Detection of Rapid Erosion in SE Spain: A GIS Approach Based on ERS SAR Coherence Imagery

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Abstract

This paper presents an integrated remote sensing—GIS approach for identifying areas vulnerable to rapid erosion in Almería Province, Southeast Spain. Earth Resources Satellite (ERS) Synthetic Aperture Radar (SAR) multi-temporal interferometric coherence imagery has been used to detect rapid erosion that causes random changes in the micro-topography of a land surface. These small scale changes result in reduced coherence of the radar signals between the initial and eroded states. However, the detection solely based on coherence imagery is not exclusive because other factors may cause losing coherence as well. A Geographic Information System (GIS) is then used to derive criteria for a set of environmental conditions favourable to rapid erosion from multi-datasets including Landsat Enhanced Thematic Mapper (ETM+) imagery and geological maps. The areas predicted to be most vulnerable to rapid erosion across the imagery are then identified where hard evidence of low coherence coincides with favourable conditions.

Introduction

Soil erosion is a widespread and long-term problem in many Mediterranean countries. Irregular and often intense rainfall in semi-arid regions can trigger rapid erosion in areas where the slopes are relatively steep, the lithologies are soft or unconsolidated, and vegetation is sparse. Tremendous damage to ecosystems can also be triggered by inappropriate land use (e.g., excessive cultivation) and engineering work (e.g., road cutting). To improve environmental management, it is important to detect and monitor the areas subject to such erosion.

Multi-temporal interferometric SAR (InSAR) coherence imagery is an effective and relatively novel technique for the automatic detection of random changes on land surface achieved by measurement of temporal decorrelation. Since erosion processes randomly change the micro-topography of a slope's surface, the technique can be used for monitoring erosion. This geometric change alters the radar scatterers, randomly changing the phase and amplitude of the signal in each pixel. The signal coherence, a measure of local correlation of phase and magnitude, between the initial and eroded states, estimated over a convenient number of neighbouring pixels, will be gradually reduced. Eventually coherence will be lost completely when the average random phase change, among pixels in a neighbourhood, exceeds half of the radar wavelength in the slant direction (Liu, *et al.*, 2001).

It has been shown that, as a type of random change, erosion can be detected effectively using ERS InSAR coherence imagery, based on the above principles, in our previous study in Sorbas basin in Almería Province, SE Spain (Liu, *et al.*, 1999a, b; Pearson, 1999). The detection has not been exclusive however, and the loss of coherence is actually the result of several factors. Additionally, coherence imagery has limitations in terms of spatial decorrelation (Lee & Liu, 2001), poor resolution and geometric distortion. A reliable result cannot therefore be achieved without the aid of other data sources. This paper reports a further development to improve reliability and expand the study to a regional scale, based on a combined remote sensing—GIS approach using integrated geospatial data and coherence imagery.

The study area covers most of Almería Province, SE Spain (Figure 1) which is one of the most arid areas in Europe (annual precipitation less than 300 mm). In this semi-arid region, *badlands* are a typical landform which develops where poorly-cemented Tertiary molasse debris and calcareous mudstones or *marls* become barren and heavily dissected by periodic torrential storms which can deposit more than 100 mm of rain in one event. Such events can also cause substantial damage through landslides and mudflows (Harvey, 1984; 1987). Rapid erosion will occur especially when the natural land surfaces are disturbed and vegetation is stripped.

Multi-Temporal Coherence Imagery for Change Detection

ERS SAR Data

Three ERS-2 SAR raw data scenes, from descending orbits with 70, 140 and 210 days separation, taken during 1996–1997, were used in this study (Table 1). The scenes were chosen based on the temporal separation, perpendicular baseline and weather conditions. Dry weather conditions at the time of each data acquisition is desirable in order to eliminate the possible decorrelation caused by moisture change which is a key factor affecting the dielectric properties of the surface scatterers. The nearest weather station from which historical meteorological records are available is at Almería. No precipitation was recorded there on any of the dates when images were acquired.

The ERS SAR raw data were processed to produce Single Look Complex (SLC) images and then three coherence images were generated by ensemble averaging, over a 4 × 16 pixel window, in the range and azimuth directions, after phase ramp correction. These coherence images are named Coh21, Coh23, and Coh31, where Coh21, for example, is derived using ALM2 as the master scene and ALM1 as the slave scene

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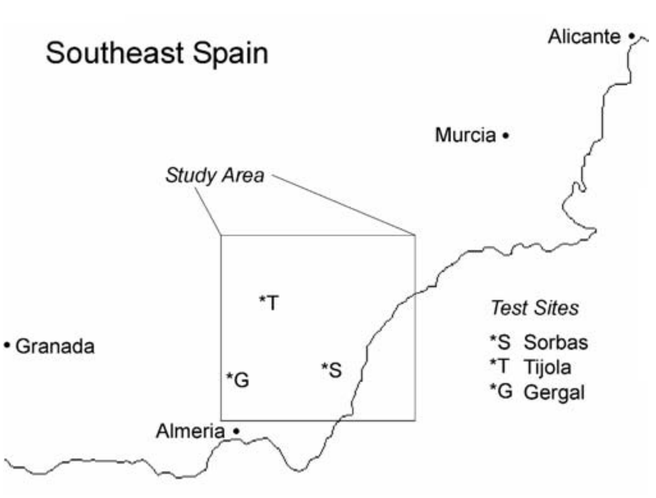


Figure 1. Location of the study area. The rectangle marks the extents of imagery used with the location of test sites.

TABLE 1. ERS SAR RAW DATA OF THE STUDY AREA

Region	Scene	Date Orbit	Temporal Separation (days) Baseline: $B_{\perp}$ (m)		
Almería Track 237 Frame 2853	ALM1	3 Oct 96 07606	70 156		210 136
	ALM2	Dec 96 08608		140 20	
	ALM3	1 May 97 10612			

for co-registration. All the coherence images are quantified to 0–100 value range.

Other data used a Landsat-7 ETM+ scene acquired on 21 July 1999, geological maps of Almería Province (Instituto Geologico y Minero de España, 1:50000 and 1:200000 series), 1:10000 topographic maps (Instituto de Cartográfia de Andalucia), and aerial photographs of a limited area in Sorbas.

Detecting Rapid Erosion Using Multi-Temporal Coherence Imagery and Limitations of the Technique

In a semi-arid region, erosion is an episodic process triggered by sudden and intense rainfall events. For a relatively long period (several months to years), the process can be regarded as accumulative because the cumulative, antecedent precipitation is proportional to the time. We therefore expect erosion phenomena to appear in coherence images as features which gradually lose coherence with increasing temporal separation. Vegetation and human activities (e.g., agriculture) are the other two major temporal decorrelation factors in the study area. Dense vegetation can produce a total loss of coherence instantaneously or over a few days. On the other hand, field investigation shows that very sparse, dry, slow-growing, natural vegetation (or *scrub*) does not significantly affect the coherence level over a period of up to even a year. Human activities such as ploughing, engineering construction, and quarrying can, however, result in a sudden loss of coherence over a short period. General guidance for interpretation is summarised below:

- Rapid erosion: High to intermediate coherence, in a few days to months, depending on whether there are rainfall events; gradually loses coherence over longer periods (several months to more than a year).
- Dense vegetation: Coherence lost in a very short period (instantaneously or over a few days).
- Human activities: Usually not related to the length of the temporal separation. The decoherence features often show regular spatial patterns, and agriculture-related decoherence features are controlled by seasons.

In our previous study, rapid erosion along a recently constructed motorway cutting in the Sorbas basin (see Figure 1 for location) is effectively detected using a colour composite of Coh21, Coh23 and Coh13 in RGB (red, green and blue), based on the above simple rules (Liu, *et al.*, 1999a; Pearson, 1999). The engineering work may have triggered rapid erosion. In field investigations conducted in May 1999–2002, progressively deepened rills and gullies were observed on the manmade slopes in marls along the road, giving firm evidence of rapid erosion since the motorway was completed in 1993 (Figure 2).

The study revealed that spatial decorrelation on the slopes perpendicular to radar illumination direction can overwhelm any temporal change phenomena. A new technique, ratio coherence technique, was then proposed (Lee & Liu, 2001). A ratio coherence image between a long temporal separation—short baseline coherence image (numerator) and a short temporal separation—long baseline coherence image (denominator) can enhance and separate topographic spatial decorrelation, in white (high ratio values), from temporal decorrelation, in black (low ratio values), on a grey background of stable areas. Then, a color composite, involving both coherence and ratio coherence images was used to refine the detection of rapid erosion in the Sorbas area (Liu, *et al.*, 1999b). The new technique eliminates the possible misinterpretation of spatial decoherence for temporal decoherence but cannot retrieve the information of temporal change on the slopes where spatial decoherence occurs.

Coherence imagery is effective in the detection of rapid erosion but the detection may not be conclusive. Vegetation may reduce coherence to varying degrees, depending on density; crop growth may follow rainfall events causing decoherence and spatial decoherence can mask off temporal decoherence. All these factors mean there are areas which may suffer from erosion but cannot be identified by the multi-temporal coherence imagery alone.

Methodology: The GIS Model Based on a Case Study

With extensive field investigation and previous studies on rapid erosion using coherence imagery, as indicated above, the Sorbas area was chosen to establish a GIS model-based

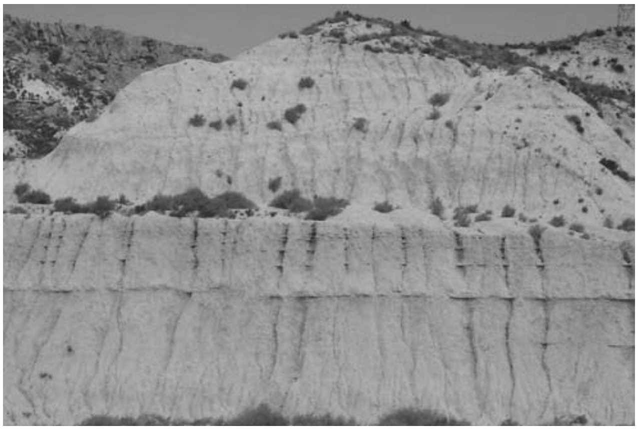


Figure 2. Field photo: erosion on manmade slopes in marls along the motorway in Sorbas area.

methodology that will then be applied to a larger region covering most part of Almería Province.

The basic approach of the methodology comprises the following steps:

1. Use of multi-temporal coherence images to locate the candidate areas subject to progressive random changes on land surface;
2. Use of multi-source data to locate the areas with favourable environmental conditions for erosion, using a GIS model.
3. Use of a logical *AND* operation to combine the results of the above two steps to identify the areas with favourable environmental condition and evidence of decreasing coherence as rapid erosion.

Coherence Image Thresholding and Major Factors Relating to Rapid Erosion

The values of 100 pixels were extracted from the Coh23/Coh21 ratio coherence image for both the marls exposed along a road cutting, and for a stable gypsum plateau. The histogram of these values shows two peaks representing each of the surface types. The value in the *dip* between the two peaks was used as threshold to separate the two in the ratio coherence image. The threshold to separate erosion and vegetation areas in Coh21 coherence image was determined in the same way. These thresholds were applied to separate the low coherence areas that may represent rapid erosion from surrounding stable and vegetated areas, and from areas where spatial decoherence has masked any evidence of land surface change, as below:

- Retain pixels where coherence ratio value Coh23/Coh21 < 0.75 to separate erosion from stable areas and from spatial decoherence, following method of Lee and Liu (2001).
- Retain pixels where Coh21 > 69 to separate erosion area from vegetation.

These thresholds are, of course, highly scene dependent and cannot be setup correctly without the data from field investigation. Once established in each case study, the thresholds are applicable to the whole scene of the same dataset.

The Sorbas study area consists of a region of marls bounded to the West by the stable gypsum plateau and to the East by limestone. Field investigations in conjunction with analysis of the coherence imagery, for the Sorbas area, have shown that the factors most significant in determining the possibility of erosion are:

- *Lithology*: The area which is subject to rapid erosion is in an area of marls and other rock types which are poorly consolidated or soft, including turbidites and mudstones. Gypsum, limestone, and conglomerate are expected to be stable.
- *Slope*: The natural slope profiles on marl outcrops are generally, gently sloping (East-West slope) and relatively stable. Erosion occurs where steep gullies form perpendicular to the main slope direction, where the rock has been dissected by drainage or artificially steepened through engineering works.
- *Vegetation*: The erosion area has very little vegetation, mostly small shrubs on the shallow stable faces, and nothing at all on some active eroding faces. The presence of vegetation is expected to decrease the effects of erosion (Cerdà, 1999).

These factors form the inputs to a GIS model for discriminating areas of rapid erosion from candidate areas located using multi-temporal coherence images.

Multiple Data Source GIS Approach

Areas which exhibit a progressive loss of coherence are reasonable candidates for true rapid erosion. These areas can be further constrained by applying the criteria of favourable conditions for erosion. Information on the criteria of *soft* lithology, *steep* slope and *sparse* vegetation were extracted from the following data sources:

- Lithology: Landsat ETM+ 531 RGB colour composite image and maximum likelihood classification made with reference to geological maps.
- Slope: SAR interferograms. Although topographic maps are available, interferograms from the same SAR data source are preferable, to minimise potential errors from data co-registration.
- Vegetation: Landsat ETM+ Normalised Difference Vegetation Index (NDVI) image.

These data were combined within a GIS (IDRISI v. 3.2). GIS allows spatial overlay of several different data layers and flexibility of data combination in a Multi-Criteria Evaluation (MCE) (Eastman, 1997).

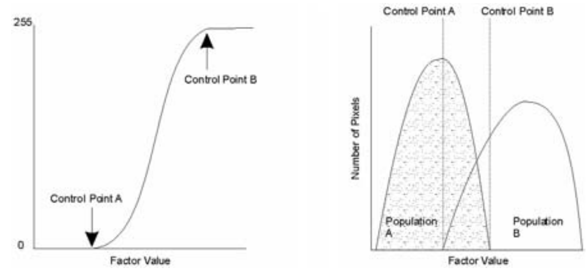
In this study, although the major factors determining erosion susceptibility were known, their interdependence and relative importance were not well understood. For this reason the factors were reclassified using fuzzy set functions. The key technical issue of the approach is to decide the fuzzy criteria and MCE model (a model of favourable conditions).

Fuzzy Set Membership Functions

With the exception of rock type, all variables under consideration in this analysis can be considered continuous. One method of dealing with such variables, in terms of determining *suitability* for rapid erosion would be to apply a hard threshold and derive qualitative classes of *suitable* or *unsuitable*. These Boolean suitability constraints can then be combined, using intersection (logical *and* operation). This method is, however, extremely risk averse, i.e., the criteria are harsh, and the method relies on knowing the threshold values accurately (Eastman, 1997). There is no possibility of acknowledging either measurement error or any uncertainty of decision rules.

The use of fuzzy sets within a multi-criterion, GIS based hazard assessment has already been demonstrated to good effect (Mason & Rosenbaum, 2002). For these reasons, fuzzy set logic has been employed. This method is implemented through application of fuzzy boundary functions between rigid membership groups or populations: A and B. The fuzzy boundary function increases over a range of values so that the threshold is effectively spread out, as shown in Figure 3. The output of this process is an image scaled from 0 – 255, with increasing likelihood of erosion susceptibility represented by increasingly higher values. Fuzzy sets were applied to two significant factors in the GIS, those of Negative NDVI and Interferogram Slope. To improve the accuracy of the rock type classification, a fuzzy set was also applied to the Posterior Probability (the likelihood of correct classification given the spectral evidence) of rock types most vulnerable to erosion, such as marl.

The control points A and B (Table 2) were determined by analysing the histograms of cell pixel values in the Sorbas area to separate the properties of erosion areas from those of the



(a) (b)

Figure 3. (a) Monotonically increasing fuzzy set membership function. (b) The control points A and B were determined using pixel value populations (histogram) in the Sorbas area.

Table 2. Control Points used in Applying Fuzzy Thresholds to the Factors in GIS Analysis

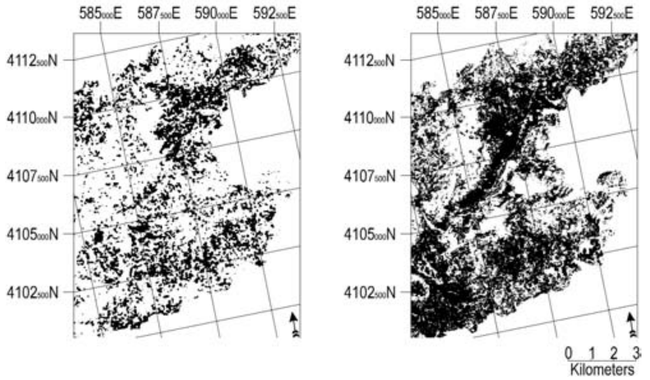
Factor	A	B
Posterior Probability	89%	99%
Negative NDVI	0.01	0.03
Slope	18°	21°

surrounding land. A rock type constraint was then applied to eliminate the area of obvious resistant rock types using a lithological classification image produced from Landsat ETM+ data.

Multi-Criteria Evaluation: Weighted Linear Combination and Logical Operation

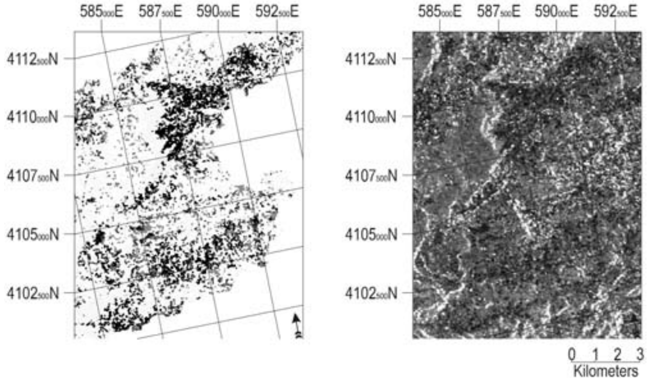
The Posterior Probability of rock types, NDVI and Slope factors were combined using Weighted Linear Combination (WLC). The raster images of the three factors were normalised to the same value range before a linear combination with equal weights. Different weights could have been used for the three factors if we had adequate knowledge of the quantitative relationship between the three factors, but this is not the case. The aggregate result was then multiplied by the Boolean rock type constraint, to remove areas classified as stable rock types (such as limestone or conglomerate). Finally, areas of favourable conditions for rapid erosion were defined by thresholding values exceeding 165. The threshold was chosen empirically to make the output best match the image of candidate erosion area, derived from multi-temporal coherence image and ratio coherence image.

The last step of MCE is a logical *and* operation to combine the erosion candidate image (Figure 4a) derived from coherence imagery with the image of favourable conditions (Figure 4b) derived from multi-source data. This operation eliminates the pixels which fail to satisfy the favourable conditions from the candidate areas and retains those which satisfy both as the most definite identification of rapid erosion. Comparing the logical *and* image with the favourable condition image, we can identify areas which have favourable conditions for erosion but are not identified by coherence imagery, as showing random change. This often occurs on east-facing steep slopes where the spatial decorrelation is significant. In this case, a previously excluded area of steep slopes, rejected on the basis of spatial decorrelation, should be included if it is adjacent to the pixels retained after the *and* operation. The final MCE result is shown in Figure 5.



(a) (b)

Figure 4. (a) Boolean image of potential erosion areas (in black) created by applying thresholds to coherence imagery. (b) Boolean image of areas with favourable conditions for erosion (in black).



(a) (b)

Figure 5. (a) MCE result of combination of the two images in Figure 4. Black pixels represent result of logical *and* operation—these are pixels strongly believed to subject to rapid erosion. Dark grey pixels are those identified by the coherence imagery but ruled out by WLC favourable conditions—these are likely to be human activity rather than erosion. Light grey pixels are areas with favourable conditions for erosion as defined by the WLC but with no evidence from the coherence imagery—some of these areas are spatial decoherence. (b) Coherence ratio image Coh23/Coh21. White pixels represent spatial decoherence. Black areas show surface change, whereas the grey areas are stable. The grey area in the west of the image is the gypsum plateau. Some of the white areas correspond in location with areas of light grey pixels in (a).

The result shows, in black, a large area with both favourable conditions for rapid erosion and evidence of land surface change. The MCE methodology also highlights a large number of pixels in light grey along the edge of the stable gypsum plateau which do not have evidence of land surface change due to spatial decoherence. These areas can be confidently predicted to be eroding since they have favourable conditions and are located adjacent to the known erosion area.

The MCE rules out some areas identified by the coherence imagery in the center-South of the area (in dark grey). These areas, lacking favourable conditions for erosion, are likely to be exhibiting land surface change as a result of human activity, such as ploughing.

Application to Other Test Areas in SE Spain

Following the establishment of the method outlined above for the Sorbas case, the same technique was used over the larger study area, shown in Figure 1, to identify further areas subject to rapid erosion across Almería province. The method was used primarily in the sedimentary basin areas, since soft lithologies in the basins were assumed more likely to behave in a similar way to those in Sorbas than basement lithologies. After manually masking off basement lithologies, based on ETM+ imagery and published geological map, a further test has been conducted in five basin sites (Tijola, Gergal, Galeras, Partaloa, and Vera) which were selected on the basis of the coherence imagery having identified extensive areas of possible erosion. For the purposes of illustration, only two of these test sites are discussed below. The Tijola site was chosen for discussion since it is a good example of how the use of ancillary data can help to restrict the area identified by coherence imagery to likely erosion pixels. The Gergal area is chosen since it highlights some of the areas showing favourable conditions but without evidence from coherence imagery.

Tijola

The Tijola region, like Sorbas, is composed mainly of marl lithologies, with a band of conglomerate in the South of the area. In this region, the coherence imagery picked out an extensive area of land surface change. When combined with the favourable conditions, using MCE, a large proportion of the area identified by the coherence imagery is ruled out (Figure 6, Dark Grey). The areas ruled out on the basis of lithology, slope, and vegetation information, probably represent ploughed land. These areas are likely to have been ploughed during spring giving a similar coherence signature to rapid erosion. Once again, areas of spatial decoherence which have favourable conditions for rapid erosion were also identified by the method. These pixels can be confidently identified as erosion pixels since the lithology is similar to the known erosion area in Sorbas. Field investigation has been conducted in this area which confirms that many of candidate areas defined by coherence imagery are in fact cropped fields or olive plantations. Such areas were ruled out successfully by MCE for their flat topography. Areas ruled in by the MCE image, and therefore subject to rapid erosion, are usually steep slopes where the natural calcrete *crust* has been stripped off. These areas often represent failed crops and plantations, now abandoned. It is well known that erosion in this region is commonly triggered by poor agricultural management. Most natural, non-cultivated land surfaces are protected by the calcrete crust and are stable, even though the environmental conditions considered in our model are favourable for erosion. Such areas are eliminated by coherence imagery.

In this test area, the use of multi-source data and the MCE technique has proved invaluable in raising confidence for reliable identification of the areas under rapid erosion (Figure 6, Black). Without the MCE, the coherence imagery suffers from the ambiguity that ploughing may be incorrectly identified as erosion.

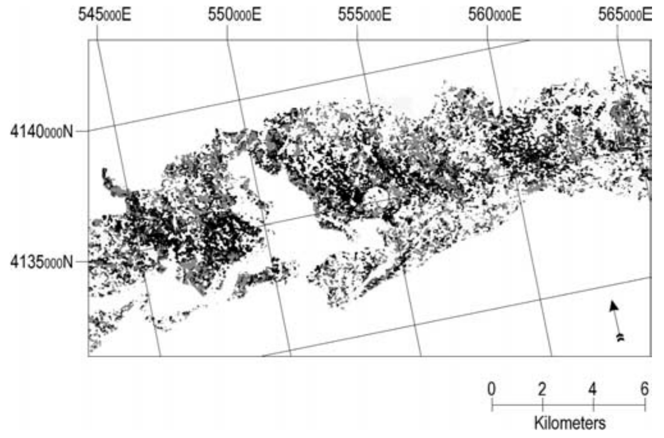


Figure 6. Tijola test area. Final MCE image of coherence erosion candidates combined with WLC favourable conditions. Black: evidence of land surface change and favourable conditions for erosion. Dark grey: evidence of land surface change but not favourable conditions (likely to represent agriculture). Light grey: favourable conditions but no evidence of erosion.

Gergal

The Gergal region represents quite a different case. The area is characterised by *badland* geomorphology, but the rock type here is different. Generally, the geology comprises patches of basement schist as well as sediments derived from the basement schist which are characterised by very similar spectral signatures in the ETM+ imagery.

Almost all of the pixels identified by the coherence imagery are found to have favourable conditions for rapid erosion (Figure 7, Black). This seems reasonable, since from the ETM+ imagery, there seems to be no agricultural activity which often causes erosion-like decoherence features. On the other hand, a large number of pixels showing no evidence of surface change from coherence imagery are deemed to have favourable conditions by WLC (Figure 7, Light Grey). The presence of these pixels can only partially be explained by spatial decoherence. Another reason is the cemented surface crust, as in the case of Tijola. Alexander and Calvo (1990) reported a lichen crust on similar rocks near Tabernas, around 3 km to the East of the edge of the Gergal region, which increases resistance to erosion by overland flow or surface run-off. The Tabernas area, though nearly completely barren and with steep slopes, has

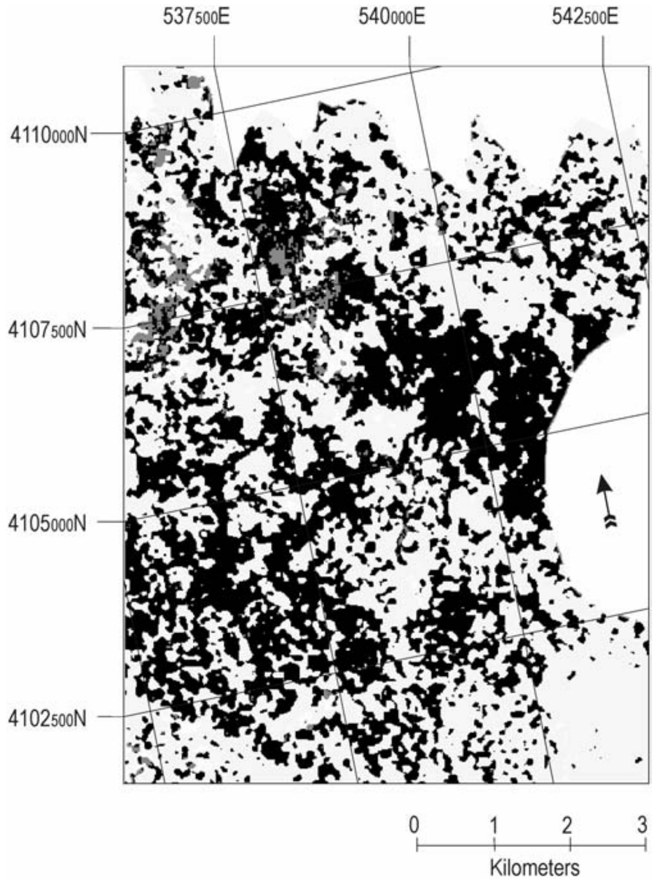


Figure 7. Gergal test area. Final MCE image of coherence erosion candidates combined with WLC favourable conditions. Black: evidence of land surface change and favourable conditions for erosion. Dark grey: evidence of land surface change but not favourable conditions (likely to represent agriculture). Light grey: favourable conditions but no evidence of erosion.

shown high coherence in all the three coherence images used in this study, indicating a very stable land surface. A similar crust has been observed in the Gergal area, which changes the surface properties of the rock, and although the lithology can be considered soft, it may have rather resistant surface, which prevent rapid erosion. A few clusters of dark grey pixels in Figure 7 representing land surface change without favourable conditions for erosion are orange groves on red soils, as confirmed by recent field investigations.

This case shows that coherence imagery makes our methodology superior to those only based on the analysis of environmental conditions. The method enables separation of areas actually experiencing rapid erosion from those which merely show favourable conditions for rapid erosion.

Discussion and Conclusions

The new GIS approach used in this study, to identify possible erosion areas with greater confidence than in previous studies, is summarised as follows:

(1) Multi-temporal coherence images are used to detect candidate areas for rapid erosion.
(2) Resistant basement lithologies are separated from *soft* basin sediments by masking of ETM+ imagery, based on visual interpretation in reference to a geological map.
(3) A fuzzy criterion for eliminating dense vegetation, based on fast decoherence features and ETM+ NDVI is decided.
(4) A fuzzy criterion for eliminating flat areas, using a DEM or interferogram derived slope gradient is decided.
(5) A Boolean constraint for lithology and a fuzzy criterion for eliminating poorly classified pixels are decided.
(6) Weighted Linear Combination is performed to locate the areas with favourable conditions for erosion (on the basis of 2–5).
(7) A logical operation between the coherence detected candidate areas and the favourable condition areas defines the pixels most likely to be subject to rapid erosion.

The last two steps form the, so called, Multi-Criteria Evaluation (MCE) methodology.

The MCE methodology enhances the use of coherence imagery as a tool for detecting erosion, making the results of detection more reliable. It enables effective detection and assessment of rapid erosion across a wide area without the need for a detailed physical model. Detection of erosion areas is important in land management, because agriculture must be carefully controlled in these areas (Machín & Navas,1998); creation of vast plantations can destroy the natural land surface crust and could trigger widespread rapid erosion. There are also civil engineering considerations, such as the stability of rocks outcropping near roads.

The value of this approach has been shown in the Sorbas and Tijola areas, where the MCE for each test area successfully refines the classifications made from coherence imagery alone. Areas which show evidence of land surface change, but which are of the wrong rock type have too shallow slopes or have too much vegetation can be ruled out by this method. These rejected areas often show evidence of agriculture and human activity. The reason for their exclusion is not that erosion does not occur, but that the land surface change is more likely caused by anthropogenic factors than by natural, progressive erosion. For east-facing steep slopes, characterised by spatial decoherence (which are ruled out as erosion candidates by ratio coherence imagery), the MCE has a further advantage of correct interpretation, in terms of rapid erosion likelihood, on the basis of favourable conditions and the context of adjacent pixels.

The approach is still under development. The current form is limited to three factors to determine susceptibility to erosion, but this list can be added to where necessary. These three factors of lithology, vegetation, and slope are all known affect the way the land surface responds to erosion. The interdependence and relative importance of these factors is not well known, however, and thus the precise weight in the WLC for each factor cannot be determined. The result from the Gergal area indicates that there are likely to be other factors, such as surface crusting, which affect erodability. Despite its evident importance, it is not possible to measure or account for surface crusting without intensive fieldwork and laboratory experiments. On the other hand, the lack of direct evidence of surface change from coherence imagery has enabled to avoid incorrect identification for rapid erosion in the area protected by a lichen crust. Finally, detailed weather data should form an important addition to the method.

In order to gain a quantitative appreciation for the accuracy of the results, a statistical approach would need to be taken based on a comparison between model predictions and field evidence of erosion. It is important that further field study should be carried out in the Tijola, Gergal, and other test sites to verify the results of this study.

As presented in the paper, the method successfully delineates erosion areas in the Sorbas, Tijola, and Gergal areas showing that the method has realistic potential for application to land management. The major achievement of the method is the combination of direct evidence of land surface change from InSAR coherence imagery with the assessed favourable conditions for erosion, derived from multiple data sources, to achieve a confident identification of areas believed to be undergoing rapid erosion.

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References

Alexander, R.W., and A. Calvo, 1990. The influence of lichens on slope processes in some Spanish badlands, *Vegetation and Erosion*. Chichester, J. B. Thornes (Editor) Wiley:385–398.

Cerdà, A., 1999. Parent material and vegetation affect soil erosion in Eastern Spain, *Soil Science Society of America Journal*, 63:362–368.

Eastman, J.R., 1997. *Idrisi for Windows User's Guide Version 2.0*, Worcester, Massachusetts, Clark University.

Harvey, A.M., 1984. Geomorphological response to an extreme flood: A case from Southeast Spain, *Earth Surface Processes and Landforms*, 9:267–279.

Harvey, A.M., 1987. Patterns of Quaternary aggradational and dissectional landform development in the Almería region, southeast Spain: A dry-region, tectonically active landscape, *Regionaler Beitrag* 118:193–215.

Lee, H., and J.G. Liu, 2001. Analysis of Topographic Decorrelation in SAR Interferometry using Ratio Coherence Imagery, *IEEE Transactions on Geoscience and Remote Sensing*, 39, No. 2:223–232.

Liu, J.G., H. Lee, and T. Pearson, 1999a. Detection of rapid erosion in SE Spain using ERS SAR interferometric coherence imagery, *Proceedings of the EOS/SPIE Symposium on Remote Sensing, Florence, Italy* 3868:525–535.

Liu, J.G., H. Lee, and T. Pearson, 1999b. Erosion and Landuse Change Detection Using ERS SAR Interferometric Coherence Imagery (ESA ERS AO3-113), *Fringe99,* 10–12 Nov. 1999, Liege, Belgium (www.esa.int/fringe99/; last date accessed 27 July 2004).

Liu, J.G., A. Black, H. Lee, H. Hanaizumi, and J. McM. Moore, 2001. Land surface change detection in a desert area in Algeria using multi-temporal ERS SAR coherence images, *International Journal of Remote Sensing*, 22, No. 13:2463–2477.

Machín, J., and A. Navas, 1998. Spatial analysis of gypsiferous soils in the Zaragoza Province (Spain) using GIS as an aid to conservation, *Geoderma*, 87:57–66.

Mason, P.J., and M.S. Rosenbaum, 2002. Geohazard mapping for predicting landslides: The Langhe Hills in Piemonte, NW Italy, *Quarterly Journal of Engineering Geology*, 35, 4, in press.

Pearson, T.D., 1999. *Land surface change detection using ERS-SAR coherence imagery in Southeast Spain*, Unpublished M.Sc. Dissertation, University of London.