Analysis of ASTER Multispectral Stereo Imagery to Produce DEM and Land Cover Databases for Greek Islands: the REALDEMS Project

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Abstract. High accuracy determination and visualization of topography of the Earth's surface is very important for local level environmental applications, however Digital Elevation Models (DEMs) of usable details are still not available for much of the Earth. Land cover is one of the most important products of remote sensing and it is a primary input of hydrologic models. While there are land cover maps in global and regional levels, there is lack of these products in many localized areas. In this study, early results of the project REALDEMS (REmote sensing Application for Land cover and DEMs Service) are presented. This project aims at providing accurate DEM and land cover databases for Greek islands, capable of being used in local studies. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images are used in combination with Global Positioning System (GPS) data and field observations. A digital stereo correlation approach is applied to produce DEM from ASTER stereo pairs, whereas supervised and hybrid classification techniques are applied for land cover mapping. Three main stages have been planned in REALDEMS: In the first stage, ASTER images will be pre-processed and the field measurements and observations will be performed. The second stage includes all remote sensing analysis tasks, whereas the third stage is related to GIS analysis and validation of results in terms of application of produced DEM and land cover for watershed characterization. This type of application has been selected because of the great importance of water resources for Greek islands. Thus, REALDEMS also aims at introducing satellite remote sensing data and methodologies in support of local level watershed management providing also valuable information to hydrological modelling.

1 Introduction

Watersheds have been identified as planning units for administrative purposes to conserve these precious resources. The main objectives of watershed studies include watershed segmentation, identification of drainage divides and the network of channels, characterization of terrain slope and aspect, catchment configuration and routing of the flow of the water. The automated watershed segmentation and extraction of channel network and sub-watershed properties from raster elevation data represents a convenient and rapid way to parameterise a watershed. The integration of spatial data handling capabilities of a Geographic Information System (GIS) with hydrologic models, offers the advantage of having information content of the spatially distributed data to analyse the involved process. The quantitative assessment of the processes depends on the topographic configuration of the land surface, which is one of the several controlling boundary conditions [1], [2], [3], [4]. Moreover, hydrologic models require different types of data depending on the process modelled and the relevant time and space scales of these processes. These data include surface representation (slope, aspect, plain geometry), soil characterization (permeability, conductivity, storativity), antecedent moisture conditions, land cover/use condition, vegetation characteristics and biomass, as well as a number of watershed topological properties such as the structure of the channel network and its contributing sub-catchments. Hydrologic models are classified spatially as either lumped or distributed. The more spatially complex distributed models attempt to describe more fully the spatial variation in topography, soils, surface characteristics and meteorology to explicitly include these in the model. The watershed surface is discretized in to a spatial grid and the characteristics of the watershed are described within each grid cell. It is not feasible to construct databases at optimal resolutions for hydrologic modelling on anything but the smaller basin or sub-basin scale due to the lack of suitable data and computational resources for the model [5]. The grid resolution of 10 m has been suggested as appropriate for hydrologic modelling [6]. However, at this resolution the data are not available over large areas. Hydrologic studies are normally conducted using raster datasets at spatial resolutions of 30 m or less if possible.

Remotely sensed data make it possible to extract hydrologic parameters and to update these parameters at relevant temporal scales (monthly, seasonally, annually) over very large spatial domains. Following acquisition, the satellite data must be processed to correct for the influence of the intervening atmosphere, remapped to a geographic or spatial grid and analysed to derive information required specifically for watershed characterization or for hydrologic modelling. Image classification is usually part of this analysis in order to produce thematic maps capable of being used in GIS analysis. Previous research [3], [7] has demonstrated the variability of techniques for automatically deriving a wide variety of topographic and topologic information, that are meaningful to watershed runoff process, directly from a Digital Elevation Model (DEM). It is therefore obvious that watershed characterization requires at the first step, the construction of a DEM to be completed by thematic maps for land cover or land use. For the production of DEMs from optical satellite data, the respective satellite sensors should have stereo coverage capabilities. To obtain stereoscopy with images from satellite scanners, two solutions are possible [8]: a) the along-track stereoscopy with images from the same orbit using fore and aft images; and b) the across-track stereoscopy from two different orbits. The first solution is used in ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery. The ASTER method gives a strong advantage in terms of radiometric variations versus the multi-date stereo-data acquisition with across-track stereo, which can then compensate for the weaker stereo geometry. The viability of stereo correlation for parallax difference from digital stereoscopic data has been described and evaluated in previous studies [9], [10], [11], [12]. Moreover, the production of orthorectified raster images, a necessity for incorporating image data in a GIS database, requires a DEM [13], [14], because raw satellite images usually contain such significant geometric distortions that they can not be use directly with map base products in a GIS [15]. Recently, at the local level, a number of data sources have been used to derive land cover products for high resolution studies [16]. One of the main problems when generating land cover maps from digital images is the confusion of spectral responses from different features. The accuracy of the map depends on the spatial and spectral resolution and the seasonal variability in vegetation cover types and soil moisture conditions [17]. The integration of GIS with ancillary information has the potential to improve classification accuracy [18], [19], [20].

In this study, early results of REALDEMS (remote sensing application for land cover and DEMs service) project are presented: ASTER imagery was analysed in combination with Global Positioning System (GPS) data and field observations to provide accurate DEM and land cover/use thematic maps for the area of NW Heraklion, Greece and to examine the potential of high spatial resolution remote sensing to support watershed analysis at Greek islands. GIS techniques were also used to extract watershed physical parameters, capable of supporting watershed characterization and hydrologic modelling.

2 Data and Methodology

The data used in this study was an ASTER image, acquired on August 10, 2000, over the region of Heraklion and GCPs (Ground Control Points) derived from differential GPS measurements provided by the GPS base station of FORTH (Foundation for Research and Technology – Hellas). Field observations have been also used for training site selection for the supervised classification of ASTER multipsectral imagery. A Transverse Mercator projection was applied (Projection System: Hellenic Geodetic Reference System 87 - HGRS87) in order to have all data in the same geodetic system. The study area located around Giofyros river watershed and includes 12 Municipalities of the Prefecture of Heraklion, as shown in Figure 1.

ASTER is an advanced multispectral imager that was launched on board NASA's Terra spacecraft in December, 1999. ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared with high spatial, spectral and radiometric resolution. ASTER consists of three separate instruments subsystems, each operating in a different spectral region, using separate optical system. These subsystems are the visible - near infrared (VNIR), the short-wave infrared (SWIR) and the thermal infrared (TIR). The spatial resolution varies with wavelength: 15 m in the VNIR, 30 m in the SWIR and 90 m in the TIR. The VNIR subsystem consists of two telescopes – one nadir looking with a there band detector (Channels 1, 2 and 3N) and the other backward looking (27.7° off-nadir) with a single band detector (Channel 3B). The city of Heraklion is clearly depicted in bluish tones in the upper part of Figure 1, which is a pseudocolor combosition of the ASTER channels 1, 2, and 3N (RGB: 3N-2-1). The most important specifications of the ASTER stereo subsystem that govern the DEM generation capabilities, include: stereo geometry; platform altitude of 705 km and base to height ratio (B/H) of 0.6 [9].

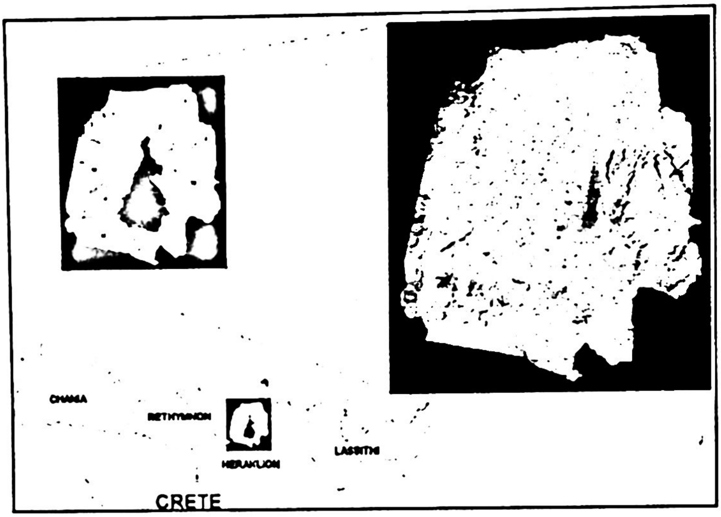

Fig. 1. The study area

As it has been already mentioned, the work carried out in this study is part of the REALDEMS project. Three main research stages have been planned in this project: In the first stage, all available ASTER images will be selected and pre-processed and the field measurements and observations will be performed. The second stage includes all remote sensing analysis tasks, whereas the third stage is related to GIS analysis and validation of results, in terms of application of produced DEM and land cover for watershed characterization and mapping. The REALDEMS methodology is shown in Figure 2. Thus, ASTER 3N and 3B images, were used for DEM production, whereas VNIR imagery were used for land cover/use classification and mapping. Field measurements with the use of GPS were also performed to provide GCPs for DEM correction and geo-location, as well as to support field observations and training site selection for the supervised classification process. DEM extraction from ASTER stereo imagery is based on the principle of automatic stereo correlation. The accuracy to which absolute elevations can be derived by photogrammetric techniques is governed by: a) B/H ratio i.e. geometric stereo disposition, b) reliability of the correlation procedure and c) accuracy and density of GCPs. A digital stereo correlation approach used to calculate parallax differences from ASTER stereo pair [9]. Relative ground elevations were determined by measuring the parallax differences in the registered images. The parallax differences were converted to absolute elevations with the use of GCPs. The image coordinates of the GCPs in conjunction with their HGRS87 map coordinates allowed the development of transformation equations needed to register the stereo images and eventually geodetically rectify them to the Earth's surface. The used geometric model was a rigorous parametric model developed at the Canada Centre for Remote Sensing [21]. The Root Mean Square Error (RMSE) in xy (planimetry) and z (elevation) were used for the DEM accuracy assessment. Assuming parallax difference correlation errors in the range of 0.5 to 1.0 pixels (7-15 m), elevation errors (RMSEz) are expected to be in the ±12 m to ±26 m range.

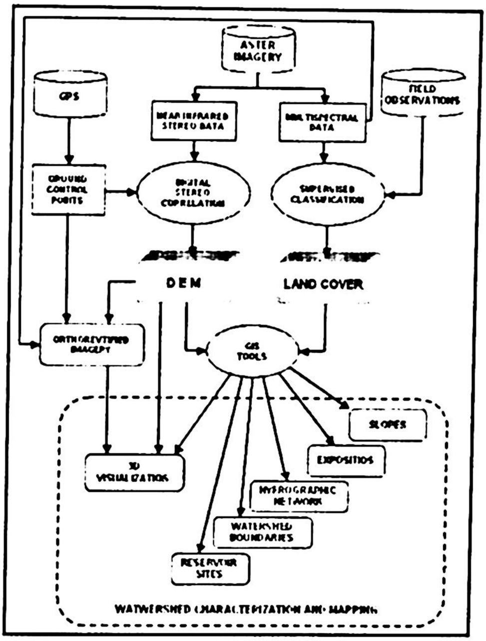

Fig. 2. Flowchart of the REALDEMS methodology

The produced DEM was used for a GIS-based watershed characterization to determine: a) the hydrographic network and outlets; b) the maps of slopes and aspects and c) the limits, the boundaries and the area of the watershed and sub-watersheds. Four steps were carried out to delineate the drainage network: a) removing depressions and flat areas in the DEM to eliminate indefinite downslope drainages, b) assigning flow direction per cell, c) assigning flow accumulation values per cell, and d) determining the threshold flow accumulation value that best represented the drainage pattern [3]. Additional analysis steps were carried out to derive physical characteristics of the watershed. Depressions are groups of raster cells completely surrounded by other cells of higher elevation. They are usually artifacts that arise from data inaccuracies or limited horizontal and vertical resolution of the DEM. The depressions are removed by raising the elevations within each depression to the elevation of its lowest outlet. Areas of limited relief can translate into perfectly flat surfaces in DEMs due to the following reasons: a) too low a vertical and/or horizontal DEM resolution to represent the landscape, b) filling the depressions and c) landscape that is truly flat. Whatever their origin, flat surfaces are problematic because flow direction on a perfectly flat surface is indeterminate [4]. Elevation and flow direction were the essential data from which all of the other drainage computations were made. The slope was determined from the change in elevation divided by the distance between cells, determined between the centres of the cells in question. The surface drainage pattern defined by these overland flow directions allows for the derivation of the upstream drainage area or flow accumulation for each cell. In-house software tools [22] developed in ESRI ArcView script language were used to query the flow direction grid to identify those cells deemed to be upslope of the cell in question and create a grid of accumulated flow to each cell by summing the weight for all cells that flow into each down-slope cell. Once the flow direction and flow accumulation were determined, stream networks were identified by setting a threshold for the flow accumulation to define the beginning of a stream. Watersheds for any point were determined by identifying all cells that flow into a particular cell of interest. With the aid of the flow accumulation, the location of the watershed outlet was determined and an outlet feature point was created. A minimum threshold was defined and all of the DEM points upstream from the defined outlet were connected together to form a stream network of feature lines. Using the outlets on the stream network and the flow directions, the contributing DEM points for each outlet were assigned the proper basin id. The boundaries between DEM points with different basin ids were converted to feature polygons. Once the boundaries of the sub-basins were determined, geometric properties important for hydrologic modelling (area, slopes, aspects, etc.) were computed from the DEM data. The geometric dimensions of overland areas (hill slopes that drain directly into a channel link) may be represented within the GIS by using the Triangulated Irregular Network (TIN) method. In this method, an area is represented by irregular triangles with the elevation specified at each triangle vertex; the elevation is assumed to vary linearly over the triangle. This formulation allows for the specification of irregular features which might not be possible with gridded data and is commonly employed in hydrologic modeling [23], [24].

Land cover/use is a primary input for hydrologic models determining the runoff characteristics of a specific catchment area. A supervised land cover classification system is being developed in REALDEMS project, however, in this study, a hybrid classification method was applied for land use mapping using ASTER VNIR imagery and field observations. Initially the raw imagery was orthorectified using the produced DEM and the GCPs. Afterwards, a supervised classification was performed to derive land cover types as explained above. Following, a semi-automatic extraction of land use classes took place based on the produced land cover types in combination with other ancillary spatial data. Points of interest (i.e. airport, port, industrial zones, etc.) were located and polygons covering these areas were digitised. These polygons were used to create a digital mask for VNIR imagery in order to mask pixels corresponding to the following land use types: a) main commercial zones; b) industrial zones; c) public buildings and areas; d) airport; e) port; f) coast; g) major hotel installations; h) sporting installations and i) archaeological sites. Once pixels corresponded to the aforementioned areas had been masked, the remaining VNIR pixels corresponded to residential developed land or to undeveloped. Therefore, the supervised classification scheme was applied again to these pixels, resulted in seven more classes: a) residential developed areas; b) sea and wetlands; c) vineyards; d) olive groves; e) other cultivated land; f) areas with natural vegetation and g) mixed areas.

3 Results and Discussion

ASTER stereo imagery was used for DEM production with the use of PCI photogrammetric software (Orthoengine). DEM was directly produced by digital cross-correlation between ASTER 3N and 3B channels, read from the distribution file (HDF format) by the software. It was possible to automatically create a relative DEM from 3N and 3B input files, using just tie points to adjust the images together. However the addition of GCPs permitted more precise geocoding and scaling of the final product (absolute DEM: elevation referenced to mean sea level). Once tie points and GCPs had been collected, then a bundle adjustment operation was performed. This operation computes a photogrametric model using the orbital and sensor ephemeris information plus the GCPs and tie points, so that images were located relative to each other and to the ground. Afterwards, epipolar images were created for both input files. These versions of the original 3N and 3B files removed any offsets between them in the y-direction.

Figure 3 shows the produced DEM. Catchments and mountainous areas are clearly depicted. The planimetric accuracy of the produced DEM was at ± 15 m (1 ASTER pixel), whereas its vertical accuracy was checked by using survey monuments (TPoints). TPoints are shown with the red crosses in Figure 3. The elevation of each TPoint was compared with the elevation of the respective DEM pixel. A very good correlation (R^2 = 0.9971) was observed as shown in Figure 4, where a scatter-plot between TPoints derived ($Z_{TPoints}$) and ASTER DEM derived (Z_{ASTER}) elevation values is presented. The mean absolute value ($|\Delta Z|$) of elevation difference between $Z_{TPoints}$ and Z_{ASTER} was equal to 10.36 with a standard deviation of 6.86. The RMSE was used for a more quantitative evaluation of DEM's vertical accuracy. RMSE encompasses both systematic and random errors and is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \delta z_i^2} \tag{1}$$

where, δz_i is the $Z_{Tpoint(i)}$ - Z_{ASTER} differences and n is the number of TPoints.

It was founded that RMSE was 12.41 m. whereas the the majority (88%) of the |ΔZ| values were less than 20 m: 73% were less than 15 m: 50% were less than 10 m and 30% were less than 5 m. Moreover, the maximum error was less than 30 m. an acceptable value yielding that the distribution of errors is within the normal extent.

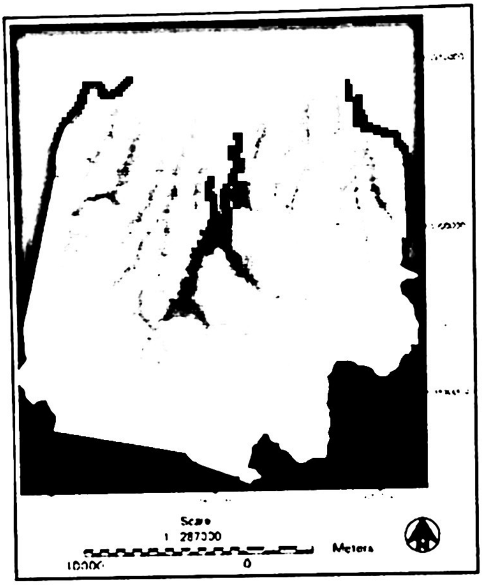

Fig. 3. The produced DEM for the NW Heraklion

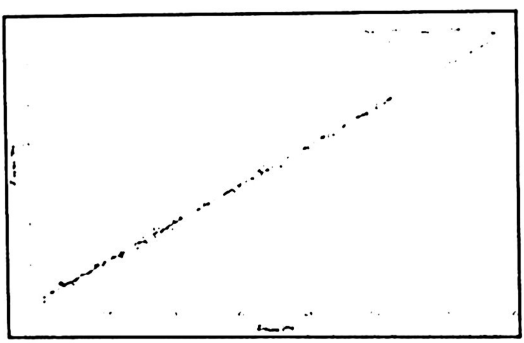

Fig. 4. Scatter-plot between $Z_{TPoints}$ and Z_{ASTER}. An excellent correlation was observed

Once the DEM was produced, GIS techniques were used for slope and aspect spatial distributions extraction. Figure 5 (left) shows the slope image of the area. Slope images are usually colour-coded according to the steepness of the terrain at each pixel. The calculated slopes have been grouped in four main categories. Using the elevation and the slope information, aspect values for each pixel were calculated and classified in four main categories as shown in Figure 5 (right).

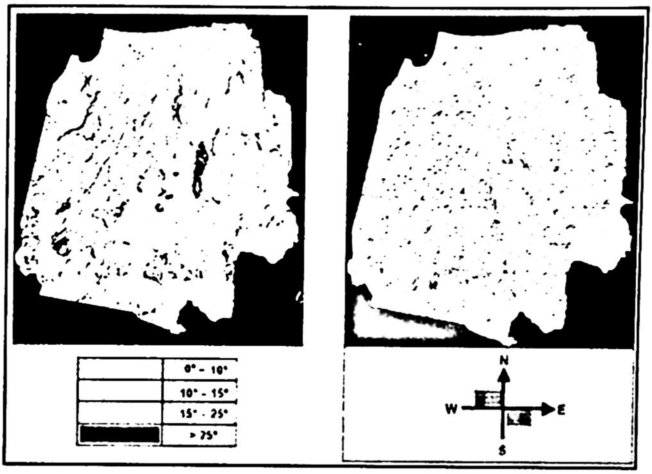

Fig. 5. Slope (left) and aspect (right) spatial distributions as derived from ASTER DEM

DEM, slope and aspect products were also used as inputs in GIS analysis for the watershed characterization process as shown in Figure 2. Elevation and flow direction were the essential data from which all of the other drainage computations were made. Using the developed GIS tools, the location of the watershed streams was determined and stream feature lines were created. Moreover, the location of outlets was determined and outlet feature points were created. The watershed was subdivided into sub-basins by converting the nodes along the stream feature arcs to outlet nodes. Figure 6 shows the watershed hydrographic network and outlets. The watershed segmentation result is shown in Figure 7. An id number has been assigned to each sub-basin. Once sub-basins have been identified, spatial calculations can been performed using GIS capabilities.

As it has been already mentioned, surface features may be represented within the GIS by using the TIN configuration, because it allows for the specification of irregular features which might not be possible with gridded data and is commonly employed in hydrologic modelling. Using the ArcView 3D Analyst a TIN elevation representation was produced from ASTER DEM. This product is capable of being used in application of hydrologic models in the area of concern. It is also capable of performing quantitative 3D spatial calculations, as for example the calculation of the area between different elevation levels as shown in Figure 8.

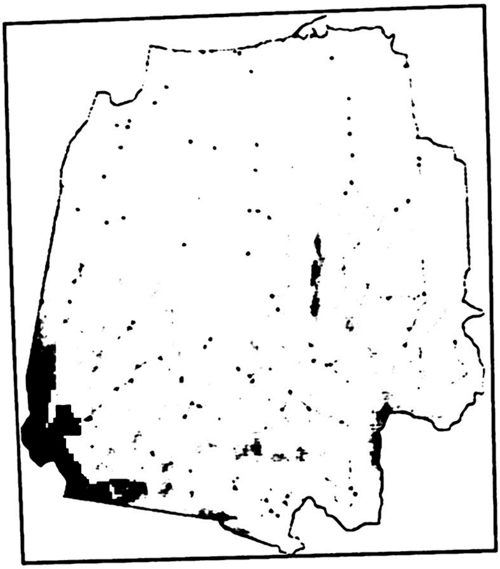

Fig. 6. Watershed hydrographic network and outlets

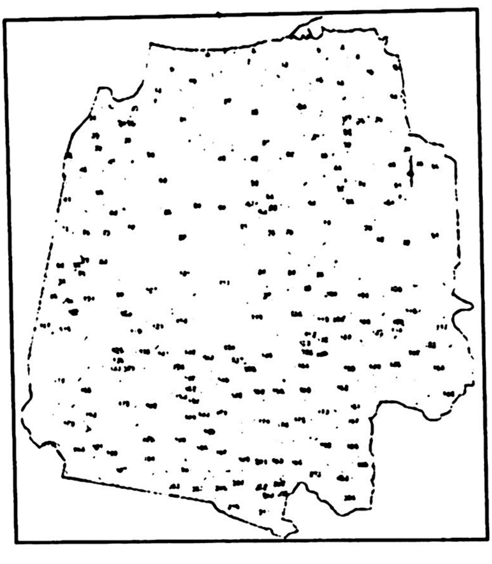

Fig. 7. Sub-basin identification

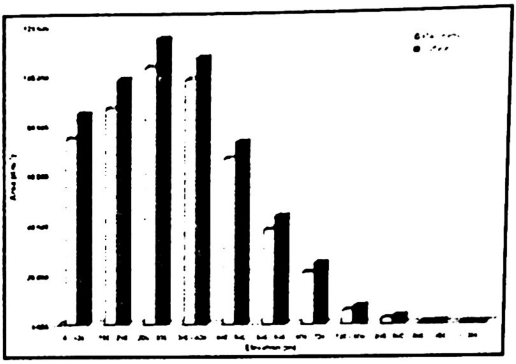

Fig. 8. Area between different elevation levels

The ASTER derived DEM and the GCPs were used to orthorectify VNIR ASTER channel. Figure 9 shows the orthorectification result for the upper part of the study area as a pseudocolor composition of the ASTER VNIR (RGB: 3N-2-1). It is the area around the metropolitan city of Heraklion (Municipalities of Heraklion, Gazion and Nea Alikaranasos), which is depicted in bluish tones, whereas the vegetated areas are shown in red and green tones.

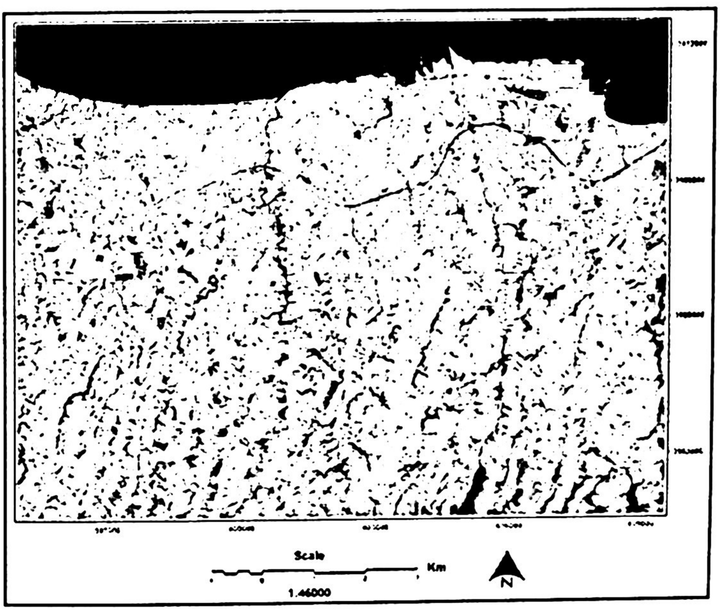

Fig. 9. Orthorectified ASTER VNIR image (pseudocolor composition RGB: 3N-2-1)

Fig. 10. Land use classification for the study area around the city of Heraklion

Since field observations were available for the study area the production of land cover was straightforward through the application of a supervised classification method on ASTER VNIR imagery. However, for the upper part of the area of concern, which is a mixed (urban, industrial, agricultural and natural) area as shown in Figure 9, the supervised classification algorithms were not appropriate for the land cover/use production. For this reason the hybrid classification scheme described in Section 2 was applied. Figure 10 shows the land use classes as derived by combining the land cover classification product with available vector data and in-situ observations. Eighteen land use types have been derived in total. Eight of them represent undeveloped land (cultivations, natural vegetation, wetlands and coastal zone), one type is referred to residential developed areas and the remaining nine types represent other developed areas (industrial and commercial zones, airport, road network etc.). This detailed mapping provides valuable information for land parameterization by models dealing with surface processes.

4 Conclusions

The work carried out in this study was a part of REALDEMS project aiming to provide accurate DEMs and land cover maps for Greek islands, capable of being used in local studies. REALDEMS is also aiming to introduce satellite remote sensing data and methodologies in support of local level watershed management. In this framework, high spatial resolution ASTER imagery was analyzed in combination with GPS data and field observations to provide DEM, land cover/use thematic maps and watershed characterization products for NW Heraklion, Crete. The ASTER method was used because it gives a strong advantage in terms of radiometric variations versus the multi-date stereo-data acquisition with across-track stereo, which can then compensate for the weaker stereo geometry. Near infrared stereo imagery was used for DEM production, whereas VNIR imagery was used for land use classification and mapping. GPS measurements were performed to provide GCPs for DEM correction and geo-location, as well as to support field observations and training site selection for the supervised classification. A hybrid GIS-based classification scheme was applied for urban areas, combining the supervised classification results with ancillary spatial data. GIS methods were used for the watershed analysis. GIS tools were employed to estimate watershed characterization parameters offering the advantages of spatial data handling capabilities and automatic extraction of thematic information. The sub-basins were located and the drainage pattern was extracted providing a generally representative depiction of the watershed. The planimetric and elevation accuracy of the produced DEM (± 15 and ± 12.41 m, respectively) are considered quite satisfactory for large catchment hydrological parameterisation, indicating the high potential of ASTER imagery to support watershed management. The resultant DEM can be used as a data product in its own right and/or as the DEM needed to orthorectify other satellite images acquired over the same area. Following the orthorectification, these images (original or classified) are ready to be used alongside other spatial data sets.

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