SPATIAL AND TEMPORAL VARIATION OF b-VALUE IN THE GARHWAL HIMALAYAN REGION AND ITS IMPLICATION AS AN EARTHQUAKE PRECURSOR

A DISSERTATION REPORT

Submitted in the partial fulfilment of the requirements for the award of the degree
of

MASTER OF TECHNOLOGY

in

EARTHQUAKE ENGINEERING

(With specialization in Structural Dynamics)

by

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February, 2020

CANDIDATE'S DECLARATION

I hereby, declare that the work which is being presented in this report entitled, "**SPATIAL-TEMPORAL VARIATION OF B-VALUE IN GARHWAL HIMALAYAN REGION AND ITS IMPLICATION AS EARTHQUAKE PRECURSOR**", being submitted in partial fulfilment of the requirements for the award of degree of " Master of Technology" in "Earthquake Engineering" with specialization in Structural Dynamics, to the Department of Earthquake Engineering, Indian Institute of Technology Roorkee, under the supervision of **Dr. S.C. Gupta**, Associate Professor, Department of Earthquake Engineering, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out during the period of June 2018 to February , 2020.

I declare that I have not submitted the material embodied in this dissertation for the award of any other degree or diploma.

Place: Roorkee
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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Place: Roorkee
Date:

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ABSTRACT

The Garhwal Himalaya Region is one of the seismically active region of the Himalaya. This is characterized by the occurrence of moderate to large sized earthquake activity in this belt. The local earthquake data collected from the deployment of a 12 station seismological network by the Department of Earthquake Engineering, IIT Roorkee funded by the THDC India Ltd, Rishikesh around Tehri dam, the data for the period from 2008-2018 has been taken here for analyzing the seismic attributes in the Garhwal Himalayan Region i.e. the variation in value of b as an Earthquake precursor in terms of Spatial & Temporal variation.

The study region i.e. Garhwal Himalaya region has been divided into **Four Cluster** with these Latitudinal & Longitudinal position **i.e. 77.5ºE-79.0ºE** to **29.50ºN-30.7ºN** (**Tehri Region**) , **76.70ºE-78.60ºE** to **30.70ºN-32.0ºN** (**Himachal Region**) , **79.70ºE-80.75ºE** to **29.20ºN-30.70ºN** (**Pithauragarh Region**) & One **Diagonal Element i.e.** (**Chamoli-Uttarkashi Region**) having coordinates **78E, 30.70N - 80E, 30.5N to 79.60E, 29.90N - 78.60E, 31.20N**) **for** carrying out **spatial variation in b-value** & the same has been analyzed for temporal analysis of the data. The **Mc**, **b** and a-**values** has been estimated with respect of each zone, and the variations in the values of these parameters has been analyzed.

The catalogue i.e. the chosen data for the period from 2008-2018 contains, the total no. of events 3972 in magnitude ranges $0 < M < 5.0$ & Maximum no. of events has occurred in the range of $1 < M < 2.0$, which has been shown clearly in figure no. **4** of Histogram of magnitude.

The whole Garhwal Himalayan Region has divided into four cluster for area specific studies and among the four regions, the **Tehri region** is showing **lesser b-value i.e. 0.71**, it implies that this region is still stressed and there are high chances of near future Earthquake in this region.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 General

There are number of different physical spectacles such as cyclones, earthquakes, floods have occurred, and there are chances of occurrence of these due to the advancement of the planet earth. The economically, politically and publically these phenomena's have a great bearing on individuals life and also harmful from societal point of view. Earthquakes are one of the most terrible, scary and shocking natural calamity, in a course of few moments, a large number of population lose their health, belongings, life of their loved ones or their own. To avoid by this instant up to some extent the seismic hazard assessment in an area is an important factor. Out of the various basic seismological parameters, the b-value is used to define an ensemble of earthquakes in the frequency-magnitude relation. It defines the distribution of earthquake over the witnessed range of magnitudes. Here, in the Region of Garhwal Himalayan we are trying to find out *b*-value parameter, also known as earthquake precursor for further carrying out seismic hazard analysis in this area. One of the pre requisite for finding out this parameter in an area is the quality & reliability of data set on the past and present existence in a region.

Earthquakes, which are defined generally as sudden discharges of accumulated tectonic stress in the Earth's crust, are assumed to follow the empirical Gutenberg–Richter (1944) frequency-magnitude relation:

$$\text{LogN} = a - b\,M$$

Where N is the Cumulative number of events with magnitude greater than M and a & b are seismicity constants. The b-value is the slope of the cumulative number v/s magnitude trend line i.e. frequency magnitude distribution curve, b-value is generally used for reckoning seismicity .The parameter b is supposed to depend on the stress system and seism-tectonic character of the area concerned. The b-value is uses as an input parameter for seismic hazard assessment.

The constant "**a**" is a parameter of seismic activity level of the given region. It depends on the size of area concerned, the return period, frequency of earthquakes occurring in the region.

Mc is the magnitude of completeness for a given data set. The b-value is normally 1.0, but it varies from 0.5 to 1.5 depending upon the seismotectonic setting of area (Pacheco et al. 1992; Wiemer & WYSS 1997; Singh et al. 2008, Singh & Chadha 2010). So many reasons are there behind deviation in b-value from its normal value of 1.0. A less b-value directs that the area is highly strained and a high b-value indicates that the area has previously experienced tectonic phenomenas.

1.2 Objectives of Study

To evaluate the Spatio-temporal variation in b-value of **Garhwal Himalayan region** and its implication as an earthquake precursor, this name has suggested by many authors because they individually taken into practice of predicting about near future Earthquake in selected region of study. Here, in **Garhwal Himalayan Region,** this is emphasized using the past and present earthquake occurrence in this region for the period from 2008-2018.

1.3 Organization of Report

The dissertation has been described in Ten (10) chapters.

Chapter 1: Introduction.

Chapter 2: Seismicity in Garhwal Himalayan Region

Chapter 3: Literature review & Methodology.

Chapter 4:.Data Collection & its Analysis

Chapter 5: Study Area & Division into clusters

Chapter 6: b-value by Maximum Likelihood method

Chapter 7: b-value by sliding window method

Chapter 8: Spatial variation in b-value

CHAPTER 2

SEISMICITY IN GARHWAL HIMALAYAN REGION

2.1 General:

Earthquakes are known to have occurred in the region of the Indian sub-continent from the ancient time. Moderate characterizes the Garhwal Himalayan Region that forms the western part of the Himalayan mountain ranges to large sized earthquake activity. In the recent past two moderate sized earthquakes, namely, the Uttarkashi earthquake of 1991 and the Chamoli earthquake of 1999 was experienced by this region.

Tectonic framework of Indian subcontinent covering an area of about 3.2 million sq. Km which is spatio-temporarily varied and complex. The rapid movement of Indian plate towards Himalayas in the northeastern direction along with its low plate thickness might be the cause for an increase in the seismicity of the Indian region (Kumar, 2008). Indian plate is moving in northern direction at a rate of 50 mm/ per year and in doing so, it will successively collides with the Eurasian Plate. Eurasian Plate encompass of the Tibet plateau & central Asia. Upon merging of the different continents, the shortening & thickening take place in continents, like at the Himalayas and the Tibet. Because of massive collision, the Himalayas are under highest thrust condition and due to which enormous numbers of earthquakes are generated in this process. This is the foremost cause of earthquakes from the Himalayan regions to the Arakan Yoma.

Geographical statistics of India show that almost 54% of the land is vulnerable to earthquakes. Keeping above in mind the Department of Earthquake Engineering, IIT Roorkee is carrying out the seismicity monitoring through deployment of a local seismological network around Tehri dam reservoir in the Garhwal Himalayan sponsored by THDC India Ltd. The seismic risk in the country has been increasing rapidly in the recent years, as there were large magnitude earthquakes in recent times even in the stable Continental region. The latest version of India's seismic zoning map given in India's earthquake-resistant design code (IS 1893: Part-1:2016) assigns for India as a whole four levels of seismicity in terms of various zone factors. In other words, India's earthquake zoning map divides India into four seismic zones (Zone II to V) as shown in Figure 1, though its previous version consisted of five zones. According to present zoning map, Zone-V expects highest level of seismicity whereas Zone - II is associated with lowest level of seismicity. The present study region i.e. Garhwal Himalayan region is falls in the seismic Zone IV.

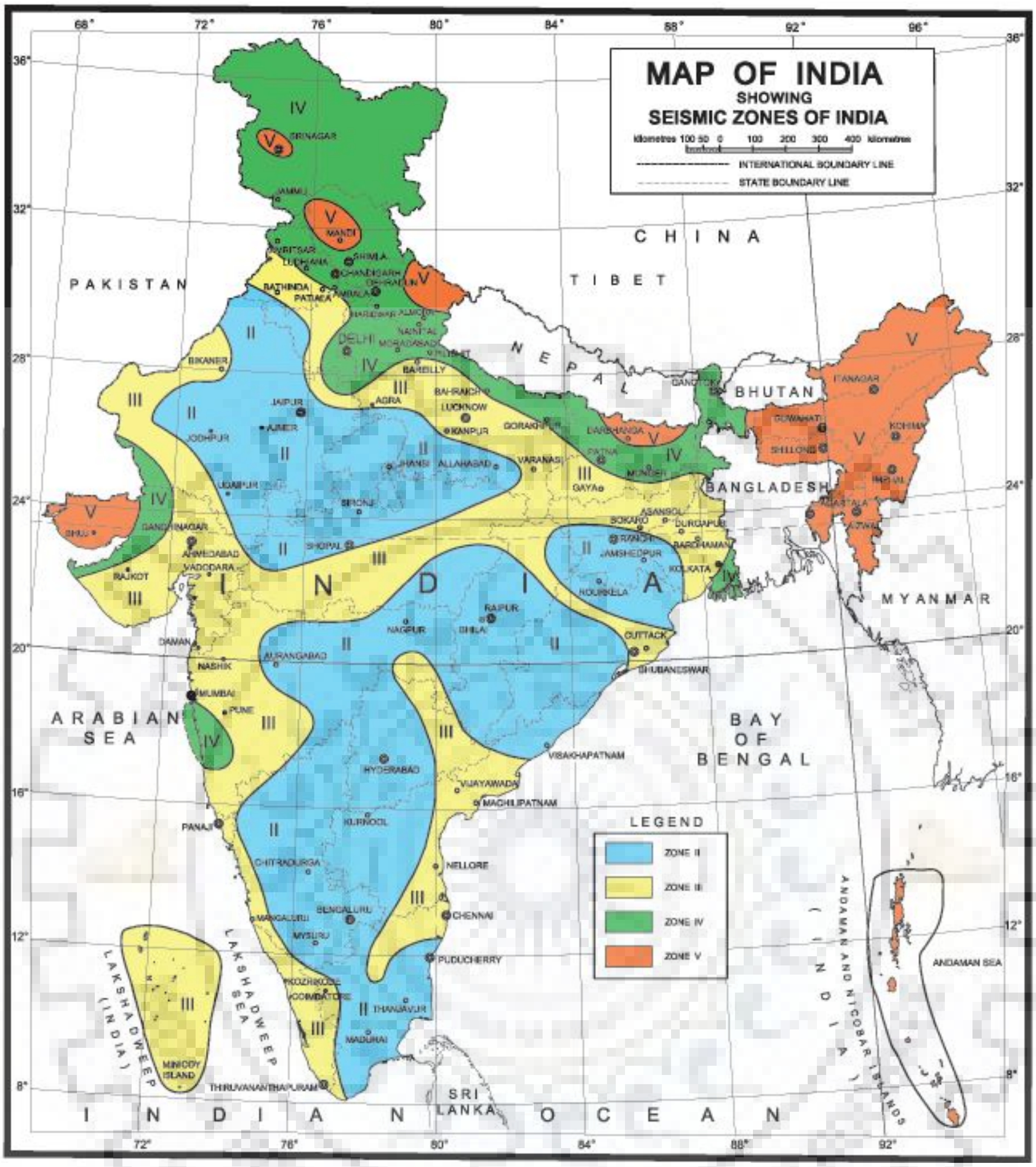

Figure 1 : Seismic Zones map of India (BIS:1893:Part1:2016)

2.2 b-value

Gutenberg-Richter law (G-R law) interconnects the correlation between the magnitudes and adds up to no. of earthquakes in any provided locale and time period of at least that greatness. Charles Francis Richter and Ben-Gutenberg to begin with the proposed correlation. The relationship is shockingly vital and does not change basically from locale to locale or over the time.

G-R Relationship: $\log N = a - bM$

The slope of frequency-magnitude distribution curve i.e. b-value is also called earthquake precursor. High b-value is associated with aftershock and low b-value is associated with foreshock. Low b- value relates to higher level of accumulated stress (Monakou and Tsapanos, 2000). The b-value decrease, observed prior to the failure of samples distorted in the laboratory has led to the suggestion that this is a precursor to main macro-failure. In both laboratory experiments (Scholz, 1968) and mine excavations (Urbancic et al. 1992), b-values displayed an inverse relationship with stress. A high b-value means occurrence of small number of earthquake (from the given earthquake data set) in higher magnitude range compared to lower magnitude range, whereas a low b-value implies vice-versa.

2.3 Variation of b-value in space

The variation of b-value in different regions may be related to structural heterogeneity and spatial distribution of stress (Mogi, 1967; scholz, 1968), by finding out the b-value in different regions we can also predict about the epicentral location of near future earthquake along with the stress level of that particular region. A low *b*-value indicates that the most of the earthquake of higher magnitude are expected to occur in high resistance and homogeneous region. A high b-value is an indication towards most of the earthquake of lower magnitude occur in the region of low stress and heterogeneous medium

2.4 Distribution of b-value

High b-values is generally observed in upper part of the slab at depths of around 80-110 km. b-value scientifically vary for different classes of faulting. System. Normal fault is linked with the highest b-values, strike-slip events show intermediate values and thrust events the lowest values. This observation means that b acts as a stress meter, inversely varies with the differential stress.

CHAPTER 3

LITERATURE REVIEW & METHODOLOGY

3.1 Basic observations on b-value given by various authors

The various authors concluded that the b-value is normally 1.0, but it varies from 0.5 to 1.5 depending on tectonic setting of a seismically active region..

Wiemer & Benoit (1996) stated that even though increased material heterogeneity or crack density and thermal state can have influence on b-value up to some extent, but on a large scale they do not seem to have any noteworthy effect on this parameter .

Nuannin et al. (2005) observed that the region around the epicenter of two mega Sumatra-Andaman earthquakes of 2004 Mw 9.0 and Mw 8.7 Nias earthquake of 2005 occurred within the zones of low b-values. This implies that the b-value near epicenter location decreases because of more accumulation of stress near epicenter.

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3.2 Methodology

1. Entire-magnitude-range method (EMR)
2. Maximum curvature-method (MAXC)
3. Goodness-of-fit test (GFT))
4. M_C by *b*-value stability (MBS)

Although there are various methods of calculating b-value but in the present study, the maximum likelihood method used here for the estimation of b-value, which is often claimed to be better in comparison to least square method (Hirata 1989). By this method, the b-value is defined as

$$b = \frac{\log e}{\bar{M} - M_0}$$

Where $\overline{M}$ is the average magnitude and M_0 is the threshold magnitude used in the analysis and $\log e = 0.4343$. For b-value evaluation in space, the entire region consisting of 3972 events has been set into 0.01x0.01 degrees grid. All the calculations in the present study has been done by using the ZMAP software package (Wiemer 2001).

Even various methods are available as sub-methods of Maximum Likelihood method but here we are using here the method of **Maximum Curvature method**, which gives result promptly.

3.3 Maximum Curvature (MAXC)

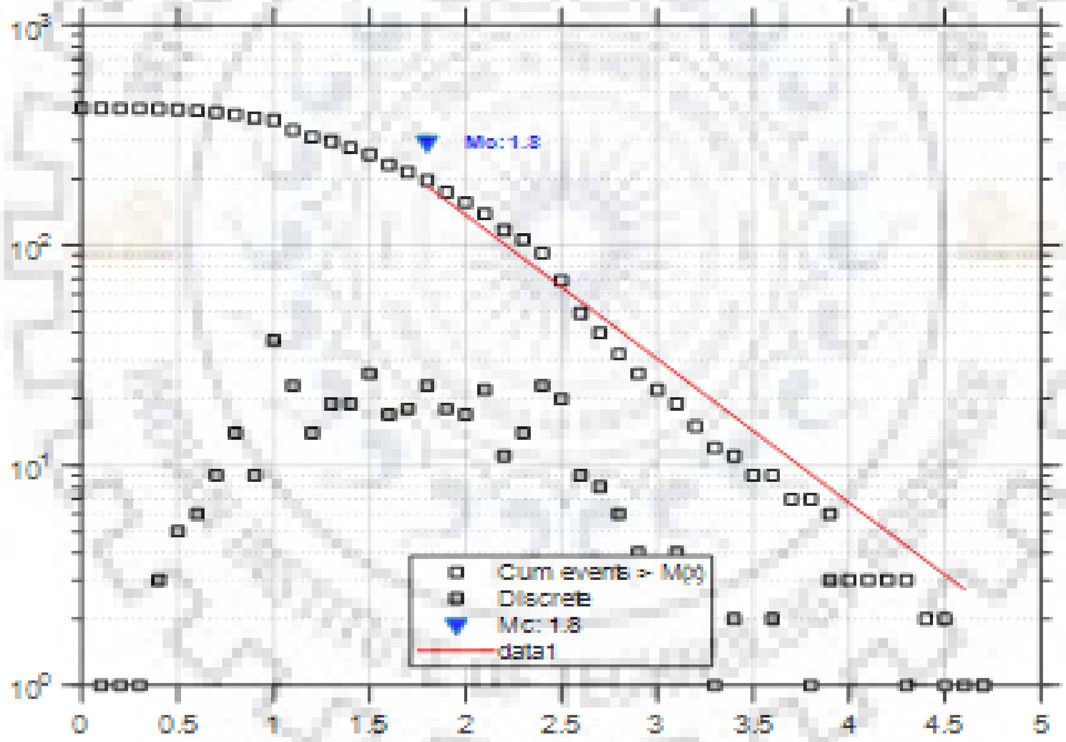

Figure 2 : Frequency-Magnitude Distribution Curve

Wiemer and Wyss (2000) researched on two methods assuming self-similarity. A quick and reliable assessment of Mc is to declare the point of the maximum curvature (MAXC) as magnitude of completeness by evaluating the maximum value of the first derivative of the frequency magnitude curve.

In actual practice, this matches the magnitude of highest frequency of events in the non-cumulative Frequency-magnitude distribution, as mentioned in above figure. Despite the easy applicability of this approach, Mc is generally underestimated especially for gradually-curve frequency-magnitude distributions that end from spatial heterogeneities. Using ZMAP software the b-value by Maximum Curvature method can be find out easily.

CHAPTER 4
DATA COLLECTION & ITS ANALYSIS

4.1 Data Set

The local earthquake data collected for the period from 2008-2018 from the deployment of 12 stations seismological network by the Department of Earthquake Engineering, IIT Roorkee, funded by the THDC India Ltd, Rishikesh.

For the given period total 3972 earthquake events are there in magnitude ranges from $0 < M < 5$, in which the maximum no. of events are falling in the magnitude range of $1.0 < M < 2.0$ shown in figure no. **4**.

4.2 Homogenization of catalogue:

Earthquakes are recorded in different kind of magnitude like Body wave Magnitude (Mb), Surface wave magnitude (Ms), Local/Richter magnitude (M_L) etc. So, for seismic hazard assessment it is pre-required to homogenize the catalogue, means conversing different kind of magnitude scale into single type. Here, in our case the chosen catalogue is already homogenized since the recording of the data is being carried out in Local magnitude (M_L) i.e. Richter magnitude scale only.

4.3 Declustering of data:

In declustering mainly, dependent events like foreshock and aftershock are needed to remove from the catalogue and also repeated earthquake events segregated from the catalogue. In our case, for the time being, as per manual analysis the data been considered declustered since there is no repetition of same magnitude earthquake, no need to remove dependent events like foreshock and aftershock because of non-occurrence of higher magnitude earthquake in the given period.

Although, the data set been considered declustered manually but even though the data has been declustered by the method given by Gardner and knopoff (1974) using ZMAP Software.

Here, the b-value estimation is been done by considering both kinds of data type by Maximum Likelihood method with the help of using ZMAP software.

1- Considering whole data set from 2008-2018, containing 3972 events (figure no.4)
2- Considering declustered data set by Gardner and Knopoff (1974) method using ZMAP software, In this, the declustering found 613 clusters of earthquake, a total of 2428 events out of 3972. The map window now displays the declustered catalogue containing 1544 events represented by blue dot in seismicity map & individual clusters are displayed as magneta pluses (figure no.**5**). Histogram of events after declustering process is also been displayed in (figure no.**6**).

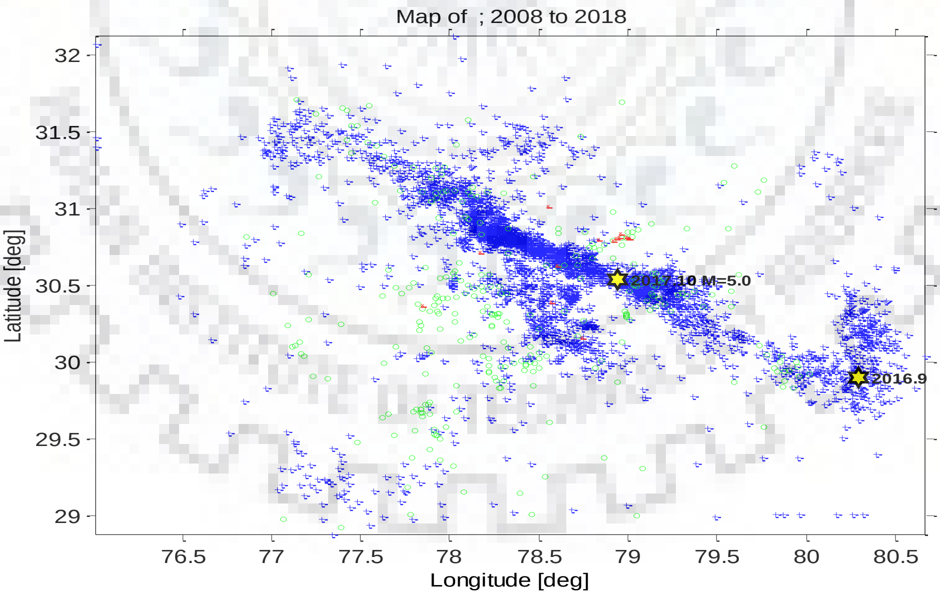

Figure 3 : Seismicity map before declustering of data

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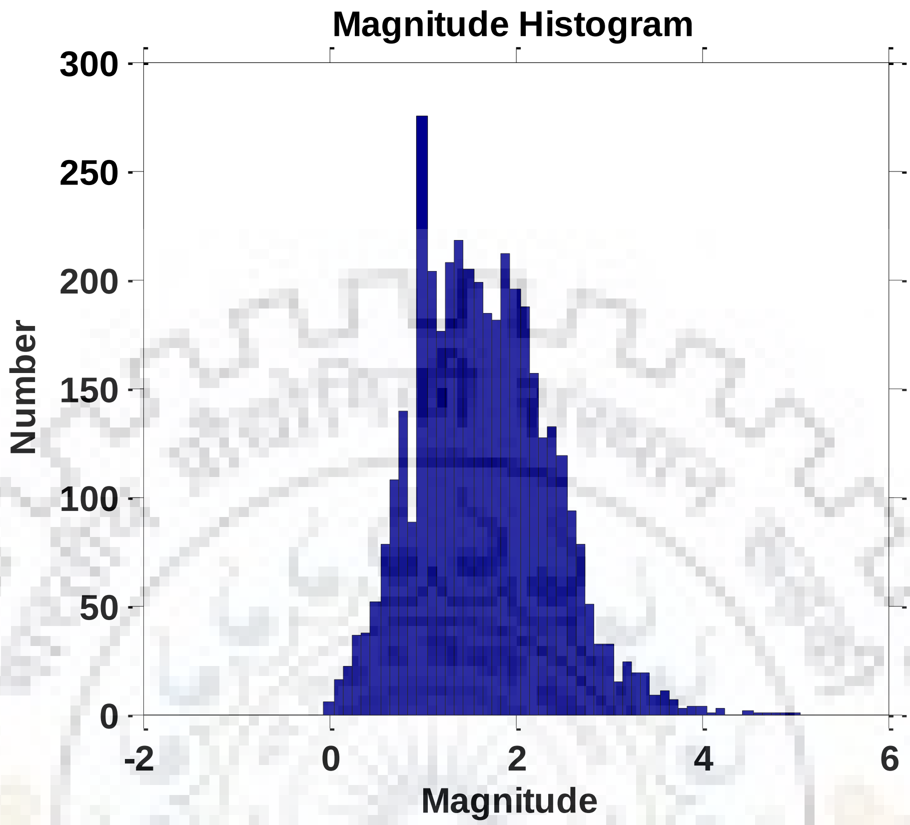

Figure 4 : Magnitude Histogram before declustering of data

Likewise, the declustering is done in yearly data set and then the b-value estimation is done for each selected region (detailed in chapter no.**5**), and after that the comparison graph corresponding to various regions showing temporal variation in b-value is also depicted in various figures of chapter no.(**6**).

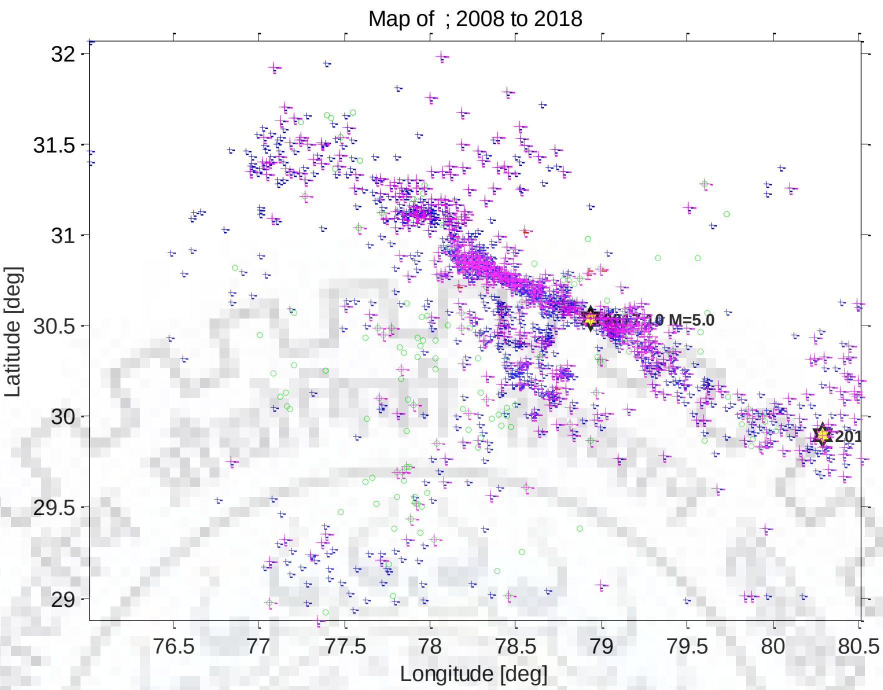

Figure 5 : Seismicity map after declustering

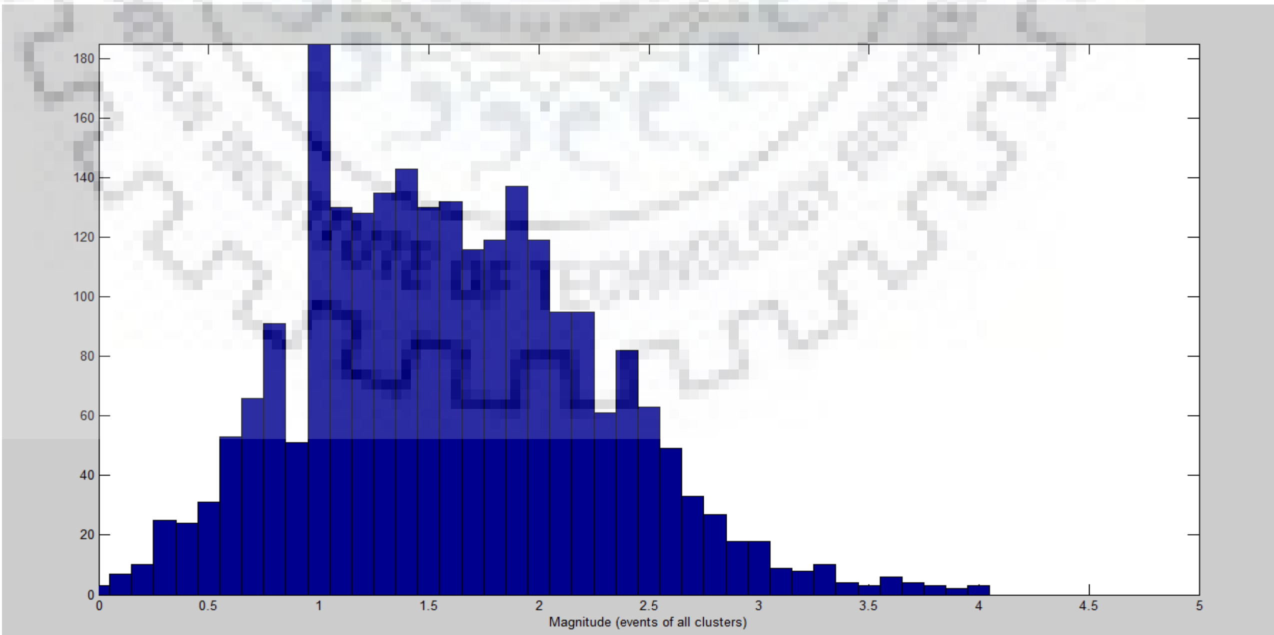

Figure 6 Magnitude histogram after declustering of data

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CHAPTER 5

STUDY AREA & DIVISIONS INTO CLUSTERS

5.1 Area of study

For analyzing Spatio-temporal variation in b-value, the Garhwal Himalayan Region has taken for study purpose.

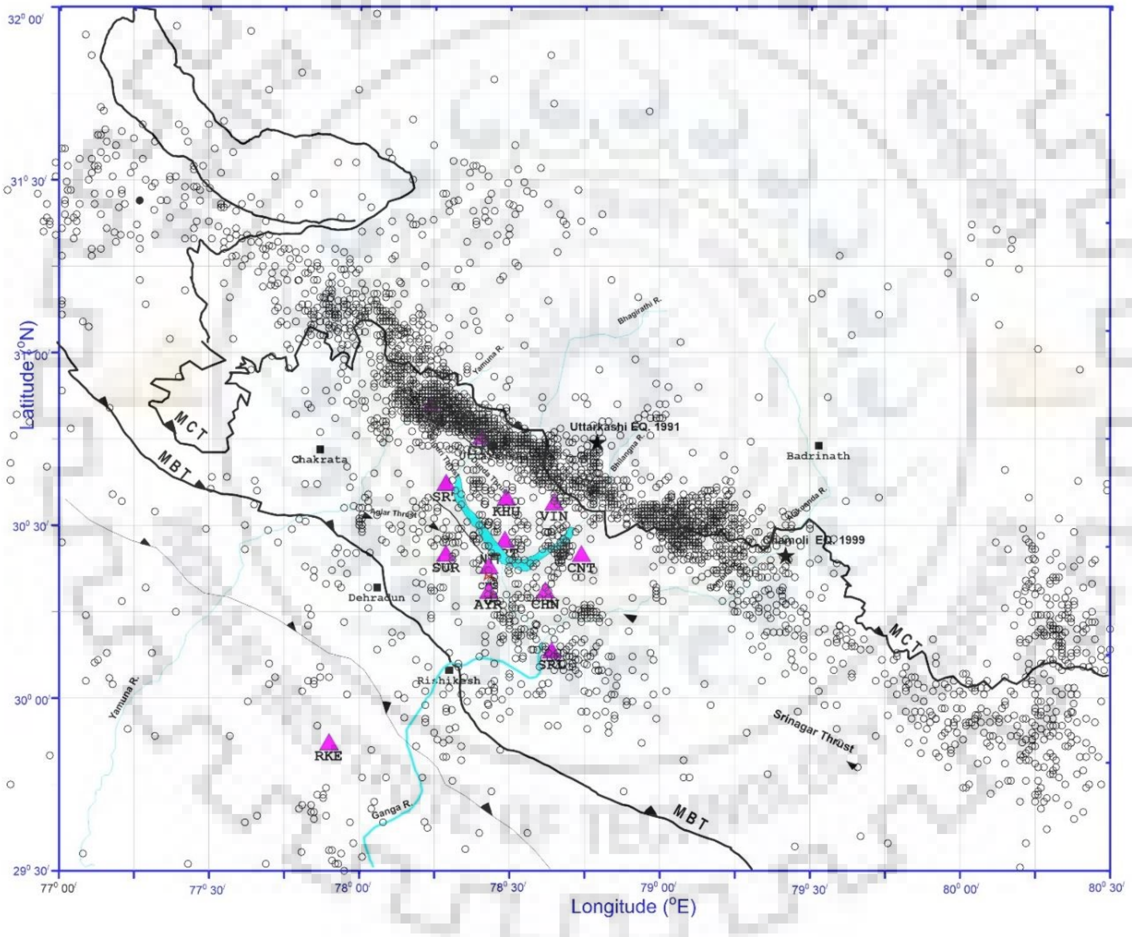

Figure 7 : Seismicity map of whole Garhwal Himalayan Region

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In the above figure the distribution of events shown for the chosen data from 2008-2018. In entire Garhwal Himalayan Region, total 3972 events occurred in magnitude range 0 < M < 5.0 and the same will be analyzed for seeing the spatial-temporal variation in b-value.

5.2 Division into four cluster

The whole region has been divided into four clusters namely **Cluster1**- Himachal portion region, **Cluster 2**- Tehri around region, **Cluster 3**- Chamoli-Uttarkashi region & **Cluster 4**- Pithauragarh region, for better optimization of b-value in space & temporally.

b-value with respect to each zone is estimated in chapter no.(6)

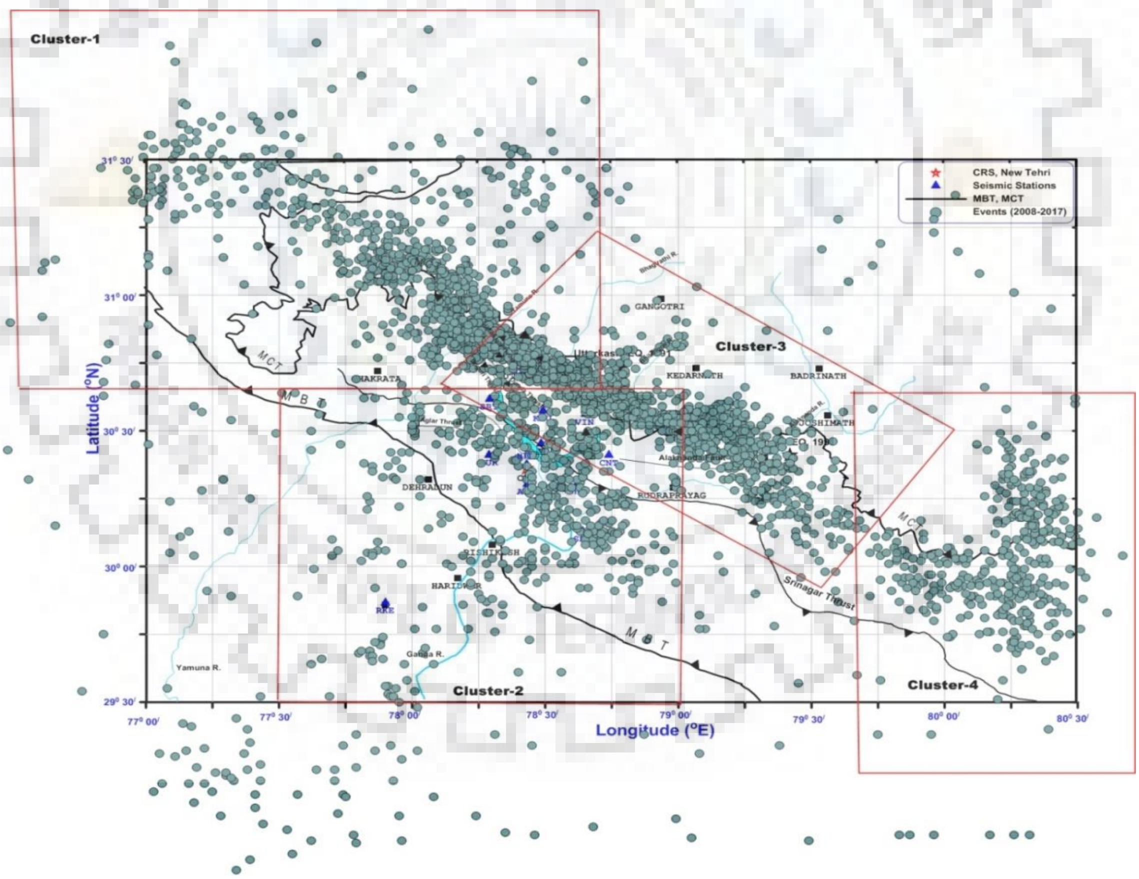
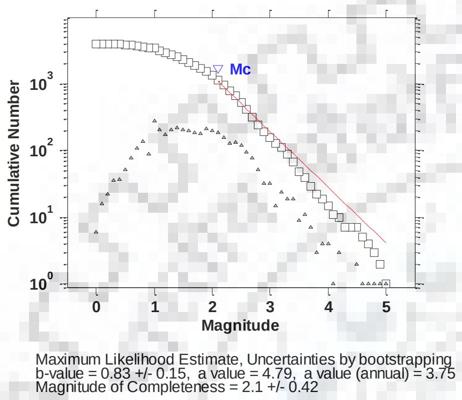


Figure 8 : Division into Four cluster

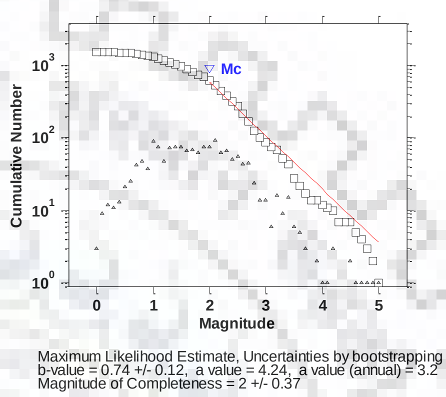
CHAPTER 6

B-VALUE BY MAXIMUM LIKLIHOOD METHOD

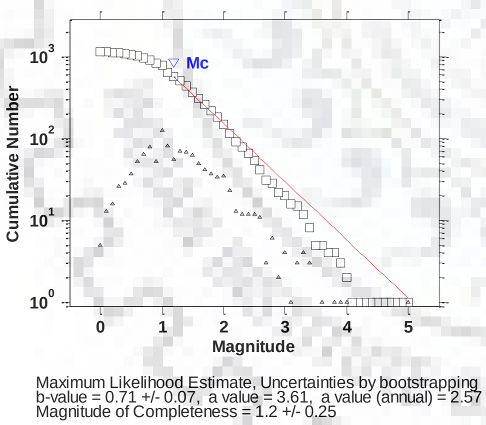
6.1 b-value estimation in whole Garhwal Himalayan Region & in its four clusters before and after declustering by gardner and knopoff (1974) for catalogue from 2008-2018



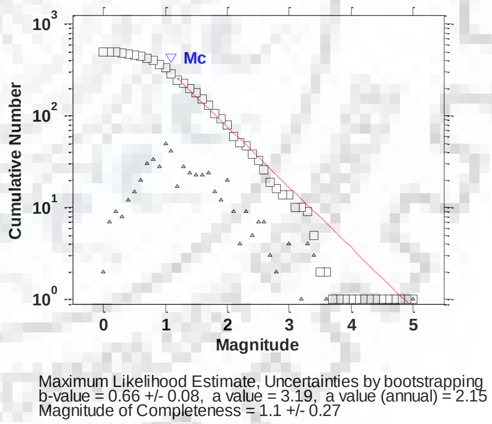
Entire Garhwal Himalayan Region Before declustering



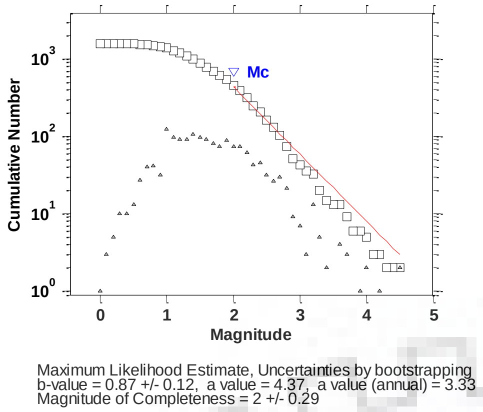
Entire Garhwal Himalayan Region after declustering



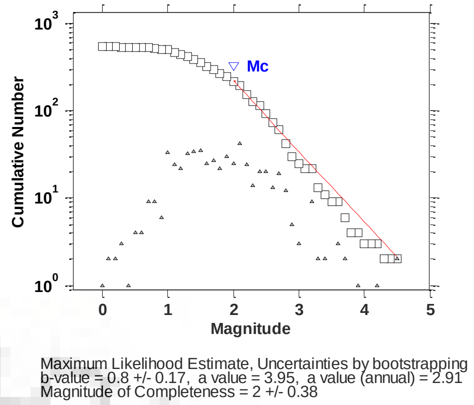
Tehri Region Before declustering



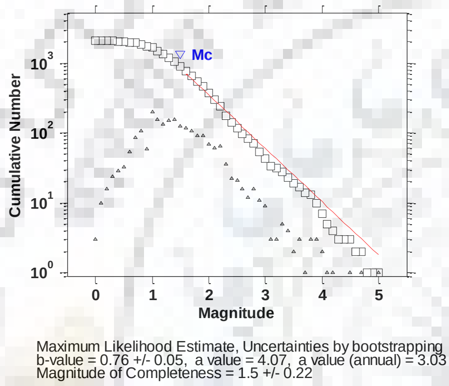
Tehri Region after declustering



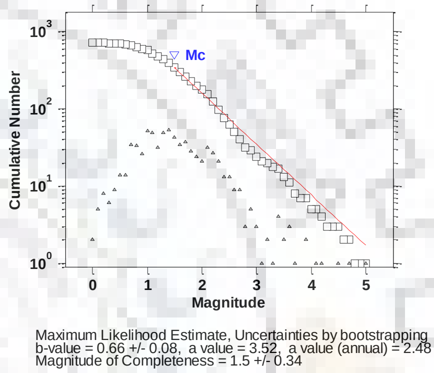
Himachal region before declustering



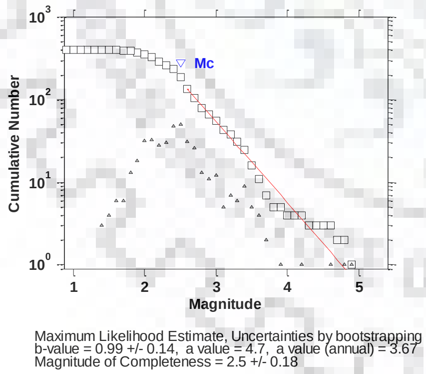
Himachal region after declustering



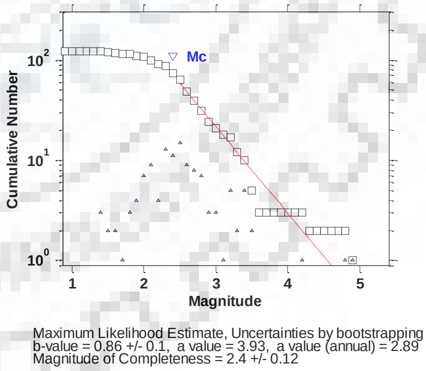
Chamoli-Uttarkashi Region before declustering



Chamoli-Uttarkashi Region after declustering



Pithauragarh Region before declustering



Pithauragarh region after declustering

Figure 9 : b-value, Mc value estimation by Maximum likelihood method for earthquake catalogue from 2008-2018 before declustering and after declustering of catalogue by gardner and knopoff (1974).

Table 1: Comparison table for whole catalogue from 2008-2018

Region name	Period	b-value before declustering	b-value after declustering	Mc- before declustering	Mc-After declustering
Whole Garhwal Himalayan	2008-2018	0.83	0.74	2.10	2.00
Tehri	2008-2018	0.71	0.66	1.20	1.10
Himachal	2008-2018	0.87	0.80	2.00	2.00
Chamoli-Uttarkashi	2008-2018	0.76	0.66	1.50	1.50
Pithauragarh	2008-2018	0.99	0.86	2.50	2.40

6.2 b-value estimation in Garhwal Himalayan Region year wise

Table 2 : Events, b, Mc values for Garhwal-Himalayan Region

Entire Garhwal Himalayan Region	Events before declustering	Events after declustering	b-value before declustering	b-value after declustering	Mc-before declustering	Mc-after declustering
2008-2018	3972	1544	0.83	0.74	2.1	2.0
2008	391	191	0.84	0.86	1.6	1.6
2009	484	199	1.18	1.25	2.0	2.2
2010	419	197	1.34	0.97	2.0	1.8
2011	399	135	1.07	1.00	2.0	2.0
2012	333	109	0.68	0.65	1.8	1.9
2013	241	115	0.6	0.75	1.3	1.8
2014	309	139	0.65	0.62	1.6	1.4
2015	321	133	0.59	0.53	1.6	1.4
2016	300	120	0.63	0.56	1.7	1.6
2017	341	113	0.61	0.62	1.1	1.4
2018	434	153	0.81	0.82	1.7	1.9

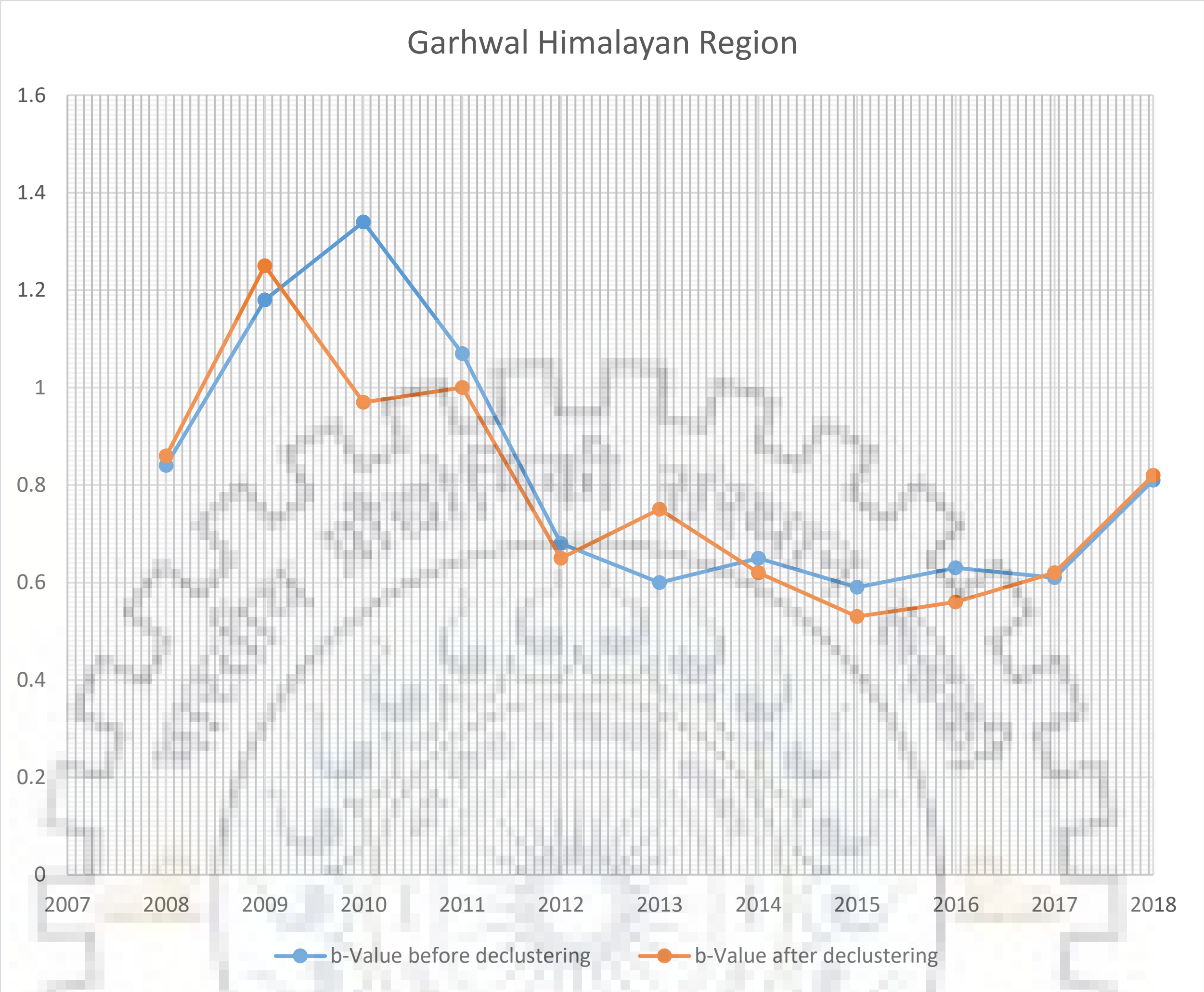


Figure 10 : Temporal variation in b-value in Garhwal Himalayan Region

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6.3 b-value estimation in Tehri Region year wise

Table 3: b-value, Mc value in Tehri Region

Tehri Region(77.5-79E to 29.5-30.7N)	Events	b-value before declustering	b-value after declustering	Mc-before declustering	Mc-after declustering
2008-2018	1135	0.71	0.66	1.2	1.1
2008	161	0.87	0.68	1.2	0.95
2009	139	0.81	0.72	1.2	1.1
2010	93	0.76	0.8	1.1	1.0
2011	98	0.82	0.76	1.2	1.2
2012	83	0.69	0.74	1	1.6
2013	62	0.89	0.85	1.3	1.5
2014	74	1.1	1.24	1.2	1.2
2015	76	0.81	1	0.97	1.0
2016	80	0.74	0.64	1.1	1.1
2017	120	0.71	0.78	1	1.2
2018	145	0.69	0.79	0.93	1

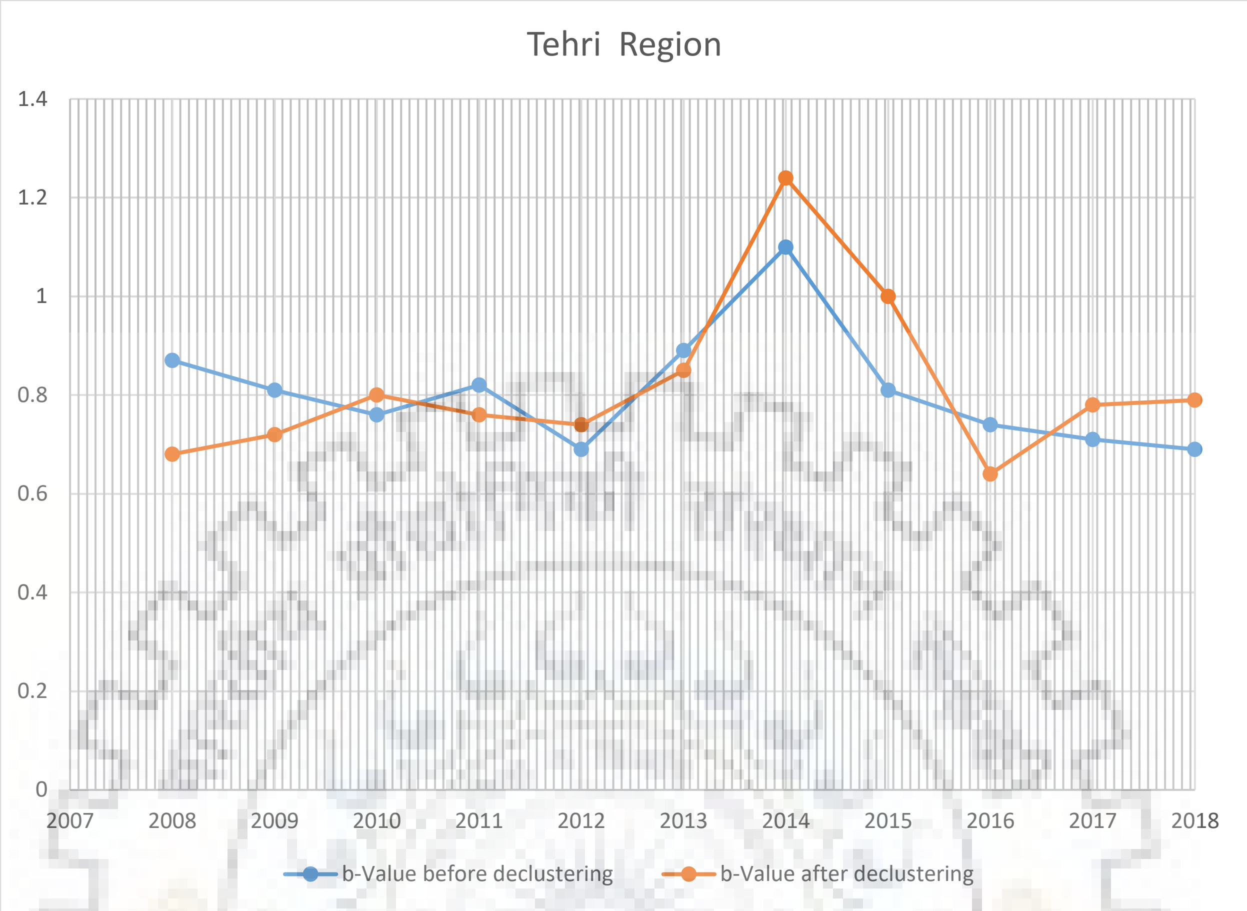

Figure 11 : Temporal variation in b-value in Tehri region

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6.4 b-value estimation in Himachal Grid yearwise

Table 4:. Events, b, Mc values for Himachal around Region

Himachal Grid(76.70-78.60E to 30.70-32.0N)	Events	b-value before declustering	b-value after declustering	Mc-before declustering	Mc-after declustering
2008-2018	1825	0.87	0.8	2.0	2.0
2008	126	0.91	1.15	1.6	1.7
2009	177	1.03	1.35	1.6	2.1
2010	156	0.85	1.13	1.4	1.8
2011	165	1.28	1.48	2.1	2.2
2012	149	0.64	0.73	1.2	1.7
2013	85	0.62	0.66	1.3	1.6
2014	105	0.72	0.94	1.4	1.7
2015	99	0.83	0.73	1.5	1.4
2016	38	0.61	0.61	1.4	1.4
2017	102	0.98	0.87	1.4	1.4
2018	175	0.76	0.85	1.3	1.8

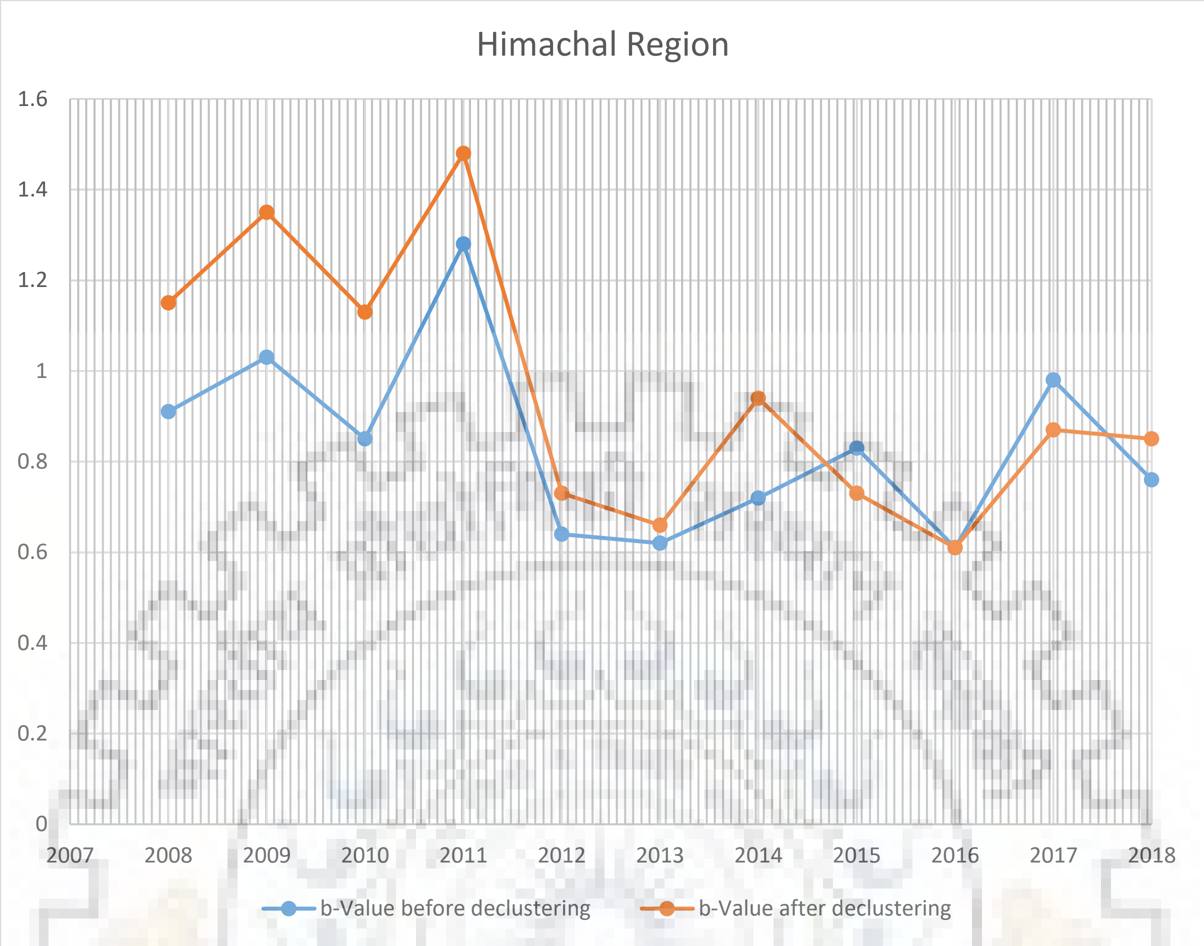

Figure 12 : temporal variation in b-value in Himachal Region

6.5 b-value estimation in Chamoli- Uttarkashi Region yearwise

Table 5: Events, b, Mc values for Chamoli-Uttarkashi Region

Diagonal Element(78, 30.70-80,30.5 to 79.60,29.90 to 78.60,31.20)	Events	b-value before declustering	b-value after declustering	Mc-before declustering	Mc-after declustering
2008-2018	1941	0.76	0.66	1.5	1.5
2008	209	1.32	1.05	1.6	1.3
2009	313	1.03	1.01	1.5	1.7
2010	217	0.95	1.12	1.4	1.5
2011	183	0.85	0.82	1.5	1.5
2012	161	0.7	0.62	1.3	1.5
2013	52	0.71	0.83	1.2	1.5
2014	136	0.91	1.04	1.1	1.4
2015	157	0.57	0.56	0.87	1.0
2016	133	0.63	0.55	1.1	1.2
2017	139	0.6	0.53	0.93	1.2
2018	241	0.79	0.78	1.1	1.4

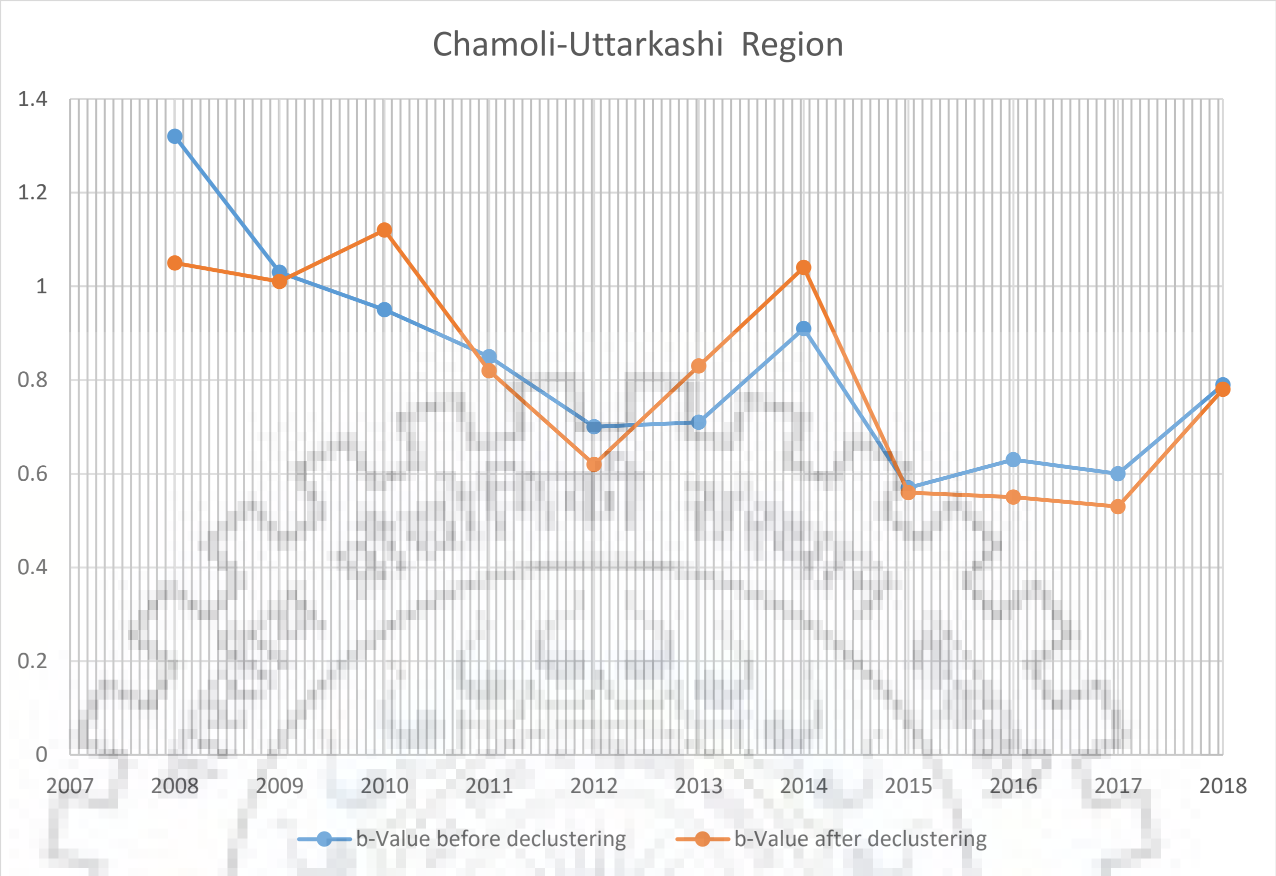

Figure 13: Temporal variation in b-value In Chamoli-Utarkashi Region

6.6 b-value estimation in Pithauragarh Region yearwise

Table 6: Events, b, Mc values for Pithauragarh Region

Pithauragarh (79.70-80.75E to 29.20-30.70N)	Events	b	Mc
2008-2018	238	0.99	2.5
2008	12	2.35	2.5
2009	25	2.39	2.4
2010	24	1.88	2.5
2011	40	1.67	2.3
2012	45	0.99	2.5
2013	12	1.08	2.7
2014	42	0.94	2.5
2015	26	0.86	2.3
2016	18	0.76	2.6
2017	12	1.08	2.1
2018	16	0.96	2.6

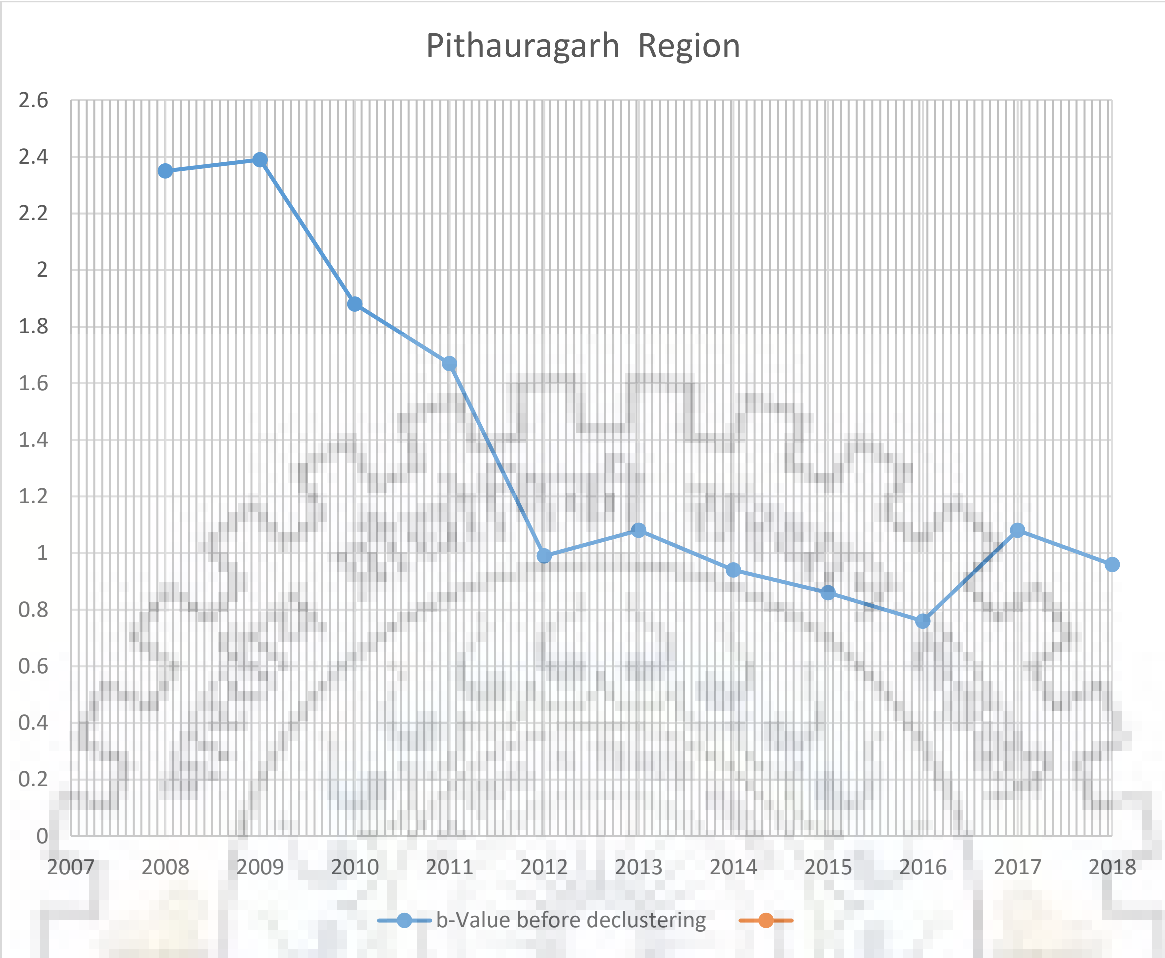

Figure 14: Temporal variation in b-value in Pithauragarh Region

Here, in this Pithauragarh region, the temporal variation i.e. Yearwise evaluation in b-value has not done after declustering of the data since the events are already very less in numbers.

So, b-value evaluation in this region has done considering the whole data set prior to declustering only.

CHAPTER 7
B-VALUE BY SLIDING WINDOW METHOD

For temporal variation in b-value, when we are going to evaluate the b-value with time in ZMAP then automatically, the default window size of sample it takes of 500 events and minimum no. of 50 events with overlap of 4 events.

In some case, where the sufficient events are not available in that case this method does not give good result viz. in our case while evaluation of b-value in **Pithauragarh Region**, which is a **sub-region** of **Garhwal Himalayan Region** and for which we did evaluation in previous chapter by **Maximum Likelihood Method** also. So, by the sliding window method as shown in figure no.**29** , the result is coming absurd due to less no. of event available but by **Maxmimum Likelihood Method** some pattern of graph been identified.

By the above observation, this can be conclude that this **sliding window method** although provide us the smooth curve since it is based on moving average method but it is useful in area where sufficient window size is available otherwise it may provide absurd results, which may not be useful. Therefore, for the time being, for whole **Garhwal Himalayan Region** & its **four sub-region**, the evaluation in b-value by both methods has been done for comparison purpose and also to avoid by any discrepancy in evaluation.

7.1 Garhwal Himalayan Region:

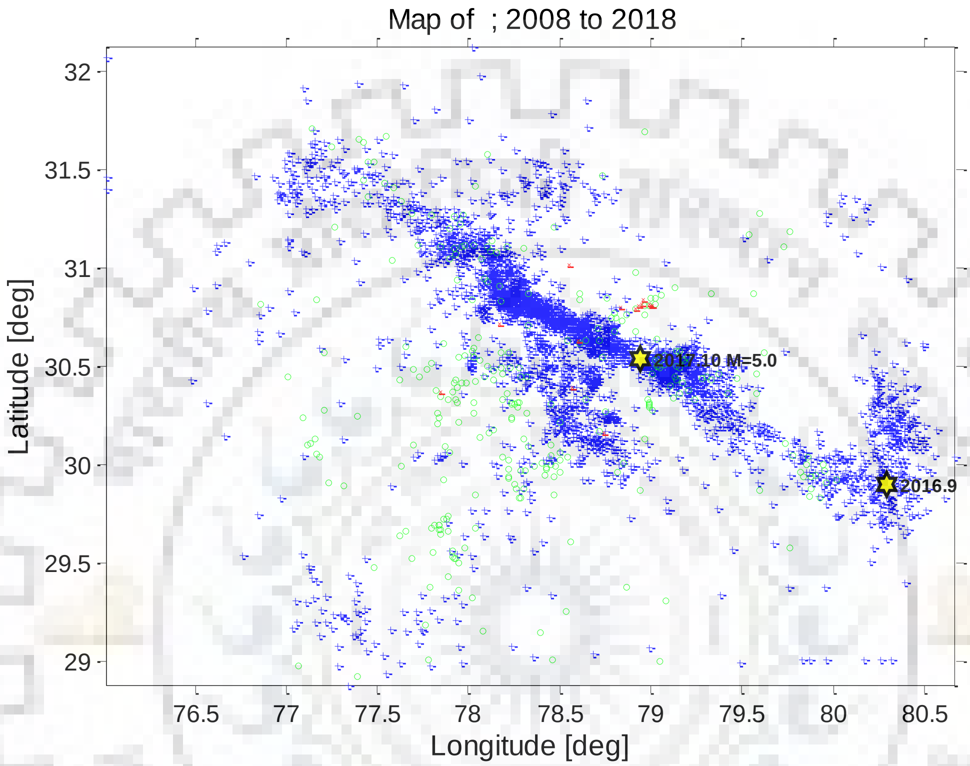

Figure 15: Seismicity Map of whole Garhwal Himalayan Region

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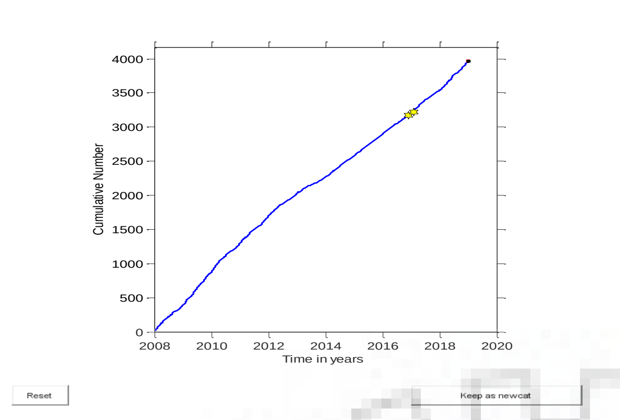
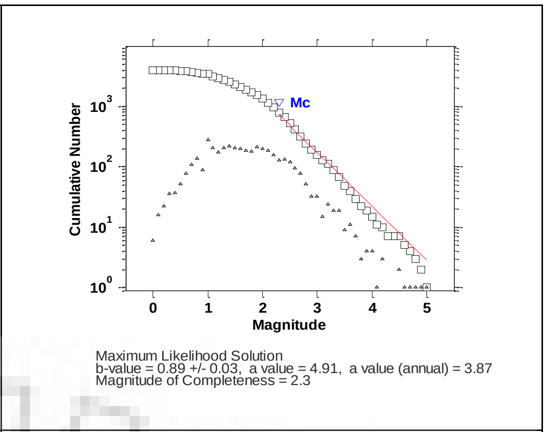




Cumulative Graph

B, a and Mc value

Figure 16 : Cumulative & b-value Graph by Sliding window method

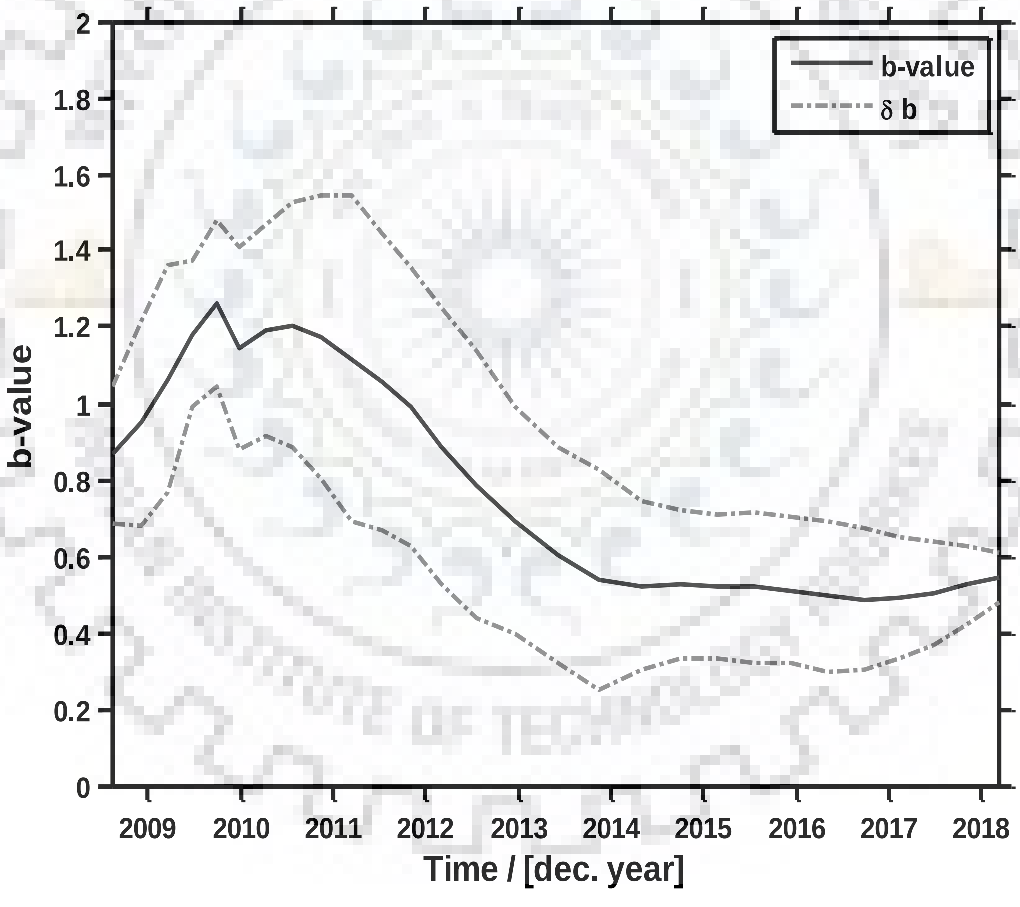


Figure 17 : Temporal variation in b-value using sliding window method

7.2 Tehri Region:

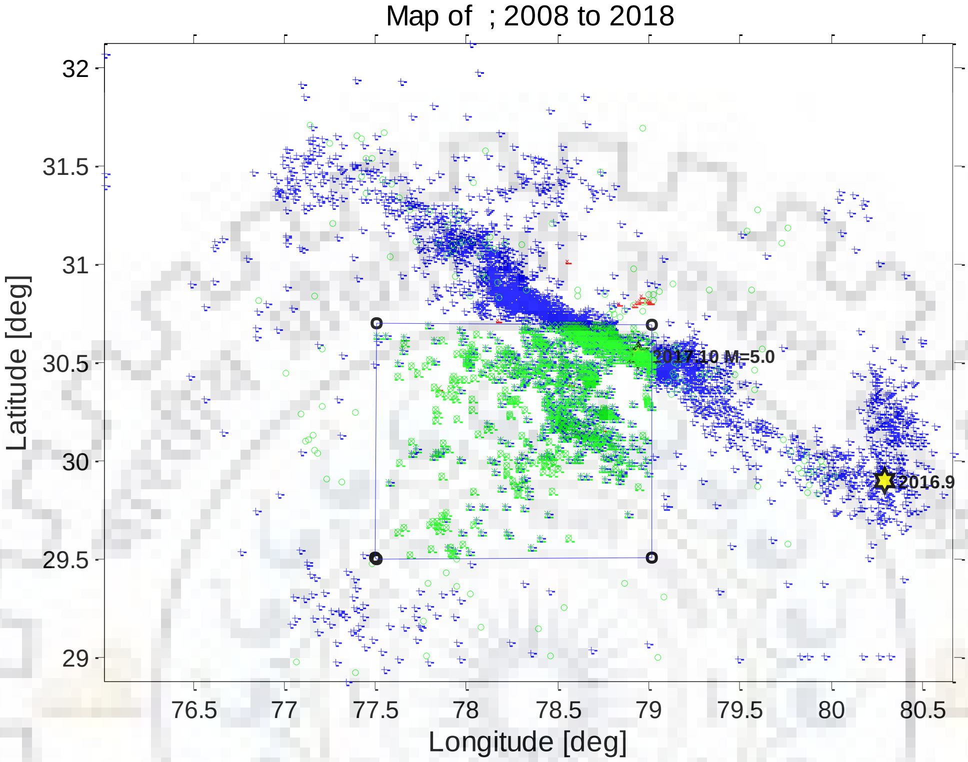
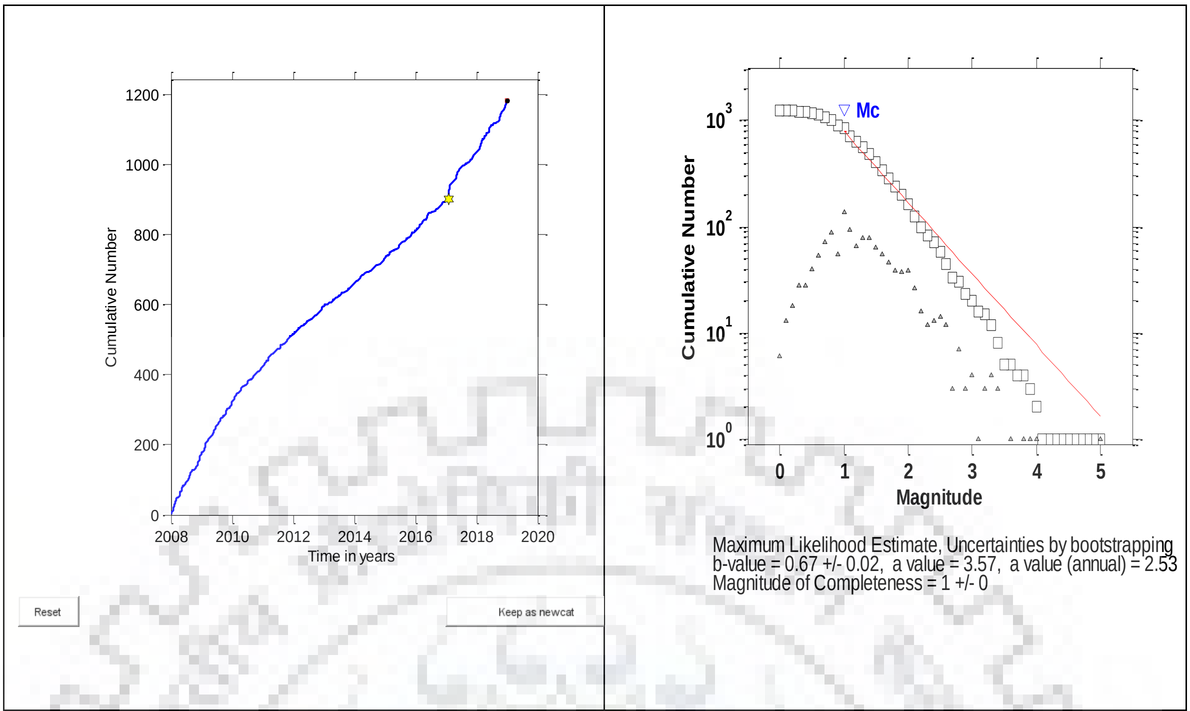


Figure 18 :Seismicity map (Selected Rectangular Grid) of Tehri Region



Cumulative Graph	B, a and Mc value

Figure 19: Cumulative & b-value Graph by Sliding window method

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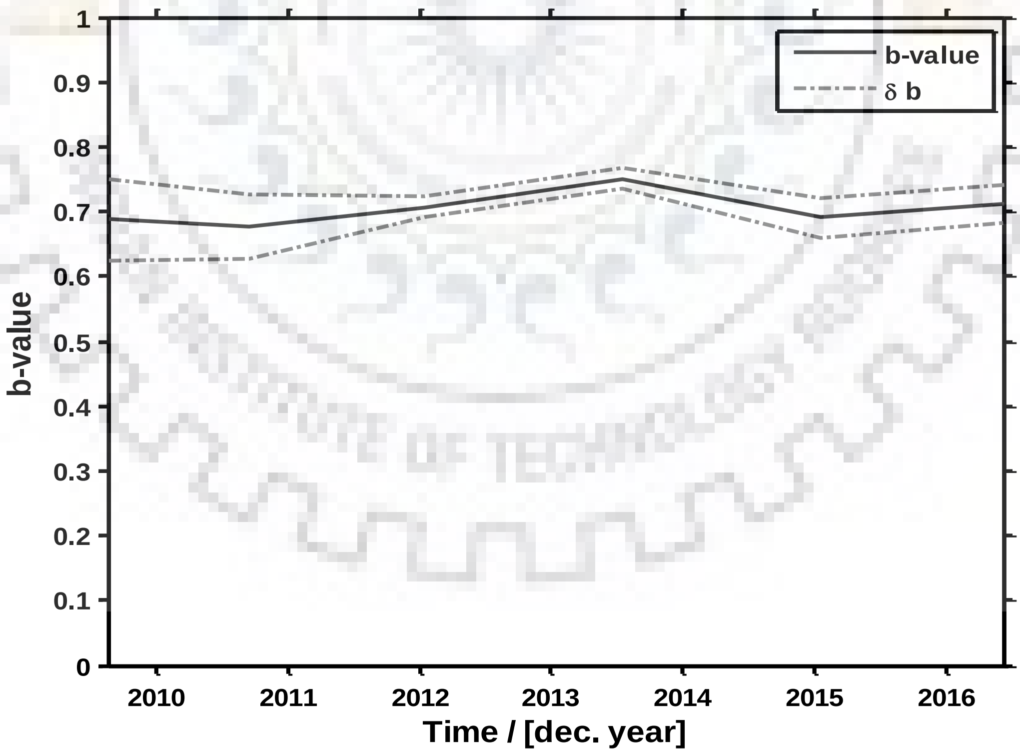


Figure 20 : Temporal variation in b-value using sliding window method

7.3 Himachal region:

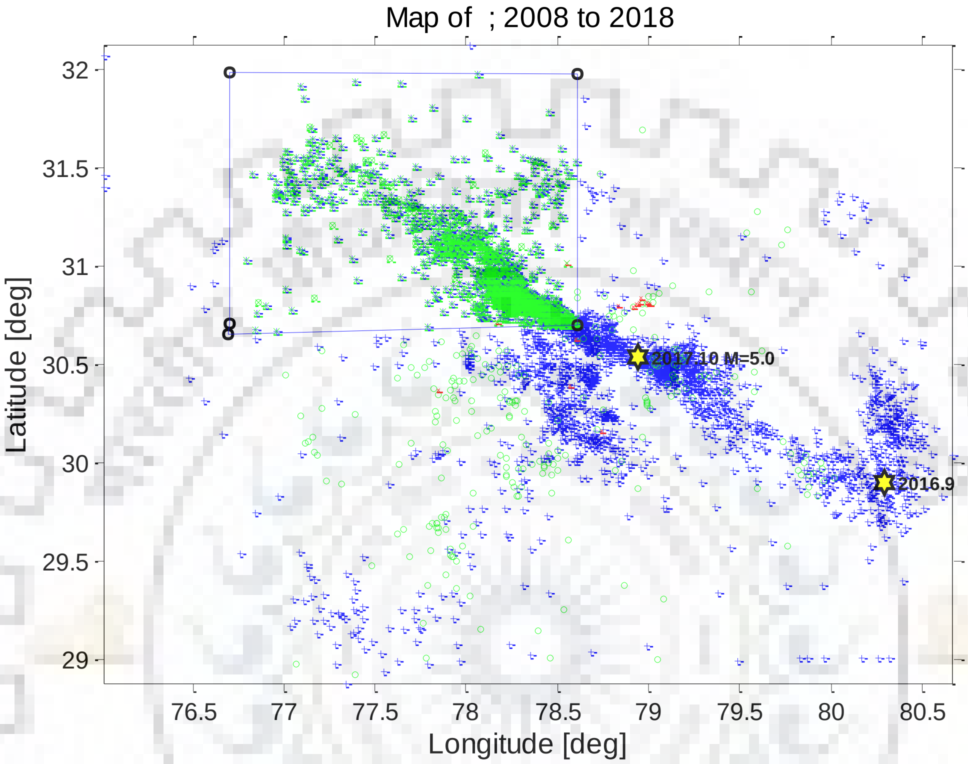
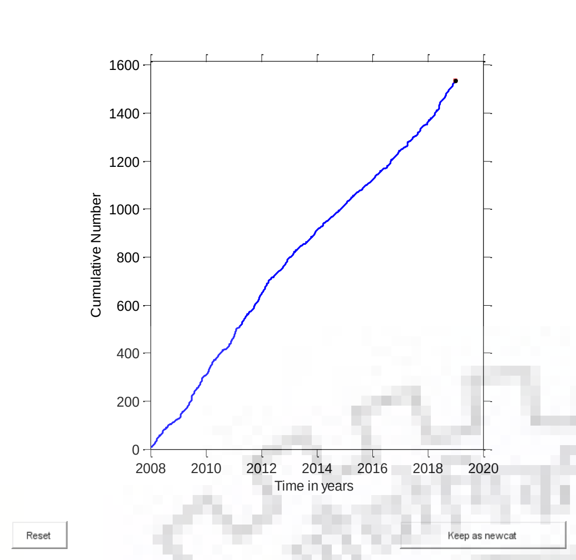
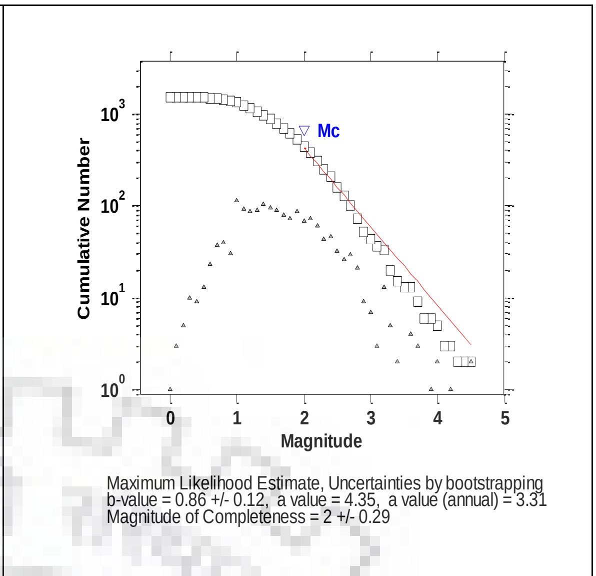


Figure 21: Seismicity map (Selected Rectangular Grid) of Himachal region





Cumulative Graph	**B, a and Mc value**

: **Figure 22**: Cumulative & b-value Graph by sliding window method

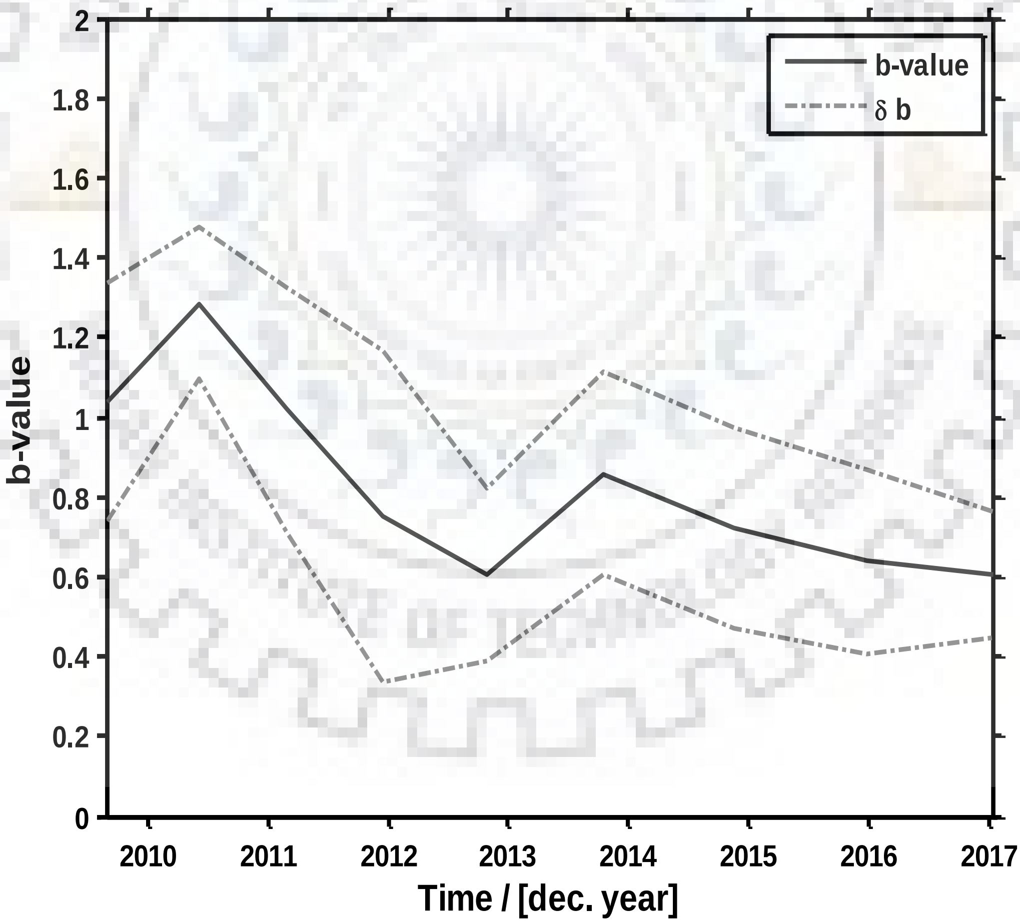


Figure 23 : Temporal variation in b-value using sliding window method

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7.4 Chamoli-Uttarkashi region

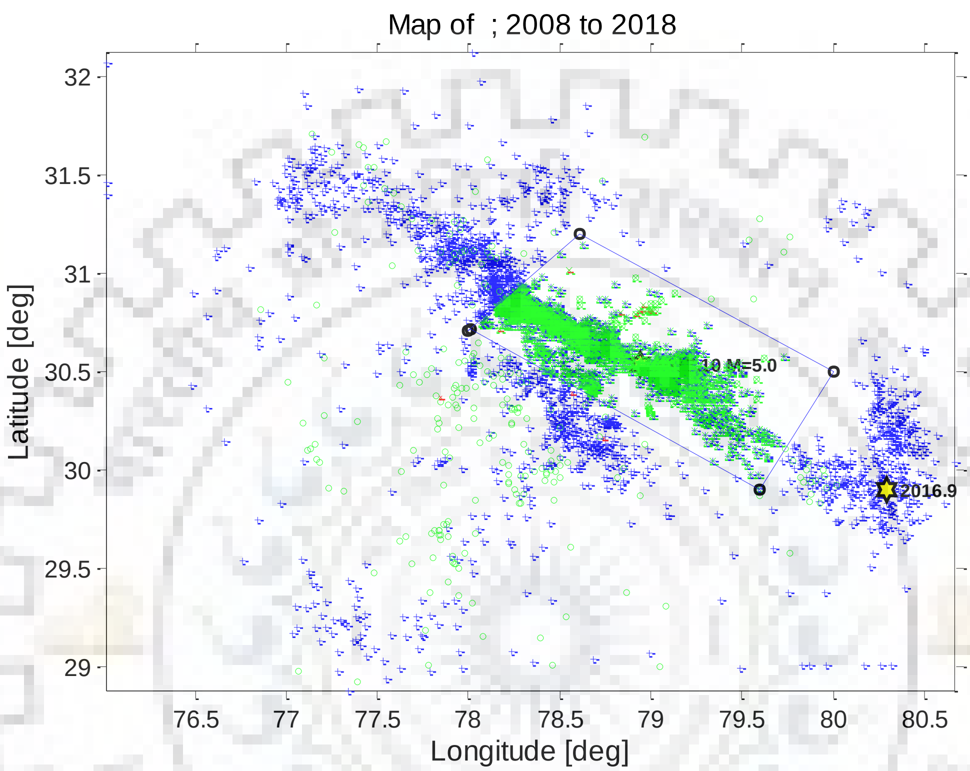
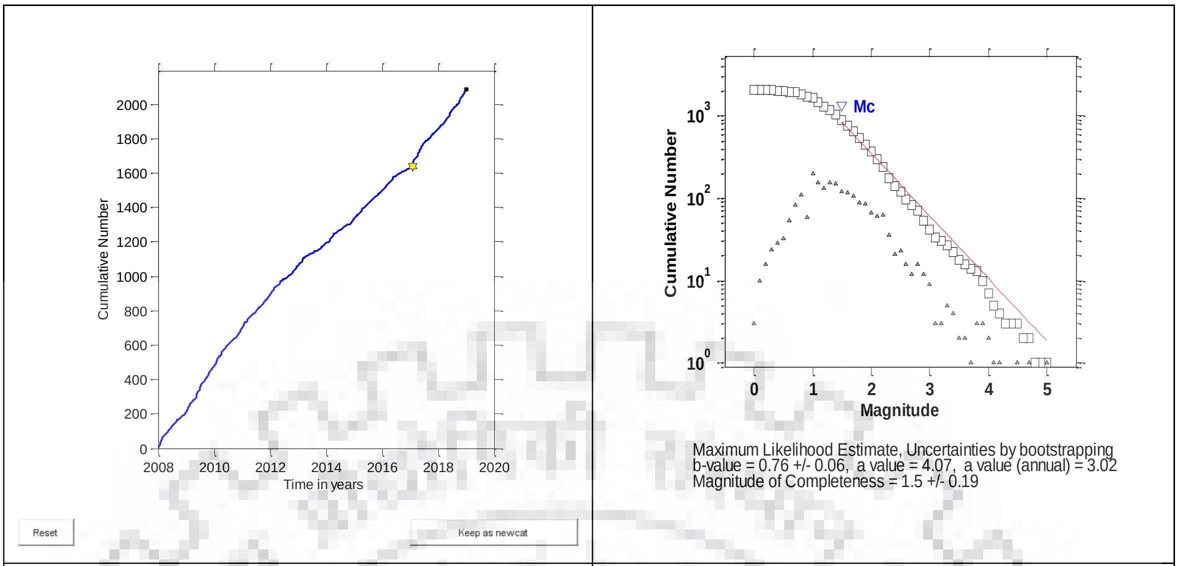


Figure 24: Seismicity map (Selected Rectangular Grid) of Chamoli-Uttarkashi region



Cumulative Graph	B, a and Mc value

: **Figure 25**: Cumulative & b-value Graph by sliding window method

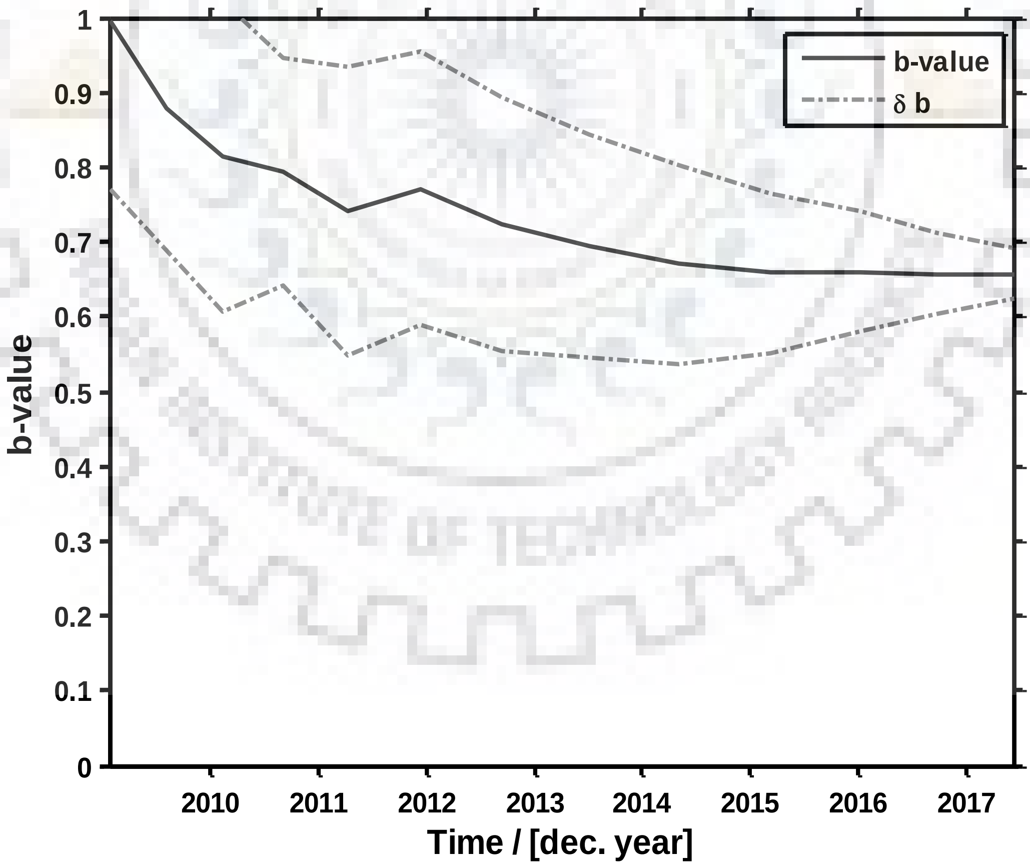


Figure 26: Temporal variation in b-value using sliding window method

7.5 Pithauragarh Region

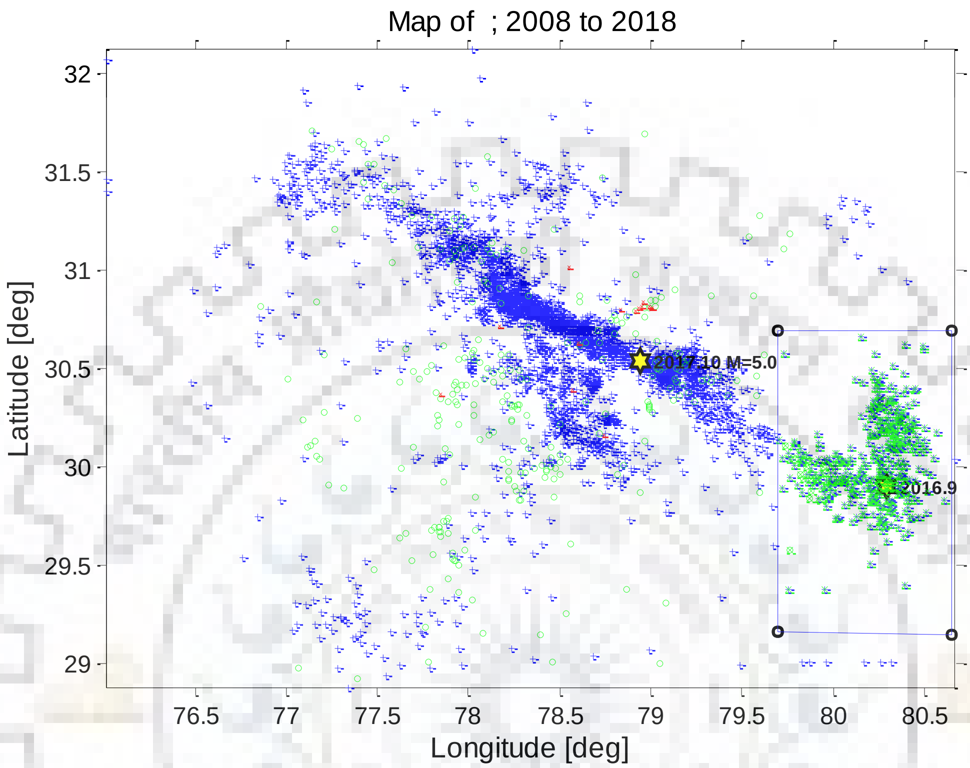
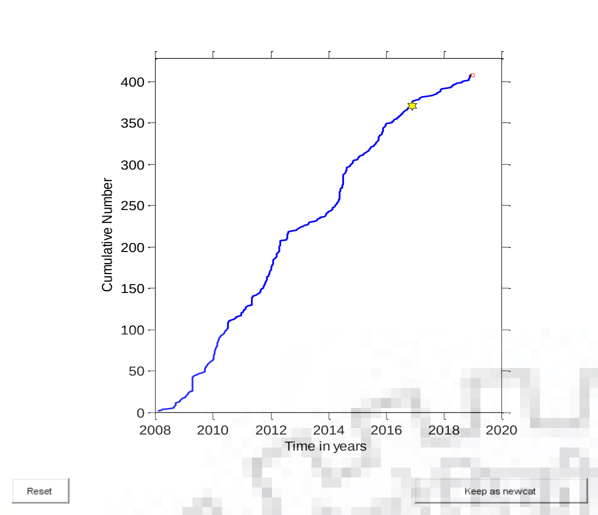
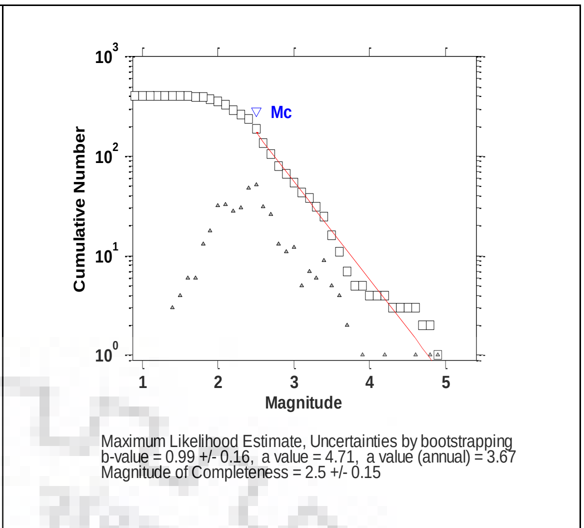


Figure 27: Seismicity map (Selected Rectangular Grid) of Chamoli-Uttarkashi region





Cumulative Graph	B, a and Mc value

Figure 28: Cumulative & b-value Graph by sliding window method

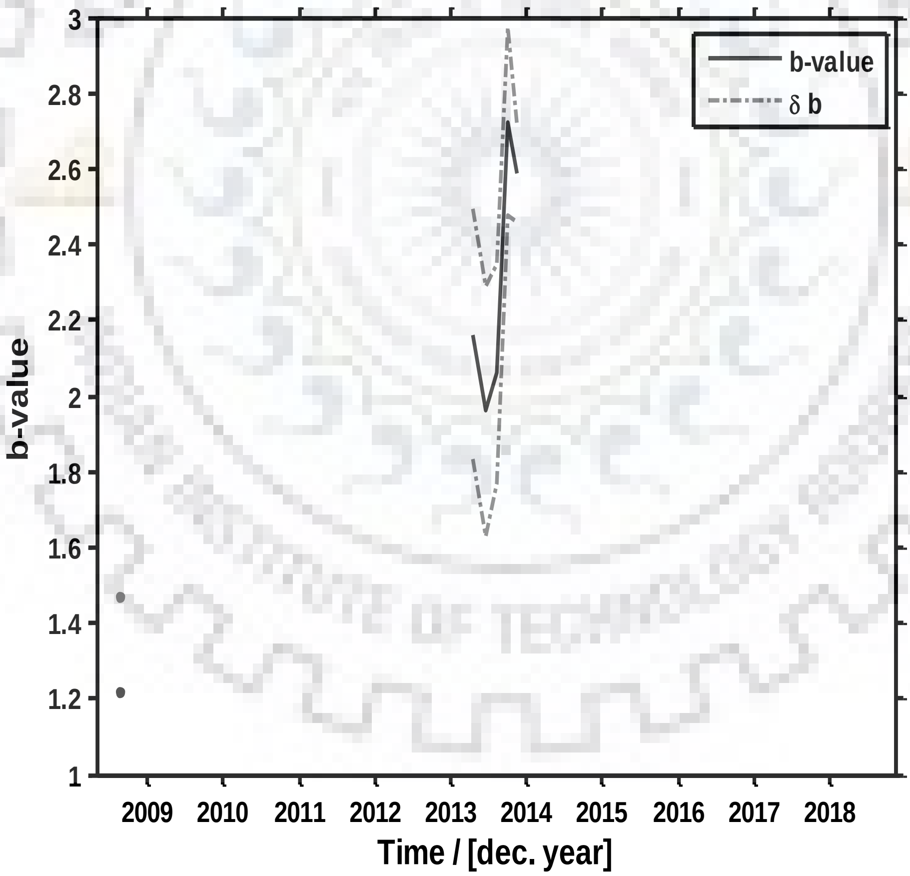


Figure 29: Temporal variation in b-value using sliding window method

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CHAPTER 8

SPATIAL VARIATION IN B-VALUE

8.1 Whole Garhwal Himalayan Region:

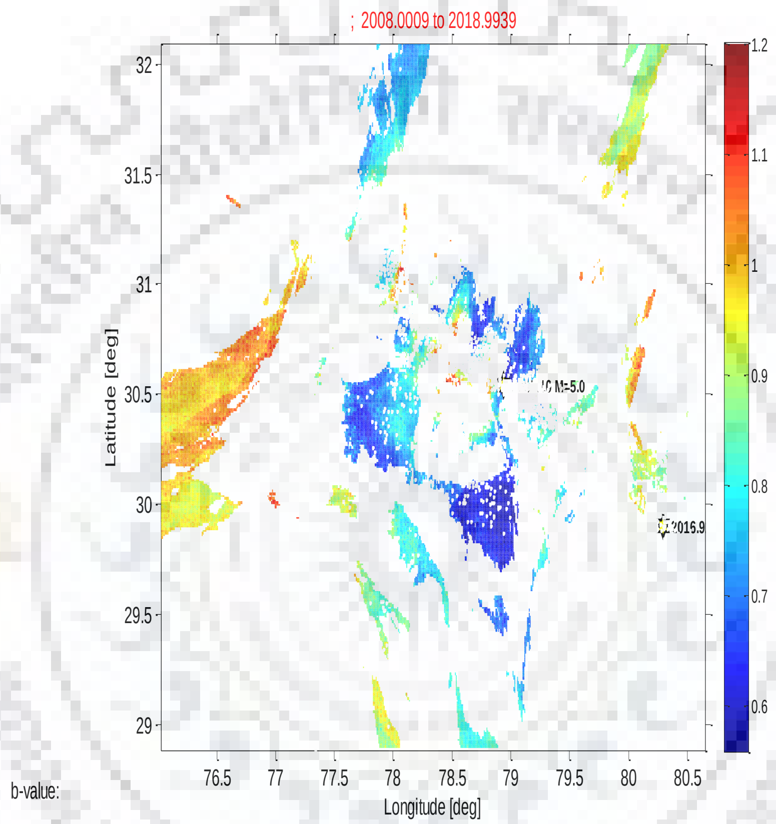

Figure 30 : Spatial variation in b-value for whole Garhwal Himalayan Region

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For spatial variation in b-value, I have divided the entire region into 0.01x0.01 degree grid for evaluating b-value in space. The dark blues colour showing less b-values area means high stressed region, yellow colour with intermediate b-value and red colour with higher b-values, means less stressed region.

CHAPTER 9

RESULT & DISCUSSION

Considering the Graph of **whole Garhwal Himalayan Region** by both **Maximum Likelihood method** (In which before and after declustering of catalogue data) and **Sliding window method**, the variation pattern in b-value is almost same all the three arisen cases means the trend of graph with respect to years is almost same in all the cases, this implies that our estimated b-value pattern is error free.

Now, some observation are enlightens here at some point in Graph keeping in view the decreasing and increasing pattern in b-value and how does it actually depends upon the occurred earthquake of 3.0 < M <5.0.

- Since, the b-value in year 2008 is 0.84, which is below then normal value of b i.e. 1.0, this implies that the chances of near future earthquake are there, which can be verified by January EQ of 2008 had magnitude 4.0, 4.90 and August EQ of 2008 had magnitude 4.0, 4.2 respectively. After that numerous greater then 3.0M earthquake came due to which accumulated stress has been released that may resulted to increase in b-value. Further the declustered catalogue showing the decreasing pattern in b-value followed by February, 2010 EQs of 4.5M and 4.70M EQ of May month respectively. Consequently, before occurrence of higher magnitude i.e. >4.0M particularly in our case for the chosen catalogue, the decrease in b-value need to take place because of accumulation of built-up stress.
- Further, b-value started decreasing and reach to its lower limit i.e. 0.53 in our case this is because of many earthquake many earthquake of greater then 4.0M observed in 2015, 2016 and respectively.
- The chosen data for our study is for the period from 2008-2018 i.e. of 11 years which is comparatively not much for prediction far future EQs, it means evaluated b-value here can be used as short term(month-years) earthquake precursor.

- Likewise, we can elaborate the temporal variation in b-value and its usefulness as Earthquake precursor, since this parameter is inversely related to accumulated stress level in tectonics.
- Currently in 2018, the b-value of Garhwal Himalayan Region is **0.81** that is approximately equal to **0.83**, the average value obtained for whole catalogue chosen for period from 2008-2018. Moreover, this whole region experienced, maximum magnitude of EQ of **5.0** came so far in February 2017. b-value attained its lower values in 2015 & 2016 i.e. 0.53 and 0.56 respectively, so there was chance of occurrence of higher magnitude, which was actually the above-mentioned February 2017 Earthquake. After this , the graph of b-value is increasing in nature and the value is almost equals to average value also, so there are less chances of higher magnitude in just near future but considering 11 years pattern of graph there are high chances that the b-value will show its decreasing nature in coming 2 to 3 years.
- This was the overall picture of whole Garhwal Himalayan Region in respect of temporal variation of b-value but we can further go for more area specific studies within this region for spatial variation in b-value and afterwards for predicting the epicentral location of EQs.
- For area specific studies, we have divided the whole Garhwal Himalayan Region into 4 clusters as mentioned in figure no. **8**. Respective plots of graphs have shown the temporal variation in previous chapters for each regions separately.
- Out of the above four regions, the area around Tehri with this latitudinal and longitudinal Grid i.e. **77.5ºE-79.0ºE** to **29.50ºN-30.7ºN,** shows lesser b-value, which is an indication of more stressed region among all regions, so there might be chances of near future EQs in this area particularly as compare to other regions.
- I, also tried to find out the variation in b-value with respect to space separately as shown in figure 30, in which the portion with lower b-value is having dark blue

colour and higher b-value is marked with red colour. The area in dark blue colour is around Tehri region and Chamoli-uttarkashi region, which are common to our 2 clusters considered for study.

- This area is needed to be further study upon because its shows some kind of pattern in its temporal variation of b-value, which need to be monitored for hazard analysis purpose.

CHAPTER 10

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