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Road extraction through digital processing and visual interpretation of satellite images

Aikaterini Karagianni *1

[1]*Aristotle University of Thessaloniki, Faculty of Engineering, School of Civil Engineering, Lab. of Photogrammetry–Remote Sensing, Thessaloniki, Greece*

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ABSTRACT

Road extraction plays an important role in urban planning and city extension issues, as well as in road monitoring, traffic management and map updating. Technological advances may offer a wealth of data and techniques that could be implemented in road delineation and extraction, as well as in change detection projects. Among the various methods that have been developed for this purpose, remote sensing techniques and especially digital processing of satellite data could contribute significantly in this direction. This paper presents the study of a road network which concerns the city of Kastoria located in northwestern Greece and its surrounding area. The special character of the road network is closely related to the city's cultural value which is depicted in its structure. Satellite images of various spatial resolutions were employed for digital processing. Landsat 8 imagery was used in order to detect and delineate the linear features through spatial enhancement, while Landsat 5 images were used to detect changes over time through visual interpretation. Semi-automatic techniques were applied to SPOTmaps products to extract the road network, while an object-oriented approach was applied to QuickBird imagery in order to combine the spatial components with spectral properties. Through semi-automatic digitization and object-oriented workflows, the export of the studied part of the road network in vector format was achieved, thus facilitating the process and reducing the required time. The resulted data are efficient in road network delineation and could be combined with other data for road maintenance and extension, change detection issues, as well as for cultural and touristic purposes.

1. INTRODUCTION

Among the various elements that play an important role in urban and peri-urban development is the extraction of information related to the corresponding road network. Technological advances may offer a variety of data and techniques that could be used for road delineation and extraction. Remote sensing could contribute significantly in this direction (Cleynenbreugel et al. 1990; Wang et al. 2016).

Through digital processing of optical satellite images and visual interpretation, valuable information could be extracted regarding the road network of an area, its structure, possible changes over time, as well as the road connections it offers (Liu et al. 2016; Karagianni 2019).

Several approaches have been implemented in order to delineate road structures on satellite imagery which are closely correlated with the regional characteristics of the study area as well as the relevant technological development (Alshehhi et al. 2017; Hong et al. 2019).

Past studies have used combinations of methods to extract road networks of various forms, such as unpaved road networks exploiting archival data and utilizing a convolutional neural network (Kearney et al. 2020), while other studies have focused more on deep learning and multi-source remote sensing data (Huang et al. 2019) or on spectral indices to facilitate classification (Shahi et al. 2015; Hamedianfar and Shafri, 2015).

While some methods require extended time to be performed, others require extensive knowledge in terms of computational or programming literacy. Therefore, fast and effective techniques are valuable, especially in preliminary studies.

This paper presents the study of a road network which concerns the city of Kastoria and its surroundings located in northwestern Greece. The long history of the city and its wider area, as well as the special structure of the road network in the historic districts of the city center make this study of particular interest (Lazaridou and Karagianni 2014).

* **Corresponding Author**

*(aikateck@civil.auth.gr) ORCID ID 0000-0003-3423-5265

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Several satellite images of various spatial resolutions were processed in order to highlight and extract useful information regarding the road network. As a first step of the study, images with lower spatial resolution were processed and subsequently the study proceeded with the processing of images with higher spatial resolution.

Landsat 8 imagery was used in order to detect and delineate the linear features through spatial enhancement, while a pair of Landsat 5 images was used to detect road network changes of the surrounding area occurring over time through visual interpretation. Semi-automatic techniques were applied to SPOTmaps products to extract the road network, while an object-oriented approach was applied to QuickBird imagery of higher spatial resolution in order to combine the spatial components with spectral properties. The efficiency of using satellite imagery for road network delineation is presented in the results. The output data could be combined with other types of data in order to be used in further studies concerning road maintenance and extensions, change detection issues, as well as for cultural and touristic purposes.

2. STUDY AREA AND SATELLITE DATA

2.1. Study Area

Study area is located in medium-high altitude (630m) in the north western part of Greece, region of Western Macedonia and it concerns Kastoria city and its surroundings (Fig. 1). The city is located on a peninsula at the western shore of Lake Orestiada (Latitude: 40.52, Longitude: 21.27) and it has a long cultural history, which is depicted in its structure (old city, newer city and urban extension). The lake which surrounds the city is included in the Natura 2000 network offering unique habitats for many endangered fauna and avifauna species (Ponce de León 2015).

The city has a high architectural and urban value. Rich elements of Byzantine culture (Byzantine Justinian walls and medieval churches) as well as traditional mansions of the 17th and 18th centuries, unique for their architectural design are located in the city center (Doltso & Apozari traditional districts) (Moutsopoulos 1989).

Figure 1. The location of the Regional Unit of Kastoria in Greece (left image) and the city of Kastoria in the red circle (right image) (Karagianni 2019)

2.2. Satellite Data

The data employed for this study concern Landsat 5 and Landsat 8 satellite imagery downloaded free of charge from U.S. Geological Survey (USGS-Earth Explorer), as well SPOTmaps products and QuickBird imagery covering the study area.

Landsat 5 was a low Earth orbit satellite launched on March 1, 1984 and was officially decommissioned in 2013. The satellite carried the Multispectral Scanner (MSS) and the Thematic Mapper (TM) instruments. Thematic mapper had seven spectral bands, including a thermal band. The resolution is 30 meters for bands 1 to 7 and thermal infrared band 6 was collected at 120 meters, however was resampled to 30 meters (Landsat Data Report 1997).

In this study, two cloud-free Landsat 5 images were used. The first image was acquired on 12-09-1987, while the second image was acquired on 14-09-2011. The level processing of both images is Level 1T-Standard Terrain Correction (systematic radiometric and geometric accuracy) with projection information: UTM, zone 34, spheroid & datum WGS 84. The two images were selected to correspond to the same season (month and date as possible), in order to accomplish a similar reference (Fig. 2a and Fig. 2b).

Figure 2a. Landsat 5 true color composite subset of the study area for the year 1987

Figure 2b. Landsat 5 true color composite subset of the study area for the year 2011

Landsat 8 satellite was launched on February 11, 2013 and carries two instruments, the Operational Land Imager (OLI) sensor and the Thermal Infrared Sensor (TIRS). These sensors both provide improved signal-to-noise (SNR) radiometric performance, quantized over a 12-bit dynamic range (4096 potential grey levels in an image compared with only 256 grey levels in previous 8-bit instruments). Improved signal to noise performance enables better characterization of land cover state and condition (USGS 2012). Satellite data acquired from Landsat 8 consist of eleven spectral bands with a spatial resolution of 30 meters for Bands 1 to 7 and 9. The resolution for Band 8 (panchromatic) is 15 m and for Bands 10, 11 (thermal bands) is 100 m. Among the eleven spectral bands, Landsat 8 includes one band that measures the near infrared (Band 5-NIR) and two bands that cover different slices of the shortwave infrared (Bands 6 and 7-SWIR).

The Landsat 8 image data that were used in this study were acquired on 14-03-2014 with level processing 1T-Standard Terrain Correction (systematic radiometric and geometric accuracy) and projection information: UTM, zone 34, spheroid & datum WGS 84. (Fig. 3).

Figure 3. Landsat 8 true color composite subset of the study area

The SPOT satellite observation system was designed in 1977 by CNES (Center National D'Etudes Spatiales) in France with the participation of Sweden and Belgium. It was the first European Earth-observation satellite programme. The system consists of a series of satellites and terrestrial installations for the control and programming of satellites, as well as the production and distribution of images. SPOT satellites are equipped with two independent imaging instruments (series of detectors operating with pushbroom scanning technique). They collect multispectral and panchromatic imagery, offering high geometric accuracy. Each image covers a square of 60 km or 120 km on a side with a ground resolution of 10 m for SPOT 1 to SPOT 4 and 2.5 m for SPOT 5.

The SPOTmaps data that were used in this study were provided by the Technical Services Division of Kastoria Prefecture and they were acquired on 20-12-2012. SPOTmaps products derive from SPOT 5 color satellite images and include orthorectified coverage at a resolution of 2.5 m (Airbus Defence and Space 2013). They consist of three spectral bands with projection information: WGS84/UTM zone 34N. These color products are obtained after merging two separate images, a panchromatic image with 2.5 m resolution and a multispectral image (three spectral bands) with 10 m resolution (Fig. 4).

QuickBird satellite was launched on October 18 of 2001. The sensor has 4 multispectral bands with a resolution of 2.44 m at nadir: Band 1 - Blue (0.450-0.520 μm), Band 2 - Green (0.520-0.600 μm), Band 3 - Red (0.630-0.690 μm), Band 4 – Near Infrared (0.760-0.900 μm) (QuickBird Information Sheet 2021).

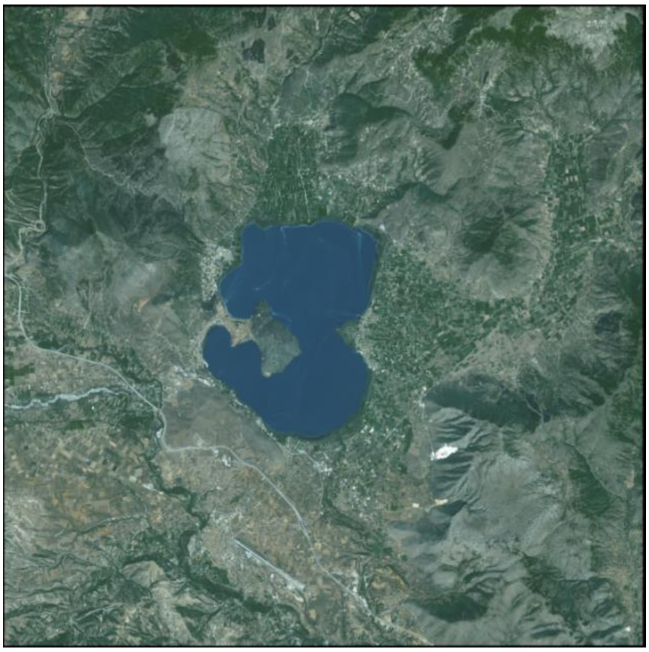

Figure 4. SPOTmaps imagery covering the study area

To get detailed information about the study area and especially the road network of the extension of the city, high resolution multispectral QuickBird satellite imagery was used that was acquired from DigitalGlobe on 29-07-2010. It is a cloud-free, standard ortho-ready Level-2A product (radiometrically and geometrically corrected) with projection information: UTM, zone 34, spheroid & datum WGS 84. The subset that was selected for digital processing covers an area representing the newer part of the city where the urban fabric presents organized structuring (Fig. 5).

3. DIGITAL PROCESSING METHODS AND RESULTS

For the delineation and extraction of the road network, digital processing techniques were implemented through non-automatic and semi-automatic techniques, as well as through an object-oriented approach. The software that was used to process the images is ERDAS Imagine. Visual interpretation performed before and after the processing also contributed to the study. The general procedure that was followed, as well as the corresponding satellite data that were used in each step are presented in Fig. 6.

Enhancement techniques are often used in feature extraction, locating areas or objects on the ground and gaining useful details. Image enhancement refers to the creation of new images from the original data, in order to increase the information that can be visually interpreted from the data (Lillesand and Kiefer 1987). Spatial enhancement modifies the pixel values based on neighboring pixel values. More specifically, spatial enhancement operations improve the interpretability of features within the data by modifying neighborhood pixel values based on the value of a targeted pixel. It is largely related to spatial frequency within an image, which is the difference between the higher and lower value of a continuous group of pixels. Convolution filtering uses a matrix to average small sets of pixels across the image in order to change the spatial frequency characteristics (ERDAS Field Guide 2013).

Figure 5. QuickBird subset covering the extension of the city of Kastoria

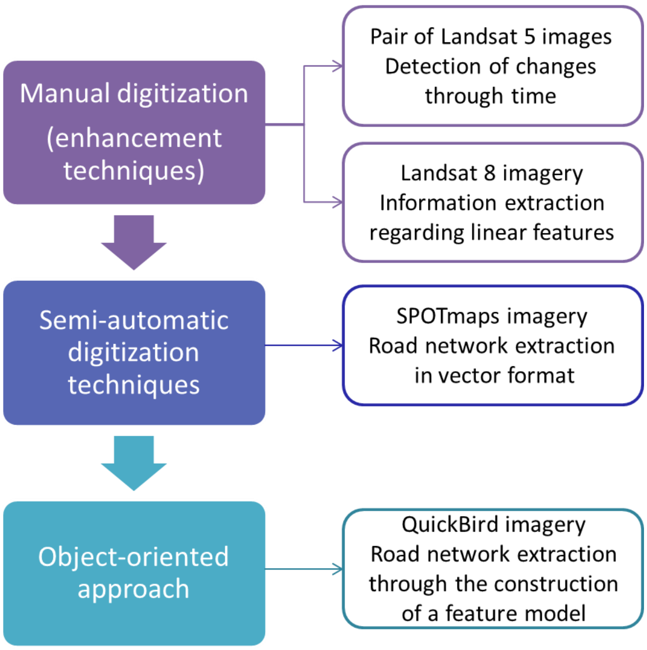

Figure 6. Workflow of the overall study

Among the various techniques available, 'edge enhance' and 'edge detect' filtering are significant enhancement techniques in digital image processing, especially in the study of urban features or in linear features mapping, such as road networks (Ziou and Tabbone 1998; Karagianni 2019).

In this study, a pair of Landsat 5 images was used in order to delineate the changes of the surrounding road network through time. Spatial filtering, and especially a 5x5 filter for edge enhancement, was considered effective for making the images more interpretative. Visual image interpretation was done on the basis of geometric (shape, size, etc.) and radiometric (tone-color, texture) characteristics.

The enhanced subset images and their interpretations are presented in Fig. 7 and Fig. 8 for the years 1987 and 2011 respectively. The blue line represents the drainage network, the red line represents the road network (variations in line thickness depict the category of the network) and yellow polylines represent the built-up areas.

The availability of satellite data acquired at different dates could offer change detection possibilities. Regarding the changes in the road network of the study area, observation of features over time could be very useful in road monitoring and maintenance, as well as in urban planning issues and city extensions.

The comparison of the two interpretations shows that built-up areas have been extended over time, while the road network has changed with the completion of a main branch in the southwest of the area.

Spatial enhancement techniques were also applied to Landsat 8 imagery (after subsetting the data according to the area of interest) in order to improve the appearance of the image and facilitate the extraction of useful information regarding the linear features which are delineated. The resulted subset image after the implementation of a 3x3 convolution filter for edge detection is presented in Fig. 9. Edge detection processing highlighted linear features (including the road network) and urban features. Additional maps of the study area or other auxiliary data were also used to facilitate the process.

Subsequently, road extraction could be performed manually using the enhanced image as a base layer in order to create a top vector layer which would contain the road network.

For the digitization of various features as well as related changes (changes in road networks, changes in infrastructure networks, urban development issues, etc.) classic, manual digitization techniques are frequently used, which however can often be time-consuming and tedious (Tao et al. 2019).

Extraction of information from satellite images in vector format (digitization of linear elements and boundaries, such as road network, lake outline, etc.), could be accomplished through semi-automatic digitization techniques or object-oriented approaches, in addition to the manual detection/design process through visual interpretation. In this way, the process is simplified while the required time is reduced.

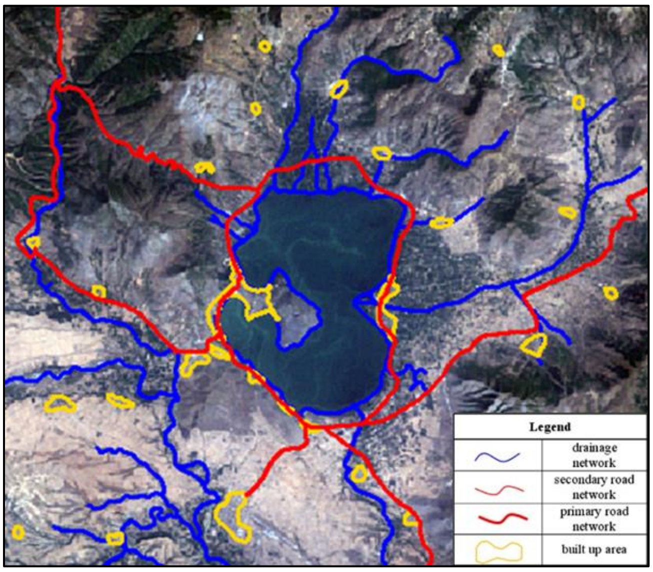

Figure 7. Landsat 5 enhanced subset image and interpretation for the year 1987 (modification from: Karagianni 2019)

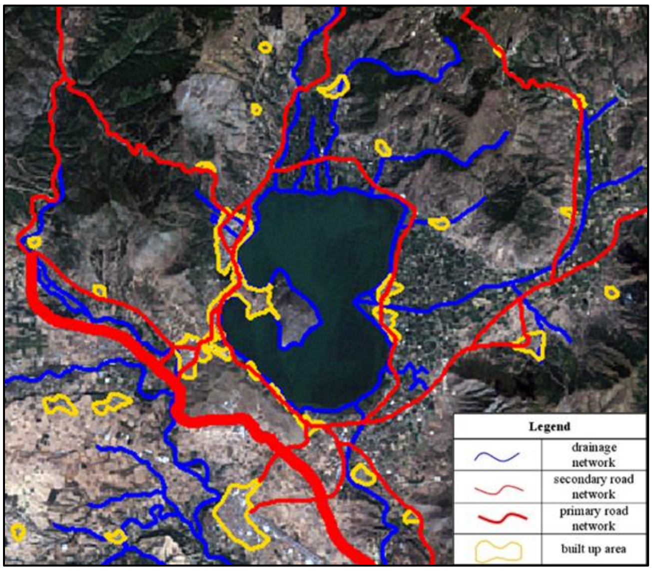

Figure 8. Landsat 5 enhanced subset image and interpretation for the year 2011 (modification from: Karagianni 2019)

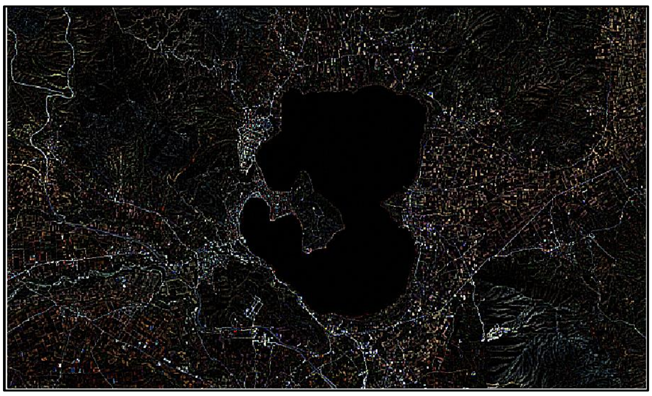

Figure 9. The final Landsat 8 subset image after convolution filtering for edge detection (Karagianni 2019)

Most image processing software offer add-on modules that could facilitate the extraction of linear features through assisted digitization reducing the required amount of non-automated workload when collecting different types of features.

In this study, a module offered by Erdas Imagine software was used in order to digitize the road network of the study area. This interactive tool is guided by the operator who recognizes features from the screen image (IMAGINE Easytrace User's Guide 2010). The process was performed in SPOTmaps image as it offers higher spatial resolution and consequently higher accuracy in the results.

The definite and nearly constant width, as well as the similar texture (pattern) along the extension of the road network were exploited in order to draw ribbon features by centerlines, setting the appropriate parameters. Boundary features such as road edges were detected through the discontinuity of intensity or color which indicated different areas, as well as due to the consistent texture (whiter or blacker than the background).

Vertices were automatically inserted between the neighboring manually measured vertices based on the underlying raster imagery, in comparison to the classical digitizing method in which manually measured vertices are only used. The results were saved in a vector file. In Fig. 10 the digitized road network is presented in yellow color, while in Fig. 11 the area of the city extension is shown (subset of the newer part of the city) which presents a more organized structuring.

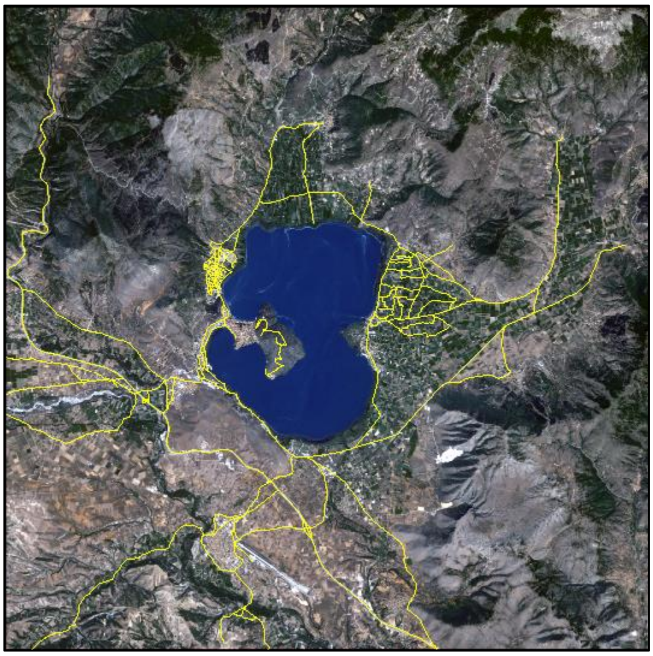

Figure 10. Road network of the city of Kastoria and the wider area (yellow line) on the SPOTmaps satellite product (Karagianni 2019)

The final step of digital processing included the construction of a model in order to extract information regarding the road network of the newer part of the city, thus facilitating the process. Through the exploitation of the high spatial resolution that QuickBird imagery offers, an object-oriented approach was selected employing the spatial components in addition to spectral properties.

Based on the model, visual image interpretation cues for the specific feature are quantified, while machine learning components are trained using these cues which are ultimately applied to the imagery in order to extract the features. The quantification is achieved through algorithms which perform raster contouring, but also incorporate object and vector level processing in order to yield a spatially matched, precise shape depicting the studied features. The generated output accurately reflects the image content (IMAGINE Objective 2010).

Through the aforementioned modifiable and extensible feature models, the spatial components that are produced are also measurable and available for further processing.

Figure 11. Road network of the city extension (yellow line) on the SPOTmaps satellite product subset (Karagianni 2019)

The steps that were followed in this study in order to build the road extraction model were performed in Erdas IMAGINE Objective software and include five basic operations:

1. Raster Pixel Processor operation (RPP): Classification of road and non-road pixels from the original image by sampling and training road pixels and subsequently classification of the image.
2. Raster Object Creators (ROC): The segmentation operator is used to generate raster objects exploiting the probability attribute obtained from the raster pixel processor in the previous step by computing the mean value of the pixel probability. Different homogenous regions are separated by the spectral properties based upon multiple region growing processes. After segmentation, the results generated contain the information derived from both spatial and spectral domains.
3. Raster Object Operator (ROO): A further reduction of the number of non-road raster objects can be performed employing a probability filter to remove all raster objects with low probabilities of being the studied object (road network). A size filter can also be used to remove all small-scale objects which present similar spectral properties. A centerline convert is applied to convert all possible road raster objects into linear raster objects with a single-pixel width.
4. Raster to Vector Conversion (RVC): Line trace is used to convert centerline objects to vector objects, producing a shapefile layer.
5. Vector Object Operators (VOO): The generalize operator is used to reduce the vertices of each line. As the centerlines that have been extracted at this point may not fully match the exact road centerlines presenting several gaps, a line link operator is used to link the collinear centerlines. In order to extend lines to the junction points which reflect the topological structure of the road network, a line snap operator is used, while isolated short lines could be removed using a line remove operator.

The workflow that was followed is presented briefly in Fig. 12, while the results of the performed model are presented in Fig. 13.

The final layer includes the extracted road network which is depicted in red color. In general, the workflow generates results that represent the network to the greatest extent. Minor issues are detected in some parts of the network where variations in width, texture and color are evident.

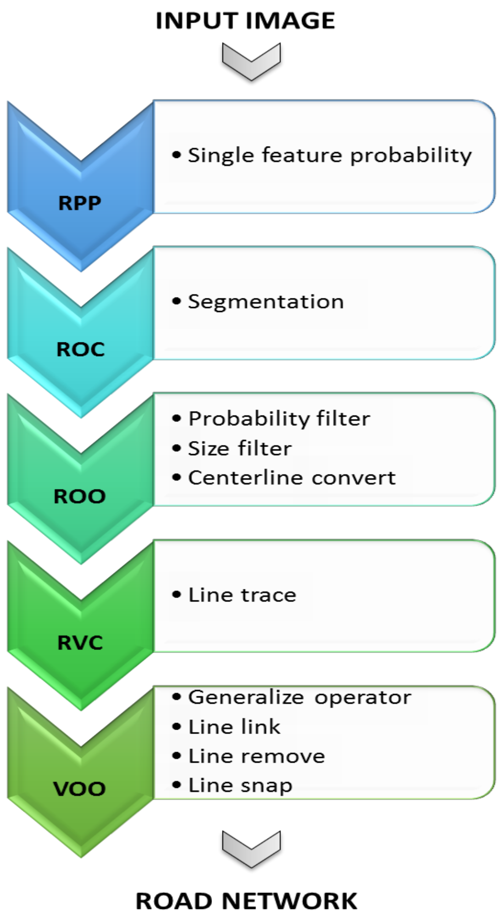

Figure 12. Flowchart of the object-oriented approach for road network extraction

Figure 13. Road network of the city extension (red line) on the QuickBird subset image, as extracted after the employment of the object-oriented approach

4. CONCLUSION

Several methods could be applied to satellite images in order to delineate and extract road networks for urban planning and road monitoring. In the selection of the most appropriate method several parameters should be taken into account, such as the type of the project, the study area, the available time and the required workload, as well as the final cost and the specialization of the personnel. Therefore, the need to search for easy, fast and efficient tools is imperative.

Spatial filters could be used to sharpen or emphasize the edges in the image, offering effective results especially in preliminary studies which do not require special details but must be carried out in a short time. In this study, convolution filtering for edge detection and edge enhancement was applied in order to delineate the linear features. The resulting images after the implementation of spatial enhancement techniques present an improved appearance and are suitable for the delineation of linear features. The road network is effectively highlighted facilitating the subsequent manual extraction process.

Changes through time regarding the road network of the surrounding area were detected through the processing of Landsat 5 pair images covering the same area on different dates. A similar reference was accomplished by selecting images that corresponded to the same season. Landsat 8 imagery was also processed applying a spatial filter in order to highlight linear features and enable the extraction of useful information regarding the study area. Additional maps of the study area or other auxiliary data, as well as data collected after visiting in situ some parts of the network were used in order to discern linear features in the results that correspond to the road network.

Further digital processing included the exploitation of satellite images of higher spatial resolution, which facilitated the process offering better final results at a shorter time.

Semi-automatic digitization offers satisfactory results in the urban areas of the imagery, where the urban fabric presents organized structuring. Satisfactory results are also obtained in areas where there is a strong differentiation between the road network and the environment (road network in cultivated areas, in the mountainous area of the peninsula or in bare ground areas).

In intricately structured areas presenting a more anarchic structuring (road network of narrow width and shading interference), the semi-automatic method appears to have weaknesses in digitization as there are difficulties in finding the edges (center of urban fabric on the peninsula). Similar problems also arise when attempting to digitize sections of the road network with variable width or large differences in texture.

Especially in multispectral images, features that are normally sharp enough to be clearly visible on the screen may not be properly detected, as the module processes image intensity information only (large color differences may not correspond to large intensity differences). This issue could be solved if one of the color bands is used for digitization or if the image is digitally enhanced before digitization. Additional corrections to digitization can also be made manually, combining the semi-automatic with the manual process.

The object-based approach was selected as the final step of the study in order to effectively combine the spatial and spectral information to enhance reliability by exploiting the higher spatial resolution of QuickBird imagery.

The workflow that was selected includes an automated process of various steps based on the selection of several parameters according to image characteristics. The intermediate results of the workflow were utilized in order to improve the final results by modifying the input parameters or settings accordingly, taking into account the particular characteristics of the part of the road network under study. The image that is produced after applying the probability filter could be used to ascertain if the intermediate operations offer satisfactory results.

The final output layers could be very useful for interpretation purposes and urban planning. The general workflow could be adopted by other studies concerning the extraction of road networks that present similar characteristics, adjusting the individual parameters accordingly.

Issues regarding the classification of the road network in comparison with its background may arise in parts which contain occlusion and noises (cars on the road) or in areas where the presence of thick vegetation near the road is evident. The classification results in this study were improved by adding new training samples.

Additional issues may arise due to color discontinuities/differentiations at some parts of the network. Ambiguities in the final results related to variations in size, color or shading of the road network were addressed using several representative samples during the first step of the process.

In conclusion, through semi-automatic and automatic digitization, the process is facilitated and the amount of non-automated workload required when collecting different types of features could be reduced, providing products which could be efficiently combined with other types of data for road maintenance and extension, change detection issues, as well as for cultural and touristic purposes.

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Conflicts of interest

The author declares no conflicts of interest.

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