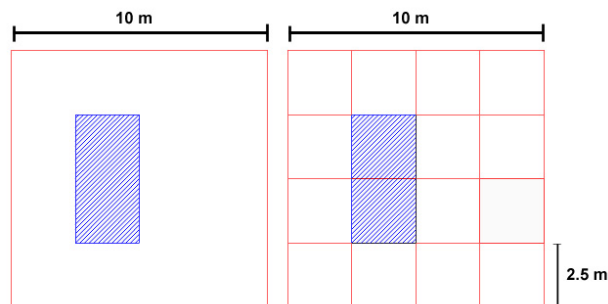


Figure 2: Schematic representation of land cover “undetected” in the case of a 10m x 10m pixel, but clearly “detected” with a 2.5m x 2.5m pixel

Having said that, on the basis that the absolute difference between the resolution of the images that will be offered by the next satellite in the Spot series will be considerably less, then in the future there will be much greater precision in the quantification of change. For example if Spot5 images were used as the baseline data then future images comparing change with the Spot5 images would be more reliable.

Clearly for monitoring urban development, the question of the scale of interest is crucial. For example, the results from the MURBANDY/MOLAND project show the spatial evolution of a group of urban areas, with the objective of proposing a methodology for strategic monitoring of the environmental impact of urban development. (See for example Figures 5.1-5.3, pages 49-50 EEA, 2002). However this overall ‘strategic’ scale of interest is very different from the ‘local planning’ scale of interest shared by the UPC and the MMAMB in the context of the current study.

On the one hand, this overall strategic vision of the change experienced in urban development of the Metropolitan Area of Barcelona can clearly be appreciated from the comparison of the 1995 and 2002 images used in this study, as indicated by Figure 3. Here the blue tone refers to existing development in 1995 and the red tone highlights new and/or (re)development over the period up to 2004. On the other hand, focusing on this same change at the more ‘local’ scale, is where the notion of graphical distortion arises, and where when such change is quantified, the certainty concerning this exaggeration of the results is confirmed. This is illustrated in Figure 4, which shows a close-up view of a small town, Matarò, lying to the north of Barcelona. Matarò has undergone considerable development pressure in recent years, but not to the extent that this image would lead one to believe. Here the red tone indicates new development (2002) and the orange tone represents existing development (1995). This figure exemplifies the difficulties arising from the comparison of different sized pixel images, in urban areas where such urban development is undergoing consolidation.

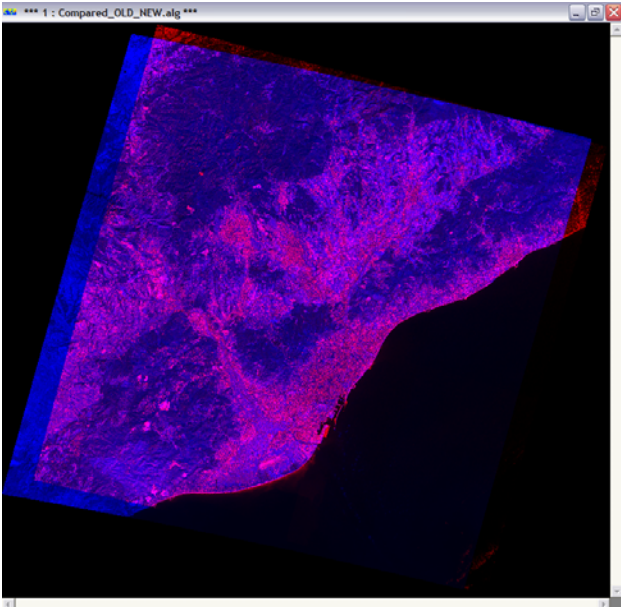


Figure 3: Change in residential development experienced throughout the study area between 1995 and 2002
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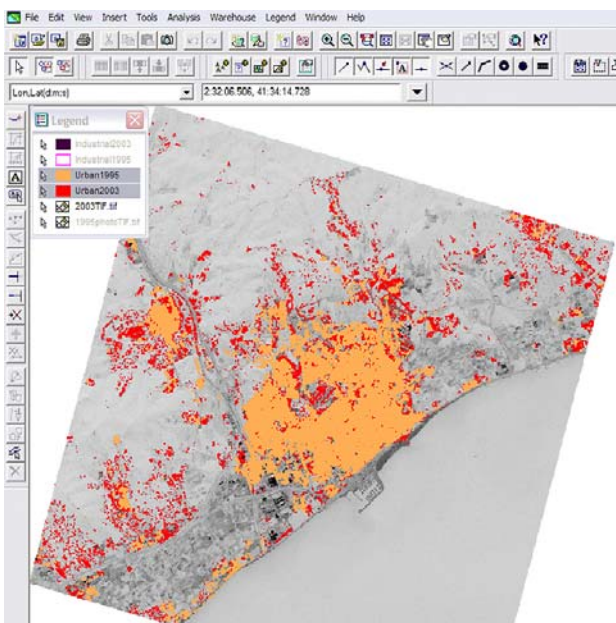


Figure 4: Identification of areas under development pressures between 1995 and 2002, in the vicinity of Matarò, by virtue of the overlay of the Spot 3 and Spot 5 images in vector format
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4.3 Conclusions

The results of the study provide a broad indication of the magnitude of change in urban land cover classes experienced in the metropolitan area of Barcelona over the study period. This increase of some 180 km² in urban land cover uses denotes a corresponding decrease in the other land cover classes, indicating the magnitude of the outward encroachment of urban development into the surrounding countryside.

There would appear to be clear advantages for planning and monitoring needs, from the enhanced results emanating from the supervised classification processes undertaken in this study. The greater degree of precision afforded by the pixels, will guarantee considerably less error than will occur with classifications from images of a lower resolution. For public authorities such as the MMAMB with responsibilities in monitoring land use activity over time, whether it be at the municipal or regional scale, the increased reliability in the determination of different land uses is clearly of crucial importance. While for the moment planners and public decision makers have to reconcile these shortcomings in precision and scale, it is suggested that a turning point has been reached in which future comparative research drawing upon remote sensing will be ever increasingly more accurate by definition, overcoming the need to reconcile issues of this nature.

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