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Assessment of Heatwave Vulnerability Index and its Spatial Distribution Over Uttar Pradesh, India

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***Abstract*: The recurring extreme events are garnering a lot of attention these days, understanding heatwave vulnerability has been a hot topic among researchers due to its parameters which solely depend upon the local climate, socio-economic conditions, physiological conditions, and also on its local environmental conditions. This study looks into the spatial distribution of heatwave vulnerability over the Uttar Pradesh (UP) region divided into 75 districts. An index has been developed called the Heatwave Vulnerability Index (HVI) employing three variables namely Exposure, Sensitivity, and Adaptive capacity. In these variables, various environmental and socio-economic factors were considered. Spatial distribution for Land Surface Temperature (LST) and Normalized difference vegetation index (NDVI) have also been analyzed in this study. Furthermore, this study evaluated that a total of 11 districts have been found to be in the extremely vulnerable category. Uttar Pradesh is the most populous state in the country, and this study can provide valuable insights into planning various mitigation strategies and formulating various policies for coping with heat waves.**

***Keywords*: Heatwave; Vulnerability, Land Surface Temperature, Exposure, Sensitivity, Adaptive capacity.**

I. Introduction

Weather extremes such as heat waves have become a recurring phenomenon these days owing to climate change which results in a temperature rise which again causes global warming (Ho et al. 2015; Azhar et al. 2017). Thus heat-related diseases (e.g., stroke due to heat waves, exhaustion due to heat waves) and deaths have risen all over the world, particularly in those climatic regions that are prone to high temperatures(Rinner et al. 2010; Ho et al. 2015). Very old people (aged > 60 years) and infants (aged< 5 years) are at risk of getting negatively affected by these events (Aubrecht and Özceylan 2013). These events have caused innumerable mortalities over the years both globally and in India. Some examples are the European 2003 and Russian 2010 heat waves where the casualties are number greater than tens of thousands (Robine et al. 2008; Shaposhnikov et al. 2014). Events like these have also occurred in India during the year 2015-16. While the evidence is mostly from North America and Europe, it is said that deaths are highly underestimated in India.

A study shows that the temperature rise can cause over two hundred additional deaths per 100,000 populations each year globally by the twenty-first century (Carleton et al. 2022). The situation becomes worse when it comes to the Indian subcontinent. A study conducted earlier shows that around 1,500,000 more deaths could happen in India per year due to extreme heat wave events by the year 2100 (Carleton et al. 2022). This study also suggested that the average temperature of extremely hot days may increase over 42^{0}C. Such extreme rises in temperature may cause innumerable deaths in upcoming years. A study shows that the rate of overall mortality for extreme heat wave events has risen to over 60 percent over the last twenty years from the year 2019 (Ray et al. 2021). Over 17000 people have lost their lives due to these extreme heat wave events in the period 1971-2019 out of about 141,000 deaths due to all extreme weather events which is about just over 12% of the total EWE deaths. As per the NCRB reports over 2500 deaths have occurred only in Uttar Pradesh and Bihar from year 2012-21. These reports also suggest that out of these over 2500 deaths about 1500 deaths have occurred only in Uttar Pradesh.

Heatwave vulnerability consists of three factors: namely exposure (E), sensitivity (S), and adaptive capacity (A) (Mac and McCauley 2017). Exposure denotes the people's presence,

resources, and services related to the environment, social, economic, or cultural assets in proximity to heatwave events, which have the potential to cause future harm, damage, or loss. Sensitivity is the physical tendency of the suffering of human beings, the environment, and the infrastructure from the extreme heat event because of a lack of resistance (Zuhra et al. 2019). Adaptive capacity means the ability to adapt to changes in the climatic conditions or environment, of a person, family, social group, or community which guarantees them sustainability and survival. Recent studies that are related to heat wave vulnerability have emphasized sensitivity and exposure while developing an HVI (heat wave vulnerability index) (Johnson et al. 2012; Wolf and McGregor 2013; Nayak et al. 2018). Consideration of all three latent factors of vulnerability has been done by only a few studies such as (Inostroza et al. 2016). The study mentioned in the previous sentence has used a GIS-based approach that uses remote sensing and socio-economic data for heat wave vulnerability index development. Another such research has been done by (Zuhra et al. 2019) and (Raja et al., 2021).

This study will use the heatwave vulnerability index (HVI) to identify more susceptible districts of Uttar Pradesh to heat waves. This study has used the district-wise multidimensional poverty index (MPI)which was developed by the Department of Planning, Uttar Pradesh in 2023 for describing poverty during sensitivity analysis. This index is being incorporated first time in a study for defining poverty during the development of HVI.

II. Materials and Methods

Study Area

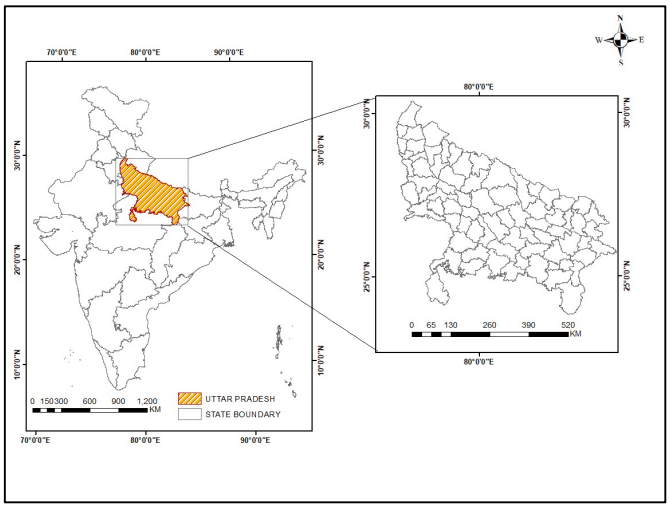

Fig. 1 Study area description.

Uttar Pradesh, a state in the north-central part of India extends from 23°52′Nto 31°28′N latitudes and 77°3'E to 84°39'E longitudes. It is situated east of Delhi which is the capital city of the country and shares a border with Haryana, Rajasthan, Uttarakhand, Madhya Pradesh, Himachal Pradesh, Jharkhand, Bihar, and Chhattisgarh. As per census 2011, it had 71 districts but at present, there are 75 districts in 2024 at the time when this study was being conducted. The state of Uttar Pradesh has a generally humid and subtropical climate with a mostly dry winter. The state ranked as first in terms of population in the country as per data of census 2011. Although UP lags behind the national average of urbanization which is 31.6% but still its urban population increased from about 20.78% in 2001 to about 22.28% in 2011 which shows a rise of about 1.5%. This shows that urbanization is increasing and if the recent census had happened much more rise in urbanization would have occurred. **Fig. 1** depicts the description of the study area of Uttar Pradesh.

Heatwave Vulnerability Index (HVI)

In this present study, the estimation of the heatwave vulnerability index was done by calculating the exposure, sensitivity, and adaptive capacity of the locals living in the area. As per the calculation done in this study exposure and sensitivity add to the HVI positively and adaptive capacity negatively (Raja et al., 2021).

Heatwave vulnerability index (HVI) = E+S-A……..(1)

Here exposure is represented by E, sensitivity by S, and adaptive capacity by A. Many literatures were reviewed to decide the variables which are present in this study. The variables were also decided based on their easy availability. They are expressed such that minimal spatial bias occurs.

Exposure

This study was conducted using land surface temperature (LST) and population density as variables of the respective districts. Many studies in recent times show that LST can be used for measuring heat exposure intensity(Raja et al. 2021).Its influence as a variable on the heatwave vulnerability index is highest among all other variables. If occurs in excess it can induce many cardiovascular and respiratory-related diseases. There are many pieces of evidence available that indicate that a rise in land surface temperature could be linked to increased vulnerability due to heatwaves (McGeehin and Mirabelli 2001).Similarly, there are other studies which show that areas with very dense populations are much more susceptible to heat (Tomlinson et al. 2011).

Sensitivity

On the basis of various other studies which were performed similarly, ten variables are selected which are mentioned in Table 1. People aged>60 years are categorized as older people and most of these people have underlying medical conditions due to their old age and have cardiovascular problems(Aldrich and Benson for CDC 2008).Children with age less than 6 years are also at risk of getting affected by heat waves due to their vulnerability to various diseases that are vector-born (Wilhelmi and Hayden 2010). There are many studies that suggest that illiteracy also makes people somewhat sensitive towards heatwave events as they do not know about the risks (Uejio et al. 2011). Studies also suggest that socioeconomic factors may also be associated with such extreme events. For instance, the people who are affected by poverty cannot afford various utility

facilities (e.g. fans, coolers, AC) and it also makes them vulnerable and sensitive to heatwaves (McMichael et al. 2008). The poverty was explained using the multidimensional poverty index (MPI) which was developed by the Department of Planning, the government of Uttar Pradesh. The MPI was developed by focusing on various qualitative aspects across three dimensions which are health, education, and living standards. This MPI was inspired by the global MPI published by Oxford Poverty and Human Development Initiative. There are studies that suggest that the female population is more sensitive to heat waves in comparison to men(Johnson et al. 2012). The nature of work also affects the sensitivity towards heat waves. For example, people in occupations like agriculture and industrial work have more susceptibility towards extreme events such as heat waves(Cutter et al., 2003). Scheduled Tribe (ST) and scheduled caste (SC) populations are also under developed and lag behind the other social groups on various parameters such as education (Khatoon 2018).The houseless population is always exposed to various extreme events such as heatwaves.

TABLE 1
Description of Data Used in the Study

Variables		Description	Unit	Data source
Latent	**Observed**			
Exposure	LST	Pixel wise LST	°C	United States Geological Survey (USGS), Landsat 8, May 2023
	Population density	Number of people living in per km^2	Person/km^2	Census 2011
Sensitivity	Very old population	Elder people (>60 years) in the percentage of the total population	%	Census 2011
		Children (0-6 years) in percentage of total population	%	Census 2011
	Illiteracy rate	Illiterate people in Percentage of the total population	%	Census 2011
	MPI	Multidimensionally poor people in Percentage of the total population	%	Department of Planning, the Government of Uttar Pradesh, 2023
	Sex ratio	Female population per 1000 male population	Ratio	Census 2011
	Workers	People working outside their homes in percentage of the total population	%	Census 2011
	SC	SC population in the percentage of the total population	%	Census 2011
	ST	ST population in the percentage of the total population	%	Census 2011
	Houseless households	Houseless households in the percentage of the total population	%	Census 2011
Adaptive capacity	Access to electricity	People with access to electricity in the percentage of the total population	%	Census 2011
	NDVI	Health of vegetation in the area	Ratio	USGS, Landsat 8, May 2023
	Number of primary Healthcare centers (PHC)	Number of PHC/ (Lakhs of population)	Ratio	National Family Health Survey, 2019-21
	Road density	Roads in kilometres per 1000 km^2	Road length/1000 km^2	Basic road statistics, ministry of road transport and highways, 2018-19
	NDWI	Spatial water distribution over the area	Ratio	USGS, Landsat 8, May 2023

Adaptive capacity

There are five variables that were decided on the basis of the study of various kinds of literature for measuring adaptive capacity: Normalised Difference vegetation index (NDVI), access to electricity, road density, normalized difference water index (NDWI), and a number of primary healthcare centers (PHC). NDVI tells about the distribution of vegetation in the area. A good proportion of vegetation in the area can reduce its overall temperature(Kinney et al. 2008).The road density of the area is associated with congestion due to traffic. A good road infrastructure with adequate density in the area would decrease the generation of heat by decreasing the congestion due to traffic (Inostroza et al. 2016). NDWI tells about the distribution of the water in the area. It was found in various studies that water bodies can reduce the intensity of heat as it has an inverse correlation with temperature (Mushore et al. 2018). There are various studies that suggest that at times of extreme weather events load on health facilities gets heavy which in turn increases the need for hospitals and other facilities (Mason et al. 2022; Lee et al. 2024). This study incorporates the number of Primary Healthcare Centers (PHC) as an adaptive measure in this study.

Satellite data processing

Various satellite data processing works were performed using various Landsat 8 images of thirty-meter resolution. LST was calculated using band 10 which are Thermal InfraRed Sensor, spectral band. This approach was used by (He et al. 2019) in their study. NDVI was already used for the calculation of vegetation cover in many studies by using band 5 and band 4 Landsat 8 images (Anyamba and Tucker 2005). Similarly, the NDWI was already used for highlighting water bodies using Band 3 and Band 5. However, these two indices have never been used together for representing adaptive capacity in any of the HVI calculations. The average of the values of LST, NDVI, and NDWI was taken for calculations.

Factor analysis

There could be multicollinearity among the indicators taken for the assessment of HVI. That's why correlation coefficients were used to check the relationship between these indicators (Schober and Schwarte 2018). There was not that much collinearity among the indicators. But still factor analysis was brought into use for the reduction of dimensions and thereby its complexity(Harlan et al. 2013). Kaiser-Meyer-Olkin (KMO) test and also Bartlett's sphericity tests were performed to check the adequacy of the sample and the resulting usefulness respectively. The values obtained for the KMO test for each of E, S, and A were 0.50, 0.76, and 0.66 respectively. Performing varimax rotation and using Kaiser-eigen value rule extraction of independent components was done. The regression method was used for factor score estimation. Then the obtained scores were used in the previously mentioned formula for HVI calculation. The values that we obtained were then classified into five classes- very low (VL), low (L), medium (M), high(H), and very high (VH).

Distribution of HVI spatially

The results obtained as HVI scores for each district are then taken and used for preparing a spatial distribution map for UP. ArcGIS was used for this operation. The five classes obtained are shown in different colors and can be identified very easily. The method discussed above has advantages like the remote sensing can help in reaching inaccessible areas and provide data for LST, whereas the interference from cloud can alter the actual LST which is a major disadvantage of this method.

III. Results and Discussion

LST, NDVI and NDWI Calculations

The average of the LST calculated over the region was 34.83°C with a standard deviation of 4.52. The LST was observed to be higher in areas attached to or near Rajasthan, New Delhi, and the southern part of Madhya Pradesh (MP). The areas that observed high temperatures were Mathura, Lalitpur, Jhansi, Jalaun and Mahoba. The temperature in these areas had almost touched 47°C to about 50°C. **Fig 2** depicts the LST variation over the area. The average NDVI of the region was observed to be about 0.19 with a variation of the standard deviation of 0.08 (**Fig. 3**). The areas associated with high NDVI and thus high vegetation covers were from the northern part and north-eastern part of the region. Some of the districts that observed high NDVI values were Lakhimpur Kheri, Pilibhit, Maharajganj, Kushinagar and Gorakhpur. There was a negative correlation observed between LST and NDVI. The regions that observed high temperatures were mostly those regions that had low vegetation cover or NDVI.

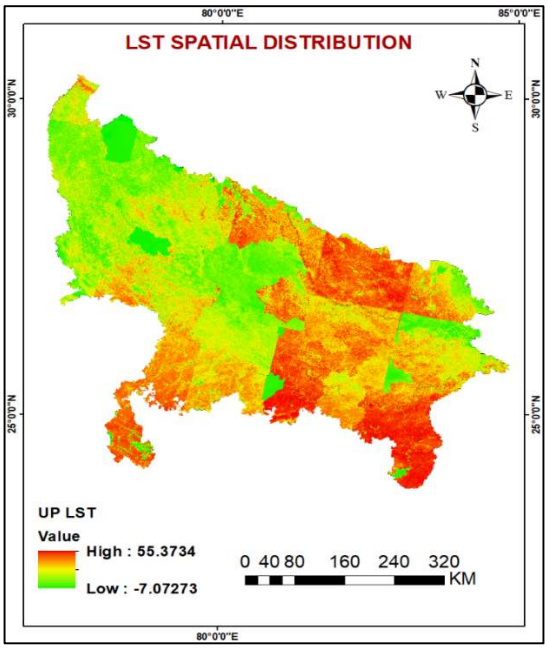

Fig. 2 LST Variation Map of the Area

The average of the NDWI of the region was observed to be about -0.16. the areas that observed high wetlands or water bodies were Bahraich, Allahabad, Ballia, Fatehpur, Hardoi, Lakhimpur Kheri, and Lalitpur.

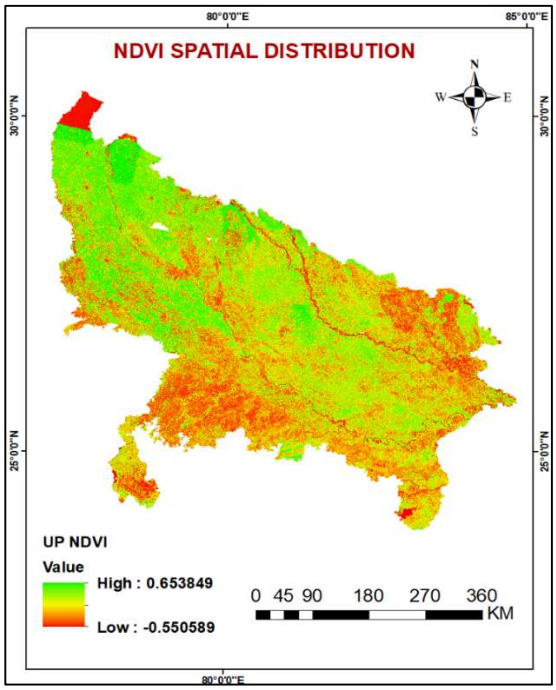

Fig. 3 NDVI Distribution Map of the Area

Factor Analysis

After performing factor analysis, there was one component extracted in the exposure category which accounts for about 61% of the total variation (**Fig 4**).The component was extracted using the Kaiser rule which suggests an eigen value greater than 1 for factor extraction. the range of factor scores valuated was -1.90 to 1.74. the high factor loading of 0.706 for land surface temperature suggests high vulnerability for regions having high temperatures. There were four components extracted for sensitivity which in addition cumulated to 78.615% (**Fig 5**). For sensitivity analysis, after applying the varimax rotation method with Kaiser normalization it took 5 iterations to converge.

After rotation, the first component yielded an eigen value of 2.827% accounting for 31.415% of the total variation. Components 2, 3, and 4 yielded eigenvalues of 1.753%, 1.374% and 1.121% respectively. These components explained 19.481%, 15.270%, and 12.450% of the total variation. In component 1 high positive loadings were observed for the variables MPI (0.898), illiteracy rate (0.900), and under six years (0.890). A similar sort of result was obtained by (Asefi-Najafabady et al. 2018).In component 2 the variables such as SC (0.809) and workers(0.704)showed high factor loading. For component 3sex ratio stands out with a high factor loading of 0.925. For component 4, a factor loading of 0.961 was observed for the ST variable. These high values suggest that the regions having a high percentage of these respective variables will be highly vulnerable to heat waves.

An extraction of 2 components was observed for a total of 5 variables in adaptive capacity (**Fig 6**). It took 3 iterations to converge for this extraction. The Yielded eigenvalues were 1.920 and 1.239 for components 1 and 2 respectively. The percentage of variation observed was 38.393 and 24.778 for components respectively. The variables like access to electricity and road density had shown high factor loadings of 0.791 and 0.811respectively. The variables such as NDVI and NDWI resulted in high factor loadings of 0.803 and 0.753 respectively for component 2. The high factor loadings for NDVI and NDWI suggest that regions having high vegetation cover and water bodies will have very little vulnerability for heatwave.

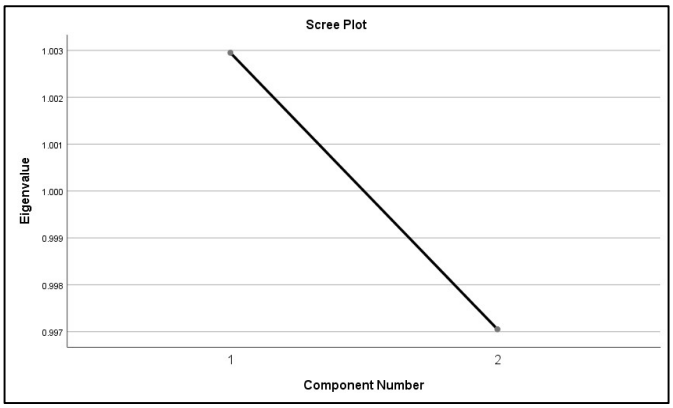

Fig. 4 Scree plot generated for component extraction in exposure category

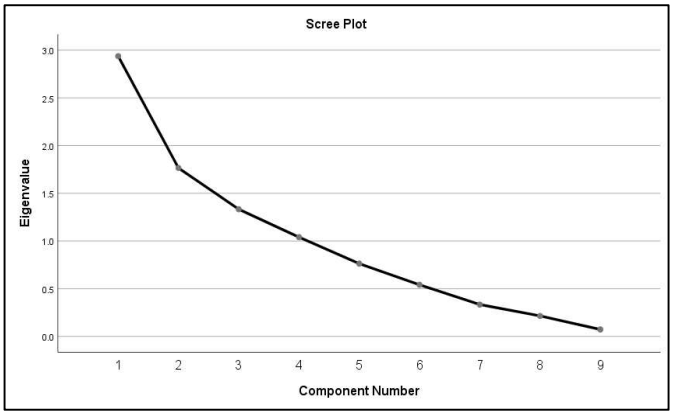

Fig. 5 Scree plot generated for component extraction in sensitivity category

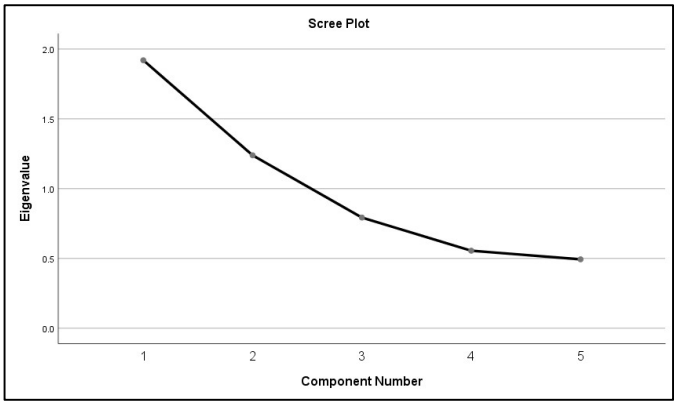

Fig. 6 Scree plot generated for component extraction in the adaptive capacity category

TABLE 2
Component extraction results of factor analysis

Variables	component	Proportion of variance	Cumulative proportion	Factor score
Exposure	1	61	61	-1.90 to 1.74
Sensitivity	1	32.637	32.637	-3.42 to 2.93
	2	19.615	52.252	-2.20 to 2.54
	3	14.809	67.061	-3.20 to 2.47
	4	11.554	78.615	-0.76 to 2.57
Adaptive capacity	1	38.395	38.395	-2.27 to 3.91
	2	24.775	63.170	-1.77 to 2.71

The factor scores estimated for different components of the variables are now disintegrated at the district level. High factor values were estimated in the exposure category for districts such as Sonbhadra, Mahoba, Lalitpur, Mainpuri, and Hamirpur suggesting that high land surface temperature was obtained in these districts. The highest score was obtained in Lalitpur district. In sensitivity categories again the districts mentioned in previous lines topped the list. The districts in the western part of the state yielded low factor scores in the sensitivity category as they performed well on various sensitivity parameters such as MPI and literacy rate. One of the districts that was very low on the list in the sensitivity category was Gautam Buddha Nagar due to the reasons mentioned in previous lines. The districts that performed well on adaptive capacity parameters were Sonbhadra and other districts from the northern part of the states such as Kheri and Pilibhit. These districts had high vegetation cover as they had high NDVI values. The districts from the western parts of the state such as Gautam Buddha Nagar had high scores in terms of access to electricity so they also performed well in terms of adaptive capacity. **Table 2** depicts the component extraction results of factor analysis with the factor score ranges.

HVI for UP

The exposure had a mean of 0.06 and a standard deviation of 0.87 (Fig.7). However, the sensitivity variable yielded a mean of -0.09 and a deviation of 1.70 (Fig.8). This shows that there was more variation in sensitivity than exposure and this can also be stood by the spatial variation diagram of both exposure and sensitivity. The adaptive capacity factor scores yielded a mean of 0.03 with a standard deviation of 1.28 (Fig. 9). It has more variation than exposure but less variation than sensitivity and again this can be understood from the spatial variation diagram of all three variables. The districts in northern parts of the state such as Pilibhit and Bijnor were very less exposed to the heatwave and also in terms of sensitivity they were low on the list. However, they yielded high scores in the adaptive capacity category thus making them overall very less vulnerable to heatwaves, and hence they were categorized as very low vulnerable districts in terms of HVI. The districts in the southern part of the state such as Lalitpur, Jhansi, Mahoba, and Jalaun were highly exposed to heatwave. They also yielded very high scores in the sensitivity category making them very fragile. They lag in the adaptive capacity category with negative scores thus overall making them highly vulnerable to heatwaves and hence they were in the very high category of HVI.

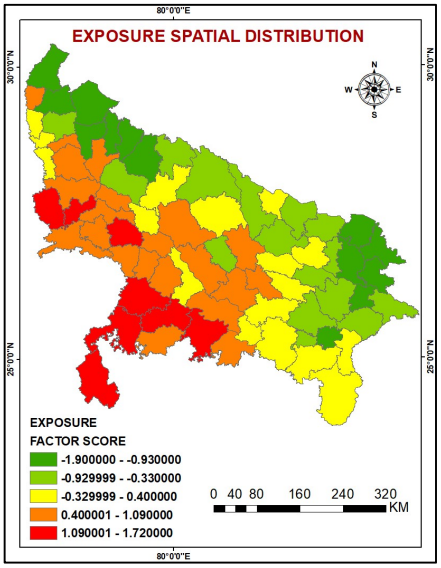

Fig. 7 Exposure Factor Score Variation Map of the Area

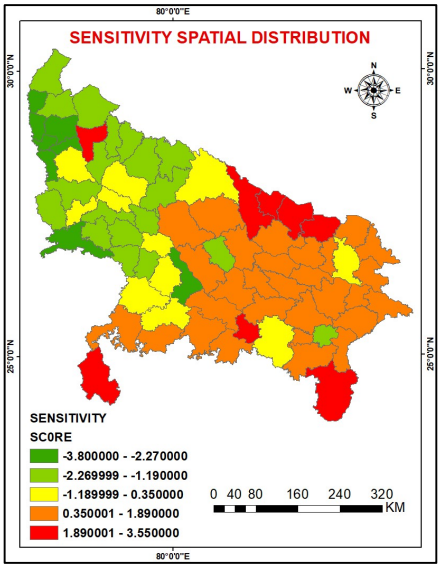

Fig. 8 Sensitivity factor score variation map of the area

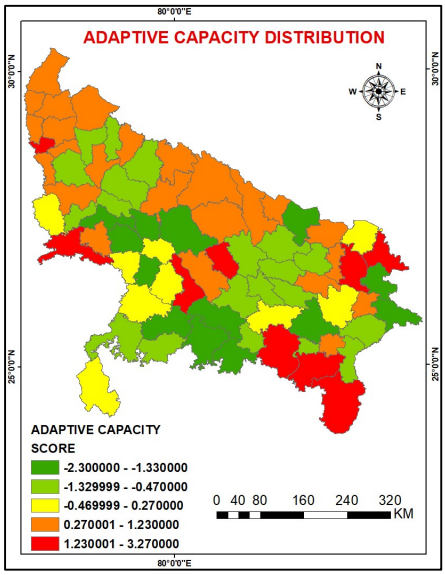

Fig. 9 Adaptive capacity factor score variation map of the area

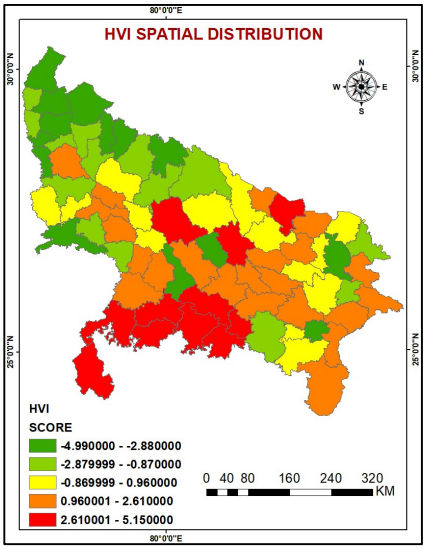

Fig. 10 HVI spatial distribution map of the study area

The districts in the central part of the state such as Hardoi and Unnao also yielded a high positive score in the exposure category. They were also at the top of the list for being sensitive with higher sensitive scores. However, in the adaptive capacity category, the Unnao district was in the high category but still couldn't overcome its bad performance in the other two categories making it vulnerable and in the high category of HVI. The other district Hardoi was again on the bottom list of adaptive capacity thus making it very vulnerable and thus in the very high category of HVI. The capital city Lucknow was in the very low category of HVI due to its negative scores in exposure and sensitivity categories while scoring a high positive score in the adaptive capacity category. The capital city performed very well in terms of MPI and literacy rate and also was good in terms of access to electricity and road density.

The districts in the eastern part of the state such as Mau, Ballia, Ghazipur, and Deoria had low scores in the exposure category. However, they yielded high positive scores in the sensitive category because of their bad performance in the MPI and literacy rate category and were found fragile. The districts such as Ballia, Ghazipur, and Deoria were not good in terms of adaptive capacity with low negative scores due to lack of both access to electricity and road density and thus were categorized in the high category of HVI. However, Mau has a high positive score in adaptive capacity due to its richness in terms of vegetation cover and thus was overall in the low category of HVI.

The districts in the west of the state such as Baghpat, Ghaziabad, and Gautam Buddha Nagar had medium scores in exposure categories. They had very low negative scores in the sensitivity category owing to their good performance in the MPI and literacy rate categories. They were also good in terms of adaptive capacity as they have a high population percentage with access to electricity and they also have good road density. These all factors when taken together resulted in low HVI scores and they were in the very low vulnerable category. Fig 10 depicts the HVI variation over the area. Similar process was adopted by Mac and McCauley 2017 by using three variables.

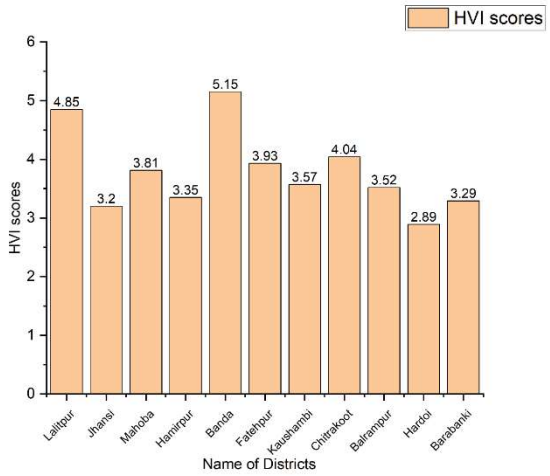

Fig. 11Districts in the very highly vulnerable category

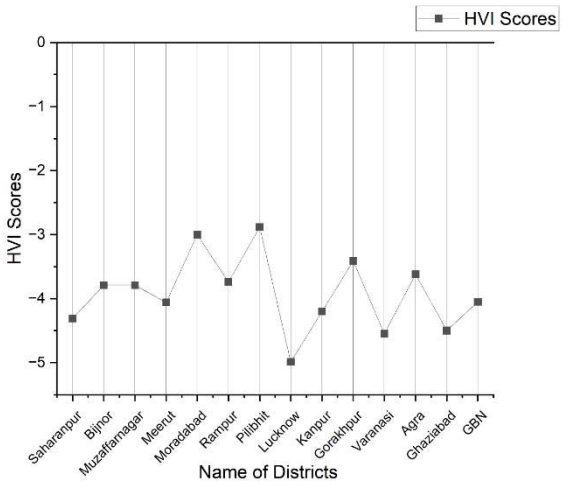

Fig. 12 Districts in the very low vulnerable category

IV. Conclusion

As extreme weather events have become a recurring phenomenon, Heatwaves have also become frequent these days owing to climate change and high urbanization. This resulted in high morbidities and a large population has become vulnerable to these heatwaves. Though the process of formulating an HVI is a complex phenomenon this study has used exposure, sensitivity, and adaptive capacity variables to quantify HVI. The satellite data processing for LST, NDVI, and NDBI performed over the UP state has resulted in a mean of 34.83°C, 0.19, and 0.16 respectively. The variation obtained in terms of standard deviation for LST and NDVI were 4.52°C and 0.08 respectively. The districts that observed high temperatures were Lalitpur, Mahoba, Jhansi, and Hamirpur. High vegetation cover was observed in terms of high NDVI values in districts such as Kheri, Pilibhit, Moradabad and Bijnor. After the factor analysis, the factor scores generated for exposure, sensitivity, and adaptive capacity categories were-1.90 to 1.74, -3.80 to 3.55, and -2.3 to 3.27 respectively. After the calculation of factor scores for each category HVI was calculated and the score for HVI was evaluated in a range of -4.99 to 5.15. These factor scores are then divided into five categories very low, low, medium, high, and very high. It was found that there were 14 districts in the very low category, 14 districts in the low category, 14 districts in the medium category, 22 districts in the high category, and 11 districts in the very high category. Fig. 11 and Fig. 12 show very high and very low vulnerable districts respectively.

This study has a few limitations like the unavailability of recent data. The census data used in this study was from the census 2011 which was done about 13 years today. Because of the unavailability of observed temperature, this study used satellite data for land surface temperature from the 15th of May 2023. Since there were no images with 0% cloud cover for the Saharanpur district image with10% cloud cover was used which resulted in negative temperature over a small region. Despite these few limitations this study provides a comprehensive vulnerability assessment of heatwaves and could be used as a basis for future mitigation planning for heatwaves. This study will use the heatwave vulnerability index (HVI) to identify more susceptible districts of Uttar Pradesh to heat waves. To overcome the limitation of this study, further studies related to unavailable data will be conducted in the near future by our research group.

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