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Knickpoint finder: A software tool that improves neotectonic analysis

G.L. Queiroz *, E. Salamuni [1], E.R. Nascimento

The Federal University of Paraná, Neotectonics Research Group, Curitiba, PR, Brazil

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ABSTRACT

This work presents a new software tool for morphometric analysis of drainage networks based on the methods of Hack (1973) and Etchebehere et al. (2004). This tool is applicable to studies of morphotectonics and neotectonics. The software used a digital elevation model (DEM) to identify the relief breakpoints along drainage profiles (knickpoints). The program was coded in Python for use on the ArcGIS platform and is called *Knickpoint Finder*. A study area was selected to test and evaluate the software's ability to analyze and identify neotectonic morphostructures based on the morphology of the terrain. For an assessment of its validity, we chose an area of the James River basin, which covers most of the Piedmont area of Virginia (USA), which is an area of constant intraplate seismicity and non-orogenic active tectonics and exhibits a relatively homogeneous geodesic surface currently being altered by the seismogenic features of the region. After using the tool in the chosen area, we found that the knickpoint locations are associated with the geologic structures, epicenters of recent earthquakes, and drainages with rectilinear anomalies. The regional analysis demanded the use of a spatial representation of the data after processing using *Knickpoint Finder*. The results were satisfactory in terms of the correlation of dense areas of knickpoints with active lineaments and the rapidity of the identification of deformed areas. Therefore, this software tool may be considered useful in neotectonic analyses of large areas and may be applied to any area where there is DEM coverage.

1. Introduction

Morphometric analysis of drainage networks in studies with a neotectonic emphasis has been used by several authors (e.g., Volkov et al., 1967; Hack, 1973; Burnett and Schumm, 1983; Seeber and Gornitz, 1983; McKeown et al., 1988; Marple and Talwani, 1993; Merrits and Hesterberg, 1994; Schumm and Spitz, 1996; Rodriguez and Suguio, 1992; Etchebehere et al., 2004 and Martinez et al., 2011).

Current knowledge of geomorphic systems and drainage network behavior indicates that natural drainage channels are sensitive to changes in geodesic reference levels, particularly when such changes occur quickly, and are the first element of the landscape to respond to deformations imposed by active tectonic systems. Morphotectonic elements, namely morphologic structures created by tectonic processes, are features derived from crustal deformation at the geodesic level, and in the case of rivers, disparities in relief are one of the most notable features of the crustal surface. These relief breaks are important drainage gradient anomalies that, together with other anomalies, for example, the watersheds of rivers, presence of bends or abrupt deviations, the subsidence of restricted portions of the watershed basin or the formation of structural patterns, indicate that the major traits of the primitive landscape of a region are controlled by its tectonic structure, primarily by the distortion of primitive flat surfaces. This situation is amply demonstrated in the Mississippi River basin.

Hack (1973) proposed the use of the SL index (ratio of slope to length), which was applied in studies with a neotectonic focus in diverse areas of the rivers in the Arkansas Valley, Boston Mountains and Salem Plateau and was applied by Seeber and Gornitz (1983) in the Himalayas and in the USA by McKeown et al. (1988) in Arkansas and Missouri, by Merrits and Hesterberg (1994) in areas crossed by the San Andreas fault, and by Marple and Talwani (1993) in South Carolina. In Brazil, this index was used in the Peixe (Fish) River basin by Etchebehere et al. (2004) and in the Pirapó River basin by Martinez et al. (2011).

Although these studies constituted effective geomorphic analyses, the complexity of manual analysis makes the use of the SL index difficult in large areas with a relatively high level of detail. For this reason, a software program called *Knickpoint Finder* was developed, programmed in the Python language. This program was developed with the goal of accelerating the process of geomorphic and morphometric analysis, using digital topographic data in a matrix format, and allows a greater degree of accuracy and detail in studies of regional neotectonics.

* Corresponding author.
E-mail addresses: gustavo.queiroz@ufpr.br (G.L. Queiroz), salamuni@ufpr.br (E. Salamuni), deni_ern@ufpr.br (E.R. Nascimento).
[1] Tel: +55 41 3361 3691.

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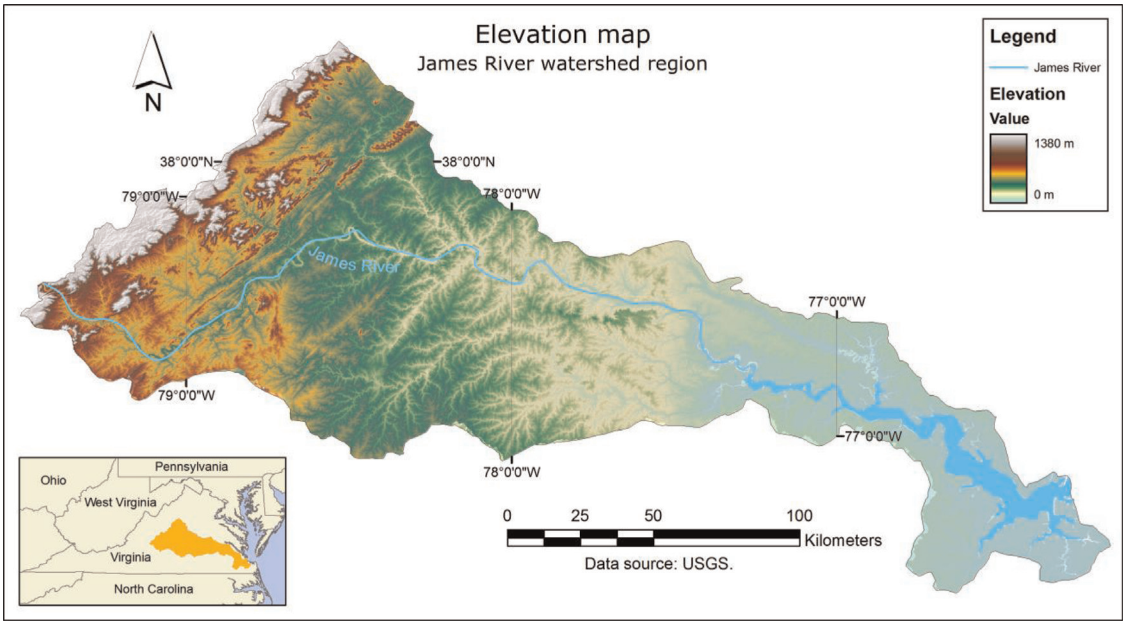

Fig. 1. Location and hypsometric map of the study area.
Source: National Elevation Dataset (NED).

The primary objective of this paper is to describe the development of the software. The application of *Knick Point Finder* in the Piedmont Virginia (USA) seismogenic area (Fig. 1) is a case study, with the aim to evaluate the ability of the software to identify individual knickpoints, which are structures that relate to current seismogenic processes, resulted from the active tectonics in central Virginia. The seismic events in this area have been studied by several authors, such as Bollinger and Hopper (1971), Bollinger and Sibol (1985), Bollinger and Costain (1988), Çoruh et al. (1988), Obermeier and McNulty (1998), Zoback (1992), Wheeler (2006), Hough (2012) and Wolin et al. (2012). Most of these studies used seismic data that revealed a need to identify morphotectonic elements that assist in the interpretation of recent crustal movements. The software was designed to characterize these relief breaks (knickpoints) and facilitate their identification.

2. Methods and theoretical bases

The theoretical approach to the development of the software was based on a geomorphometric parameter proposed by Hack (1973), the stream length-gradient (SL) index. This parameter pertains to the longitudinal profiles of rivers or drainage stretches and has been called the *Hack index* in the literature. This parameter is calculated by multiplying the slope gradient of the stretch of river by the distance between this stretch and the source of the river, which then determines the knickpoints of interest in morphotectonic, morphostructural and neotectonic studies. Keller and Pinter (1996) found that the SL index in the San Gabriel Mountains, southern California, displays abnormally high values, which are linked to high rates of uplift.

Etchebehere et al. (2004) proposed a derivative of the Hack Index, the relative slope-extension (RDE) index, which gives an indication of the current energy in a particular drainage stretch and varies with the slope of its surface and the discharge of water at the end of the stretch. According to these authors, the RDE index for a stretch (RDEs) may be calculated using the relationship (Fig. 2)

$$\mathrm{RDEs}=(\Delta H/\Delta L).\ L \qquad (1)$$

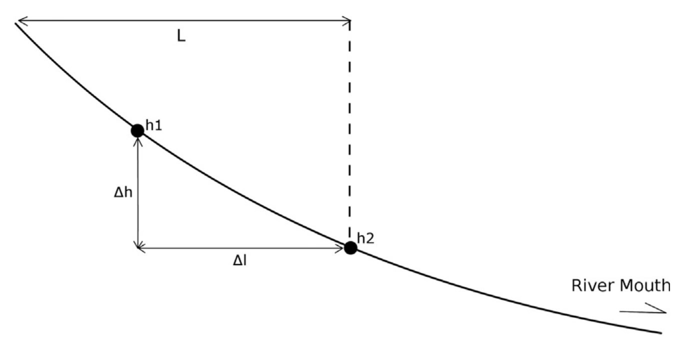

Fig. 2. Longitudinal profile of a river showing how the RDEs index is measured for a stretch with a length of Δl, an elevation difference of Δh, and a distance L from the source of the river to the point measured ($h2$).

where ΔH=the elevation difference between the two extremities of a stretch along a river; ΔL=the length of the stretch being studied; and L=the distance between the lower end of this stretch and the source of the river.

The total RDE index (RDEt), which in turn refers to the total length of a river, takes into account the total slope between the source and mouth and the natural logarithm of its entire length (Seeber and Gornitz, 1983; Etchebehere et al., 2006). This index is calculated using the relationship

$$\mathrm{RDEt}=(\Delta H/\Delta L).\ln(L) \qquad (2)$$

The final goal, after measuring the RDES indexes of various stretches and the RDET indexes of their respective drainages, is to compare them to determine which stretches have anomalous slopes. According to , when the value of the ratio RDEs/RDEt ≥ 2, the drainage stretch under analysis can be considered anomalous. A value of RDEs/RDEt between 2 and 10 represents an anomaly of the 2nd order, whereas a value of RDEs/RDEt greater than 10 is an anomaly of the 1st order.

3. Software development

The RDE index was used to create an algorithm that identifies knickpoints, which in turn was used as the basis for developing a

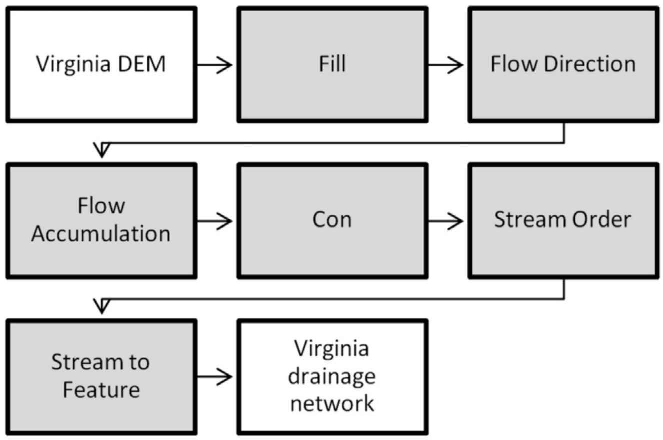

Fig. 3. Flowchart of the procedure sequence required to generate the drainage network of a selected area from a digital elevation model.

software tool to operate on the ArcGIS platform. This tool was programmed using the Python programming language, primarily using Python's integrated development environment (IDLE). The algorithm works in a manner very similar to that described by Etchebehere et al. (2004), which has the advantage of using raster images that contain elevation data, for example an shuttle radar topography mission (SRTM) mission. The three-dimensional drainage system is extracted from these images for analysis, and the RDEs and RDEt are calculated, which then indicate the knickpoints.

The first work step in the use of the tool is to generate a drainage network in the image area for later analysis. This step is done in accordance with a common procedure, using tools included in the GIS programs that calculate the flow direction based on the topography. In the case of ArcGIS, the sequence used may be seen in the flowchart in Fig. 3.

To calculate the RDE indexes, one must have the complete longitudinal profiles of all of the rivers being studied. However, each feature in the drainage network resulting from the *Stream to Feature* tool represents only one drainage stretch. Therefore, one must unite all of the stretches in each of the drainage lines so that they may be recognized as a single feature extending from the source to the mouth. For this process, as there is no specific tool for this purpose in ArcGIS, a unique algorithm called *River Merge* was created. This algorithm is very effective but sometimes works slowly when the number of features is very great.

3.1. River merge

Each drainage stretch resulting from the tool *Stream to Feature* is a feature that has a starting node (*from_node*) and an arrival node (*to_node*), plus a length given in meters. The objective of *River Merge* is to unite the features such that the arrival node of one stretch coincides with the starting node of the next and, if there are several features with coincident arrival nodes, the union will be made to the stretch with the longest length. An important aspect of this procedure is that it first joins the features closer to the headwaters of the rivers, and stretches of higher order are the last to be united, as the program only allows the correct calculation of the lengths of stretches that do not have any upstream segment with a pending union.

River Merge contains a primary loop that continues to run until all the features are ready for the final union (Fig. 4). Simultaneously, a second loop runs analyzes all of the features one by one, looking for additional features with nodes coinciding with previous ones. If there is another feature with an arrival node that coincides with the starting node of the feature being analyzed in the second loop (feature under consideration), this feature is put

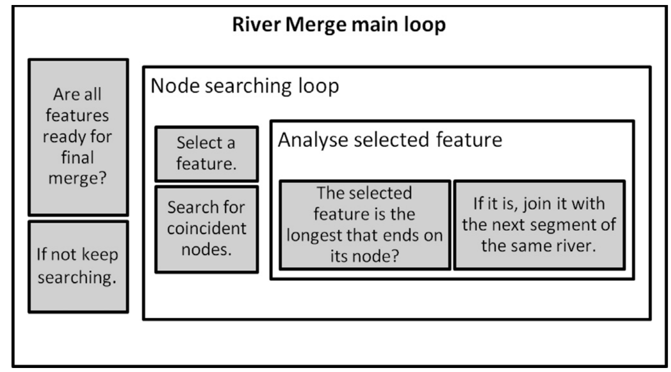

Fig. 4. Diagram of the loops in the subprogram *River Merge*.

on hold because its length cannot yet be calculated correctly (as explained earlier). If the feature is not put on hold, the program searches for other features that have arrival nodes coincident with the arrival node of the feature under consideration (convergent drainage stretches), and if these others are not pending and none of them has a length greater than the feature under consideration, the program looks for the feature that has a starting node coincident with the starting node of the feature under consideration (continuation of the drainage stretch in focus) and links this with the *feature* under consideration in the same “union group”.

When all of the featuresbecome part of union groups, the routine exits the primary loop of *River Merge* and starts a tool common in GIS programs, which in the case of ArcGIS is the tool is *Dissolve*, found in your ArcToolbox. This tool brings together all of the features within each union group, resulting in a virtual drainage network in which each feature represents a river from its source to its mouth.

3.2. Measurement of the RDE index

After the uniting of the drainage stretches, a tool transforms the 2D lines of the drainage network into 3D lines by adding the elevation values (Z), obtained from the image containing the elevation data. In the case of ArcGIS, the tool *Interpolate Shape* is used. After this step, the nodes of each line have the values of elevation (Z) and coordinates X and Y, as each line will have a node for each pixel of the raster image.

Finally, the RDE indexes are calculated. There is a loop for this process that analyzes the longitudinal profiles of all of the rivers one by one (Fig. 5). First the RDEt of the river in question is calculated using the relationship RDEt=drop between source and mouth/natural logarithm (Eq. (2)) relative to the total length of the river. A nested loop then analyzes all of the river nodes, measuring the drop since the last RDEs measurement, and when this value exceeds the elevation equidistance provided by the user, the program calculates new RDEs. If the RDEs isat least ten times greater than the RDEt, the program designates a first-order knickpoint; if the RDEs is two to ten times greater than the RDEt, the program designates a second-order knickpoint.

Each point created, in addition to the X and Y coordinates and the degree of abnormality, also stores the RDEs, RDEt and RDEs/RDEt values of the stretch. The lower the value of the elevation equidistance provided by the user, the greater the amount of data in the results. Therefore, the final result of *Knickpoint Finder* is a network of points of variable density, depending on the value chosen for the work scale.

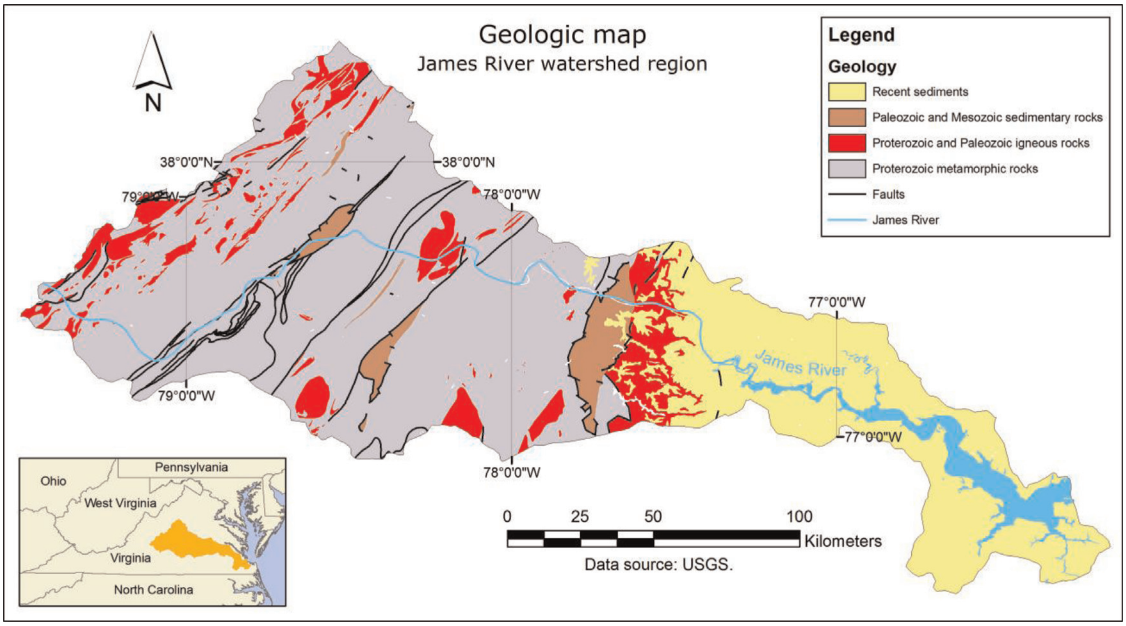

Fig. 5. Simplified geological map of the study area.
Source: USGS.

4. Case study: *Knickpoint finder* application

4.1. Geological and geomorphological context

The geology of the study area (Fig. 5) consists of geological domains that correspond well with morphologic domains. The area through which the middle reach of the James River flows is dominated by Proterozoic basement schists and gneisses, which are intruded by igneous batholiths (granitic and/or granodioritic) whose ages are intermediate between Proterozoic and Paleozoic. Between the middle and lower reaches of the river, there are units of Paleozoic sedimentary rocks, deposited in grabens and half-grabens, and granitic massifs. The lower reach is dominated by recent alluvial-colluvial sediments. The Proterozoic and Paleozoic rocks are cut by NE-trending reverse and strike-slip faults that constitute tectonic contacts between allochthonous blocks.

According to Bollinger and Sibol (1985), the central Virginia seismic zone is an approximately circular region of constant seismicity with a diameter of 120–150 km in Piedmont Virginia. Bollinger and Costain (1988) have suggested a correlation between the hypocenters of earthquakes and subsurface structures interpreted from seismic reflection data in the area. The authors also found that the seismic activity in Piedmont Virginia may be related to the reactivation of thrusts and/or other faults superimposed on an antiformal structure and that the eastern most, deepest of the hypocenters are most likely related to a wide zone of Mesozoic dikes. The most damaging earthquake in this seismic zone had an estimated magnitude of 5.9 and occurred on May 31, 1897, in Giles County, Virginia (Bollinger and Hopper 1971). The most recent major earthquake was the M_w=5.8 event in Mineral, Virginia, which occurred on August 23, 2011 (Hough, 2012). discussed the apparent contradiction of the occurrence of large earthquakes, such as the 2011 event in Virginia, along a passive margin or in similar geologic areas where plate tectonic theory does not predict intense seismic activity.

Obermeier and McNulty (1998) studied well preserved liquefaction features in recent sediments in the seismic area of Virginia. These features consist of small sand dikes and/or sand volcanoes with an estimated age of a few hundred years and are interpreted as geological features resulting from recent earthquakes. These authors describe highly weathered sand dikes, which are interpreted as being relatively old, and conclude that the central Virginia seismic zone has not experienced an earthquake with a magnitude greater than 7 for at least the last 2000 years.

To test the ability of the software to identify relief anomalies in a specific drainage and characterize these features as evidence of neotectonic activity, the James River watershed, located in east-central Virginia, was selected as the study area. This region is an active seismogenic area on the east coast of the United States.

This study area was chosen because of its active fault systems, which control the neotectonics and seismicity in east-central Virginia, and the fact that the geomorphic domains are well defined. These characteristics allowed us to evaluate the ability of the software to identify morphologic structures resulting from deformation of the geodesic surface. The use of *Knickpoint Finder* is suitable to the analysis of drainage channel characteristics, and thus the study area focused on the regional watersheds. Specifically, the study area consisted of the middle and lower watershed basins of the James River, in the east-central part of the state of Virginia, whose limits are based on mapping of the limits of the hydrologic units on a scale of 1:2,000,000 by the U.S. Geological Survey (available at: http://nationalatlas.gov/).

4.2. Data used and results

After the development of the software and its application in the study area, the knickpoint data were analyzed together with geological, geomorphological and seismic data. The elevation data used to analyze the area was obtained from the National Elevation Dataset (NED), available online from the United States Geological Survey (USGS). The local geology data are from the USGS cartographic documents and represent a regional synthesis. The epicenter data was obtained from the same source.

It was therefore possible to identify significant correlations between the physical characteristics of the land, produced by tectonic deformation of the landscape, and the presence of certain relief anomalies.

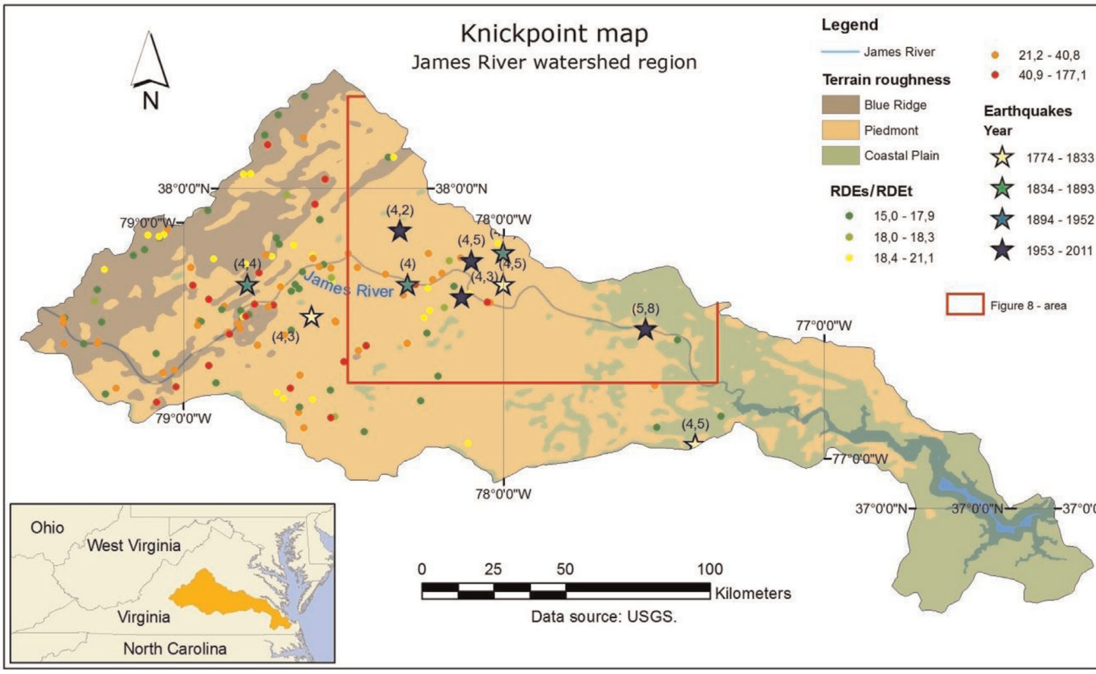

Fig. 6. Map of land roughness units showing the primary knickpoints identified in the study area after filtering using the RDEs/RDEt ratio. The highlighted portion of the map represents the smaller area shown in Fig. 8.

The morphological subdivision of the study area is on a regional scale in Fig. 6, as well as the division of the area according to the roughness of the terrain: the central plateau area, the mountain region positioned in the west and the coastal plain positioned in the east. By applying the *Knick Point Finder* in the three regions initially considered, about 25,000 points (knickpoints) were obtained. As the number of knickpoints recorded was very high, the data used to identify the most important concentrations were processed before analysis using two geostatistical methods: (a) filtering using the RDEs and the proportion RDEs/RDEt so that only the largest local anomalies are presented, and (b) analysis of the density of points using RDEs and the proportion RDEs/RDEt, which allowed the generation of a raster image displaying the RDE density to assist in the visual recognition of anomalies, and (C) analyze each point generated to identify natural knickpoints (falls and rapids) and artificial knickpoints (bridges, rapids) in the Google Earth software. There are many differences between a display of the processed data using only the RDEs and a display using the proportion RDEs/RDEt. In the first case, the data processing indicates the highest values of local slope gradients, which

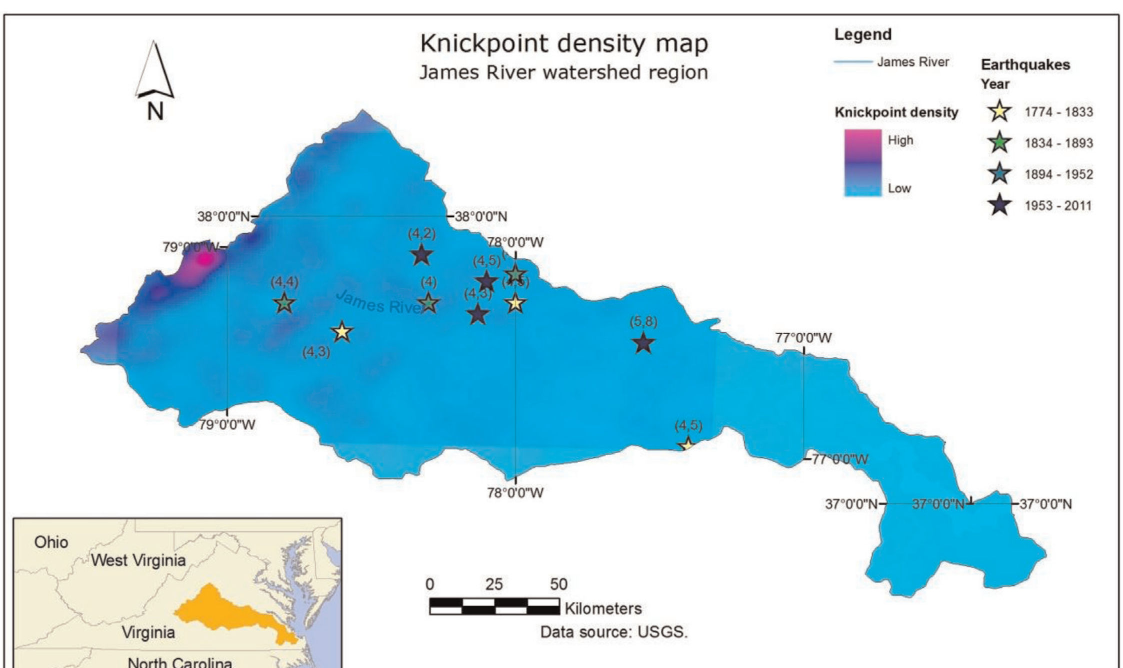

Fig. 7. Knickpoint density map after filtering using the ratio RDEs/RDEt and locations of major earthquake epicenters. Due to the age of the MDE data, earthquakes after 1950 were not taken into consideration.

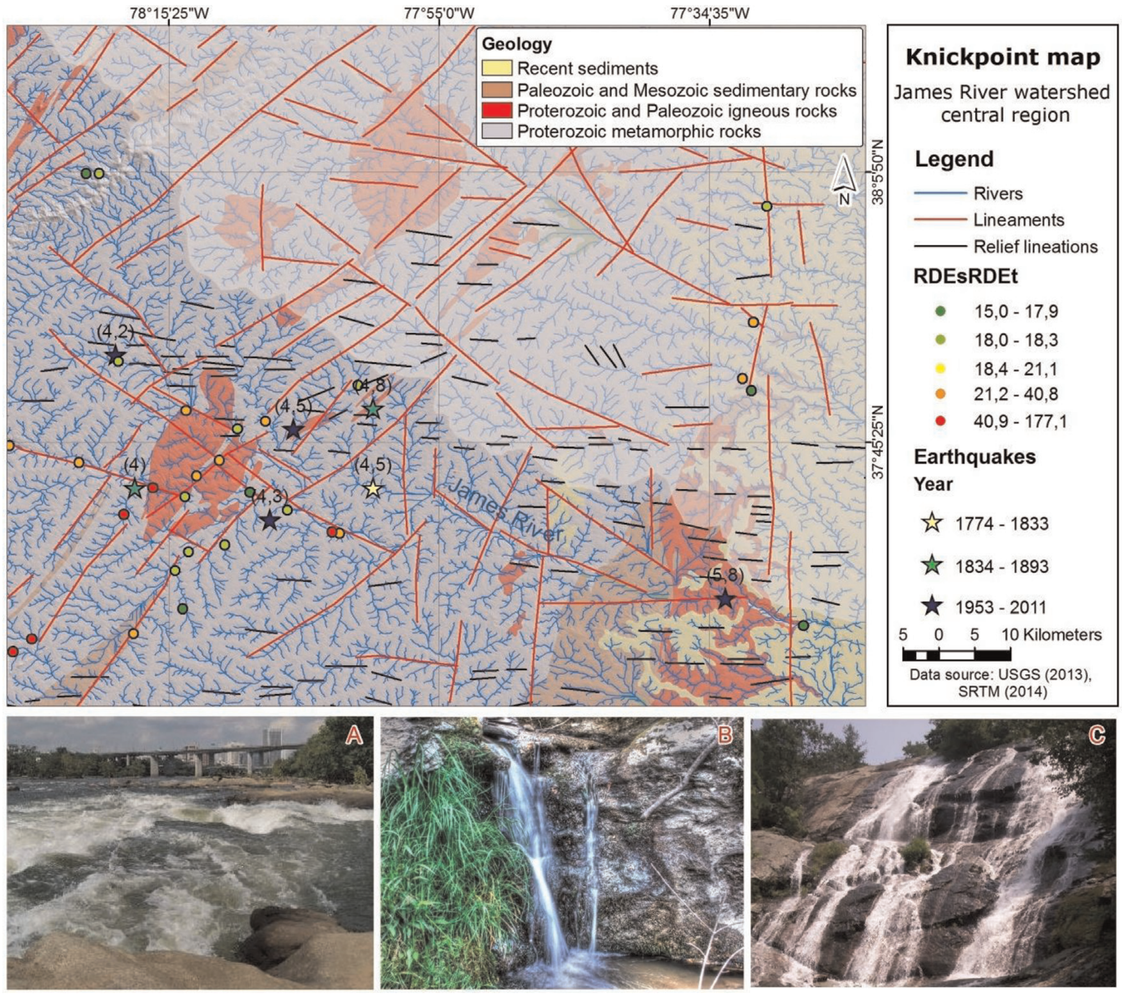

Fig. 8. Example of Knickpoints identified by *Knickpoint Finder*: (A) Rapids (37°31′′49.10′′N, 77°27′′17.31′′W-photo by Chris Sanfino), (B) Small Fall (Lat: 37°26′′24.00′′N; 78°28′19.20′′W photo by Brock S.), and (C) Big Fall (37°50′′52.48′′N, 79° 4′′39.33′′W photo by Andy Keller).
Source: Google Earth.

are typically the largest waterfalls and rapids. In contrast, data processing using the ratio of RDEs to RDEt results in identifications of areas with the greatest local anomalies, which are not necessarily the steepest slopes but can be of major interest in neotectonic studies, as they will constitute anomalies in areas of gentler slopes.

To build a raster image that represents a knickpoint density map (Fig. 7), a surface density was calculated from the knickpoints confined to an area around individual cells. This surface, in turn, was multiplied by another surface interpolated from the points through the use of the inverse distance weighting (IDW) calculation to increase the representativeness of the highest RDE values.

In a case study of the area of east-central Virginia, which coincides with the north central portion of the plateau region (Fig. 6), only a small portion of the available seismic data were considered relevant to the present study because the available NED (USGS) images are mostly older than the recent major earthquakes that occurred in the area, such as the $M_w = 5.8$ event in Mineral. The area is dissected by drainage with rectangular and sub-parallel patterns as well as minor portions of trellis or sub-dendritic pattern (see Fig. 8). The photo interpretation of satellite images showed that significant drainage anomalies are present, such as elbows and captures, probably controlled by recent or active tectonics. Such anomalous patterns increase the possibility of the existence of a knickpoint linked to morphotectonic processes.

The density map of points obtained from the RDEs/RDEt filtering showed that the densest area of knickpoints is located in the Blue Ridge Mountains. This dense area is continuous and trends NE (Fig. 7). In the region of Piedmont Virginia, however, the densest areas of knickpoints are generally discontinuous and correspond to stretches of the James River or display linear NE trends corresponding to the faults and Paleoproterozoic geologic contacts or WNW trends perpendicular to the geologic structures. It is noteworthy that, with the exception of the mountainous region, there are fewer knickpoints in areas with no earthquake epicenters older than 1953.

Relatively high levels of seismicity have been recorded in the northern part of the Piedmont Province (Fig. 6), particularly in the vicinity of the boundary between this province and the Blue Ridge Province, which are parts of the Appalachian Mountains. The boundaries between these two provinces and other important segments of the Piedmont Province consist of major thrust faults of low to moderate dip angles to the SE. The geologic structures control the geomorphologic evolution of the area, which is dominated by indentation scarps initiated by relatively deep dissections this is an obvious local morphostructural feature.

On the other hand, the seismicity in the region indicates that the morphologic structures are not merely inherited from old fracture planes, produced by the old structural framework, but behave as though they are attributable to the recent morphotectonic processes. The NE–SW elongated ridges in the Blue Ridge Province are composed of igneous and sedimentary rocks, and the current deformation in the Piedmont Province and secondarily in the Coastal Plain are the primary factor controlling the locations of the knickpoints in the study area.

Correlating the morphotectonic data with the statistical density of the knickpoints makes it possible to verify that the epicenters of earthquakes (Fig. 7) also correlate well with these areas. It is likely that recent earthquakes in Piedmont Virginia have reactivated NE–SE trending Precambrian structures and smaller NW–SE trending structures. The structures coincide with particularly straight stretches of the James River and higher densities of knickpoints. This correspondence may explain the amount and anomalous density of knickpoints in a relatively low-gradient area, where one would not expect such features (Fig. 7).

The morphostructural correlation with epicenters of earthquakes is shown in Fig. 8 (map). The framework of structural alignments was obtained by photo interpretation and allowed the determination of probable seismic faults, mainly directed to N30–45E and N45–60W and relief lineations aligned in E–W direction. The N–S fractures are scattered in the core area and more frequently in the eastern portion, where normal faults determine the contact between recent sediments in the coastal plain and the oldest sediments overlying the basement in Piedmont.

The traces of normal faults frequently coincide with small knickpoints in the segments of drainage plans which are controlled by local fractures (Fig. 8A–C). On the other hand, in the west of the area it is clear that the knickpoints are positioned on probable seismic faults with undetermined kinematics.

The analysis and correlation of the data confirm that the majority of knickpoints in Piedmont Virginia are controlled by the neotectonic regime. However, any analysis of landscape evolution should not dispense with other morphostructural analysis methods, such as analysis of other relief anomalies and the symmetry of watersheds.

The *Knickpoint Finder* software is capable of detecting relief breakpoints or anomalies in the topographic drainage gaps. Thus, due to the automation of the search operation it is possible that human artifacts constructed along portions of rivers such as dams, are classified as pseudo knickpoints. This undesirable situation occurs mainly when calculating RDEs/RDEt runs on larger scales approaching the object.

Therefore, it is necessary to have a knickpoint filtering process, which can be accomplished by careful observation of digital satellite images, accompanied by field work, where there is a need for it. This will allow sufficient approach to the studied object in order to determine the nature of the knickpoint. Field research will also provide the certainty that the knickpoints are found attached to morphotectonic processes, confirming the photo interpretation previously performed.

In this study, a careful observation of knickpoints, point by point, through the use of the images available on Google Earth® was performed. It was possible to interpret that the vast majority of reported knickpoints are connected to morphostructures connected, in turn, to the local tectonic processes.

The local geology and neotectonic regime lead us to conclude that the knickpoints found in the study area originate from recent seismic activity. In relation to this type of relief anomaly, Felis et al. (2003) and Hancock and Harbor (2003) studied migrating knickpoints across the entire profile of the James River and its tributaries and estimated rapid rates of incision of the river in Piedmont Virginia, which suggests a morphotectonic imbalance. Carlson (1988) studied river profiles in five tributaries of the South River, in Virginia, and migration of headward knickpoints associated with the formation of limestone dams that slow the migration of the headward erosion.

4.3. Problems of scale: a discussion

The identification of knickpoints should consider the topographic base scale used for the automatic generation of the drainage network. For example, a topographic base 1:100,000 used for generating streams with scale equal to or less than 1:100,000.

From the hydrographic base automatically generated, the software considers the altimetric range, which was originally defined by the user to determine drainage segments along each river-or stretch of river-profile. Thus, a segment with an altimetric gap of 5 m can be several meters long in a waterfall, tens of meters in rapids and even kilometers in the lower course of the same river. This definition must be grounded on experience and knowledge that user has of the area. For example, it is known that the area used as a case study would not allow for altimetrics with intervals of 50 m in an analysis of scale 1:100,000, as virtually no knickpoint would be identified. On the other hand, the choice of very small values for altimetric intervals would cause the software to generate a huge number of knickpoints, making it difficult to perform morphometric interpretation.

In order to set an elevation range that allows the software to determine the amount of knickpoints, the study must take into account the topographic base and the characteristics of regional relief because a region of floodplain without significant tectonic deformation, for example, has generally dispersed and less pronounced knickpoints than a similar region with active tectonics. In this particular case, a subtle or very mild slope in a floodplain can be identified through a defined knickpoint where there were determined altimetric intervals of less than 1 m. In the present case study where the relief is quite diversified, it is particularly unusual for knickpoints to occur in a flat region, considering that the altimetric range of 10 m was applied in the analysis used to determine consistent knickpoints from the east plain up to the mountainous area in the western portions.

The scale of analysis is essential for determining a set of acceptable knickpoints for effective morphometric interpretation. The gain from the implementation of the *Knickpoint Finder* software is the facility with which one can set or reset the scale by changing the quantitative parameter of the altimetric range. The importance of automatic routine is the subsequent attempt to obtain the best result with respect to morphometric knickpoints without the mandatory need to restart all the work, as is usual in manual analysis.

Furthermore, the automatic analysis of cartographic software not only finds points where there are relief breakpoints, but also indicates primary targets for the field visit, which will attest to the true nature of the knickpoint, be it natural or human-generated artifacts (see Fig. 8).

5. Conclusions

The *Knickpoint Finder* software was designed to run together with other GIS software; ArcGIS proved to be efficient in this regard. A fundamental advantage of the automatic identification of knickpoints is the rapid analysis of such anomalies in the fluvial profile and the identification of these morphometric elements in the topographic data, which may be of any nature or scale, as long as the data are in a raster format.

Due to the gain in data processing speed, the difficulty of manual analysis, and the ability to correlate the knickpoints with neotectonic features, the software has shown itself to be an effective and efficient tool in geoscience, particularly for morphometric and morphostructural analysis of regional drainage networks.

The identification of knickpoints should consider the altimetric range in the drainage segments interval, which in turn depends on the topographic base scale, used for the automatic generation of the drainage system. The *Knickpoint Finder* software allows the altimetric range to be determined from user-defined parameters. These parameters should be based on experience and knowledge that the user has of the analyzed area.

After processing the data using *Knickpoint Finder* and using spatial data representation techniques, it was possible to correlate the knickpoints in the study area with the regional geologic structures, linear drainage anomalies and recent earthquakes recorded in Piedmont Virginia. In this region, the knickpoints define part of the morphostructures especially those representing local relief breakpoints.

The knickpoints should not be considered the only morphotectonic analysis elements but are one of several important elements in modeling the neotectonic features of an area of interest, particularly those that are seismogenic.

The software and its source code are open to the community and available as a digital file on the website of the Federal University of Paraná Neotectonics Research Group (http://www.neotectonica.ufpr.br).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.cageo.2014.11.004.

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