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Pre-earthquake Anomaly Detection and Assessment through Lineament Changes Observation Using Multitemporal Landsat 8-OLI Imageries: Case of Gorkha and Imphal

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Abstract

Pre-earthquake anomaly detection and assessment was performed in the present study through lineament changes observation by using multitemporal Landsat 8 OLI satellite imageries. These data found convincing results to identify relevant anomalous variations prior to the two recent earthquakes, that is, Gorkha of Nepal 7.8 M_w (major) (25 April 2015) and Imphal of Manipur (eastern India) 6.7 M_w (strong) (4 January 2016) compared with normal behavior in the absence of earthquake. Epicenter-based single tile of five multitemporal Landsat 8 OLI data was considered for each case, where one image was considered to show the normal behavior of lineament (in the absence of earthquake) and three for anomalous behavior prior to earthquake (in the presence of earthquake), and the rest one used to represent post-earthquake behavior (in the absence of earthquake), respectively. The derived lineament data were used further in different forms to observe pre-earthquake anomalies. The research results witnessed major changes of lineaments and observed anomalies prior to the two impending earthquakes while it was observed normal behavior in the absence of earthquake event. The results obtained using the automated and geo-integrated techniques help us to detect earthquake in advance prior to its strike could be used an alternative method in worldwide for future earthquake monitoring.

Keywords: pre-earthquake anomaly, lineament change, multitemporal, Landsat 8 OLI, Gorkha, Imphal

1. Introduction

In the modern geoscientific time frame, remote-sensing and GIS techniques have been tremendously used for obtaining reliable information from satellite imageries at macro- to microscale investigations. Studies of linear geologic features (lineaments) from macro- to microlevel have been increasing rapidly. Lineament extraction from satellite imagery either by visual or automatic interpretation has been a long interest of geologists, where the character and extent of these features have been realized and lineament analysis of remotely sensed data using automatic extraction, is a valuable source of information for studying the structural settings of an area. The term “Lineament” has been widely used in the field of geology, and literally, it expresses by different scientists through their research work in different ways. The term lineament was first described as significant line of landscape within the basement rocks [1]. The lineament defines as linear features in a landscape identified on satellite images and aerial photographs, most likely have a geological origin. Generally, lineaments are underlying by structural zone, fractured zone, a series of fault or fold aligned hills zone of localized weathering and zone of increased permeability, porosity, seismicity, landslide formation [2], active erosion, and karst development [3].

Lineament extraction and analysis have been studied by different distinguished scientists [4–11]. Besides these, lineament analysis has been used extensively for geologic interpretation, particularly from the 1930s with the advent of photogeology [12]; because satellite data provide quick and useful baseline information on the parameters controlling the occurrence and movement of groundwater like geology, lithology/structural, geomorphology, soils, land use/land cover, and lineaments. With the advancement of remote sensing techniques, identifications of lineaments for earthquake have become a rapid and cost-effective procedure. One of the main features of geological interpretation of satellite imagery has been the recognition of lineaments varying in length from a few kilometers to hundreds of kilometers [13]. The lineament is a mappable linear or curvilinear feature of a surface whose parts align in a straight or slightly curving relationship [14], which differs from the pattern of adjacent features and reflects some subsurface phenomena [15].

Moreover, lineament mapping and analyses have been gaining popularity with the increasing availability of satellite images [16]. Since satellite images are obtained from varying wavelength intervals of the electromagnetic spectrum, they are considered to be a better tool to discriminate the lineaments and to produce better information rather than conventional aerial photographs. Recently, two earthquakes were badly hit in the geologically complex regions, that is, Gorkha region of Nepal ($7.8 M_w$) on 25 April 2015 and Imphal region of Manipur, Eastern India ($6.7 M_w$) on 4 January 2016, respectively. By observing the severity of the two earthquakes, these two study areas have been considered for our present research.

The main objective of this study is to extract lineament features through automatic approaches by using Landsat 8 Satellite imageries, which further used to calculate lineament length and directional change measurement through rose diagram and to know the pre-earthquake anomaly through lineament changes observation in the presence and the absence of an earthquake. Therefore, vector overlay technique was performed on lineament temporal data considered for the two impending earthquakes (major and strong). The earthquake occurrence signals were noticed in individual case by interpreting five satellite scenes of Landsat 8 OLI sensors.

2. Materials and methods

2.1. Study area

The study area for each case covers 370 km² in size of each single satellite scene. The first study case is Nepal, which lies toward the southern limit of the diffuse collisional boundary where the Indian plates under thrusts the Eurasian plate, occupying the central sector of the Himalayan arc [17]. In Gorkha of Nepal case, the northern part of the satellite scene is covered by parts of China. Gorkha earthquake in Nepal (7.8 M_w) is a shallow earthquake occurred on 25 April 2015 (epicenter position: 28.147° N and 84.708° E) at a depth of 15 km created massive destruction. This earthquake was caused by a sudden thrust or release of built up stress along the major fault line [18].

On the other hand, the second case study is Imphal earthquake (6.7 M_w), which occurred in northeast regions of India in the state of Manipur. This earthquake was struck on 4 January 2016 at a depth of approximate 55.0 km (measured by United States Geological Survey, USGS) and about 15 km west of the fault coinciding with the edge of the Imphal valley. The epicenter (position: 24.804° N and 93.651° E) was in Manipur's Tamenglong district, and bordering area with Myanmar is in the right section of that corresponding image. According to Gahalaut V.K., and Kundu B., this earthquake was occurred on steep plane due to typical intraslab type movement within Indian plate, which predominantly moves toward north, and developed crack which was N-S oriented along with oblique motion (1–2 cm), and it was observed during field visit [19]. The regional plate boundary in eastern India-the Indo-Burmese Arc is oriented approximately in south-southwest-north-northeast direction (see [20]). The location of study areas is shown in **Figure 1**.

Figure 1. Location of study area.

2.2. Data

Datasets utilized for the present study included Landsat 8 Operational Land Imager Images. The details of data sources of Landsat 8 OLI imageries for both regions are shown in **Figure 2**: 2A and 2B, respectively, which were acquired from USGS Landsat archives (OLI, <http://earth-explorer.usgs.gov/>) path: 142, row: 40 for case 1, considering snow and partial cloud coverages and path: 135, row: 35 for case 2, considering partial cloud coverage.

The data product considered for the present research has a 30-m spatial resolution based on different days' interval prior to earthquake occurrence, the absence of earthquake and after the earthquake event. Detailed descriptions regarding the datasets used for this research are shown in **Table 1**.

These satellite images are a digital representation of the Earth's surface for the identification of lineament and its corresponding directional change that may represent the surface expression of geological structures [21, 22]. The digital image processing, thematic mapping of lineament, overlay operation and directions of lineament were obtained using the ENVI 5.3, PCI Geomatica 9.1, ArcGIS 10.5, and Rock Works 16 software, respectively. To investigate the normal behavior of lineament in the absence of earthquake, it has been found suitable imagery of 31 January 2015 only for case 1 (85 days before earthquake strike). From 31 January 2015 to 20 March 2015, all the available imageries suffer with extensive cloud; thus, they were neglected. Meanwhile, in case 2, from 19 March to 30 November 2015, three earthquakes (low category: 4.1–4.3 M_w) were struck in the study area, and most of the available imageries also suffer with cloud; thus, those

Figure 2. The details of data sources of Landsat 8 OLI imageries for two study areas: (A) Nepal and part of China shown in different time series Landsat 8 OLI data (FLAASH atmospheric corrected image): (a) 31 January 2015 (absence of EQ); (b) 20 March 2015 (presence of EQ); (c) 5 April 2015 (presence of EQ); (d) 21 April 2015 (presence of EQ); and (e) 7 May 2015 (post EQ); (B) Manipur and part of Myanmar shown in different time series Landsat 8 OLI data (FLAASH atmospheric corrected image): (a) 19 March 2015 (absence of EQ); (b) 30 November 2015 (presence of EQ); (c) 16 December 2015 (presence of EQ); (d) 1 January 2016 (presence of EQ), and (e) 17 January 2016 (post EQ).

Satellite sensors	Date of image acquisition	Days interval	Path/row	Resolution (m)
Gorkha of Nepal (case 1): category: major				
Landsat 8 OLI	31 January 2015 (absence of EQ)	85 days (before)	142/40	30
Landsat 8 OLI	20 March 2015 (presence of EQ)	36 days (before)	142/40	30
Landsat 8 OLI	5 April 2015 (presence of EQ)	20 days (before)	142/40	30
Landsat 8 OLI	21 April 2015 (presence of EQ)	4 days (before)	142/40	30
Landsat 8 OLI	7 May 2015 (post-EQ)	12 days (after)	142/40	30
Imphal of Manipur (case-2): category: strong				
Landsat 8 OLI	19 March 2015 (absence of EQ)	292 days (before)	135/43	30
Landsat 8 OLI	30 Nov 2015 (presence of EQ)	36 days (before)	135/43	30
Landsat 8 OLI	16 Dec 2015 (presence of EQ)	20 days (before)	135/43	30
Landsat 8 OLI	1 Jan 2016 (presence of EQ)	4 days (before)	135/43	30
Landsat 8 OLI	17 Jan 2016 (post-EQ)	13 days (after)	135/43	30

Brackets terminology in the 1st column OLI refer Operation Land Imager and 2nd column EQ refer Earthquake. *Source:* USGS-Earth explorer Landsat 8 Archive.

Table 1. Details of data used in this research.

imageries automatically neglected like case 1. Therefore, looking forward, it has been found that suitable imagery of 292 days before earthquake strike contains very less percentage of cloud.

From the visual observation of datasets, it has been confirmed that all considered Landsat 8 OLI images used for the automatic lineament feature extractions were partially covered by snow and cloud in case 1 and only by cloud in case 2, which did not affect too much of the lineament data volume. The present test has been conducted based only on satellite data without giving any importance of ground validation data. Traditional research application always required field surveys with ground validation data to match properly with satellite data. However, in this test, it has been used popular traditional technique of automatic line algorithm of PCI Geomatica for lineament data extraction, which clearly highlights the lineament changes in the study areas. The automatic LINE algorithm technique generates sufficient number of lineament data over the two study regions, which were used to know the pre-earthquake anomaly detection and assessment by considering multi-dates Landsat 8 OLI imageries. Though, very limited errors have been observed in extracted lineament data which is further checked by overlaying the highways, railroads, etc. These identified errors were checked with available vector shapefiles of those regions, thus finally neglected and removed from extracted lineament database. The present results which have derived automatically from satellite imageries clearly defined lineament datasets and do not need further validation, as the technique was commonly used by numerous researches. However, if validation required, the extracted data can be verified with superposition of layers with geological map of the specific areas. These are the scientific achievements of space technology application over the traditional surveys, as each satellite scene covered in large area in a single acquisition time, where ground surveys need longer period of time and sometimes not possible due to high rugged terrain or any other natural obstacles present in the Earth's surface.

2.3. Methodology

Satellite images (multispectral or digital elevation models) and aerial photography are broadly used to extract lineaments for different purposes, like defining geological structures and tectonics fabrics. Each image consists of 11 spectral bands and scene size is 185 km north-south by 185 km east-west, which enables the delineation of the geological lineaments in the study area. In this experiment, automatic extraction of geologic lineament performed through different steps including from raw satellite imagery pre-processing like DN value conversion into radiance, radiance to reflectance and later atmospheric correction using the FLAASH (Fast Line-of-sight Atmospheric Analysis of Hypercubes) module. Thereafter, enhancement-linear 5% stretch performed over R, G, B (5, 4, 2) band combinations respectively to get the better visualization image and at the end of this stage, all images were assigned to WGS 1984 datum with projection parameter of UTM zone 45 N (case 1) and 46 N (case 2), respectively.

In the next stage, principal component analysis (PCA) was performed on each atmospheric corrected image and each PC-1 image was created by considering best band selection, based on Eigen number and Eigen value, thus finally help to enhance image discontinuities corresponding to structural lineaments. For the present research, at initial stage, we have developed the theoretical model (**Figure 3**) to demonstrate whether the results are coherent with the theoretical model based on the different output of images.

Lineament distribution maps of Nepal and Manipur were prepared from Landsat 8 OLI satellite imagery by using four different remote sensing and GIS software's integration, where one software output was used by other to obtain the final lineament results. The OLI spectral band in gray scale was used to extract lineament. Out of five images of each case, one image used to observe the normal behavior in the absence of earthquake event, three images for "anomaly" observation (pre-earthquake stage), whereas another single image was used for after earthquake lineament change observation of Nepal and Manipur earthquake, respectively. Before the methodological description breakdown, the overall workflow of the present research is shown in **Figure 4**.

Figure 3. Theoretical model developed for the present research.

Figure 4. Flowchart of methodology used in this research.

2.3.1. Lineament extraction, line splitting, and length analysis method

There are two common methods for the extraction of lineaments from satellite images: visual extraction and automatic extraction. Most popular traditional methods based on edge filtering techniques, that is, Sobel, PCA, ICA, MNF, band rationing, RGB band combinations with high contrast, different stretch and directional filters are used worldwide for lineament extraction. In this research, PCA is considered, and the most widely used software is deployed for the automatic lineament extraction with the most common popular traditional method, that is, LINE algorithm of PCI Geomatica 9.1 v software [23], which consists of three stages [24] has accentuated and facilitated the detection of lineament in the satellite images. Various computer-aided methods such as edge detection, thresholding, and curve extraction steps [25] were carried out over derived principal component analysis (PCA) image (i.e., PC1) of the study area under default parameter windows, where user defined modification of values can be done using this software. For processing and extraction of lineaments, the following algorithm parameters and its corresponding values were used such as RADI-Radius of the filter in pixels (10), GTHR-Threshold for edge gradient (50), LTHR-Threshold for Curve length, in

pixels (30), FTHR-Threshold for Line fitting error in pixels (3), ATHR-Threshold for Angular difference in degrees (30), and DTHR-Threshold for linking distance in pixels (20).

In the first stage, RADI parameter (filter radius) specifies the size of the Gaussian kernel used as a filter during edge detection. The edge strength image was threshold to obtain a binary image. Therefore, the choice of RADI value depends on the condition, like as, the greater the value, the less noise and detail appear in the edge detection image. In the second stage, this image was defined by the GTHR parameter (edge gradient threshold) value after testing with different values, and the suitable one was considered. In the third stage, curves are extracted from binary edge image, which have several substeps. First, a thinning algorithm was applied to the binary edge image to generate pixel-wise skeleton curves, then sequence of pixels for each curve was extracted from that corresponding image. Any curve with the number of pixels less than parameter value LTHR was discarded automatically from further processing. Thereafter, extracted pixel curve was converted to vector form by fitting piece wise line segments to it. The resulting polyline was an approximation to the original pixel curve where the maximum fitting error distance between the two was specified by the FTHR parameter. Finally, the algorithm links pairs of polylines, which satisfy the last two parameters, where the angle between the two segments was less than the parameter ATHR and the distance between end points was less than the parameter DTHR. The lineament extraction algorithm takes these problems into account to extract linear features from the corresponding image.

The main geometric characteristics of a single linear line are orientation and length (continuity) and in case of curved line, curvature [26]. For line split generation, ArcGIS 10.5 Model builder was used to automate GIS processes by linking data input, tools/functions, and data output, which saved into shapefile format. These lineament features extracted as a compound line, which splitted into a single line at their vertices and recorded the polylines in a vector layer.

Thereafter, lineament line length analysis was performed using the ArcGIS 10.5 software through conversion of meters into kilometer unit. The most important factor was that the lineaments in an automated one were shorter in length, so that a few of them could be combined to form one long lineament. In this stage, we are getting lineament length of all the attribute values based on the derived products of lineaments of the two study areas.

2.3.2. *Lineament fluctuations change observation method*

To observe the lineament fluctuation change over the two study areas, satellite image-derived vector output, that is, lineaments were considered to perform overlay technique on each temporal data, helps to prepare corresponding lineament fluctuations maps. However, the criteria have the following conditions, if fluctuations of lineament persist over the study areas in the presence of earthquake, those are considered as “anomaly.” These anomalous changes of lineament data represent fluctuations over the two study areas in three different phases, that is, initial, middle, and strong phase. On the other hand, if lineament observed less in number along with other statistical information in the absence of earthquake event, it is considered as normal behavior and categorized as “no anomaly” and finally, to know lineament situation after the earthquake, it is indicated as post-earthquake phase. However, the lineament increases or decreases at this phase does not matter, and this has been done only for comparison.

For overlay change detection, day wise comparison of temporal lineament data has been performed, which ultimately help to monitor the lineament changes of the study areas.

2.3.3. Lineament direction analysis method

The processing of the orientation of lineaments simply produces a directional diagram, which shows the distribution of lineament features. For lineament direction trend analysis, previously saved lineament data as dxf format was used in the RockWorks 16v software environment, where lineament computation was performed to measure bearing (unidirectional: 0–360°), length (m), line start and ending values, respectively, ultimately helps to create rose diagram. The directional diagram that depicts the orientation of the linear features finally saved it in the required format as a tiff file. Later, following the same process, remaining rose diagrams were prepared for the two study areas to figure out the directional change of lineaments based on three different stages (i.e., in the absence, presence, and after earthquake event, respectively).

2.3.4. Statistical analysis method

The statistical approach of the geometric parameters (number of lineaments and lengths variation) of lineaments is required to describe the structure of a region. The length parameters (i.e., total number of lineament, minimum, maximum, mean, total sum, and standard deviation) are generated based on all attributes of corresponding temporal lineament data of the two impending earthquakes in the absence and the presence of earthquake event. As, the lineament data variations observed in different places, the total number of lineament and length variations, that is, mean and standard deviation values were considered for anomalies identification of the study areas, which also further compare with post-earthquake data.

For statistical comparison, the demarcated line has been drawn over the line graph to represent the change behavior of lineament in three different situations with respect to earthquake occurrence day. The left black vertical dotted line used to represent the absence of earthquake marked as “no anomaly” and the second black point dash line considered to represent “extreme anomaly” prior to strike, and black solid line indicates the earthquake occurrence day in the corresponding study areas, whereas black dash line plotted in both the graphs to indicate the anomaly still present representing post-earthquake scenario. The X-axis represents the days which considered for earthquake observation and Y-axis represents the number of extracted lineaments and lineament length (mean and standard deviation value in km), respectively. However, number of lineament and mean value of lineament length were further used to justify the lineament change, observed through scatter diagram.

3. Results and discussion

The focused study areas both are tectonically active in nature, and there is no previous research conducted in the two earthquake-stricken areas considering lineament change. This research has been tried to test using Landsat 8 OLI dataset for the first time based on the newly developed theoretical model. To quantitatively evaluate the present methods, lineaments were automatically extracted from each image after principal component analysis

(PCA). Epicenter-based single tile images were considered to observe the changes of the lineaments related to both the earthquakes.

The following sections (3.1–3.4) represent the present research derived results, based on three different situations. First, results highlight automatic extraction of lineaments data along with lineament length information; second, temporal data-based lineament fluctuations observed by applying vector overlay technique of ArcGIS 10.5 software, and third, rose diagram was created to know the directional changes. Finally, the overall integrated assessment and statistical information-based lineament change comparison were performed for the two impending earthquakes. The present significant contribution of the lineament data suggests that data have potential enough to detect pre-earthquake anomaly in advance without having integration of processed satellite imageries, geological map and field validation data.

3.1. Number of lineaments and line length analysis

The resultant lineament maps produced for all temporal images of the two study areas. Thereafter, line length information was calculated (converted in kilometer) and phase wise lineament behavior changes were observed in the presence (prior to strike) and the absence of earthquake event. The spatial distribution of lineaments of Gorkha-Nepal from 31 January 2015 to 7 May 2015 and of Imphal-Manipur from 19 March 2015 to 17 January 2016 are generated and used in overlay analysis purpose, representing with two distinct black lines (light and solid) with line weights values 0.50 and 1.25, respectively are used for each anomaly phase detection. In each phase of anomaly, every initial image was highlight with light black line and afterwards image is displayed with solid black line. In the same way, different phases were represented as normal (absence of Earthquake), initial (presence of Earthquake), middle (presence of Earthquake), strong phase (presence of Earthquake), and post-earthquake phase, respectively. In addition, corresponding statistical information of lineaments for both study areas was generated and presented in **Table 2** for case 1 and **Table 3** for case 2.

The extracted data prior to the earthquake suggest that a major number of lineaments and total number of lineaments vary from 31,613 on 20 March 2015 to 34,641 on 21 April 2015 (earthquake strike on 25 April 2015). The total lineament was certainly dropped to 27,025 in number in just 4 days before the main event. This anomaly was quite high in respect with the

Date of image acquisition	Days (b/a)	No. of lineament	Length (km)-min	Length (km)-max	Mean value (km)	Sum value (km)	SD value (σ)
31 Jan 2015 (anomaly-no)	85 (b)	11,080	0.001	11.476	1.627	18025.26	0.808
20 Mar 2015 (anomaly-yes)	36 (b)	31,613	0.030	31.658	0.677	21409.09	0.613
5 Apr 2015 (anomaly-yes)	20 (b)	27,025	0.030	31.666	0.670	18116.14	0.680
21 Apr 2015 (anomaly-yes)	4 (b)	34,641	0.060	17.426	0.634	21973.44	0.397
7 May 2015 (anomaly-yes)	12 (a)	25,917	0.030	31.666	0.632	16382.09	0.681

Brackets terminology in the 1st column refers that lineament anomaly-no means normal behavior of lineaments, and anomaly-yes means abnormal behavior of lineaments; in the 2nd column, b refers before earthquake and a refers after earthquake (earthquake occurrence date: 25 April 2015). Source: data extracted using PCI Geomatica-9.1, ArcGIS 10.5.

Table 2. Statistical information of the extracted lineament of Gorkha of Nepal and its adjoining areas.

Date of image acquisition	Days (b/a)	No. of lineament	Length (km)-min	Length (km)-max	Mean value (km)	Sum value (km)	SD value (σ)
19 March 2015 (anomaly-no)	292 (b)	14,524	0.015	5.031	0.326	4734.38	0.184
30 Nov 2015 (anomaly-yes)	36 (b)	34,018	0.030	31.411	0.676	23014.35	0.750
16 December 2015 (anomaly-yes)	20 (b)	29,358	0.030	31.398	0.670	19678.25	0.658
1 January 2016 (anomaly-yes)	4 (b)	42,840	0.030	31.423	0.688	29462.89	0.674
17 January 2016 (anomaly-yes)	13 (a)	62,332	0.030	31.404	0.673	41938.37	0.558

Brackets terminology in the 1st column refers lineament anomaly-no, means normal behavior of lineaments and anomaly-yes, means abnormal behavior of lineaments and in the 2nd column b refers before and a refers after earthquake (earthquake occurrence date: 4 January 2016). Source: data extracted using PCI Geomatica-9.1, ArcGIS 10.5.

Table 3. Statistical information of the extracted lineament of Imphal, Manipur and its surrounds, Eastern India.

absence of earthquake, where only 11,080 lineaments observed (85 days before) (**Table 2**), whereas the number of lineaments was found decreasing (25,917) in post-earthquake phase (12 days after the earthquake) probably due to the release of strain and structural damage done by the high magnitude earthquake ($7.8 M_w$), compared to its three-preceding anomaly phases. The real cause is unclear till now regarding why the change was occurred prior to earthquake strike. However, simple explanations have been given only based on the experimental output from the extracted lineament results.

The lineament changes and anomalous behavior also observed through line length statistics (**Table 2**). Total line length was observed 18025.26 km, the minimum and maximum values were found quite low and the SD value was observed the highest in the absence of earthquake event. The anomaly phases were observed in the presence of earthquake event, where the maximum length and the SD value were found almost similar in 36, 20 days before earthquake (20 March and 5 April 2015), but not similar in 4 days before earthquake (21 April 2015). The mean length was dropped 0.043 km along with the maximum and SD length of lineament (in km) was sharply decreased (**Table 2**), representing high abnormal behavior (strong anomaly) prior to earthquake event. The same variables of lineament were found increased after the earthquake event (12 days later), as high magnitude of earthquake already ruptured in this region. There was a tendency of lineament to return to its original status but failed completely to return to its initial situation.

On the other hand, similar method applied over Imphal, Manipur ($6.7 M_w$) earthquake assessment. The total number of lineaments observed 14,524 in number (**Table 3**), representing “no anomaly” in the absence of earthquake event (292 days before). However, the lineament distribution during 30 November 2015 to 17 January 2016 represents the abnormal behavior. The number of lineaments was sharply decreased (4660) from initial to middle phase (30 November 2015 to 16 December 2015). The total number of lineaments found the highest in number (62,332) than its all four preceding values, observed in the post-earthquake stage (**Table 3**).

3.2. Lineament fluctuations observation through overlay analysis

As mentioned in Section 2.3.2 under Section 2.3 (on methodology), lineament fluctuations changes were observed based on temporal data. **Figures 5(a–g)** and **6(a–g)** represent temporal lineament fluctuations over Gorkha of Nepal and Imphal of Manipur regions, respectively.

Figure 5. Lineaments fluctuations observed through overlay analysis of Gorkha of Nepal regions: (a) lineament fluctuations observed in the presence of earthquake event (comparing 36 and 20 days before earthquake), (b) same as observed in 36 days and 4 days before earthquake, (c) 4 days before and 12 days after), (d) highly observed fluctuations representing strong phase (4 days and 85 days before), (e) 20 days and 85 days before earthquake (in the presence and the absence of earthquake), (f) same fluctuations comparison between 20 March 2015 (the presence and the absence of earthquake event) and (g) lineaments fluctuations in between 7 May 2015 (post-earthquake) and 31 January 2015 (in the absence of earthquake event). The earthquake epicenter was marked with the black dotted circle point symbol.

Figure 5a represents the fluctuations of the lineaments on 20 March 2015 (36 days before: light black color) to 5 April 2015 (20 days before: solid black color) in the presence of earthquake event. Thereafter, the abovementioned data overlay with 21 April 2015, where significant fluctuations of lineaments were observed around epicenter regions 4 days before earthquake strike (see southern part of image, **Figure 5b**). These data were further overlay with post-earthquake lineament data, which try to return to its earlier position (**Figure 5c**).

However, **Figure 5d** illustrates the lineament fluctuations in the presence (4 days before) and the absence of earthquake event (85 days before) and highlights with pink color to ensure that anomaly exists over this region. Sudden increase of lineaments around epicenter region represents the abnormality over this region. This means that anomalous and unexpected fluctuations observed in lineament data on this particular date. **Figure 5e** also represents the lineament fluctuations in the presence (20 days before) and the absence of earthquake (85 days before). The fluctuations were also slightly noticed in the initial phase (36 days before) compared with the absence of earthquake event (**Figure 5f**). In the final stage, it compares fluctuations both in the absence of earthquake, though observed lineaments try to readjust but not matched exactly with the normal condition (see **Figure 5g**).

On the other hand, similar technique was applied to know the lineament fluctuations for the Imphal-Manipur earthquake, and according to USGS, it was categorized as strong earthquake (6.7 M_w). **Figure 6** represents the lineament fluctuations over these areas in the absence and the presence of earthquake event, later compares with post-earthquake data. **Figure 6a** represents lineament fluctuations observed from 36 days (30 November 2015) and 20 days (16 December 2015) before earthquake, clearly noticed from epicenter and adjoining areas. However, it is mentioned here that, at this stage, few lineaments didn't observe due to presence of clouds on image. In the same way, fluctuations were observed comparing with 20 days and 4 days before lineaments data (**Figure 6b**). Five different colors were used for fluctuation comparison in the Imphal-Manipur regions similar to Gorha-Nepal regions. The unusual lineament behaviors were observed when compared 4 days before earthquake with 13 days after earthquake (**Figure 6c**). Thereafter, anomaly observed when it has been compared 36 days before (solid black color) (in the presence of earthquake event) with 292 days before data (light black color) (in the absence of earthquake event) (**Figure 6d**). The number of lineaments observed high in number, representing anomalous behavior around epicenter and its near adjoining areas. However, the sudden lineament fluctuations were also observed 20 days before compared to 292 days before in the absence of that event (**Figure 6e**).

The highest number of variations of lineaments observed prior to 4 days before earthquake (solid black color) compared to 292 days before earthquake (light black color) in the absence of earthquake event and detected the highest anomalies for the Imphal-Manipur earthquake epicenter and adjoining regions in the presence of earthquake event (**Figure 6f**). Whereas, the lineament data anomaly still present and found extreme number of lineaments probably due to massive geological activities done by this earthquake. This unexpected behavior was noticed only after the earthquake event (**Figure 6g**) compare to normal time lineament data (292 days before: showing in light black color), indicate another probable strong earthquake will immediately occur.

Figure 6. Similar overlay change analysis performed as **Figure 5** but for of Imphal of Manipur regions. Data representing changing behavior of lineament in the absence and presence of earthquake event. The panel represents (a) lineament fluctuations observed comparing 36 and 20 days before earthquake, (b) 20 days and 4 days before earthquake, (c) 4 days before and 13 days after, (d) highly observed fluctuations in the presence and the absence of earthquake (36 days and 292 days before), (e) 20 days and 292 days before earthquake (in the presence and the absence of earthquake), (f) fluctuations comparison between 4 days and 292 days before (presence and absence of earthquake event) and (g) lineaments fluctuations between 17 January 2016 (post-earthquake) and 19 March 2015 (in the absence of earthquake event).

3.3. Lineament orientation change observation through rose diagram

In this section, the lineament direction change has been observed in the absence and presence of earthquake event along with post-earthquake directional change, based on the method discussed on Section 2.3.3 under Section 2.3 (methodology). The case wise interpretation results based on lineament length data show normal and unusual behavior of lineament directions change ((**Figure 7(a–e)**)—Gorkha and **Figure 8(a–e)**)—Imphal). **Figure 7a** represents the direction of lineament during normal behavior (82 days before) with mean strike orientation of NE-SW direction (59.3 degrees-239.32 degrees), along with E-W and SE-NW directions also observed in the absence of earthquake. Whereas, the direction was start to move from 36 days before (20 March 2015) clearly represent that its mean strike line (101.8 degrees-281.85 degrees) was rotated enough (42.5 degrees) (**Figure 7b**) from normal condition (**Figure 7a**). **Figure 7c** represents directions were in ESE-WNW, E-W, NNE-SSW and N-S positions, where the mean strike direction (81.7 degrees-261.73 degrees) was rotated back and stay around 90° position (20 days before). Major direction was observed in ESE-WNW and NNE-SSW and another one N-E directional change firstly notice at this stage. Whereas, the direction was further rotated 23.7 degrees down

Figure 7. Directional change measurement through rose diagrams for Gorkha, Nepal earthquake: (a) 31 January 2015, (b) 20 March 2015, (c) 05 April 2015, (d) 21 April 2015, and (e) 7 May 2015 (all diagrams based on temporal lineament data).

from middle phase representing 4 days before earthquake scenario, and two major trends ESE-WNW and N-S directions clearly be interpreted from this rose diagram (**Figure 7d**).

The unusual behavior of lineaments clearly seen from these three phases of rose diagrams which shows an anomaly prior to earthquake strike. Whereas, lineament direction was trying to reach its original state but failed to adjust its original position due to internal geodynamic activities that occurred by this high magnitude ($7.8 M_w$) earthquake. The mean strike position was in E-W and along with two other directions NNE-SSW and SSE-WNW were observed in the post-earthquake phase (**Figure 7e**), though still there exist anomaly compare to normal phase in the absence of earthquake event. Subsequently, all these lineaments directional change were correlated and related within the regional context of the Gorkha-Nepal and its adjoining areas which is a great indication of any structural change and considered as a vital clue to know that impending earthquake.

On the other hand, **Figure 8** illustrates the lineament directions movement around Imphal, Manipur regions from 19 March 2015 to 17 January 2016 (**Figure 8(a-e)**). In order to analyze the lineaments directional change, the present analysis has been performed in the absence

Figure 8. Directional change measurement through rose diagrams for Imphal-Manipur earthquake: (a) 19 March 2015, (b) 30 November 2015, (c) 16 December 2015, (d) 1 January 2016, (e) 17 January 2016 (all diagrams based on temporal lineament data).

and the presence of earthquake data. **Figure 8a** illustrates the lineament directions of normal condition in the absence of earthquake event where major lineament positions were in NNE-SSW and minor lineament positions were in SE-NW and mean strike was in NE-SW directions with 46.8 degrees – 226.79 degrees angle. **Figure 8b**, 30 November 2015 (36 days before earthquake), suggests, ESE-WSW direction and mean strike (63.4 degrees – 243.43 degrees) was move forward 16.6 degrees advanced from normal position.

Figure 8c represents 20 days before scenario (16 December 2015), it showed a major trend to be ESE-WNW (61.1 degrees – 241.11 degrees) with 2.3 degrees rotated back along with considering bin lengths another trend of NE-SW can also be exists. Besides those, on 1 January 2016 (prior to 4 days of earthquake events) two major trends NE-SW (61.7 degrees to 241.65 degrees) and ESE-WSW were identified by interpreting the lineament data (**Figure 8d**). Finally, **Figure 8e** represents the post-earthquake lineament direction (13 days after earthquake) which showed NE-SW (57.8 degrees – 237.83 degrees) from its immediate mean strike position data.

3.4. Statistical analysis based on lineament data

After fluctuations analysis of lineament data as shown in Section 3.2, few statistical test were performed in this section against number of lineament and length change. This statistical analyses were done based on the method discussed in Section 3.2.4 under Section 3.2, by using box-whisker for number of lineament and line trend by considering mean and SD value (**Figures 9** and **10**) in the absence and the presence of earthquake event.

The automatic extraction of lineament data values of both tables (**Tables 2** and **3**) suggests anomaly presence over the two study areas prior to earthquake strike, which was also observed even after the earthquake. On the other hand, the scenario was quite normal in the absence of earthquake event. The derived result illustrates different number of lineaments as observed through box plot and whiskers line chart (**Figure 9a**: Gorkha of Nepal; **Figure 10a**: Imphal of Manipur). However, line length value also differs in both cases (**Figure 9b**: Gorkha and **Figure 10b**: Imphal). These changes were noticed in our two cases, and probably due to

Figure 9. Results of number of lineament and lineament length change observed in the absence and the presence of Gorkha-Nepal earthquake (25 April 2015), from 31 January 2015 (85 days before) to 7 May 2015 (12 days after). (a) Number of lineament variation is represented by box-whisker with black line and (b) lineament mean length change (measured in kilometers) is represented by black dash line and solid black line with dot and light black arrow headed lines showing standard deviation (SD) value, respectively based on number of days observation.

Figure 10. Results of number of lineament and lineament length change observation in the absence and the presence of Imphal-Manipur earthquake (4 January 2016) from 19 March 2015 (292 days before) to 17 January 2016 (12 days after). The internal details of data representations of both figures are the same as Figure 9.

different geologic condition, structural arrangements, depth, and magnitude variations of the mentioned two earthquakes.

The earthquake occurrence day is represented as a vertical solid black line. The left black vertical dotted line represents the absence of earthquake event (no anomaly) at this stage, and the second black point dash line represents extreme anomaly of 4 days prior to strike and black dash line indicates the anomaly still present representing post-earthquake scenario. In both cases, the X-axis represents the days, which considered for lineament change observation during the corresponding earthquake, and Y-axis represents the number of extracted lineaments (Figures 9a and 10a), and lineament length (km) represents with the SD and mean value (Figures 9b and 10b).

Figures 9 and 10 represent data anomaly of two study areas in the presence of earthquake event (prior to earthquake). However, the number of lineament was found stable (in the absence of earthquake event) when the days observed 85 days before the earthquake event (case 1: Gorkha-Nepal) compared to the highest anomalous behavior present prior to earthquake strike (4 days before) and recorded approx. three times higher number of lineaments (Figure 9a). However, lineament anomaly was observed 2.5 times higher than stable condition (20 days before strike).

In Figure 10 (Imphal-Manipur case), anomaly exists in the absence of earthquake event, and when the observation day's progresses from initial anomaly stage, lineaments were increased (4 days before: highest abnormality presence in the anomaly stage) than two other anomaly phases (Figure 10a), whereas other two phases were also showing anomaly.

On the other hand, lineament length (km) mean value was recorded as higher (Figure 9b). However, the mean length can be shorter or longer and it can be varied due to different geological settings and underlying geological activities. Furthermore, the SD value of lineament length of the two study areas represents (solid black line with dot symbol) different trend, which is decreasing-increasing-decreasing trend in strong earthquake case (Gorkha of Nepal: 7.8 M_w) compared to the absence of earthquake (Figure 9b). Whereas, in major earthquake case (Imphal of Manipur: 6.7 M_w), it follows increasing-decreasing-increasing trend (Figure 10b).

The results, which observed in each stage based on different analyses method, have individual credit, but all these data are integrated with each other in a sense, like that, first it generated number of lineaments, then measured the lineament length and its overall statistical values. Thereafter,

overlay analyses were performed to observe the abnormal and normal behavior of those lineaments, next directional change measurement by creating rose diagrams considering the lineament number and length. Finally, statistical comparisons were performed and presented under the three phases of lineament behavior changes in respect of earthquake day. The exact epicenter, magnitude, depth, and time of occurrence of earthquake on particular strike day are quite challenging to predict through this present study, but observing lineament data anomalies from the two case studies (prior to earthquake) suggests that pre-earthquake anomaly detection is possible.

Landsat 8 OLI satellite sensors-based time series data show its credit to extract lineament data through most popular traditional automatic LINE algorithm techniques found suitable for this research and help to identify the pre-earthquake anomaly of lineaments in two earthquake prone areas. Though few lineament extractions were obstructed due to the presence of cloud around the epicenter and its adjoining areas, but the outcome showed that it has less effect on the extracted data.

The research results from both study areas suggest that, as the time progresses, the lineament behavior also changed, which identified and confirmed through the experimental results based on the theoretical model and related methods. However, this change was obvious and probably occurred during that time due to movement of the underlain structure and several unknown internal activities. Through the present analyses method, this study assessed successfully of the two earthquakes in two different locations, that is, Gorkha of Nepal (7.8 M_w with 15-m depth, major category) and Imphal of Manipur, eastern India (6.7 M_w with 56-m depth, strong category) earthquakes, respectively. The existing unusual lineament anomalies appeared all over the images in the pre-earthquake stage, especially highly observed close to the epicenter area in both cases (epicenter marked in red asterisks).

4. Conclusions

In this study, based on the Landsat 8 OLI satellite-derived lineament data of the two earthquake regions from 2015 to 2016, the spatial fluctuations of lineaments data and their behavioral changes were analyzed in the presence and absence of earthquake event, which categorized into three phases, that is, in the absence of earthquake (no anomaly), the presence of earthquake event (anomaly) and post-earthquake phase, respectively.

The Gorkha earthquake of Nepal was a result of thrusting along the Main Himalayan Thrust (MHT) [27], and the analysis of the SAR interferograms led to the interpretations that the event was a blind thrust and seismogenic fault [28–30]. However, for Imphal the existing literature suggest that the regional plate boundary in eastern India-the Indo-Burmese Arc is oriented approximately south-southwest-north-northeast directions, see [31], matching the orientation of extracted lineaments.

Present research is the first kind of study conducted and applied in both the earthquake prone areas based on the theoretical model concept. This study creates a breeze in between all four softwares, which were deployed from preprocessing to final stage output performed through geo-integration techniques of ENVI—PCI Geomatica—ArcGIS-RockWorks software's, respectively. These combined techniques were successfully applied on Landsat 8 OLI optical imageries, which

used traditional popular automatic methods and clearly showed its ability to extract different kinds of information based on lineament data.

The automatic lineament delineation using the LINE module of PCI Geomatica was deployed and found great ability of data extraction capacity, as it extracts sufficient numbers of lineaments from Landsat 8 OLI imageries. Different types of information extracted from the lineaments data of the two study areas, where number of lineaments, lineament length change, that is, mean and SD value, and directional change were observed. In both cases, their behavior is abnormal in the presence of earthquake event regarded as anomaly.

The present results also identified that the highest lineament fluctuations and abnormality exist within the anomaly phase, which marked as the highest anomaly (strong phase) just 4 days before earthquake strike. Lineaments behavior was observed quite normal (no anomaly, compared with abnormal situation) in 85 days before (Gorkha of Nepal) and 292 days before (Imphal of Manipur) the earthquake event.

However, data comparison method and lineament fluctuations successfully identified the lineament anomaly change over the two study areas. Due to progress of Earth observing satellites in different parts of the world, similar experiments can also be tested and compared with another high-resolution imagery. From this analysis, the exact position of earthquake epicenter, magnitude, and timing of occurrences was quite difficult to predict, but the extracted data can only able to identify the abnormality before the earthquake strike at least 4–36 days before. Thereafter, this lineament abnormality along with cloud presence in the images over such time period can help to target the zone of probable earthquake epicenter.

Overall, the experimental results have shown positive output, as it has been observed anomaly in pre-earthquake stage. Therefore, the first output concept was considered which developed by theoretical model and regarded as possible earthquake. On the other hand, no abnormal behavior of lineament presents in before, compared to anomaly presence prior to earthquake strike; thus, it is considered as no anomaly and declared as no possible earthquake, which supports the second concept of theoretical model. From this research, it has been observed that Landsat 8 OLI data have some power to extract lineament and helpful for pre-earthquake anomaly detection through lineament change observation. That is the only reason of acceptance of those images for the present study, which also supports the theoretical model. However, present lineament change observation technique using Landsat 8 OLI time series data is found effective for pre-earthquake anomaly study and can be used as an alternative approach for future earthquake monitoring.

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