Detection and Labeling of Sensitive Areas in Hydrological Cartography Using Vector Statistics

Elia Quirós, María-Eugenia Polo, and Ángel M. Felicísimo

***Abstract*—The recognition and delineation of hydrological stream lines has, traditionally, been a subjective manual task in cartography. However, digital elevation models (DEMs) are nowadays often employed to extract stream lines automatically, via the use of geographic information systems. Whereas the automatic generation of hydrological networks presents errors, their manual recognition can be almost arbitrary. In this paper, we propose a methodology with which to label potentially sensitive zones in the comparison of hydrological cartographic networks. Two different sources were analyzed: a conventional cartographic stream network, and one automatically extracted from a DEM. The 72 500 vectors of displacement, representing the spatial disagreement (or fit) between the stream networks, were also examined. A number of remarkable distributions of large errors were identified that were a cause for alarm; these errors are here denoted by "warnings" and are classified into six different groups. The displacement vectors were also analyzed in terms of modulus and azimuth, thereby allowing the analysis of the isotropy of the spatial displacements. We propose the use of all of the derived information as metadata for hydrological spatial quality, as well as the extension of the methodology to any other type of cartographic element (roads, cadastral, etc.) for which two different vector format information sources are compared.**

***Index Terms*—Digital elevation model (DEM), directional statistics, graphical statistical plot, hydrological network, stream lines.**

I. INTRODUCTION

THE recognition and delineation of stream lines in cartography has, traditionally, been a manual task. However, manual mapping is subjective because the results are strongly dependent on image quality and interpretation criteria. Moreover, as the results depend on the operator, they are typically not reproducible [1]. The most common alternative method employed for stream line mapping is the extraction of stream networks from digital elevation models (DEMs). This is a well-known topic and the method has proven a powerful tool in numerous studies [2], [3].

Nowadays, there are several different software tools available that allow the extraction of stream networks and other hydrological features from DEMs, either by means of different algorithms [4], [5] or the application of certain indices that underscore terrain morphological features [6].

Obviously, DEM quality is a critical issue affecting both the accuracy and spatial resolution of the extracted hydrological network [7], [8] and subsequent hydrologic predictions [9], and thus, the impact of any DEM modification must be evaluated [10].

Automatic hydrological extraction includes processes, which are highly dependent on local errors. For example, if any sink in the DEM interrupts the continuity of the flow line, an error occurs. For this reason, the generation of hydrological networks involves preprocessing stages that, in the aforementioned example, "fill" the sinks that can be caused by minor uncertainties in elevation values.

Furthermore, the algorithm employed for flow extraction is also critical. Three main algorithms are typically used in geographic information systems (GIS) and other similar cartographic software packages. The D8 algorithm contemplates flows only to and from the center of DEM cells; as a result, the flow angle can vary only by multiples of 45°. However, despite this limitation, the D8 algorithm is the most widely used in GIS-based studies. The $D\infty$ algorithm is substantially improved with respect to the D8 algorithm because it enables flow angles to be changed at 1° resolution. Finally, the kinematic routing algorithm (KRA) considers the free movement of water along the DEM without restrictions. Such routing algorithms model flow moving kinematically as a point source from the center of the source pixel until it reaches a perimeter point. Once at the perimeter, flow is transferred to the coincident perimeter point on a neighboring pixel [11]. The KRA method has a significant advantage over the previous two algorithms in that it can describe both spatial and temporal variation in rainfall and roughness [12].

Although the automatic generation of complete and topologically connected hydrological networks is possible, errors are inevitable, even when extensive precautions are taken. Similarly, the definition of the origin of the "blue lines" produced during manual recognition is almost arbitrary, with the potential for feature confusion possible [13], [14].

Unfortunately, this kind of cartographic question is poorly addressed in the literature. As a result, it remains common to experience compatibility problems when using digitized maps, heterogeneous cartographic sources (even those at the same scale) and other digital information together in a single GIS.

Most assessments examining the accuracy of automated drainage network extraction from DEMs involve some form of network comparison. Such comparisons are generally performed by matching two cartographic data sources from the

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same site, with the hydrological features obtained manually considered the "true terrain" [15], [16].

To contribute to the management of such issues, we investigated a method with which to cross-compare hydrological networks drawn from different sources, in this case, conventional cartography and automatic extraction from a DEM. Network comparison generates vectors of displacement between (approximately) homologous stream line nodes. Some works deal with computed vector statistics [17] or similar approaches [18], [19]. These vectors can then be sorted into several categories, according to the nature of the geometric deviation and, just as importantly, labeled for use as metadata regarding hydrological spatial quality. Based on this, we here propose that each hydrological network discrepancy be labeled, thereby generating error "warnings" as a function of the category of the disagreement between the original data sources. In addition, further parameters derived from the statistical analysis of the obtained errors are also proposed.

II. Objectives

The aim of this paper was to develop a methodology with which to detect and label potentially sensitive zones identified via a comparison of two different hydrological cartographic networks. The proposed procedure cannot be only applied to check and correct old hydrological maps using automatically generated networks for reference but is also useful for comparing maps obtained from different sources or production methods and drawn at varying scales.

The proposed methodology classifies potential cartographic errors in the form of different warning types, based on the nature of the geometric deviation between the two hydrological networks, and also provides more information regarding the associated metadata.

III. Area, Data and Data Processing

A. Study Area and Data

Analyses were performed in the Guadiana river basin in southern Extremadura (Spain), a region with a highly irregular flow regime. The study area itself covered 9600 ha characterized by the presence of typical Mediterranean climate vegetation. We analyzed 72.5 km of stream flowing into three basins situated at the southern end of the Guadiana River, coded according to the Guadiana Hydrological Confederation as 596, 597, and 2024 (see Fig. 1). Basin elevations range from 250 to 600 m, with their varied topographic characteristics (low, medium, and abrupt relief) considered appropriate for the testing of the proposed method.

The hydrological network comparison was performed between two sources. The first of these comprised the stream lines found on a 1 : 10 000 digital map of Extremadura, generated by means of conventional photogrammetric techniques. The second source was a stream network generated automatically from a 5-m spatial resolution raster DEM, provided by the Government of Extremadura. As discussed earlier, both the stream lines and certain associated properties, such as stream length and network densities, are strongly dependent on operator interpretation.

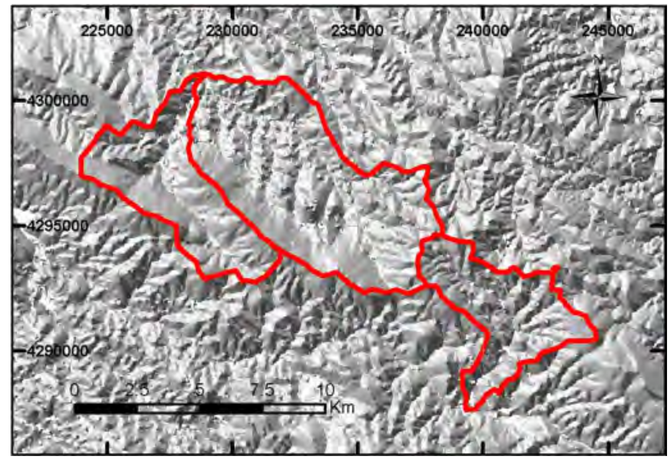

Fig. 1. Three studied drainage basins, with low (west), medium (center), and abrupt (east) relief (basins coded 2024, 597, and 596, respectively). Datum ETRS89, projection UTM, zone 30N.

B. Data Processing

The automatic stream network was calculated using ArcGIS and SEXTANTE GIS packages [20].

The following typical calculation steps were employed: 1) DEM preprocessing; 2) flow direction; 3) flow accumulation; and 4) stream line extraction.

The DEM preprocessing stage included the filling of pits, ensuring that spurious sinks did not break the continuity of the flow lines.

Flow directions were calculated via the KRA, with the obtained results used to produce the flow accumulation grid, which included an estimation of the upslope watershed surface for each DEM cell. Obviously, summit cells had very low values and the accumulated flow increased downslope, reaching maximum values in the main channels receiving runoff from large areas.

Stream lines were obtained from the flow accumulation grids defining a flow threshold value; in this paper, the selected threshold was equivalent to 2500 ha of upslope watershed area.

C. Networks Comparison

In order to quantify the spatial disagreement (or fit) between the produced stream networks, a set of points was created along both stream lines at an interval of 10 m. With this interval, 72 500 vectors were generated, a number large enough to have statistical significance.

Taking as a reference each of the points in the automatically derived (DEM) stream network, the coordinates of the respective nearest points in the cartographic (1 : 10 000) stream line were determined by generating a table in ArcGIS. Each pair of automatic and cartographic points in the table were considered homologous points, with their coordinates defining the disagreement vectors between them.

Finally, with all homologous points, a total of 72 500 vectors were generated. Each vector was defined from the point of the cartographic stream line (initial node of the vector) to the homologous point on the automatic stream line (end node of the vector). In addition to the coordinates of the initial and end nodes,

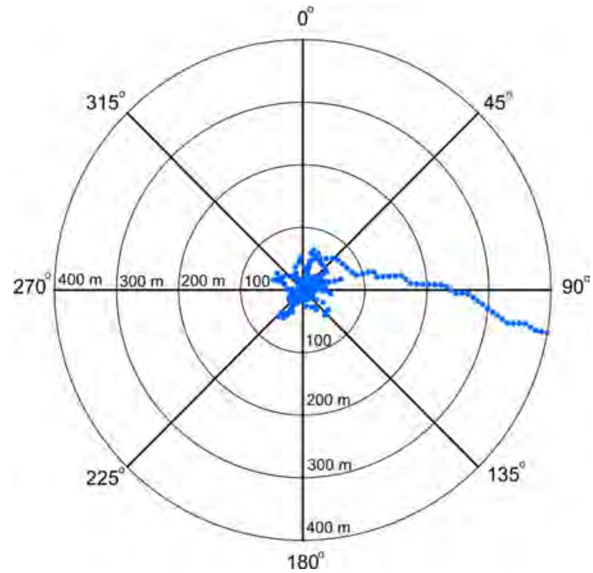

Fig. 2. Graphical plot of error spatial distribution (for basin 596).

each vector provided information regarding magnitude or modulus and azimuth, calculated from the respective coordinate points, thereby enabling the determination of not only the agreement in distance between the networks but also the angle of any displacement. Consequently, statistical processing of the vectors was employed for the analysis of the distances and angles between the two sets of stream lines, as well as of the isotropy/anisotropy of the spatial displacement.

IV. Statistical Analysis

The proposed method is based on the analysis of displacement vector modulus and direction, performed using VecStatGraphs2D, an R package designed for the statistical analysis of 2-D vectors [17]. This software program enables users to perform conventional descriptive statistical and other tests, as well as the graphical analysis of nonunit vectors. Such vector statistics can be employed to analyze both azimuths (angular) and magnitudes (linear), either jointly or independently.

The analysis was based on the evaluation of graphic plots, produced via the following procedure: Displacement vectors were moved to a common origin (0; 0), thereby preserving azimuth and modulus, with the graph representing the situation of the vector end nodes as points. As shown in Fig. 2, the produced graphs illustrate the spatial distribution of errors and thus enable a thorough evaluation. A number of remarkable distributions observed in these graphs are cause for alarm, here denoted by "warnings."

The graph analysis procedure can be divided into three steps.

A. Detecting and Labeling Large Errors

The modulus of displacement vectors typically varies from zero (perfect fit between lines) to a maximum value that is highly variable, depending on the selected cartographic sources. This modulus is generally known in cartography as "error." In order to locate and label the identified warnings, it was necessary to define a threshold value for errors in accordance with the original cartographic scale or uncertainty.

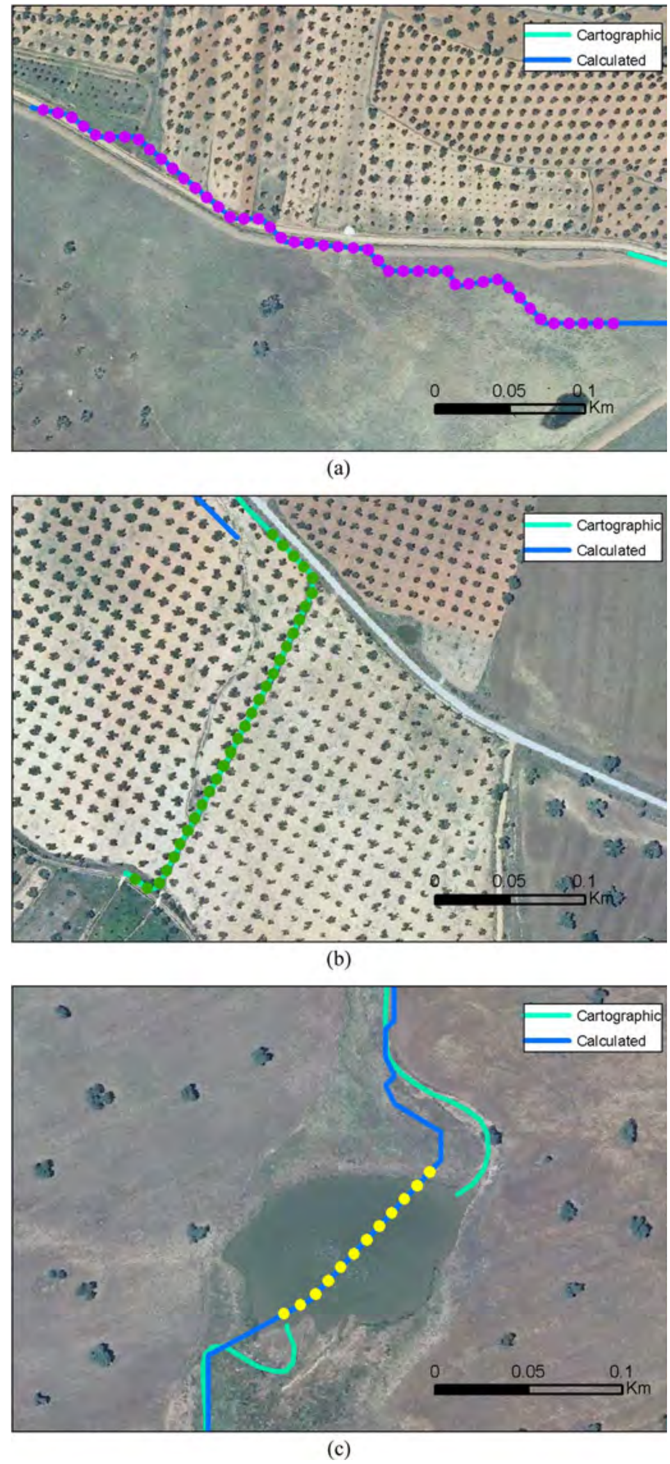

Fig. 3. Examples of each warning type, from top to bottom. (a) (Magenta warnings) Automatic stream lines longer than cartographic stream lines. (b) (Green warnings) Automatic stream lines shorter than cartographic stream lines. (c) (Yellow warnings) Ponds.

Taking into account the fact that the scale of the map being compared with the DEM-calculated network was 1 : 10 000, a limit of 10 m was considered reasonable with which to define the boundary between large and random errors. Consequently, all graph points outside a circle of radius 10 m from the plot origin were designated large errors.

It can be observed that the example large error graphical plots shown in Figs. 3 and 5 possess a number of remarkable characteristics. These errors can thus be classified into the following types (warnings).

1) Automatic Stream Lines Longer Than Cartographic Stream Lines (Magenta Warnings): In this scenario, points in the automatic stream line are measured to the same nearest point in the cartographic stream line, producing an aligned series of points in the graphical statistical plot [see Figs. 3(a) and 4(a)].

2) Automatic Stream Lines Shorter Than Cartographic Stream Lines (Green Warnings): The best method with which to detect these automatically is to calculate the modulus and direction of the error vectors in the opposite direction, i.e., from the cartographic to the automatic stream lines. The associated graphical plots are also in the form of groups of aligned points [see Figs. 3(b) and 4(b)].

3) Ponds (Yellow Warnings): Whereas cartographic stream lines are cut wherever a pond appears, automatic stream lines extend along them. In such situations, the graphical plots [see Figs. 3(c) and 4(c)] exhibit errors aligned in two directions since there are two points in the cartographic stream line, one at each end of the break, from which the distance and angle are measured.

4) Ambiguities (Red Warnings): These errors arise when the cartographic stream lines from which the automatic stream lines are measured are not appropriate. Although these errors are aligned [see Figs. 5(a) and 6(a)], the homologous point comparison shown in the ArcGIS table demonstrates that the points in the cartographic stream lines do not belong to the same identification line.

5) Straight or Wrong Direction Curves (Brown Warnings): In this case, whereas cartographic stream lines are curved, the automatic stream lines are either straight or curve in the opposite direction. As a result, the nearest distances in the midpart of the warning area are measured to the same point in the cartographic stream line, and not orthogonal to it. As shown in Figs. 5(b) and 6(b), these plots exhibit three aligned directions.

6) False Curves (Gray Warnings): These errors are associated with the opposite situation from the aforementioned brown warning, with cartographic stream lines straight and automatic stream lines curved. In this case, minimum distances are suitably measured. The graphical plots show errors aligned in a single direction [see Figs. 5(c) and 6(c)].

B. Statistical Study of Random Errors

Random errors (less than 10 m) from the three drainage basins were also analyzed in order to evaluate their linear (modulus) and angular (azimuth) distributions. Whereas moduli were analyzed as scalar values, calculating arithmetic mean, range, and standard deviation, azimuths were studied as circular data, obtaining parameters, including mean azimuth, mean modulus, circular standard deviation, and azimuth distribution. Circular data deal with angular values considering only unitary vectors [21], [22].

C. Final Analysis and Metadata

The proposed final stage involves the final graphical representation and development of a metadata file, including: 1) identification of the basin (basin code); 2) date of the control; 3) basic information regarding both hydrological cartographic sources; 4) type of detected warnings; 5) geographic location of detected warnings; 6) total length; 7) isotropy of azimuth distribution; and 8) modular standard deviation of displacement vectors.

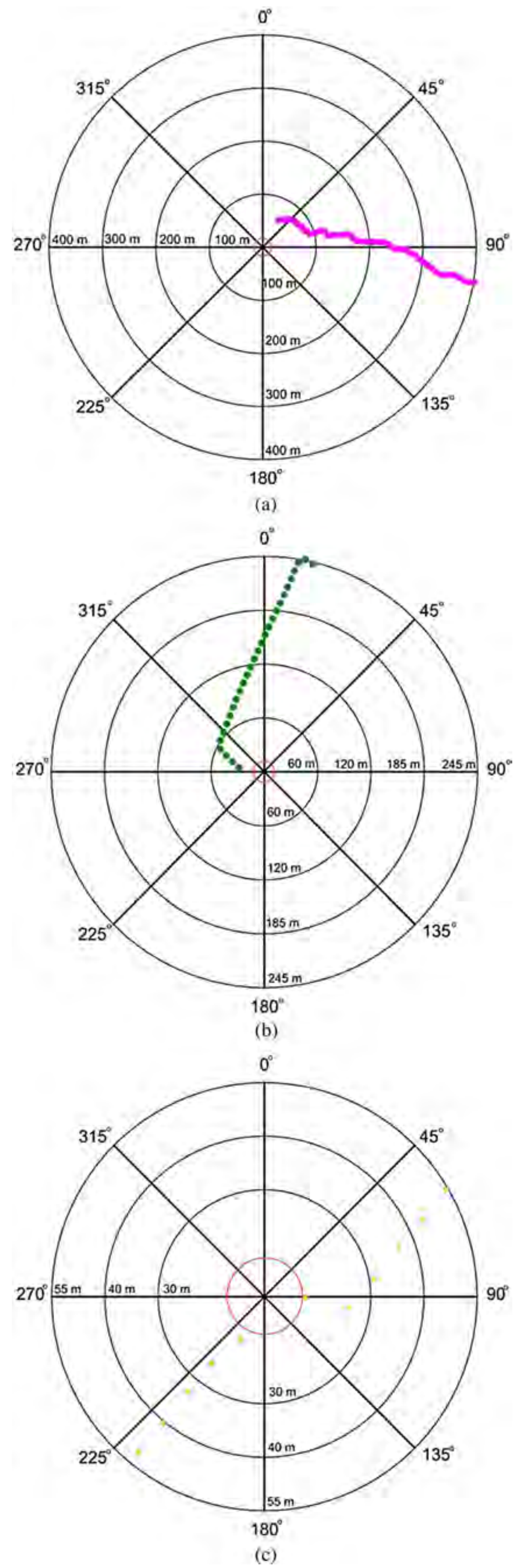

Fig. 4. Graphical statistical plots of each warning type, from top to bottom: (a) (Magenta warnings) Automatic stream lines longer than cartographic stream lines. (b) (Green warnings) Automatic stream lines shorter than cartographic stream lines. (c) (Yellow warnings) Ponds. Red circles (10 m) delimit random errors.

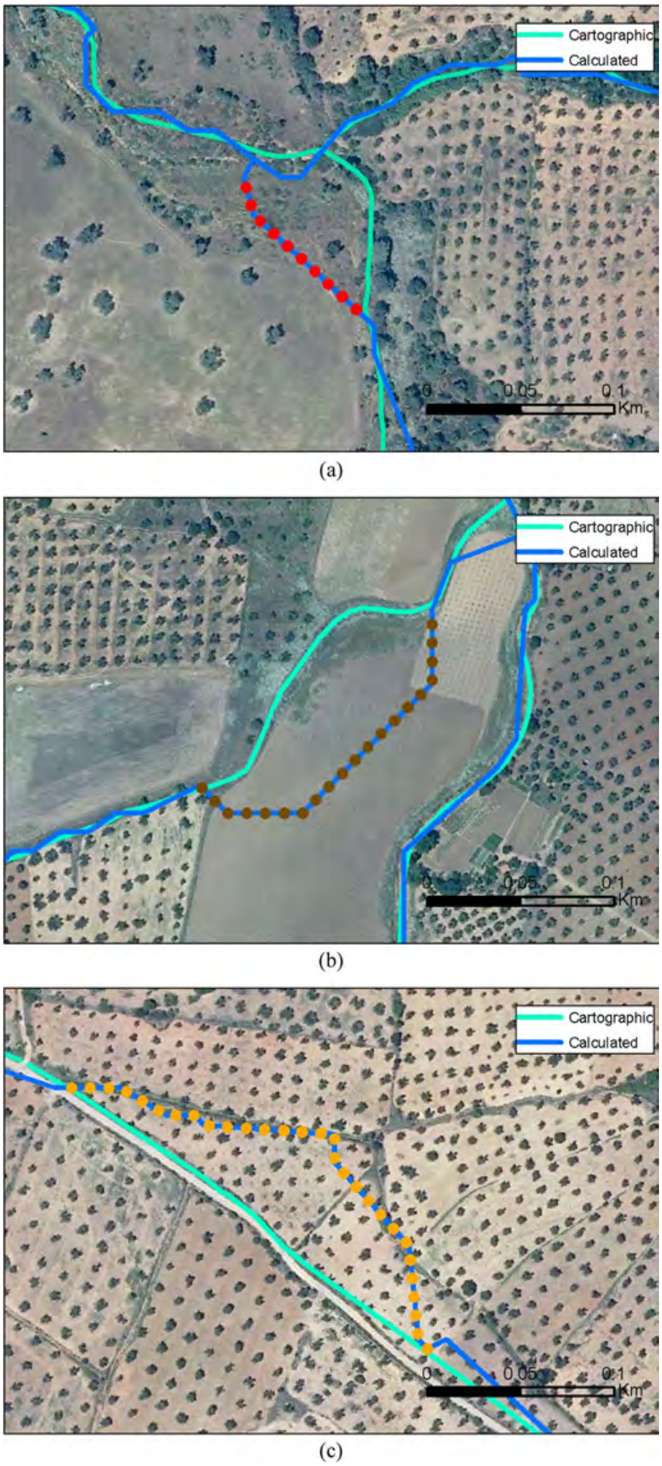

Fig. 5. Examples of each warning type. From top to bottom: (a) (Red warnings) Ambiguities. (b) (Brown warnings) Straight or wrong direction curves. (c) (Orange warnings) False curves.

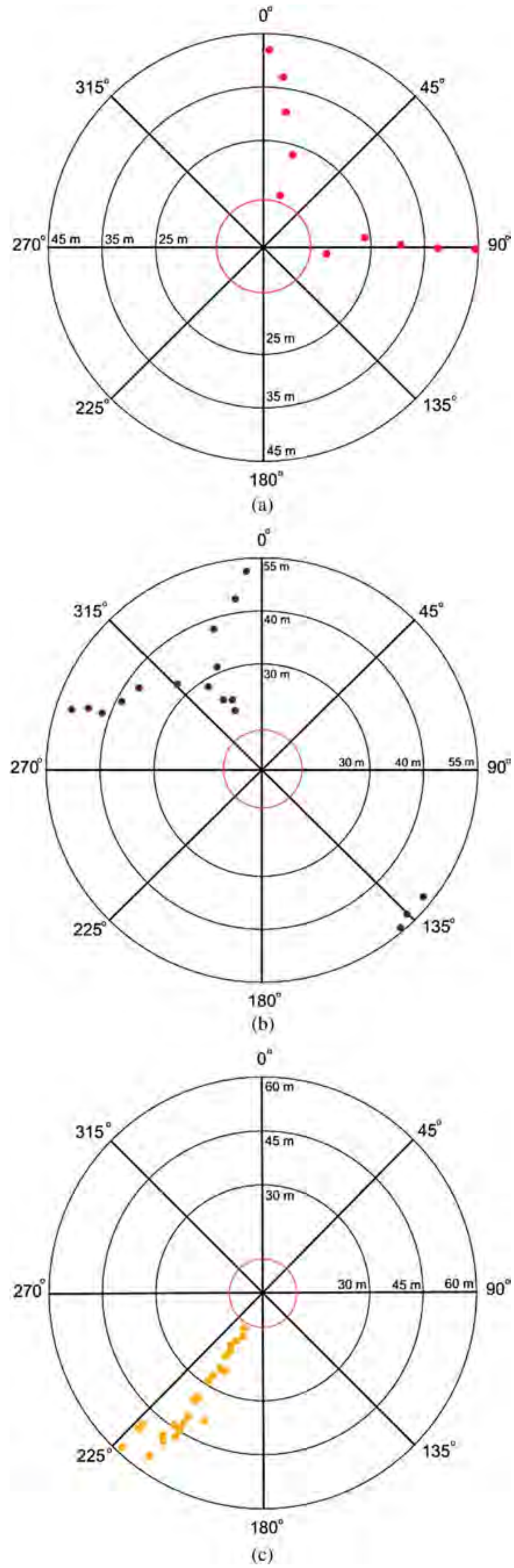

Fig. 6. Graphical statistical plots of each warning type, from top to bottom: (a) (Red warnings) Ambiguities. (b) (Brown warnings) Straight or wrong direction curves. (c) (Orange warnings) False curves. Red circle (10 m) delimit random errors.

V. Results

A. Detecting and Labeling Large Errors (Warnings)

Figs. 3 and 5 illustrate one example of each warning type detected in the study area. Figs. 4 and 6 show a graphical statistical plot for each warning type, with the red circles delimiting the random errors (10 m). It should be pointed out that whereas both the green and magenta warnings present raised modulus

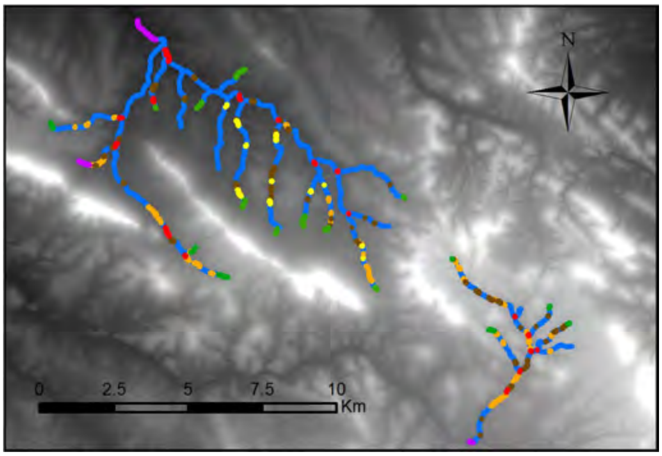

Fig. 7. Location of warnings in the study area, from west to east: Stream lines for basins 2024, 597, and 596 (Guadiana Hydrographic Confederation codes).

values (in some cases, up to 400), the remaining warnings, despite presenting lower moduli, exhibit more significant angular distribution characteristics.

B. Statistical Study of Random Errors

No special pattern was observed regarding the distribution of moduli or azimuths for random errors, including no preferred directions. Although certain data sets (drainage basin 597) exhibited a higher data concentration in an east–west direction, there was no observable relationship between this concentration and relief because this particular basin is characterized by medium relief (see Fig. 1). For the other two basins (596 and 2024), there was no preferred direction for the data; although the hypothesis of uniformity for the azimuth distributions can nevertheless be rejected in all cases.

C. Final Analysis and Metadata

As already noted, a final analysis would enable users to quantify the similarity between cartographic and automatically calculated stream networks, as well as determine the geographic location of detected warnings (see Fig. 7).

Such a map could be implemented together with a metadata file, similar to that shown in Table I, containing the following information.

TABLE I
PROPOSED METADATA (* UNITS OF CENTRAL POINT COORDINATES, STANDARD DEVIATION, AND LENGTH ARE IN METERS; ** CENTRAL POINT COORDINATES (X, Y): ETRS89 UTM ZONE 30N)

Basin ID:	596
Date of Control:	07/05/2014
DEM Resolution:	5 m
Flow direction algorithm:	KRA
Comparison source:	10 000 official cartography
Isotropy	Uniformity distribution is rejected
Standard deviation	39.8

Type of Warning	Central point coordinates (X,Y)	Length
Red	227 436;4 298 550	90
Orange	227 243;4 298 563	40
Orange	226 301;4 298 309	50
Green	225 136;4 298 294	200
Brown	227 374;4 297 829	40
Red	227 314;4 297 679	40
Brown	227 281;4 297 616	40
Brown	227 206;4 297 534	110
Brown	226 886;4 297 261	30
Orange	226 855;4 297 147	30
Orange	226 752;4 297 046	40
Orange	226 658;4 296 991	90
Brown	226 594;4 296 946	30
Orange	226 476;4 296 956	110
Magenta	226 211;4 297 007	450
Brown	227 534;4 296 349	100
Orange	228 387;4 295 555	40
Orange	228 481;4 295 456	70
Orange	228 560;4 295 380	70
Orange	228 654;4 295 257	160
Orange	228 741;4 295 141	70
Orange	228 806;4 295 044	80
Red	228 991;4 294 705	330
Brown	229 182;4 294 404	190
Orange	229 791;4 294 034	30
Green	229 910;4 294 091	240
Orange	229 693;4 293 801	140
Orange	230 055;4 293 643	280
Orange	230 489;4 293 319	30
Orange	230 554;4 293 303	30
Green	230 890;4 293 218	350

VI. DISCUSSION

Nowadays, most hydrological cartography is carried out using photogrammetric techniques. As the human factor introduces some degree of subjectivity, as well as different operational criteria, hydrological parameters, such as stream density, section order, and stream origin, thus vary over time for different map sources, scales, and versions.

In recent years, a variety of automatic hydrological algorithms based on DEM processing have been developed, and although their use is already widespread, their spatial accuracy has not yet been thoroughly investigated. In particular, Molloy and Stepinski [1] suggest that network comparison is a difficult assignment and addresses the problem by means of two phases: visual comparison and measuring the length and overlap between a delineated and an automatically extracted network. In the same way, the assessment presented in [15] is based on hierarchical matching, taking as reference the distance between network nodes. There are, however, a number of difficulties with such techniques, with none taking into account the angle component of the disagreement between networks. Although internode distance is indeed very important, in reality the angle of disagreement is also of tremendous significance, since it allows the analysis of the isotropy/anisotropy of error spatial distribution.

More detailed studies such as [10] have been undertaken in order to identify critical areas of uncertainty in drainage network extraction. However, in such studies, there is often no comparison made with other sources, with the uncertainty based on the deviation of the drainage lines produced by small variations in the angle of flow direction during network creation. In contrast, the labeling of sensitive areas outlined in this paper relies on the analysis of vectors of displacement between conventional cartography and automatically extracted networks. Consequently, these results can be better categorized as reflecting spatial uncertainty between two sources.

As discussed earlier, the proposed method can be applied to other problems, in which two sets of points or lines are compared.

For instance, automatically extracted road network comparison has been dealt with by a number of authors, including [16]. However, such studies tend to evaluate quality measures rather than conduct an absolute evaluation of their results. The essential difference between [16] and this paper is that, whereas the former did not detect wiggling effects or even incorrectly extracted data, the latter has not only identified them but has also classified them into different error categories or warnings.

In addition, the analysis of variation in (linear and polygonal) element morphology between different map scales enables the study of other issues, such as the effects caused by the cartographic generalization of a line or the patterns of morphological changes in a map. Moreover, analysis may be temporal, for instance, when dealing with changes in river network or cadastral boundaries between two or more different dates. The method may be also applied to elements extracted from satellite imagery, including roads, boundaries or vegetation patches, thus greatly expanding its application beyond conventional mapping. For instance, tracking a set of hash marks on the ground can provide quantitative data regarding the activity of possible landslides or soil flow.

If we consider all of the aforementioned arguments, it becomes clear that the statistical analysis technique proposed in this paper is a useful tool, and its implementation could settle numerous cartographic uncertainty situations.

VII. Conclusion

The proposed methodology for detecting and labeling potential sensitive zones observed during the comparison of two hydrological cartographic networks, classifies stream sections by means of labeled warnings that reflect different types of mismatches between the two compared sources. This information contributes to the identification of large errors and sensitive zones that can be considered candidates for review.

The procedure suggested here may also prove useful for many other cartographic network comparisons, as the method is applicable to a variety of fields and provides a type of information that cannot be obtained via the use of linear statistics alone.

In the same way, the proposed method of displacement vector statistical analysis provides a quantitative estimation of network accuracy, if the latter is compared with a high-quality reference source. This method generates values that can then be used as metadata regarding hydrological spatial quality, information that is nowadays not widely available.

In any case, in terms of the presented example, future investigations should focus on the detected sensitive zones, including a detailed DEM-based study of regional geology and elevation.

Acknowledgment

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