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Is digital shoreline analysis system “fit” for gully erosion assessment?

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ABSTRACT

Gully erosion represents one of the most destructive geomorphological processes at a global level. Modern methods of gully erosion measurement are typically derived from earlier techniques that have since become outdated. The increasing capabilities of technology had led to new ways of quantifying soil erosion processes (e.g. gully erosion) which must be used in erosion assessment. A tool designed to assess coastal erosion – Digital Shoreline Analysis System (DSAS), is applied to the analysis of gully erosion. To assess the usefulness of this technique, three different types of gullies were chosen (dendritic, linear, and linear that became dendritic) from the Moldavian Plateau of Romania were chosen. Different parameters (SCE, EPR, NSM, and LRR) were tested and analysed. The best results were obtained in the case of dendritic gullies with specific adjustments to the processing values (smoothing distance set to >1000 and transect spacing at values >5 m). In the case of linear gullies, the smoothing distance needs to be set to lower values compared to dendritic gullies (<= 1000). When it comes to the linear gully that evolved into a dendritic gully, the recommendation is to use smoothing distances with high values (>1000) and transect spacing values >10 m. The average erosion rates obtained with the help of DSAS are very close to the ones from the literature of gully erosion on the Moldavian Plateau in Romania (over –1.5 m/yr and under – 1 m/yr for gullies cut in sandy and clay deposits, respectively). This leads us to the conclusion that the DSAS tool is “fit” for gully erosion assessment. However, like any other software, it has limitations and possible disadvantages. The tool can be successfully used and applied in the field of soil erosion mitigation, disaster risk reduction, environmental and cultural heritage protection and in reaching the UNSDG.

1. Introduction

Gully erosion represents the most severe type of soil erosion and has significant on and off-site effects (Vanmaercke et al., 2016). In a broad sense, gully erosion can be defined as an erosion process in which deep channels are generated by runoff water removing topsoil to a certain depth (Zabihi et al., 2018); in a more detailed sense, gully erosion is a threshold-dependent process that is controlled by a set of geo-environmental factors, such as: rainfall intensity (Lanckriet et al., 2014), topographic factors such as slope aspect, degree, curvature and elevation (Pourghasemi et al., 2017), geological features (Rahmati et al., 2016), hydrological factors like topographic wetness index (TWI), stream power index (STI), drainage density and distance from the river (Nicu and Asandulesei, 2018), and land use dynamics (Gusarov, 2020). Gully erosion is a process that is spread through almost all the climatic areas worldwide: arid (Zakerinejad and Maerker, 2015) and semi-arid (Mukai, 2016), temperate-continental (Nicu, 2019), sub-tropical (Goodwin et al., 2016), continental (Hao et al., 2016), Mediterranean (Hayas et al., 2017), alpine (Bollati et al., 2019); and recently has been acknowledged in the Arctic (Sidorchuk, 2020) and Antarctic (Dickson et al., 2017) areas, as an effect of the global climatic changes.

Along with time, gully erosion initiation and development has been measured using various mathematical equations which were described by Torri and Borselli, 2003. Technological changes (Walker et al., 2020) and new statistical methods (Rahmati et al., 2016), have improved erosion studies and allowed accurate results to be gathered quickly, meaning that the effects of erosion could be mitigated faster. From the classic methods using wood or metal markers “*stakes grid method*” (Ionita et al., 2015) along with total station and GPS (Nicu, 2019), to the use of high-resolution radar data (Bargiel et al., 2013), 3-D laser scanner (Romanescu et al., 2012), significant advances have been made for gully erosion initiation and development (Kirkby and Bull, 2000; Mukai, 2016).

Statistical techniques have recently become particularly focused on future development of gully erosion (gully erosion susceptibility mapping – GESM), and have included: logistic regression (LR) (Conoscenti et al., 2014), index of entropy (IOE) (Zabihi et al., 2018), frequency ratio (FR), information value (IV) (Nicu, 2018), multivariate adaptive

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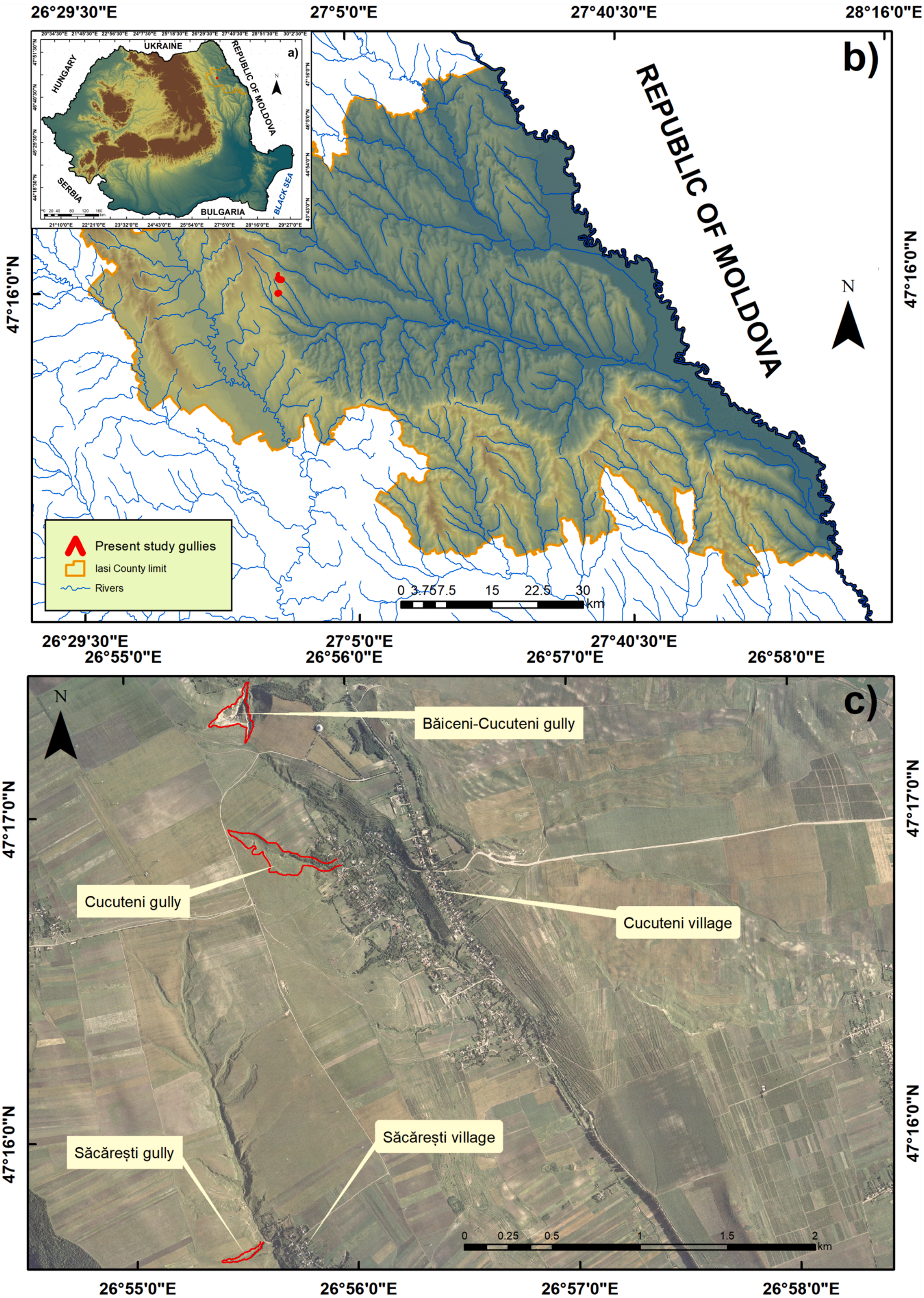

Fig. 1. a. Location of the gullies in Romania; b. Location within Iasi County of the studied gullies; c. Local context of the studied gullies.

regression splines (MARS) (Javidan et al., 2019), artificial intelligence (Tien Bui et al., 2019), machine-learning methods (Arabameri et al., 2020), and combinations between them and other statistical methods. The most common negative effects of gully erosion include reducing of soil fertility and in this way the very existence of the future of humanity's food resources are jeopardised (Seutloali and Beckedahl, 2015), severe damage to bridges, roads and human settlements (Poesen et al., 2003), siltation of reservoirs (Margineanu et al., 2007), cultural heritage degradation (Romanescu and Nicu, 2014; Nicu, 2018; Nicu, 2019; Pederson et al., 2006), among many others.

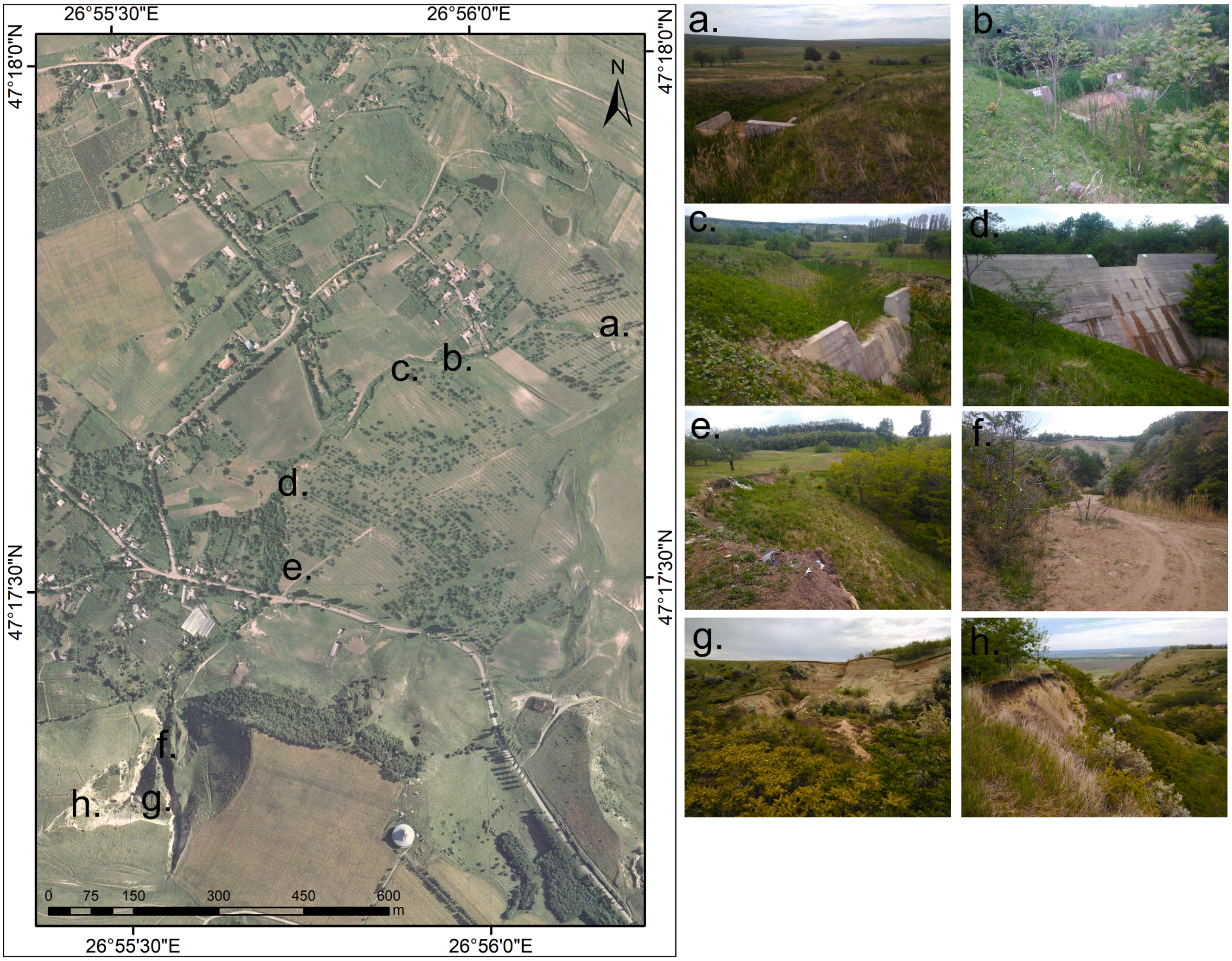

Fig. 2. Details highlighting the mitigation measures taken in the upper and in the lower part of Băiceni-Cucuteni gully; a. Details on the lower part of the gully; b, c, d. Concrete thresholds from the lower and middle part of the gully; e. Lateral erosion; f. Detail from the first concrete threshold and where the two torrents merge; g, h. Details from the upper part of the gully.

Torri and Borselli, 2003 study states that the processes taking place during gully formation and development are often similar to what happens in rivers and permanent streams. Therefore, gully processes could be connected with both rill- and river-type processes and can draw information from both. Starting from this and taking into consideration the efforts made in the study and quantification of gully erosion, we want to propose and to experiment if a tool made for coastal erosion, Digital Shoreline Analysis System (DSAS) (Himmelstoss, 2018) can be used for gully erosion assessment. Over the last years, DSAS has become a powerful tool when it comes to evaluating coastal erosion and the associated coastal hazards. Regardless that is being used for the coasts of open seas and oceans (Kabuth et al., 2014; Nicu et al., 2020; Molina et al., 2019; Zagorski et al., 2020) or inland reservoirs (Asandulesei et al., 2020), it offers an easy suite of tools to automatically evaluate erosion rates and to predict their future positions. The parameters are as follows: Shoreline Change Envelope (SCE, expressed in m), Net Shoreline Movement (NSM, in m), End Point Rate (EPR, expressed in m/yr), and Linear Regression Rate (LRR, in m/year).

To date, DSAS has only been used in coastal areas studies. This work is proposing i) a new approach for applying DSAS to assess gully erosion, ii) testing DSAS behaviour with different types of gullies, iii) to find the most appropriate settings of DSAS to be used in future gully erosion assessment studies. To do so, the DSAS was tested for three gully types from the north-eastern part of Romania. The results of this study will improve the way we understand gully erosion through the looking glass of coastal erosion; the use is obviously in favour in applying this well-known method for coastal erosion to gully erosion. In this way, erosion rates and gully-head advancement will be assessed in a more simply way. The results can be used and applied in different fields of research, future land-use planning, and mitigation measures, disaster risk reduction. The use of erosion forecasting with DSAS can be successfully applied when prioritising future mitigation works of arable lands and will be very useful in cultural heritage management and mitigation.

2. Material and methods

2.1. Study area

This study focused on the Moldavian Plateau in the north-eastern part of Romania (Fig. 1a), as this area has been studied in great detail and there is a large body of specialised literature focusing on soil erosion processes (Romanescu and Nicu, 2014). Landslides (Lombardo et al., 2020; Niculita, 2020) and gully erosion (Nicu, 2018) are of specific interest, because they cause significant material losses, environmental issues, and contribute to the degradation of cultural heritage (Nicu and Asandulesei, 2018).

Previous studies have found that terrain variables like curvature,

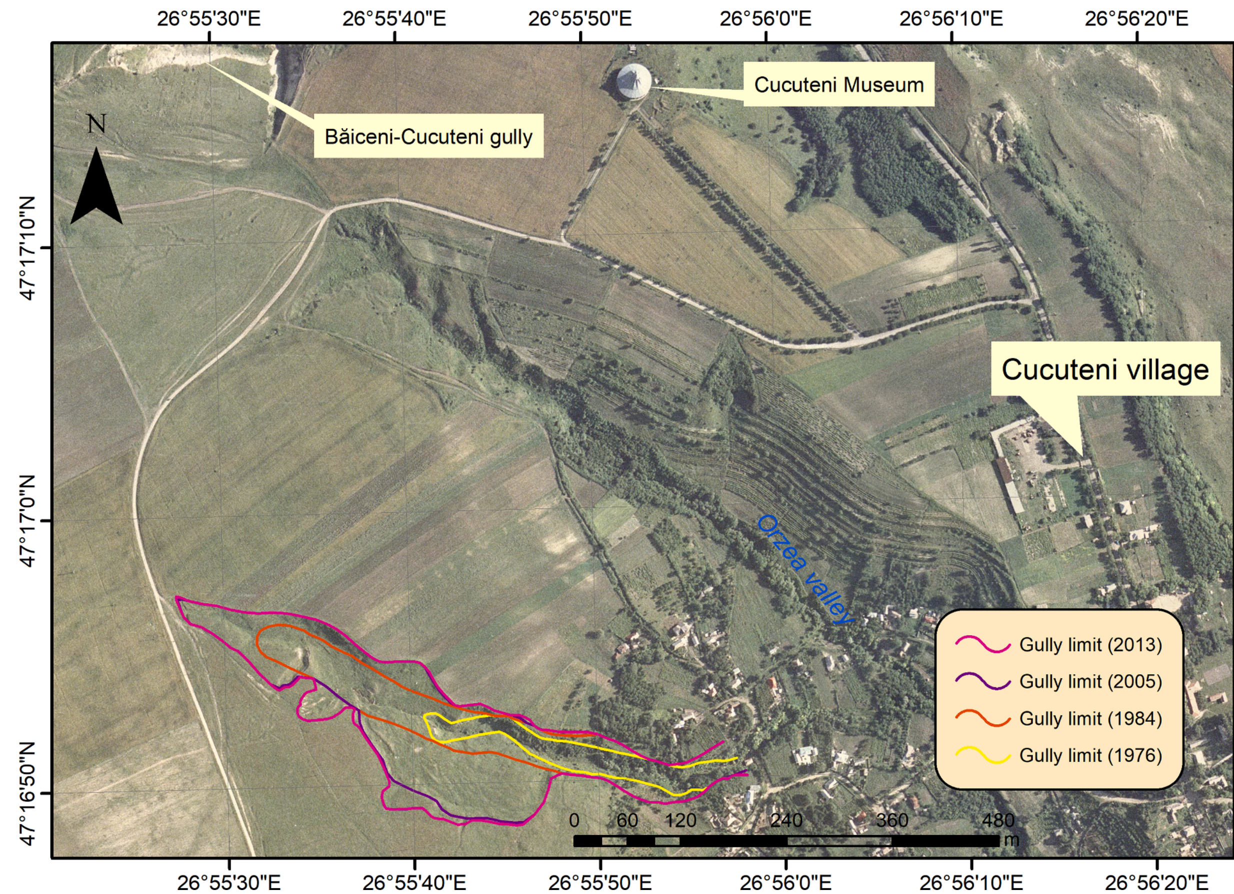

Fig. 3. Details over the area surrounding the Cucuteni gully, along with the limits of erosion lines from different years.

lithology, precipitations, landforms and distance to rivers are useful in predicting gully erosion initiation and development (Nicu, 2018); while factors such as landforms, slope, precipitations and elevation are the best predictors for landslides (Nicu and Asandulesei, 2018). The ground characteristics are the base for initiation and development of gully erosion, which mainly consists of poorly consolidated Sarmatian rock formations (Radoane and Radoane, 2017). A more detailed description of the area can be found in (Romanescu and Nicu, 2014; Nicu, 2018; Nicu and Asandulesei, 2018; Lombardo et al., 2020). The study sites are located within Iasi county limits (Fig. 1b), in close proximity of Cucuteni and Săcărești villages (Fig. 1c).

2.1.1. Băiceni-Cucuteni gully

Băiceni-Cucuteni gully is a dendritic gully, cut in sandy deposits, located at the contact between Moldavian Plain and Suceava Plateau relief units, and Sârca Hillocks and Holm – Dealul Mare Hills relief subunits (47°17′17″N, 26°55′25″E), on the territory of Cucuteni commune (Fig. 2). The gully has been an important component of several geomorphological case studies (Romanescu et al., 2012; Nicu, 2019), because by its evolution is affecting two cultural heritage sites (Nicu, 2018), one from Neolithic period – Cucuteni culture (4600 – 3600/3500 cal. BC) and another from Geto-Dacian (1st century BCE – 1st century CE) period, respectively. The left side of the gully, also referred to as the main gully, named *Râpa Adâncă* (Deep Gully), has a length of 247 m, a maximum width of 114 m, and about 30 m in depth. The right side of the gully, also referred as the secondary gully, named Râpa Prisăcii, has a length of 250 m, a maximum width of 30 m, and about 35 m in depth.

The upper part of the gully was analysed using the DSAS tool. The lower part, which stretches on a length of approximately 1.3 km downstream to Valea Oii River was the subject of mitigation measures (Nicu, 2019). Sixteen concrete thresholds were built, of different heights, through a program financed by the European Union. Some of them are visible in Fig. 2a, b, c, d, e. The project name was "*Construire infrastructură pentru prevenire și protecție împotriva inundațiilor*" (Building infrastructure for flood prevention and protection), had a budget of 5.763.975 RON (Romanian Leu) (the equivalent of 1.2 mil. EUR). The project was financed through the European Agricultural Fund for Rural Development. As shown by (Nicu, 2019; Nicu, 2020), thanks to the mitigation measures implemented (e.g. the concrete thresholds that act like sediment traps Fig. 2f), the erosion process was considerably reduced in the upper part of the gully (Fig. 2g, h).

2.1.2. Cucuteni gully

Is located on the right side of Ordea Valley (47°16′54″N, 26°55′29″E), at approximately 800 m south from the Cucuteni Museum, on the territory of Cucuteni commune (Fig. 3) and it is cut in clay deposits. Initially, the Cucuteni gully was of linear type (as it is visible in Fig. 3 as of years 1976 and 1984) and evolved into a dendritic one (years 2005 and 2013).

This is interesting not only from a geomorphological point of view but also for our present study, in order to check how the DSAS parameters behave when a gully changes its type. Along time, the gully had the following lengths 375 m (1976), 586 m (1984), 687 m (2005), 691 m (2013). Through its evolution, it is affecting the agricultural area surrounding it. However, over the last years (and as it can be seen from the lengths of the gully), the gully head advancement has gradually decreased. It is not the purpose of this paper to discuss the factors contributing to gully advancement decrease, but this is a good thing and it had to be mentioned. The right side of the gully has enlarged from 1984 to 2005 and 2013 due to sidewall processes and small landslides within the gully. Previous studies from the same catchment (Bahluiet) (Nicu and Asandulesei, 2018) have shown that there is a high incidence

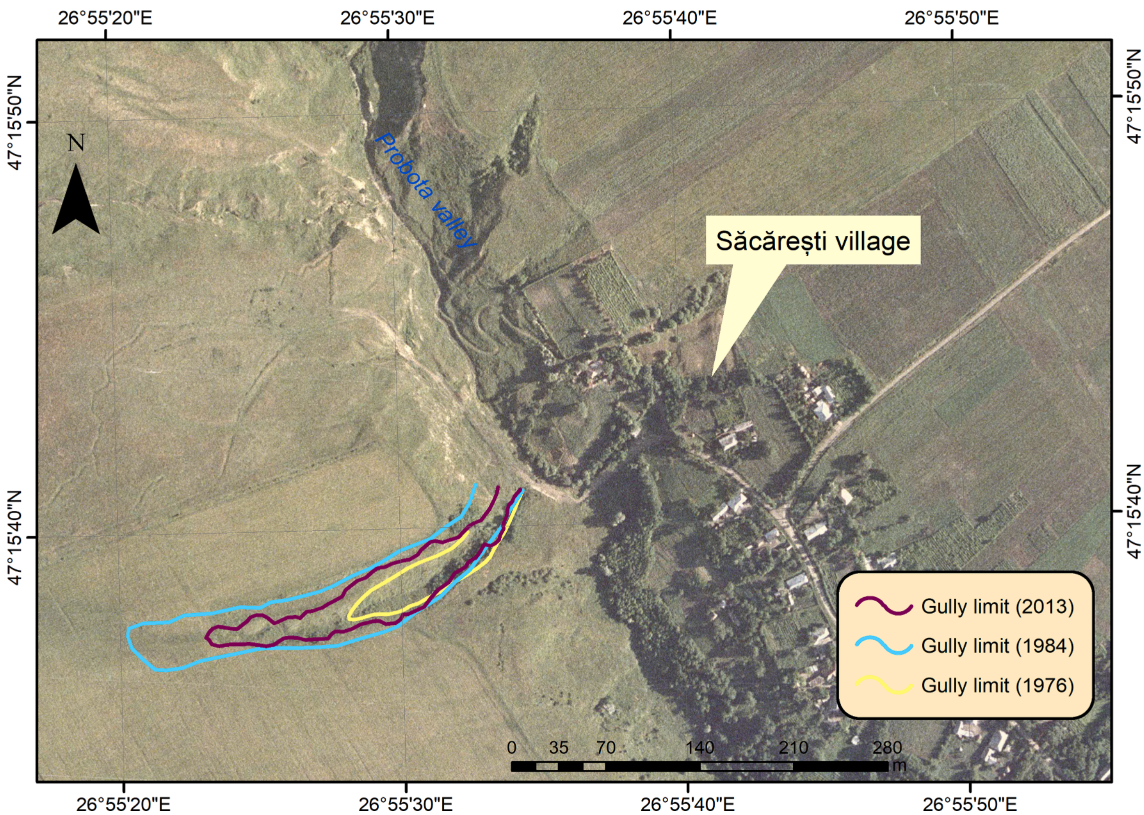

Fig. 4. Details over the area surrounding Săcărești gully, along with the limits of erosion lines from different years.

of gully erosion co-existing with landslides. Similar results were obtained in China (Qiao et al., 2017). Therefore, when the two processes co-exist, the damages are exacerbated, leading to a significant decrease in arable land surface and increase in sediment yield production, which can lead to reservoir sedimentation.

2.1.3. Săcărești gully

Săcărești gully is of linear type, cut in clays, located on the right side of Probota River, at approximately 1 km NNW from the centre of Săcărești village, on the territory of Cucuteni commune (47°15′37″N, 26°55′23″E). This gully is especially of interest, as its length has varied over time, as follows: 158 m (1976), 326 m (1984), 266 m (2013). In 2013, the maximum gully width was 43 m, and an approximate depth of 10–15 m. The gully head advancement has been mitigated probably through improvement in the way the ploughing is made. From the hill-valley direction (which is well-known in the acceleration of soil erosion processes, especially gullying, in the north-eastern part of Romania) (Romanescu and Nicu, 2014) towards ploughing along the contours (which is visible in Fig. 4).

2.2. GIS-data integration

In order to examine the evolution of the above mentioned gullies, remote sensing was employed. In order to carry this out, different datasets including cartographic, ortophotos, and LiDAR data were employed. The cartographic material consisted of topographic plans scale 1:5,000 (edition 1976), topographic map 1:25,000 scale (edition 1984), ortophotos scale 1:5000 (edition 2005), LiDAR images (edition 2013), from which the gully limits were extracted through on-screen digitization; and in some cases (Băiceni-Cucuteni gully) undertaking detailed topographic surveys with the total station and GPS. The total station used was a Leica TCR1201 model and the GPS was a Leica RTK System 1200. All the data was added to a geodatabase in ArcGIS and processed so that it could be analysed. Following this step, the classic steps of the DSAS were followed. A comprehensive flowchart of the methodological approach is visible in Fig. 5.

The DSAS v.5 extension of ArcGIS was used (Himmelstoss, 2018). The workflow for DSAS is divided into three main steps as follows: defining a baseline (located at a certain distance on-shore or off-shore), generating perpendicular transects along the shoreline (in our case erosion lines), and calculating the rates of change. Where a minimum of four erosion lines are available, future erosion forecast is possible due to the Shoreline Forecast tool built within DSAS v.5. Even though in a BETA version, it is used in estimating future locations of erosion lines for the next 10 and 20 years. It is a very useful tool especially when it is applied in the field of cultural heritage degradation estimation and future forecasts (Asandulesei et al., 2020). Therefore, we will be able to use this tool only for Băiceni-Cucuteni and Cucuteni gullies, since we have a set of four erosion lines, obtained from different remote sensing approaches, as shown above.

In order to depict if DSAS is suitable for gully erosion analysis, different working scenarios were analysed. Studies that used DSAS to depict the erosion rates do not have a standard set of settings; authors are using different input parameters, according to the length of the studied area (but this is not necessarily a rule). A parameter that is not mentioned or its value is never indicated is the smoothing distance. The smoothing value creates a long and straight orthogonal reference for DSAS to use when casting transects. A longer smoothing distance will result in adjacent transects that are oriented more parallel to each other. Smoothing distance has more influence on the curved baseline segments than straight segments. The default value of 2500 m is considered the upper limit of effectiveness (Himmelstoss, 2018). Having this in mind, it would be of high importance in the case of dendritic gullies, which erosion lines are more curved, and perhaps less significant in the case of linear gullies. A set of input parameters used in the literature are highlighted in Table 1.

The main parameters built-in DSAS v.5 extension of ArcGIS are as follows: EPR (measured in m/yr. by dividing the distance of erosion line

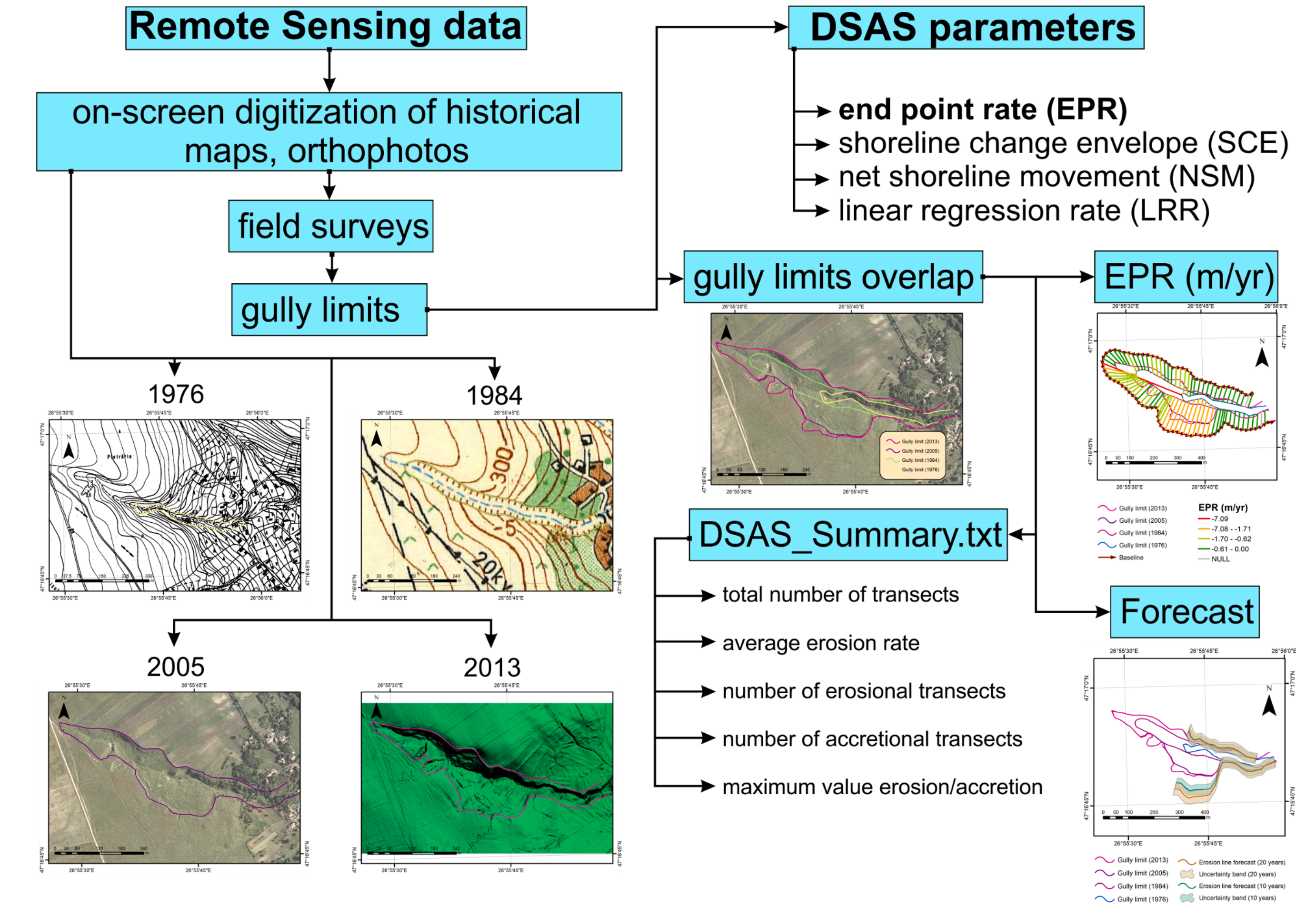

Fig. 5. Flowchart diagram of the methodology used in the study.

Table 1
Parameters used for DSAS calculation found in literature.

Baseline (m)	Transect Spacing (m)	Smoothing Distance	Confidence Interval (%)	Area Length (km)	Reference
–	10	–		~3	Ataol et al., 2019
50	50	–	95	–	Ruiz-Beltran et al., 2019
–	0.5	–	–	–	Sessford et al., 2015
150	10	–	95	~1.3	Nicu et al., 2020
–	10	–	99.7	~0.6	Asandulesei et al., 2020
3500 and 1000	20	–	–	~54	Nazeer et al., 2020

movement by the time elapsed between the oldest and most recent erosion lines); SCE (expressed in m, describes the variability of each transect considering the maximum spatial record displacement of erosion line, without taking into consideration the time span); NSM (measured in m, takes into account the dates of two erosion lines, by reporting the distance between the oldest and newest erosion lines for each transect, and as a consequence, this movement may not be the maximum erosion line displacement recorded); LRR (expressed in m/yr., is based on the overall minimum of the squared distance to the known erosion line using all available data to find the best-fit line and is being recognised as a very useful tool for computing long-term rates of erosion line change). The final classes will be classified using the Natural Breaks (Jenks) method into four final classes.

The erosion rates from the specialised literature of gully erosion on the Moldavian Plateau in Romania (over – 1.5 m/yr and under – 1 m/yr for gullies cut in sandy and clay deposits, respectively) (Ionita, 2006; Romanescu et al. 2012; Ionita et al., 2015; Radoane and Radoane, 2017), will be used to validate the results obtained within this study.

3. Results

For each gully, a set of parameters was chosen. To start with, taking into consideration the fact that the gullies are not very long, the baseline was set to a distance of 20 m (for Băiceni-Cucuteni gully) and 50 m (for the Cucuteni and Săcărești gullies), respectively. All the parameters will be presented for the Băiceni-Cucuteni gully (EPR, SCE, NSM, and LRR), whereas for the other two gullies, the focus will be on the EPR parameter; as this parameter is expressing the average erosion rate (which is the purpose of this paper) and plots the erosion rates in a comprehensible way. The results are as follows:

3.1. *Băiceni-Cucuteni gully*

In Fig. 6, the results obtained by using the baseline of 20 m from the last erosion line was used; other parameters used as input are as follows: transects spacing (2 m) and a smoothing distance of 100. When the smoothing distance is decreased, theoretically to have a more detailed analysis of the erosion rates (in the case of a dendritic gully like ours), it tends to over-estimate the rates. As it can be seen in all of the sub-figures of Fig. 6, the transects (551) are overlapping the baseline, which is

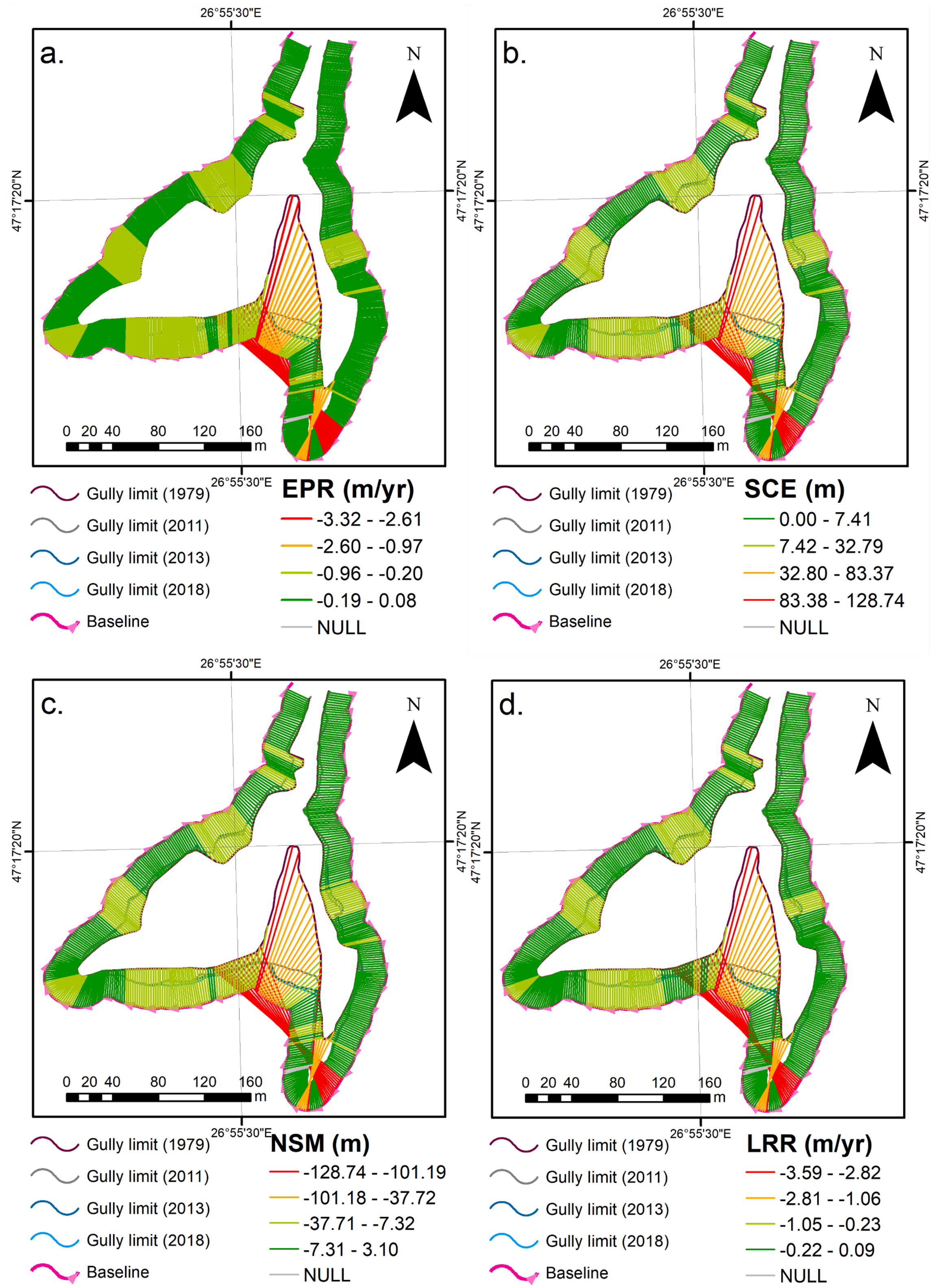

Fig. 6. Results obtained by plotting the DSAS results for the 2 m transects spacing and a smoothing distance of 100: a. EPR; b. SCE; c. NSM; d. LRR.

methodologically incorrect.

In this case, it is not always good to enter low values of smoothing distance, because the DSAS tends to over-estimate the erosion values. As can be seen in Fig. 6a, which is of interest in estimating the average gully erosion rate (EPR parameter), the high values of −3.32 to −2.61 m/yr from the first class are unrealistic, as they are registered from the transects that overlap the baseline (upper right side of the gully branch). A mean erosion rate is indicated as −0.27 m/yr, which is not realistic. This is valid for all the parameters calculated in Fig. 6b (SCE), Fig. 6c (NSM), and Fig. 6d (LRR).

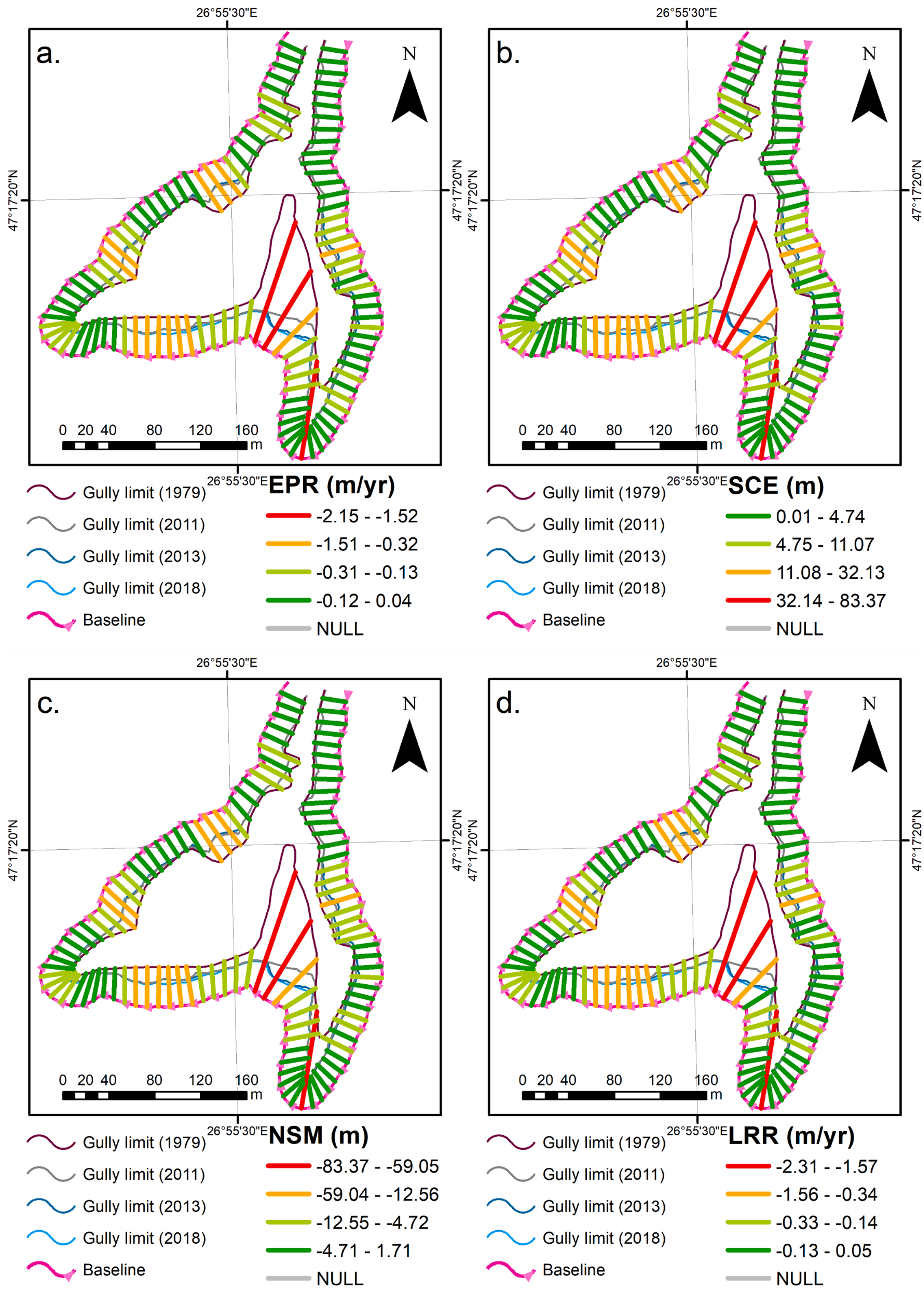

Fig. 7. Results obtained by plotting the DSAS results for the 5 m transects spacing and a smoothing distance of 1000: a. EPR; b. SCE; c. NSM; d. LRR.

When compared with the next set of input parameters: transect spacing (10 m) and a smoothing distance of 1000, things look much better. The number of transects is considerably lower (110), when compared with a smoothing distance of 100 (551). In theory, one could argue that this might not be detailed enough, but it is methodologically correct because none of the transects is overlapping the baseline.

As it can be seen in Fig. 7a, the highest average erosion rate of −2.15 to −1.52 m/yr are much closer to reality and methodologically correct. The average erosion rate was −1.3 m/yr, which is relatively close to the value of −1.5 m/yr for gullies cut in sandy deposits (Radoane and

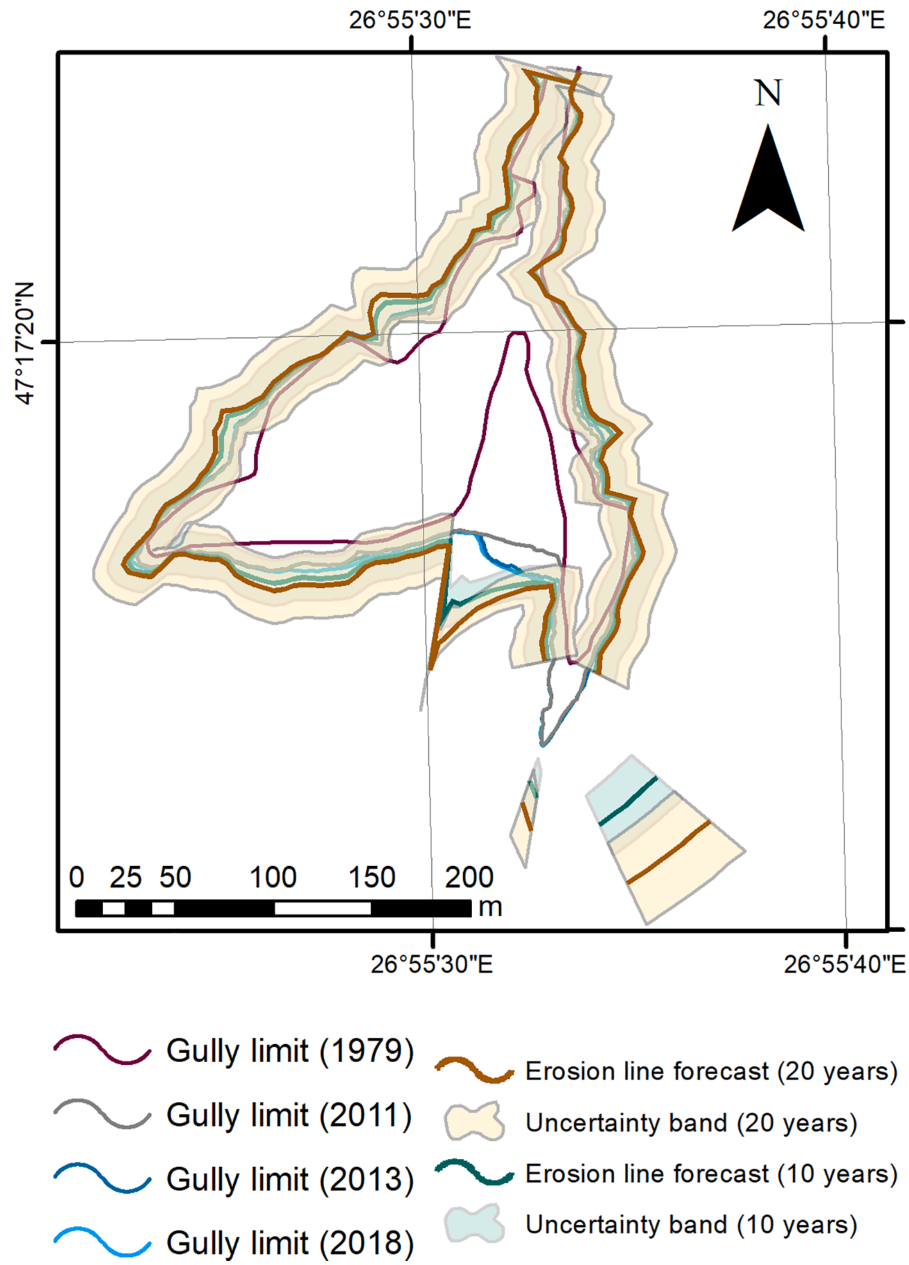

Fig. 8. Erosion lines forecast for the next 10 and 20 years, along with the uncertainty bands.

Radoane, 2017). The same behaviour can be observed for the other parameters as well, in the case of SCE (Fig. 7b), NSM (Fig. 7c), and LRR (Fig. 7d).

When it comes to analyse the forecasting tool for Băiceni-Cucuteni gully, which is visible in Fig. 8, DSAS offers good estimates, along with uncertainty bands for the next 10 and 20 years, respectively. The exception makes the area from the upper part of the gully, where the gully erosion limits are at a considerable distance from each other (for example the gully limit from 1976). However, in this case, the uncertainty band(s) can be used to estimate the future advancement of the gully branches and not the head.

3.2. Cucuteni gully

For the Cucuteni gully, as mentioned in Section 2.2, our focus will be on the EPR parameter (which represents the parameter that indicates the mean annual erosion rate). As seen in Fig. 9, the smoothing distance was set to 100 and then different transect spacing distances were tested for 10 m (Fig. 9a), 5 m (Fig. 9b), and 2 m (Fig. 9c). When using a 10 m transect spacing, the software tends to overestimate the erosion rate, and thus indicating an average erosion rate of −1.01 m/yr.

This is because of the distance between the transects that supposed to intersect the erosion lines from the baseline is too far from each other; therefore, resulting in only one red line that intersects only one of the erosion lines. When using the transect spacing of 5 m and 2 m respectively, things look a bit better; as there are enough transects in the gully head to intersect the erosion lines. The plotted images with the 5 m and 2 m transect spacing look very similar; so are the values of the average erosion rate of −0.96 m/yr. Although the transects are overlapping, they do not intersect the baseline (as in the case of Băiceni-Cucuteni gully) and do not under- or overestimate the erosion rates. Fig. 10 highlights the results of a smoothing distance of 500 and transect spacing for 20 m (Fig. 10a), 10 m (Fig. 10b), 5 m (Fig. 10c), and 2 m (Fig. 10d) distances. As the smoothing distance value was increased, the transects tend not to overlap, as they become more parallel to each other (which is methodologically correct).

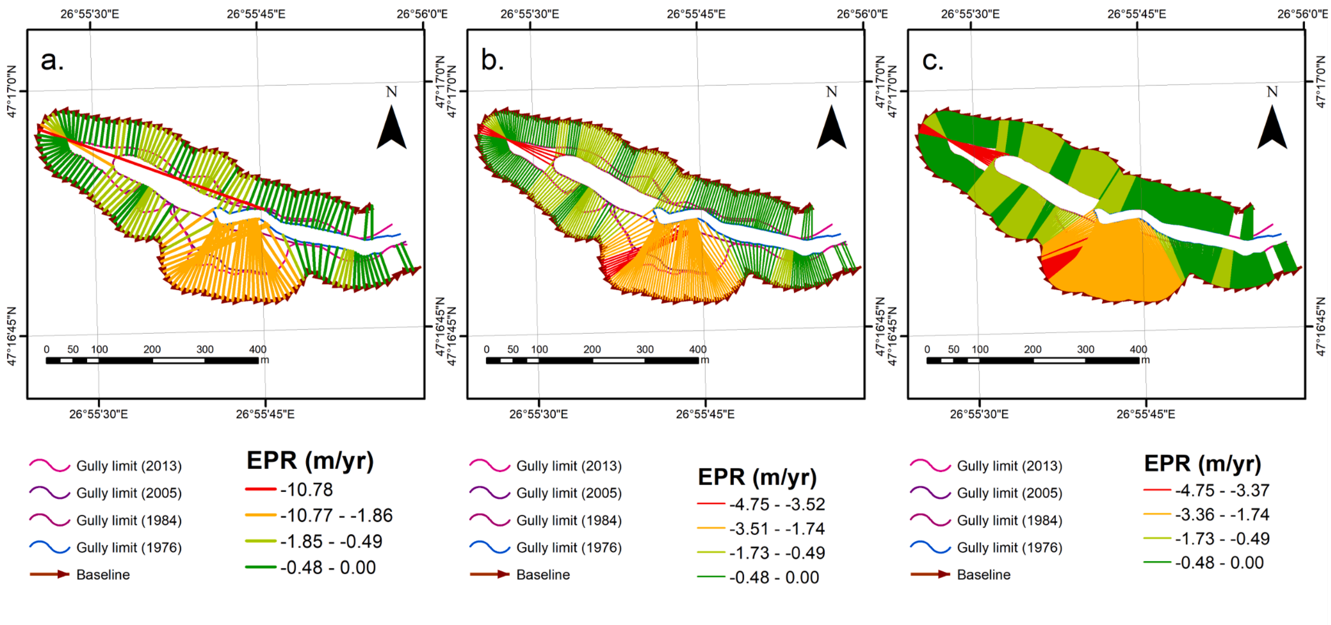

Fig. 9. Results obtained by plotting the DSAS results for the EPR parameter by using a smoothing distance of 100 and different transect spacing: a. 10 m; b. 5 m; c. 2 m.

This has more influence on the segments (erosion lines) that are more curved, like in this case. Regarding the average erosion rate, the difference is not significant when compared to the smoothing distance of 100; in this regard, the average erosion rates are −0.94 m/yr, −0.95 m/yr, −0.93 m/yr for transect spacing of 20 m, 10 m, 5 m and 2 m, respectively. These values are also relatively close to the value calculated for gullies cut in clay deposits through empirical methods for the Moldavian Plateau of −1 m/yr (Radoane and Radoane, 2017). The values are even closer to the value of −0.92 m/yr calculated by (Ionita, 2006) through direct measurements.

In Fig. 11, the results obtained by using a smoothing distance of 1000, are plotted. In this case, transect spacing of 30 m (Fig. 11a), 20 m (Fig. 11b) and 2 m (Fig. 11c) were tested. For the aforementioned values of transect spacing, the average erosion rate values are −0.91 m/yr, −0.88 m/yr, and −0.93 m/yr, respectively. Even in this case, there are not significant differences between the average erosion rates. When it comes to testing the forecast tool, the same as in the first gully case, for the gully head advance, it does not provide a future trustable trend; in this case, it does not calculate it at all (Fig. 12). It calculates future development on the gully sides. However, future erosion line forecasts calculated could easily be extrapolated manually for the gully head, by following the general trend from the gully sides.

3.3. Săcărești gully

For the Săcărești gully, the focus will be also on the EPR parameter. The results obtained from analysing the gully with the help of DSAS are visible in Fig. 13. For this, a smoothing distance of 500 was used and transect spacing of 10 m (Fig. 13a) and 5 m (Fig. 13b). Out of the three gullies analysed in this study, this is the only gully that had a "positive" evolution, meaning that the gully head did not advance, but it has retreated. Out of the two analysed transect spacing distances, the one with 10 m transect spacing (Fig. 13a) offers a better and closer to the truth overview of the gully evolution; as the transects from the 5 m transect spacing intersect the erosion lines at their lower part, which is methodologically incorrect. Since there is no data for the Moldavian Plain in what concerns the positive evolution of gully erosion, like it is the case of Săcărești gully, we are not able neither to confirm nor to infirm the reality of these rates. However, by calculating the erosion rate through empirical methods, it resulted in a rate of 0.10 m/yr. For the 10 m and 5 m transect spacing, the average rate of erosion is 0.29 m/yr and 0.24 m/yr, respectively.

In Fig. 14, the results of the EPR parameter by using a smoothing distance of 100 are highlighted. Fig. 14a and b show the results for using transect spacing of 5 m and 2 m, respectively. As can be observed, the 2 m spacing results are overestimated, due to the fact that the transect lines intersect the erosion lines at their lower part (the same as in Fig. 14b). Here it is obvious the use of different smoothing distances and what values are to be used when dealing with a linear gully. For this, the average erosion rates are 0.08 m/yr and 0.12 m/yr for the 5 m and 2 m transect spacing, respectively. In this case also, the values are not far from the average of 0.10 m/yr. However, for visual interpretation, and a higher accuracy in erosion rates, the 5 m transect spacing offers better results. An increased value of the smoothing distance (2000), as it is visible in Fig. 15, underestimates the erosion rate, because there are not enough transects to cover all the length of the gully. The average rate obtained in this case is 0.22 m/yr, which is a bit far from 0.10 m/yr.

4. Discussion

This paper analysed the strengths and limitations of DSAS for a number of three gullies from the north-eastern part of Romania. This tool could represent a future integration into tackling the United Nations Sustainable Development Goals (UNSDG) (UNHCR, 2017). Out of the 17 UNSDG, the tool tackles goal no. 9 (Build resilient infrastructure, promote sustainable industrialisation and foster innovation), as it applies a new method to better assess soil erosion processes (in this case gully erosion) in an area strongly affected by these processes on the background of the global climatic changes (Nicu, 2018). By doing so, the outputs of the tool will lead to a better resilience of cultural heritage and human settlements towards mitigation and adaptation to climate change (goal no. 13), resilience to disasters, and disaster risk management. In combination with soil erosion prediction maps, future infrastructure (the building of the A8 motorway) or development plans locations can be prioritised according to the results obtained. This will lead to a sustainable community and to a reduction in costs associated with future development plans (goal no. 11). In this way, the predicted gullies cut in sandy deposits can be prioritised to those cut in clay deposits. In this

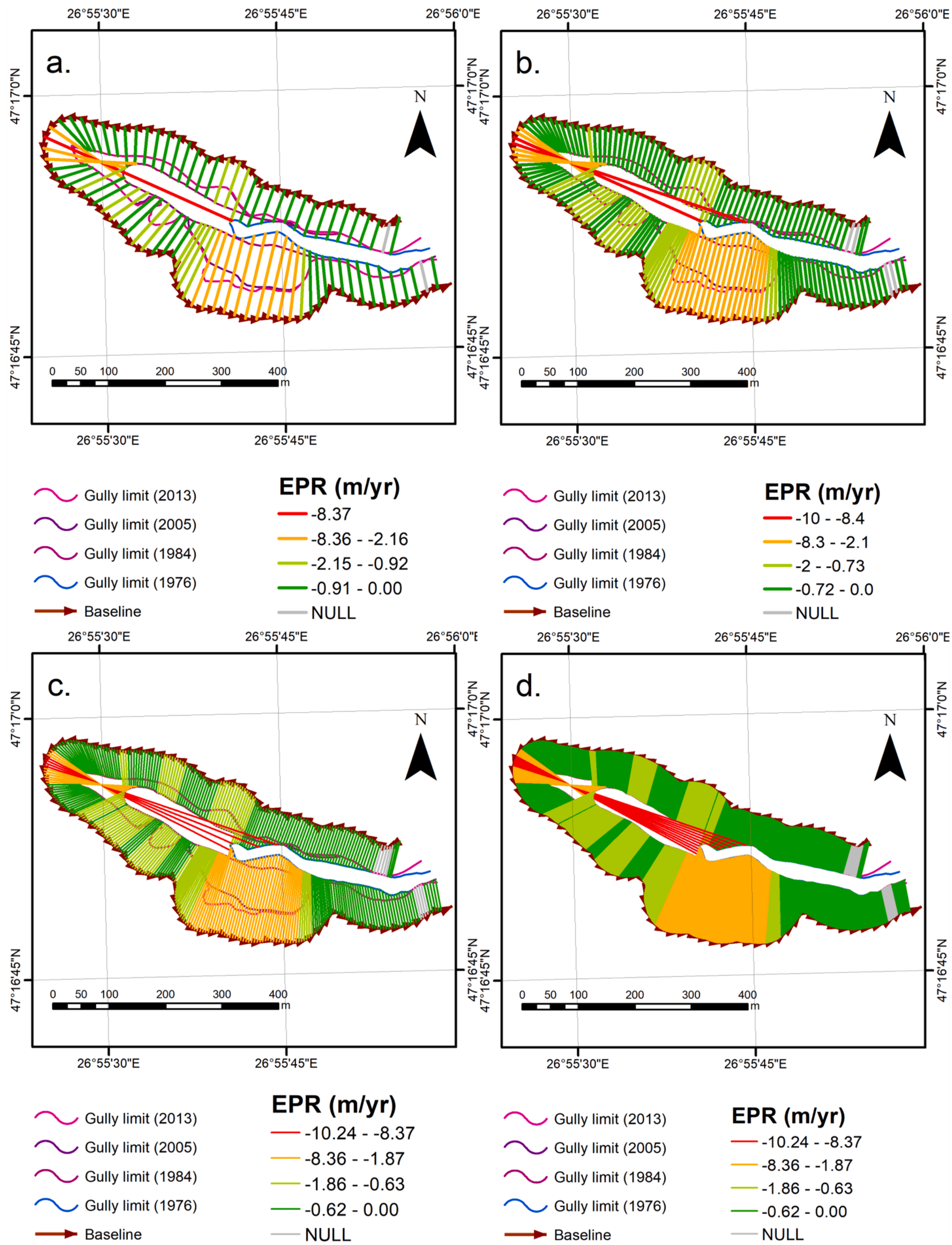

Fig. 10. Results obtained by plotting the DSAS results for the EPR parameter by using a smoothing distance of 500 and different transect spacing: a. 20 m; b. 10 m; c. 5 m; d. 2 m.

case, a more thorough analysis needs to be done, according to the presence or absence of any significant cultural heritage assets. From this point of view, it can represent a powerful if it is also combined or adjacent to multi-hazard approaches applied in the field of cultural heritage (Lombardo et al., 2020) and prioritisation of disaster risk reduction (Sevieri et al., 2020). However, a new general analysis of gully erosion for the entire Moldavian Plateau is needed, where the influence of the environmental factors, future climate change scenarios can be addressed.

The results will contribute to protect, restore, and promote sustainable use of terrestrial ecosystems and mitigate land degradation (goal no. 15). Another goal could be easily reached (goal no. 17), if there will

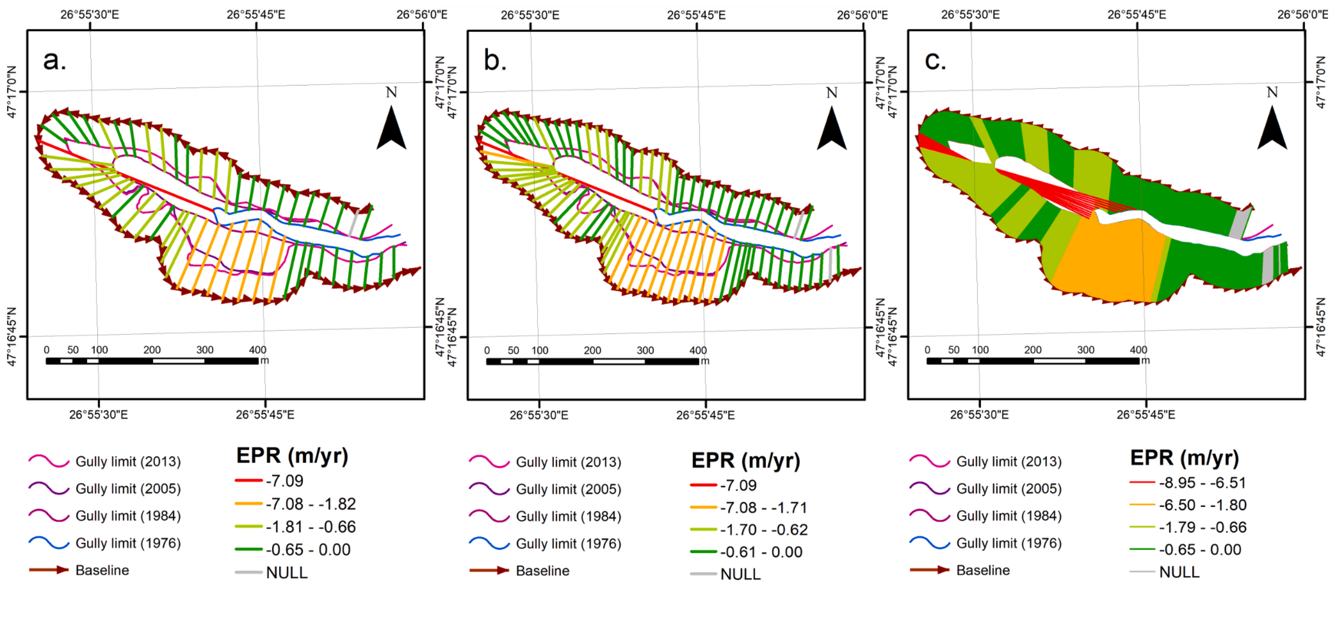

Fig. 11. Results obtained by plotting the DSAS results for the EPR parameter by using a smoothing distance of 1000 and different transect spacing: a. 30 m; b. 20 m; c. 2 m.

be a closer partnership between educational, private sector, and government institutions at a local and national level; as this represents the key to share knowledge with local authorities, which will be able to make better decisions towards a more sustainable approach in the future. From this point of view, the anti-erosion measures taken for Băiceni-Cucuteni gully are laudable and the results are already visible. The average erosion rate for this gully was established by Romanescu et al., 2012 at −0.61 m/yr (since the Second World War until 2012), which is lower when compared with the average erosion rate for the entire Moldavian Plateau of over −1.5 m/yr (Radoane and Radoane, 2017); this means that the gully has reached its morphological equilibrium (stability) (Sidorchuk, 2006). Local factors, such as geology, climate elements (rainfalls with a torrential character), and land use are known to heavily influence the estimation of gully erosion rates, which was highlighted in the case of Băiceni-Cucuteni gully. However, through the new mitigation measures implemented by the local authorities, the erosion has been reduced. This can be considered as a model of good practice in reducing the surface of degraded lands.

Another example is that of Săcărești gully, which head has not advanced, but retreated; this was done very easy, by changing the ploughing direction from the classic hill-valley direction to ploughing along the contours. Ploughing along the contours was very popular during Communist era in Romania, and today's erosion processes represent the result of the four major changes occurred in one century: the great agrarian reform in 1921, the agrarian reform from 1945, agriculture collectivization from 1949 to 1962 (Communist era), and the enforcement of the Land Law from 1991 (Marusca, 2012).

Moreover, there is still to do a lot when it comes to people being aware of their actions, especially in the north-eastern part of Romania; which is known to be one of the poorest regions of the country. Meeting and working together to tackle the UNSDG will lead to a less polluted environment, cleaner water resources, which will make the world a better place to live in.

5. Conclusions

This study has employed DSAS, a tool designed and applied in the assessment of coastal erosion, for gully erosion assessment (the average gully head retreat rate). Three types of gullies (dendritic, linear evolved into dendritic, and linear) cut in different deposits (sands and clay) from the Moldavian Plateau of Romania were selected. After the analysis, a few lessons can be learned for results that are closer to the ones from the specialised literature: i) better results are obtained in the case of dendritic gullies if the smoothing distance is set to higher values (>1000) and transect spacing values >5 m; this is due to the more curved erosion lines of dendritic gullies. ii) in the case of linear gullies, the smoothing distance needs to be set to lower values compared to dendritic gullies (<= 1000). iii) when it comes to the linear gully that evolved into a dendritic gully, the recommendation is to use smoothing distances with high values (>1000) and transect spacing values >10 m. The average erosion rates obtained with the help of DSAS are very close to the ones from the specialised literature for the Moldavian Plateau (−1.5 m/yr for gullies cut in sandy deposits and −1 m/yr for gullies cut in clay deposits); values that are calculated through empirical methods and direct measurements and validated through statistical models. Our goals set in the beginning of the study were accomplished. It can be said that DSAS is "fit" to be used for gully erosion assessment and erosion rates estimates. However, a balance needs to be reached when using DSAS for gully erosion assessment. When it comes to the forecast tool, this is not "fit" in the estimation of gully erosion future advancement. Future directions are towards validating the forecast tool in the field. In this way, we can have a better image of the forecasts provided by the DSAS. As shown in the present study, DSAS represents a powerful tool not only for coastal erosion but also for gully erosion assessment. However, each software has its own limitations and biases, and this should be considered. The method can be successfully implemented in future management plans of water resources, soil erosion mitigation measures, environmental and

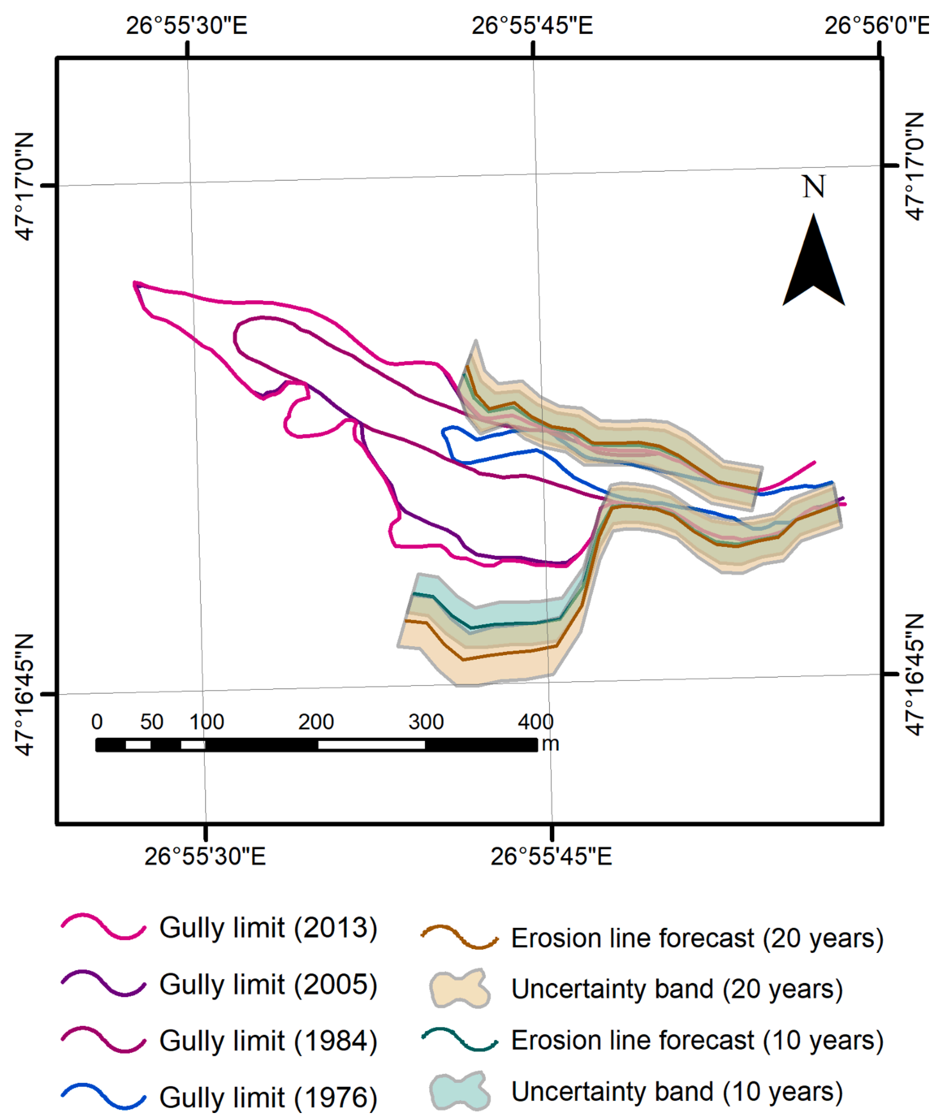

Fig. 12. Erosion lines forecast for the next 10 and 20 years, along with the uncertainty bands.

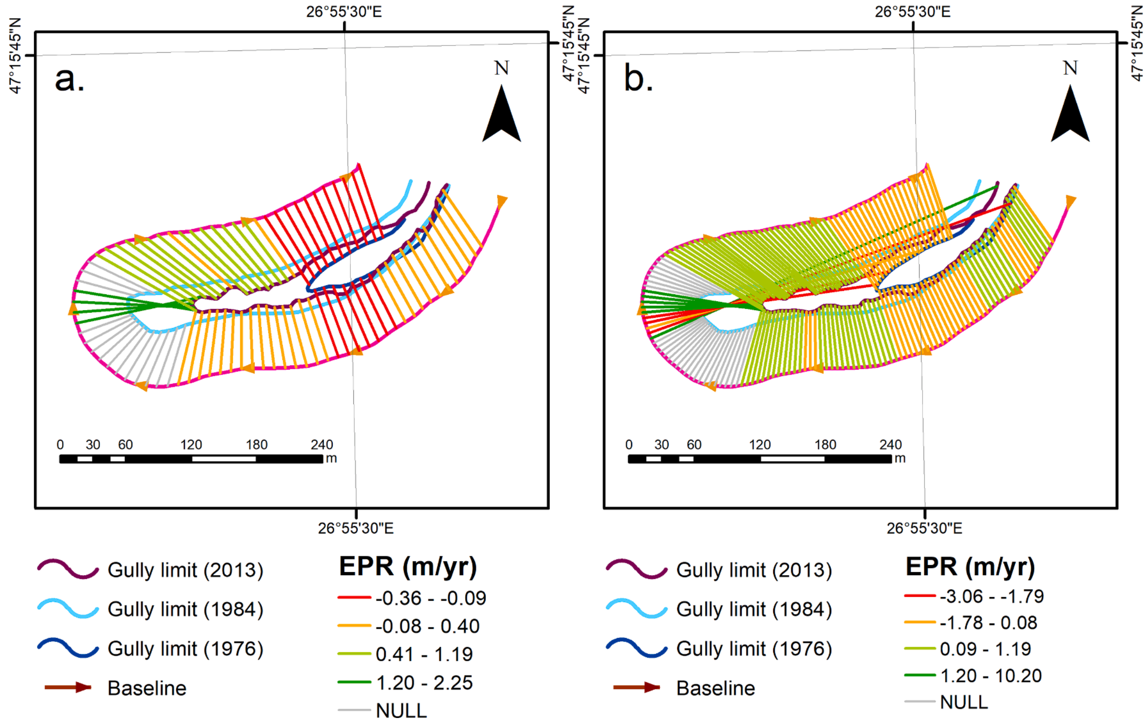

Fig. 13. Results obtained by plotting the DSAS results for the EPR parameter by using smoothing distance of 500 and different transect spacing: a. 10 m; b. 5 m.

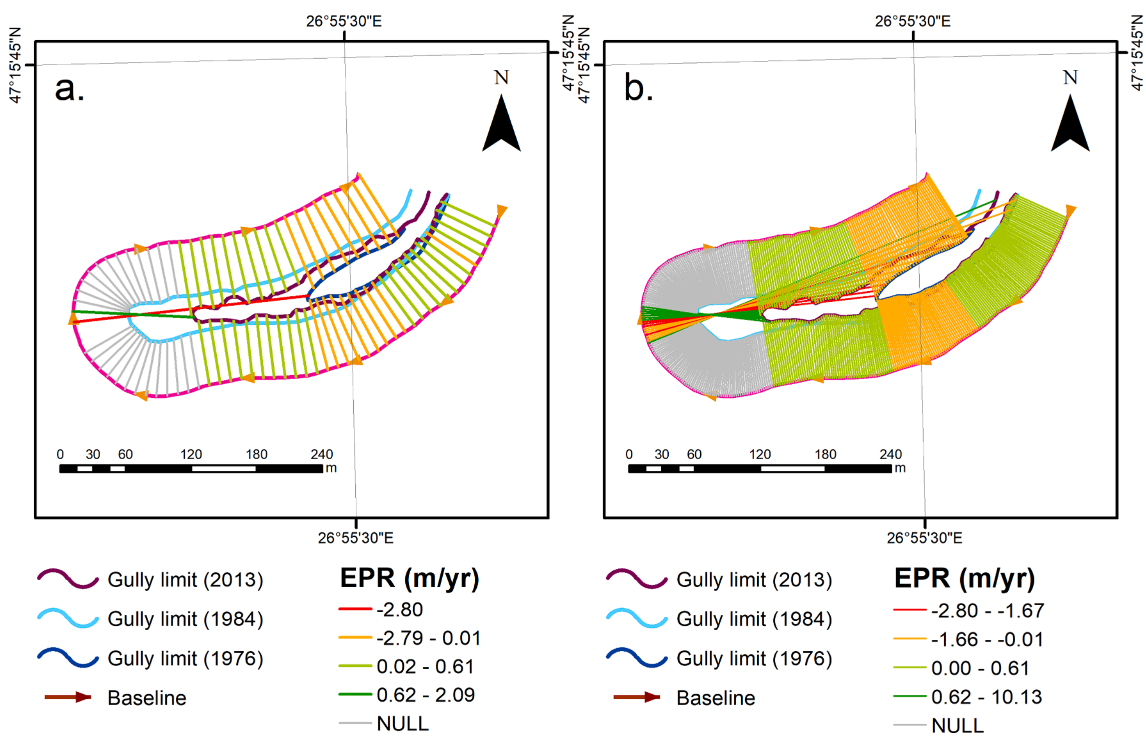

Fig. 14. Results obtained by plotting the DSAS results for the EPR parameter by using smoothing distance of 100 and different transect spacing: a. 5 m; b. 2 m.

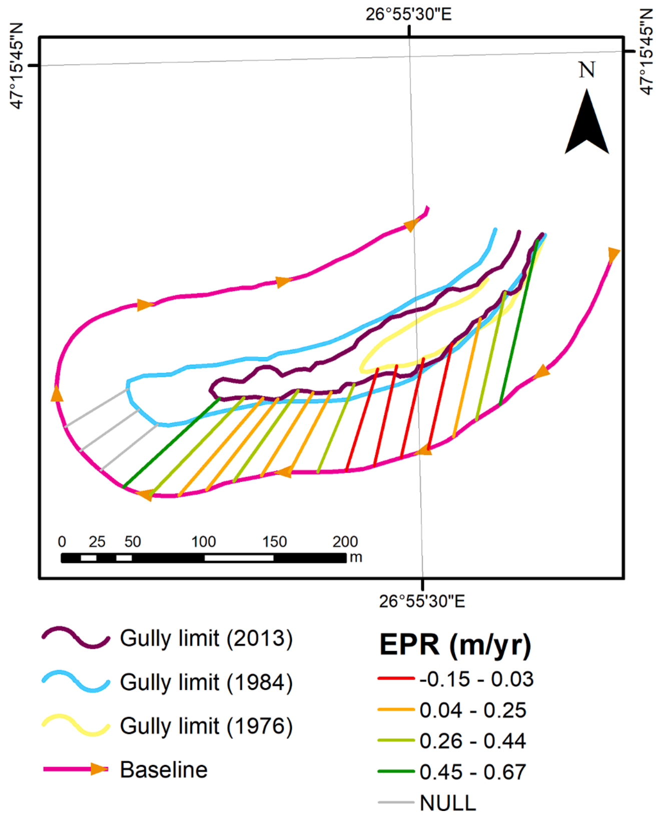

Fig. 15. Results obtained by plotting the DSAS results for the EPR parameter by using smoothing distance of 2000 and transect spacing of 20 m.

cultural heritage protection, stakeholders in planning future economic activities, disaster risk reduction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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