An approach for forewarning forest fires in Shivalik forest tracts of Uttarakhand by application of fire trends and Keetch Byram Drought Index

Jain, Harshi

Harshi Jain, "An approach for forewarning forest fires in Shivalik forest tracts of Uttarakhand by application of fire trends and Keetch Byram Drought Index," Proc. SPIE 11528, Remote Sensing for Agriculture, Ecosystems, and Hydrology XXII, 115280O (20 September 2020); doi: 10.1117/12.2572128

Event: SPIE Remote Sensing, 2020, Online Only

An approach for forewarning forest fires in Shivalik forest tracts of Uttarakhand by application of fire trends and Keetch Byram Drought Index

Harshi Jain*[a]

[a]Forest Survey of India, Dehradun, Uttarakhand, India

ABSTRACT

Limited fore-knowledge of the impending ignition potential is one of the main causes of not-so-effective forest-fire management in India. The present study is an approach to link forest fire trends and the Keetch–Byram Drought Index (KBDI) for assessing forest fire forewarning. Fire trends were analyzed based on forest fire incidents detected by MODIS remotely-sensed data in the Shivalik forest tracts of Uttarakhand State of India over a period of 16 years to identify the vulnerable window of most-prone weeks. The study further uses KBDI to calculate the drought build-up in an area based on which the severity of impending forest fires can be predicted. This is one-of the first attempts for the inclusion of KBDI in understanding forest fire regime in Indian conditions.

Based on the weekly-trends obtained from forest fire points during 2001-2016 affirm the most vulnerable time period for the occurrence of forest fire in the study region is from week 14 to week 22. The performance of KBDI proved to be a valid parameter in forecasting the severity of forest fire as its pattern over three years of study period (2014-2016) showed the same dynamics. The minimum value of KBDI i.e. the 'dip' value is significant for its use as a predictor to the severity of the fire season in the ensuing summer a full 10 weeks in advance.

The findings of the present study pave the path for identifying the high-risk areas and severity of possible fires in the following fire season by correlating remote sensing and GIS techniques with Fire trends, peak period and Keetch Byram Drought Index. This study has a potential for adoption in countries like India for modern forest fire preparedness and management in a cost-effective manner.

Keywords: Forest Fires, India, Keetch Byram Drought Index (KBDI), Fire Danger Rating, Fore-warning, Fire trends, Remote Sensing, MODIS, Vulnerability

1. INTRODUCTION

Forest fires have become a global environmental challenge[1]. India is no exception with approximately 29,000 forest fires incidents reported in the country by Forest Survey of India (FSI) in the year 2019[2]. Forest fires are considered to possess a major hindrance in protecting India's forests to maintain the country's forest cover and increase its carbon sink. Forest fire management is therefore amongst the prioritized objectives of India's Sustainable Forest Management Plan[3].

Besides upgrading technology for timely-detection and monitoring of fires in forests, improving information and knowledge-base for early-warning and prevention of fires hold immense importance. Understanding the trends of forest fires over the years is essential for tackling them effectively[4]. Such insights help in assessing patterns of fire regime in a forest for designing efficient fire prevention and response plans. Furthermore, fore-knowledge of fire potential in forests can also effectively underlie fire management plans[5]. It can help to mitigate severe impacts of forest fires on biodiversity, climate and economy[1]. Numerous fire danger indices such as Canadian Fire Weather Index (FWI)[6]; Nesterov Index (NI)[7], Keetch Byram Drought Index (KBDI)[8] have been developed worldwide to provide forecasts on fire behavior several days in advance.

*harshijn18@gmail.com; phone 0135-2756139; fsi.nic.in

Remote Sensing for Agriculture, Ecosystems, and Hydrology XXII, edited by Christopher M. U. Neale, Antonino Maltese, Proc. of SPIE Vol. 11528, 115280O · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2572128

Remote-sensing tools and techniques have been very effective in forest fire management all around the world. MODIS (Moderate Resolution Imaging Spectroradiometer) sensor aboard NASA's Terra and Aqua satellites is a well-suited and widely used satellite observation data for monitoring and detecting forest fires. Many countries like India[9], Nepal[10] have developed MODIS-based forest fire detection systems to detect fires in a timely and cost-effective manner. In India, Forest Survey of India (FSI) is the nodal organization for dissemination of near-real forest fire detections based on data from two space-based instruments i.e. MODIS and SNPP-VIIRS as e-mail and SMS alerts to the State Forest Departments and registered users of the country. Timely information on these fires enables better planning and resource mobilization during fire management process.

Temporal and regional variation in fire patterns are of immense value as they indicate which particular forest area during which particular time period is more vulnerable to fires than the others. Satellite remote sensing technique has been applied for regional vegetation fire patterns in South and Southeast Asia[11]. A forest fire trend analysis has been carried in the Jharkhand State of India using geospatial technology reporting that approximately 89% of total forest fire incidences in the State occurs during the months of March-April[4]. Analysis of such patterns and trends of forest fire facilitate better fire disaster management planning and resource allocation for improved forest fire prevention and response.

Drought provides favorable conditions for forest fires[12] as lack of soil moisture is one among the major drivers influencing the flammability of forests[13]. KBDI is one of the significant indicators that fire managers use for assessing the fire risk potential in their areas[14]. There are many studies that have attempted to relate KBDI with forest fire activity. KBDI is applied as a part of the U.S. National Fire Danger Rating System to assess the forest fire potential[15]. Dolling et al. (2005)[13] reported a strong relation between KBDI and burned area in Hawaiian Islands. Researchers have also investigated global wildfire potential based on KBDI measurements[16].

Keetch-Byram Drought Index (KBDI) is fundamentally a numerical value which relates the moisture deficiency in the top layers of soil or in deep duff to the expected fire behavior[8]. The value of KBDI ranges from 0-800 where 800 indicates the maximum drought conditions and 0 indicates saturated soil with no moisture deficiency. The index requires the maximum air temperature (^{o}F) and the previous 24 hours' total rainfall (inches) for the calculation of daily drought index value along with the mean annual rainfall (inches) of the area for one-time selection of 'drought factor' table. The KBDI record is initiated by setting it to 0 after a period of abundant precipitation[17], usually 6-8 inches in a period of a week and calculated cumulatively for the present day. The KBDI theory is based on few assumptions which could be referred from Keetch and Byram (1968)[8].

The present study has attempted to investigate the trend followed by forest fire incidences in part of Dehradun and Tehri-Garhwal districts of Uttarakhand State of India over a period of 16 years. The MODIS-detected archival forest fire points of FSI from 2001 to 2016 have been used for the analysis. Based on trend analysis, vulnerable window in terms of most prone weeks has been identified. Furthermore, it has derived the KBDI values to calculate the drought build-up in the study area for the years 2014-2016 and its temporal trends have been explored to examine the possible linkages with severity of the following fire season. The study is among the few attempts in India to adopt Keetch Byram Drought Index for relating with the forest fire activity. The outcomes of this study are expected to develop a deeper understanding of the relation between KBDI and wildfire potential in Indian scenario to provide a cost effective and reliable approach for the forest officials to anticipate the severity of the ensuing fire season and take precautionary measures well in advance.

2. STUDY AREA

The study area (Figure 1) comprised of forest ranges in two districts namely, Dehradun and Tehri-Garhwal of the State of Uttarakhand, India. Study was conducted on a pilot scale with an area of 625 sq. km selected randomly by overlaying 5-km x 5-km grids. It extended between geographical extents 30^{o} 6' 30" N to 30^{o} 20' 10" N and 78^{o} 03' 0" E to 78^{o} 19' 40" E. Dehradun district, situated in the north-west corner of the state, comprises Lachhiwala, Badkot and Thano ranges of the study area. Tehri-Garhwal district includes the Shivpuri and Saklana Chamba of the study area.

The study region experiences a subtropical climate with temperatures ranging between 16.7° C and 36° C during summers and between 5.2°C and 23.4°C during winters[18] with a mean annual rainfall of 2,025 mm[19]. It receives most of its rainfall during monsoon and some during winters. Summers are usually hot and dry. The study area is rich in different land covers such as forests, urban settlements, agriculture and water bodies. Forests cover 422 sq. km area of the study region. Different types of forests and varying species of trees, shrubs, herbs and grasses can be found in the area like Banj, Bans, Deodar, Sal, Semal, Shisham, Dhauri, Sain, Haldu, Chameli etc. Based on Forest type map of FSI, the study region is dominated by Moist Siwalik Sal Forest (62.52% of the total area of all the forest types), Ban Oak Forest (18.90%) and Upper or Himalayan Chir Pine Forest (11.02%). Other forest types are West Gangatic Moist Mixed Deciduous Forest (2.79%), Dry Siwalik Sal Forest (2.55%), Khair Sissoo Forest (0.53%) and rest 1.69% under Plantation/ Trees Outside Forests (TOF). Sal and Chir are present in abundance. *Lantana camera* can be found as a major understory species. The area was thus considered suitable for the study for yearly occurrences of forest fires, diversity in forest types, data availability and accessibility of the area.

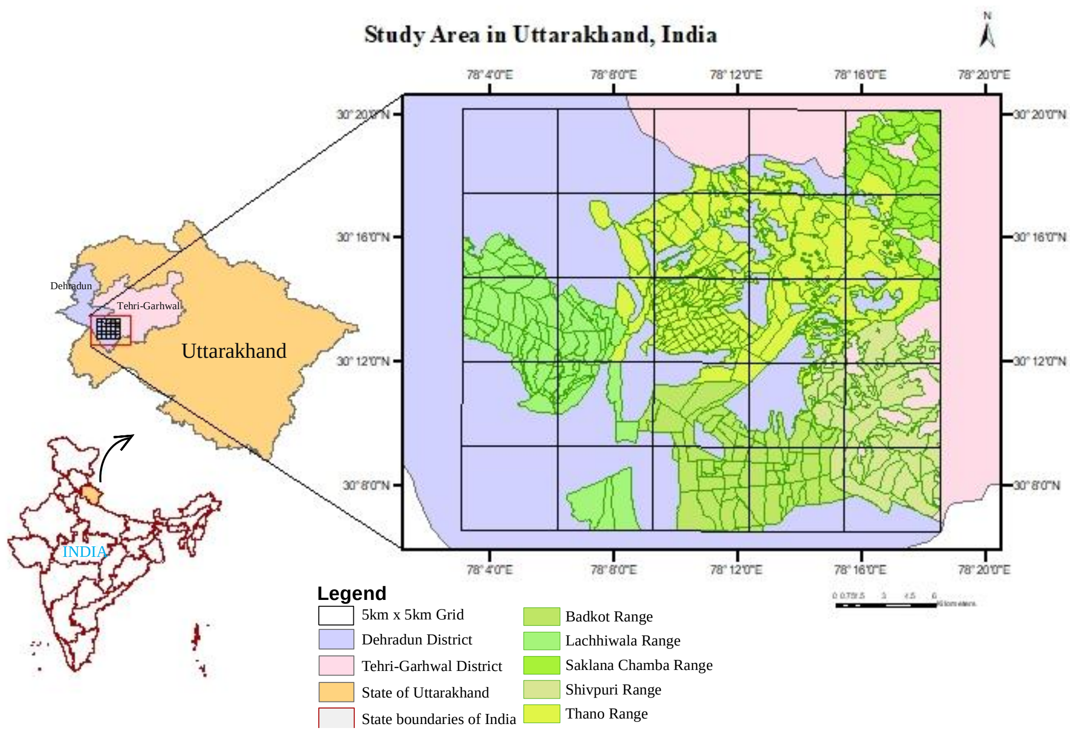

Figure 1. Location of study area (Forest ranges) in Dehradun and Tehri-Garhwal districts of Uttarakhand, India.

3. MATERIALS AND METHODS

3.1 Data and software used

MODIS forest fire points for the years 2001-2016 were obtained from FSI. Ancillary data such as Uttarakhand State boundary, Recorded Forest Area (RFA) boundary of Uttarakhand, Forest Cover Map (FCM), Forest Type Map (FTM), 5 km x 5 km grid layer etc. were also acquired from FSI. For calculation of KBDI, daily rainfall and daily maximum temperature of the study area were required for the years 2014 to 2016. The year 2016 was one of the worst-hit forest fire years in Uttarakhand[20,21]. Daily rainfall data for the years 2013-2016 was acquired from GIOVANNI for their product TRMM_3B42_Daily_v7. Daily maximum temperature was acquired from MOSDAC (Meteorological and Oceanographic Satellite Data Archival Centre) from 2013-2016. The data used was from nearest automatic weather station (AWS) ISRO0989-15F3DD (IIRS Campus. Dehradun) located at coordinates 30.34, 78.04. For missing days, data from AWS-ISRO0987-15F3DB (Agriculture & Soils Division IIRS-1) was used which is located at coordinates 30.48,77.92. For analyzing and processing the acquired data, ERDAS Imagine 2014, ArcGIS 10.3, MS-Excel were used.

3.2 Methodology

Understanding temporal pattern of forest fires (FF) in an area is important as it aids in its prevention and mitigation[22,23]. The administrative and recorded forest area (RFA) boundaries of Uttarakhand for districts Dehradun and Tehri-Garhwal were acquired from Forest Survey of India, Dehradun. By overlaying the 5kmx5km grid layer, the pilot study area was selected. To analyze the forest fire trend at the study site, the MODIS-detected forest fire points, which are also referred to as forest fire incidences/ forest fire detections in the present study, for the years 2001-2016 were overlaid. These points were enriched with information of administrative units and forest types. Week number was assigned to each of the forest fire points and yearly tables of the forest fire points were prepared for the trend analysis.

Rainfall[24] and temperature are key factors that affect forest fires. Rainfall deficit period can lead to increased proneness to fires[25] due to depletion of soil moisture[14]. Keetch Byram Drought Index is one such mathematical system widely in-use for assessing fire danger potential in an area. The KBDI was determined for the present study area using the methodology developed by Keetch and Byram[8]. The daily maximum air temperature and daily total rainfall data for the years 2014 to 2016 were used to derive KBDI over a period of three years in the study area. Average weekly rainfall was calculated for each year to determine the initiating date of the record when KBDI was considered to be '0' after a weekly rainfall of more than 6-8 inches. For all the years, KBDI recordings were started from 1st day of dry-spell at end of monsoon of the previous year when Drought Index Yesterday (DIY) i.e. KBDI value the previous day, was assumed to be '0'. Based on the mean annual rainfall of the study area i.e. 79 inches (2025 mm) [19], the suitable Drought Factor (DF) table i.e. Table-5 was selected for this study. Thereafter, Drought Index Today (DIT) alias KBDI was calculated for each day for every year based on daily 24-hr rainfall (inches), net rainfall (inches), maximum air temperature (degree Fahrenheit), DIY as reduced by net rainfall and Drought factor (DF) from the Drought factor table-5 until DIY again dropped to 0 i.e. substantial rainfall was received for soil saturation. The KBDI values were categorized into eight stages as per Table 1 for translation to the current drought stage for operational practicality[8]. Weekly average of daily KBDIs for each year were calculated for further analysis of its pattern over the study period, relationship between KBDI and number of fire incidences etc. 'Fire season' is a period of few months in a region when forest fires are very frequent due to favorable atmospheric and fuel conditions for fire ignition and spread[16]. For the present study, the trend analysis and KBDI calculation were computed for the months from January to June i.e. Week No. 1 to Week No. 29 which is considered as the forest fire season in India[26]. Also, fire potential and vulnerability to forest fire, as used in this study, represent the possible severity of the fire season in the study area.

Table 1. Stages of Keetch Byram Drought Index (as per Keetch-Byram, 1968).

Index value	Drought stage	Index value	Drought stage
0 - 99	0	400- 499	4
100 - 199	1	500- 599	5
200- 299	2	600- 699	6
300- 399	3	700-800	7

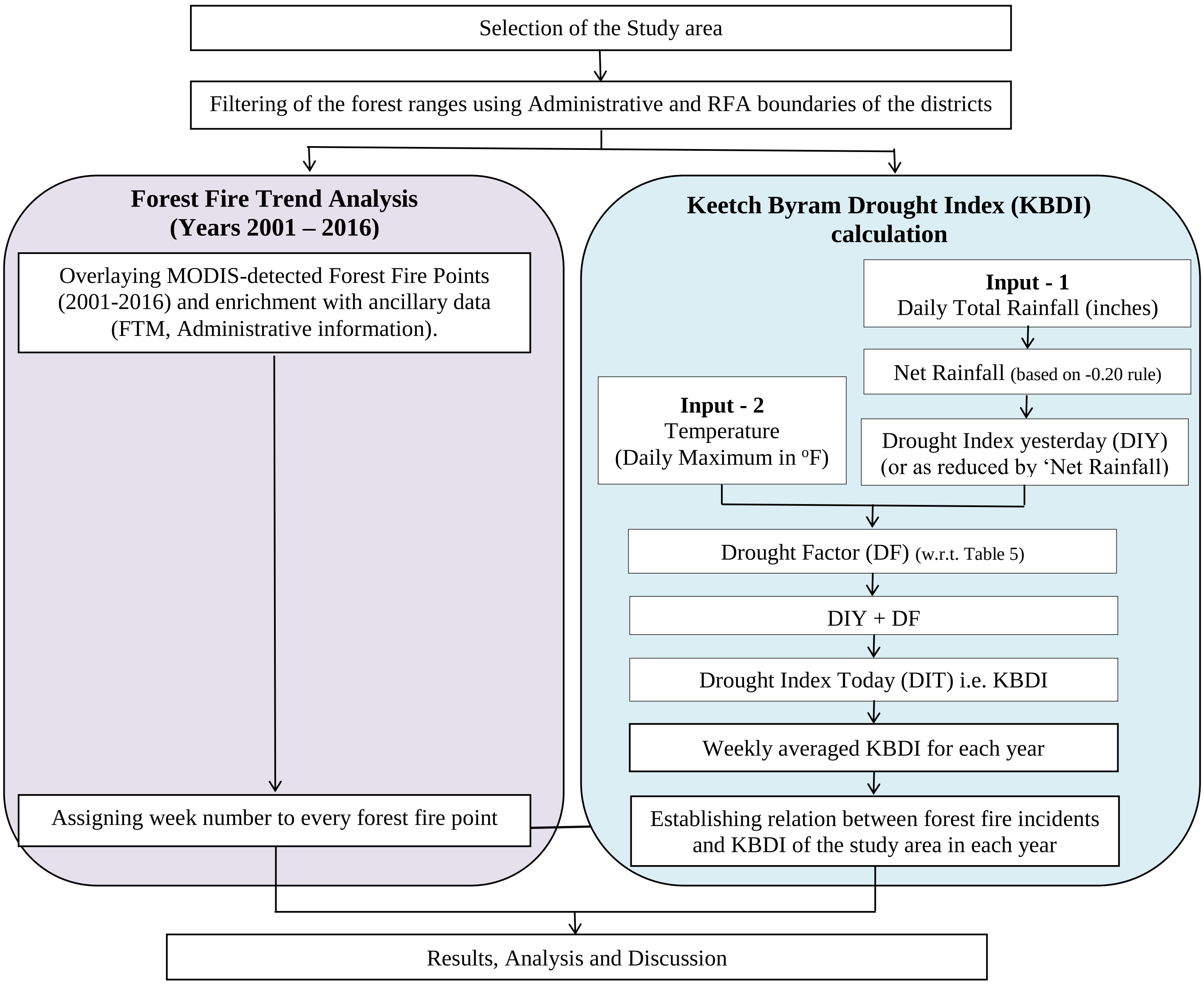

Figure 2. Methodology followed for Forest fire trend analysis (based on 2001-2016 MODIS-detected forest fire incidences) and KBDI calculation for the years 2014-2016 in the study area.

4. RESULTS AND DISCUSSION

In the present study, forest fire trends were analyzed over a period 16 years (2001-2016) using MODIS-detected forest fire incidences in the study region. Further, an attempt was made to validate the application of Keetch Byram Drought Index (KBDI) in Indian scenario by determining KBDI for the study region and analyzing its temporal patterns from 2014-2016.

4.1 Forest Fire Trends

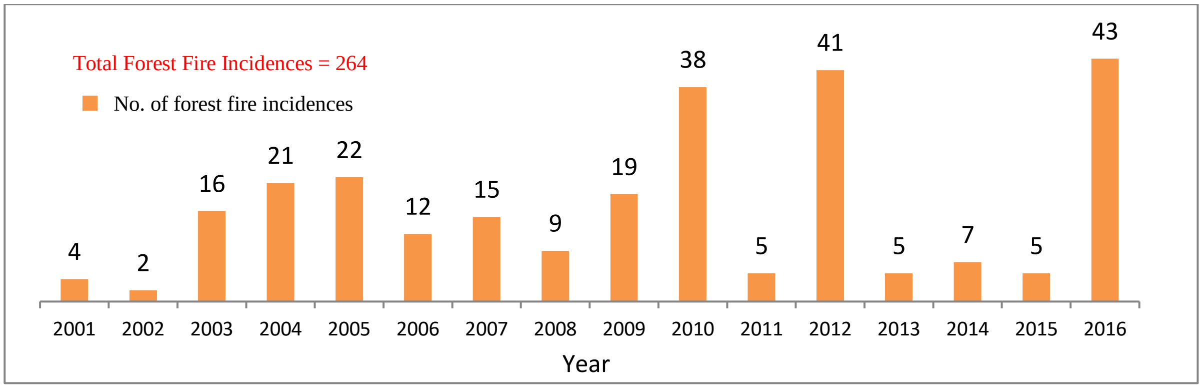

Figure 3. Graph showing year-wise distribution of forest fire incidences in the study area (2001-2016).

Annual trends of forest fire incidences occurring during the period of 2001 to 2016 is shown in Figure 3. A total of 264 forest fire incidences were recorded in the study area during this period. The graph clearly depicts that years 2010, 2012 and 2016 were the worst-hit years as they faced maximum number of fire incidences i.e. 38, 41 and 43 respectively. The results were found in agreement with the published literatures stating years 2012 and 2016 as the worst years for Uttarakhand in terms of forest fire situation[20,21,27]. It is interesting to observe that an intense fire year was usually followed by a calmer one. Further, having an insight in the weekly-trends of forest fires from 2001-2016 in Figure 4, it is quite evident that the vulnerable window in terms of 'weeks' started from week 14 till week 22. This time period had experienced maximum number of fire occurrences and therefore, was considered as the 'peak period' in the study region. Though the fire season seemed to have started from week 5 (February), the incidents of fire were very low. With the onset of summer season (March-April), the number of fire incidents climbed, reached peak and then gradually reduced with the advent of monsoon in June.

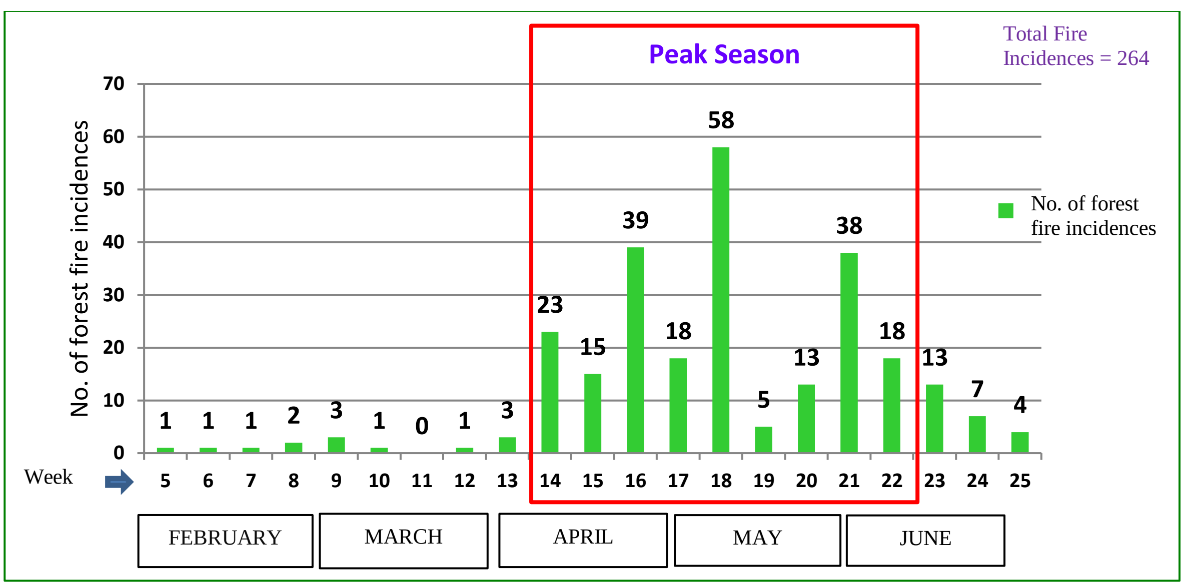

Figure 4. Graph depicting weekly forest fire trends during 2001-2016 highlighting the peak period in the study area.

4.2 Keetch Byram Drought Index

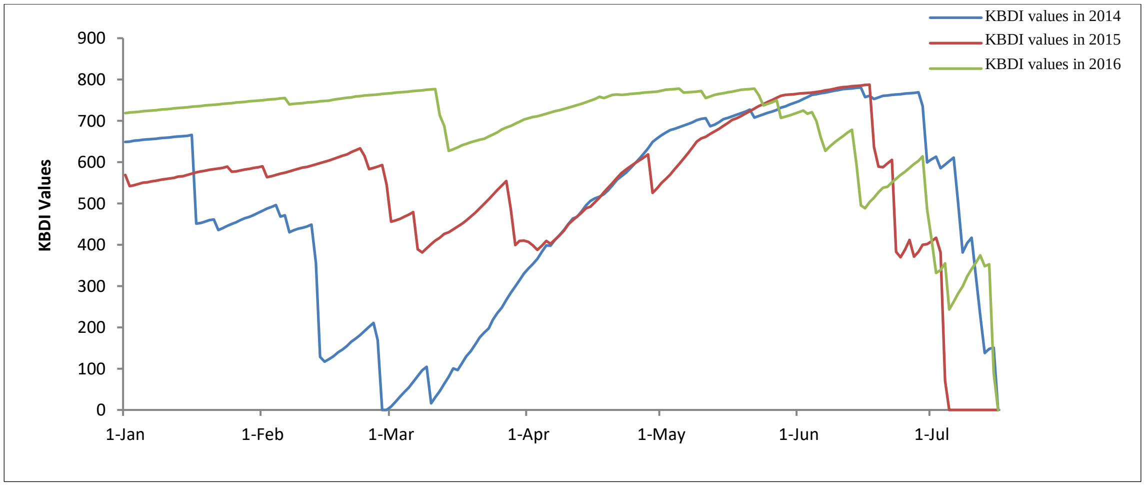

Figure 5. Graph showing temporal pattern of KBDI in the study area during 2014 to 2016.

Keetch Byram Drought Index (KBDI) showed similar dynamics over the study period of three years. The index seemed to follow a pattern where it reached high during the months of January-February due to prevalent dry conditions, dropped down in March due to winter rainfall, again peaked and reached the highest drought conditions during April-May due to high temperatures and decreased rapidly in June with the arrival of monsoon (Figure 5). Figure 6 depicts that KBDI reached its peak i.e. >700 after the 20^{th} week in the years 2014 and 2015 whereas it had hit 700 mark much earlier (18th week) in the year 2016. A direct relation could also be established between number of forest fire incidences and KBDI > 700. As the KBDI touched the 700 mark, an increase in fire incidences was noted. In the given graphs, it can be clearly observed that the maximum count of forest fire incidences coincides with the higher values of KBDI. Moreover, KBDI values in winters (week 10^{th}-14^{th}) can be used as a predictor to severity of the fire season in the ensuing summer. Carefully noticing the dip observed in all the three years during this period, it was quite evident that they differed only in their respective values but showed the same pattern. Lower the dip i.e. higher the KBDI value during this period, more severe the fire season. Thus, KBDI at 10-14^{th} week can predict the severity of the fire season a full 10 weeks earlier. It can also be seen that the mean weekly-KBDI was highest in the year 2016 (KBDI value = 681) whereas for the years 2014 and 2015, it was much lower (480 and 529 respectively) which shows that 2016 was experiencing a long dry spell with high drought conditions. Additionally, during the period of 10^{th}-14^{th} week, KBDI dropped to its minimum value i.e. 57 in the year 2014 and 401 in the year 2015. However, in the year 2016, the drop in the KBDI value was to mere 640 in the 12^{th} week after which it increased rapidly. This trend explains the severe and escalated forest fire occurrences in the year 2016.

Rainfall tends to decrease KBDI value. Figure 7 shows weekly rainfall in the study area from 2014-2016 with corresponding KBDI values. Graphs indicate that years which had received winter rainfall had lesser number of fire incidents. After a heavy rainfall, a decline in the KBDI can be seen such as during weeks 7^{th} to 11^{th} in the year 2014. When there was no significant precipitation for several days, KBDI remained high, for instance, during the year 2016. Years 2014 and 2015 had received an appreciable amount of rainfall in winters and so, the dip in drought index was higher i.e. lower KBDI values during the Weeks 10-14 were observed and thus, mild fire season was seen in the following summers. Year 2016 received almost negligible winter rainfall and hence, had a very high KBDI built-up since January-February with hardly any dip in the drought index during 10-14^{th} week period leading to an escalated number of forest fire occurrences as the following summers witnessed a severe fire season. KBDI thus validates its application in the Indian scenario and proved to be a useful operational indicator for the fire season in terms of forewarning and mobilization of resources, machinery and local people for fire prevention and management.

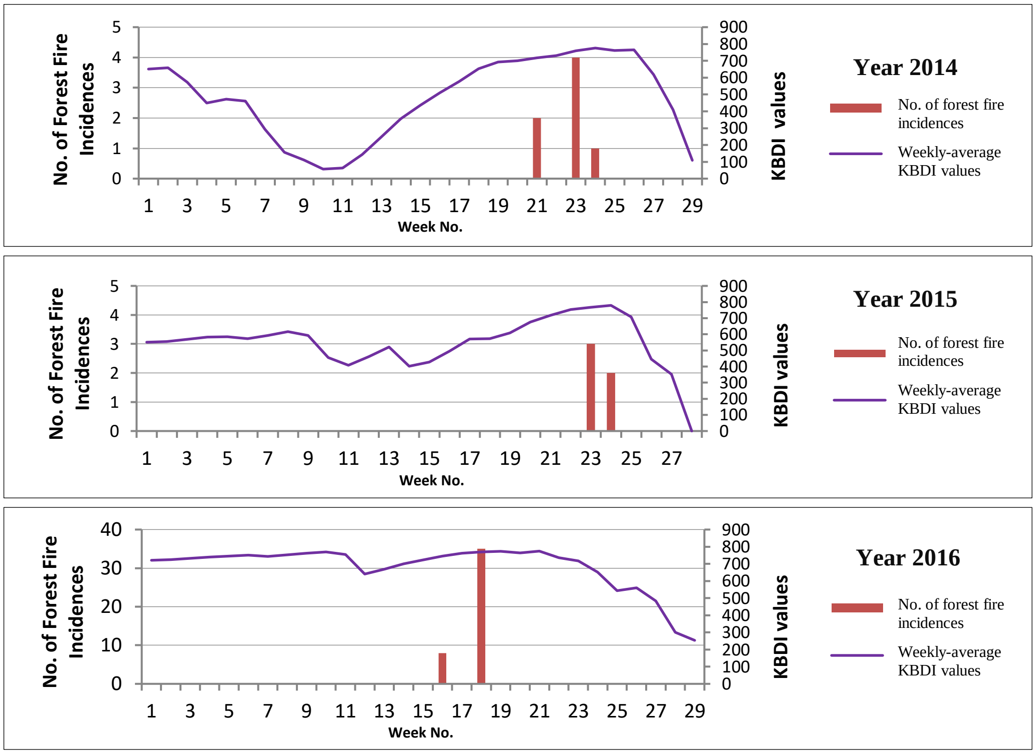

Figure 6. Graphs showing relationship between KBDI and number of fire incidents over a period of 3 years (2014-2016).

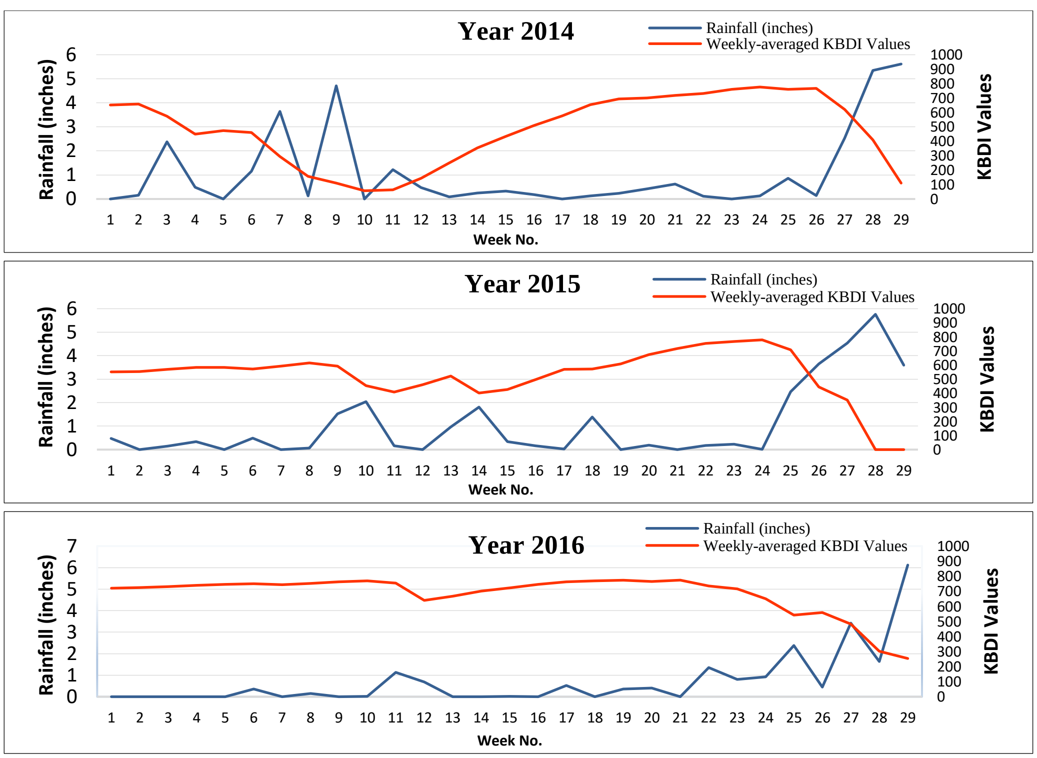

Figure 7. Graphs showing relationship between weekly total rainfall (in inches) with KBDI values.

4.3 Discussion

Fire trends were analyzed using archival data of MODIS forest-fire points (2001-2016) which resulted in developing a fire trend assessment of the study area in terms of vulnerable time window and peak period. Weekly-trends of forest fires from 2001-2016 made it quite evident that time period from week 14 to week 22 can be considered as the 'peak season' with maximum number of fire occurrences owing to high temperatures, low rainfall, high drought indices and socio-economic activities.

The fire season starts from week 5 (February) but the incidents of fire are low. This is because of lower temperatures and episodes of winter rainfall which increases the soil moisture content and hence, do not favor fire spread. Also, the anthropogenic activities, a leading cause of fires in forests[28] is limited during this time. With the onset of summer season (March-April), the number of fire incidents climbs (Week 12-14) and reaches peak because temperature increases and there is a dearth of rainfall which leads to drought build-up in the forests along with increased anthropogenic activities. With the advent of monsoon in June (Week 24), KBDI gradually reduces to zero as there is no more moisture deficiency due to excessive rainfall.

The study revealed a few reasons and facts for the peak period i.e. Week 14 to Week 22 being most-prone to forest fires. Spread of fire is fueled by high temperature (higher moisture deficit in the air) and litter fall which provides ignition fuel. During summer, when there is no rain for months, the forests become littered with dry senescent leaves and twigs, which could burst into flames ignited by the slightest spark. Vegetation type is amongst the prominent factors causing forest fires[29]. The Moist Siwalik Sal Forests which are dominant in the region, have glabrous leaves which on shedding form a huge fuel load for the initiation as well as spread of fire (Figure 8 (a)). *Lantana camera* is widely spread and highly inflammable. Even the Chir Pine needles are highly prone to fires. Oak trees have high calorific values and can burn for several days[30]. Furthermore, due to low rainfall and high temperature, the drought stage also reaches its peak i.e. KBDI >700 and hence, even the soil moisture is minimum due to evapotranspiration and therefore, have high moisture deficiency which again aids in spread of fire. A study reported that accidental fires can be caused by inhabitants living close to forested areas[31]. A similar pattern was observed in the study region. During this period, there is a lot of anthropogenic activities going on. The villagers practice purposely burning of small patches of forests for growth of healthier grasses for fodder and grazing of their livestock, collection of fuelwood and Non-Timber Forest Products (NTFPs) etc. These deliberate small fires in small areas many a times convert into unintentional big, uncontrollable fires if supported by favorable climatic and physical factors.

Peak period and high KBDI values suggest that the area is highly vulnerable and should be on high alert. The forest department should monitor these areas on regular basis to avert losses to vegetation and wildlife due to forest fires. Moreover, extra preventions and mitigative measures should be kept ready in the vicinity of these vulnerable areas. One of the key reasons behind the high number of forest fires is lack of awareness among the local people. Therefore, a communication should be conveyed to them about the fire danger level based on drought stage for tackling the situation of forest fires. Figure 8 (b) shows forest officers drowsing fire in a forest along with the local people.

Figure 8. (a). Excessive litter fall could act as huge fuel load for forest fire. (b). Active fire caught in Lachhiwala range, Uttarakhand and Forest officer along with local people drowsing it.

5. CONCLUSIONS

Effective forest fire management is a major challenge in India. Forest fires can lead to loss of forest resources and wildlife as well as human lives and property. The inability to recognize vulnerable areas, based upon building up fuel conditions, weather conditions as well as patterns and trends, to detect forest fires at nascent stage and take rapid controlling action is perhaps the most tragic flaw in the forest fire management system of the country.

Understanding the spatial and temporal variation of forest fires is necessary to envisage when and where a forest fire is likely to occur in the near future. Such trend analysis can help to identify and predict the patterns of fire ignitions along with the driving factors which could assist forest officers and decision makers to prioritize vulnerable areas during the peak period for forest fire monitoring, prevention, detection and fire-fighting resource mobilization. Weather conditions like high temperature, low rainfall[32] and surface moisture[33], presence of fire-prone vegetation species[34], excess of litter fall acting as fuel load[35] and human activities[36,37]; all contribute to the vulnerability of an area to fires and the time period when all these factors are favorable becomes the 'peak period' during which the highest frequency of forest fire occurrences can be seen.

The present research work is amongst the pioneering studies to test the validity of the Keetch Byram Drought Index (KBDI) as a measure of fire activity and pre-warning tool with number of fire incidences in Indian scenario. Soil moisture content can act as a good proxy for the fuel dryness and hence of the potential fire risk in an area[38]. KBDI seems to very aptly reflect the soil moisture content as it resulted in a reliable prediction of the fire danger in the study area over the study period of three years. The probability of occurrences of forest fires gets quite high when the KBDI exceeds its value of 700. KBDI is broadly in agreement with the severity of forest fire over the years in the study area. However, for the scale-up studies, the index might need adjustments for improved resonance and reliability.

An integral part of effective forest fire prevention is engaging with communities that are dependent on forests. Local people should be made aware of the existing fire risk in forest areas around them. If the KBDI-based drought stage is high (6-7), extremely dry conditions are prevalent in the forest making it under 'high fire danger'. At this time, anthropogenic activities should be minimum in and around forests and utmost caution should be taken to avoid any source of fire initiation. Educating locals of impending fire risks, hazardous impacts and preventive measures can be an effective solution to control forest fires. Knowledge of the fire danger level based on KBDI drought stage may also aid the forest fire officers in better planning and resource allocation during the fire management process.

5.1 Applicability

It's not economically feasible to provide the sufficient tools and manpower to control the emergency fire situations to all the regions in a country simultaneously. Therefore, forecasting the fire danger in a region is essential for distributed yet effective management of forest fires by mobilizing resources, equipment and manpower to the areas which are more vulnerable to fire rather than providing unnecessary cover where there is a low probability of fire occurrence[39]. This will help forest officials to minimize fire impacts by taking prompt actions when fire breaks out[40]. The present approach provides a low-cost and reliable method to assess fire risk potential well in-advance based on open-source datasets. This system based on fire trends and KBDI can be adopted in countries like India to predict forest fire risk and generate pre-warnings for the expected severity of fire in a cost-effective and ecologically feasible manner.

Forest Survey of India disseminates early-warning alerts for forest fires based on Fire Weather Index (FWI) to prevent and manage forest fires in India. Incorporation of fire trends and Keetch Byram Drought Index while generating the early-warning alerts are expected to improve the accuracy of the prediction. This pilot study is envisaged as the basis for the development of Fire Danger Rating System (FDRS) for the whole country to forewarn impending fire conditions and ensure appropriate states of fire monitoring, readiness, likely ignition and fire behavior.

The results of the present study show that the blend of Remote Sensing and GIS coupled with forest fire trends, peak period and Keetch Byram Drought Index will be beneficial for future studies to identify the high fire risk forest areas and predict the severity of fire behavior in the following fire season. KBDI proved to be a strong parameter to predict the forest fires in an area as high index values indicate increased flammability contributing to heightened fire severity. Better foreknowledge of the impending fire risk could aid in strengthening forest fire prevention, management and fighting strategies which in turn are anticipated to protect the forest ecosystems of the country.

ACKNOWLEDGEMENTS

I acknowledge Forest Survey of India, Dehradun, India for the provision of facilities and data to carry out the present research work. I am grateful to my supervisor, Mr. E. Vikram (IFS), Ex-Deputy Director (FSI) for his guidance and encouragement throughout. I further extend my thanks to Dr. Subhash Ashutosh, Director General, FSI and the Forest Fire Technical Team, FSI for their constant support and motivation. I would also like to extend my appreciation to Mr. Ross Smith, Consultant (World Bank) and Mr. Hrishi Patel (World Bank) for sharing their insightful suggestions.

REFERENCES

[1] Ainuddin, N. A. and Ampun, J., "Temporal analysis of the Keetch-Byram Drought Index in Malaysia: implications for forest fire management," Journal of Applied Sciences 8(21), 3991-3994 (2008).

[2] India State of Forest Report. Forest Survey of India. Ministry of Environment, Forests and Climate Change, Dehradun (2019).

[3] Dogra, P., Mitchell, A.M., Narain, U., Sall, C., Smith, R. and Suresh, S., "Strengthening Forest Fire Management in India". World Bank, Washington DC (2018).

[4] Firoz, A., Goparaju, L., Qayum, A. and Quli, S. M. S., "Forest fire trend analysis and effect of environmental parameters: A study in Jharkhand State of India using Geospatial Technology," World scientific news 90, 31-50 (2017).

[5] Taylor, S. W. and Alexander, M. E., "Science, technology, and human factors in fire danger rating: the Canadian experience," International Journal of Wildland Fire 15(1), 121-135 (2006).

[6] Stocks, B., Lynham, T., Lawson, B., Alexander, M., Wagner, C.V., McAlpine, R. and Dube, D., "The Canadian forest fire danger rating system: an overview," The Forestry Chronicle 65: 450-457 (1989).

[7] Groisman, P. Y., Sherstyukov, B. G., Razuvaev, V. N., Knight, R. W., Enloe, J. G., Stroumentova, N. S. and Aleksandersson, H., "Potential forest fire danger over Northern Eurasia: changes during the 20th century," Global and planetary change 56(3-4), 371-386 (2007).

[8] Keetch, J. J. and Byram, G. M., "A drought index for forest fire control," USDA Forest Service Research Paper, SE(38), 1-32 (1968).

[9] Technical Information Series, "FSI Forest Fire Alert System (FAST 3.0)", Forest Survey of India, 1(2) (2019).

[10] Maden, U., NASA "Satellite data aids forest fire detection and monitoring in Nepal" (2018). https://phys.org/news/2018-06-satellite-aids-forest-nepal.html#jCp

[11] Malingreau, J. P., Achard, F., D'souza, G., Stibig, H. J., D'souza, J., Estreguil, C. and Eva, H., "AVHRR for global tropical forest monitoring: The lessons of the TREES project," Remote Sensing Reviews 12(1-2), 29-40 (1995).

[12] Koutsias, N., Xanthopoulos, G., Founda, D., Xystrakis, F., Nioti, F., Pleniou, M., Mallinis, G. and Arianoutsou, M., "On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010)" Int. J. Wildland Fire 22, 493–507 (2012).

[13] Dolling, K., Chu, P-S. and Fujioka, F., "A climatological study of the Keetch/Byram drought index and fire activity in the Hawaiian Islands," Agric. For. Meteorol. 133,17–27 (2005).

[14] Dolling, K., Chu, P. S. and Fujioka, F., "Natural variability of the Keetch–Byram drought index in the Hawaiian Islands," International journal of wildland fire 18(4), 459-475 (2009).

[15] Heim, R. R. 2002. "A review of twentieth century drought indices used in the United States," Bull. Amer. Meteor. Soc. 83, 1149-1165 (2002).

[16] Liu, Y., Stanturf, J. and Goodrick, S., "Trends in global wildfire potential in a changing climate," Forest ecology and management 259(4), 685-697 (2010).

[17] Fujioka, F. M., "Starting the Keetch-Byram Drought Index". 11th Conference in fire and forest meteorology, Missoula, Montana (1991).

[18] Peel, M. C., Finlayson, B. L. and McMahon. T. A., "Updated World Map of the Köppen-Geiger Climate Classification." Hydrology and Earth System Sciences Discussions 4, 439–473 (2007). doi:10.5194/ hessd-4-439-2007.

[19] Khare, S., Ghosh, S. K., Latifi, H., Vijay, S. and Dahms, T., "Seasonal-based analysis of vegetation response to environmental variables in the mountainous forests of Western Himalaya using Landsat 8 data," International journal of remote sensing 38(15), 4418-4442 (2017).

[20] BBC News., "Uttarakhand fires: Battle to douse deadly blaze in Indian state" 2 May 2016, https://www.bbc.com/news/world-asia-india-36184817 (8 September 2020)
[21] The Hindu., "Uttarakhand battles fire crisis," 12 September 2016, https://www.thehindu.com/news/national/other-states/forest-fire-claims-five-lives-ndrf-forces-deployed-to-control-flames/article8538875.ece (8 September 2020)
[22] Yang, J., He, H.S. and Shifley, S.R., "Spatial controls of occurrence and spread of wildfires in the Missouri Ozark Highlands," Ecological Applications 18, 1212- 1225 (2008).
[23] Konoshima, M., Albers, H.J., Montgomery, C.A. and Arthur, J.L., "Optimal spatial patterns of fuel management and timber harvest with fire risk," Canadian Journal of Forest Research 40, 95-108 (2010).
[24] Pausas, J. G., "Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean Basin)," Climatic Change, 63(3), 337–350 (2004).
[25] Giambelluca, T. and Sanderson, M., The water balance and climatic classification. Prevailing Trade Winds: Weather and Climate in Hawaii, Sanderson M (ed.). University of Hawaii Press: Honolulu, 56-72 (1993).
[26] Official website of Forest Survey of India https://www.fsi.nic.in (8th September 2020)
[27] India State of Forest Report. Forest Survey of India. Ministry of Environment, Forests and Climate Change, Dehradun (2017).
[28] Technical Information Series, "Identification of fire prone forest areas based on GIS analysis of archived forest fire points detected in the last thirteen years", Forest Survey of India, 1(1) (2019).
[29] Subin, K. J., Kumar, S., Jesnamol, M.M., Sreeraj, N.K., Madhu, G. and Ambat, B., "Forest Fire Risk Analysis and Management System Using Geoinformation Technology," Applied Geoinformatics for Society and Environment (2010).
[30] Sharma, R. K., Sharma, N., Shrestha, D. G., Luitel, K. K., Arrawatia, M. L. and Pradhan, S., "Study of forest fires in Sikkim Himalayas, India using remote sensing and GIS techniques," Climate Change in Sikkim—Patterns, Impacts and Initiatives, 233-244 (2012).
[31] Jaiswal, R.K., Mukherjee, S., Raju, D.K. and Saxena, R., "Forest fire risk zone mapping from satellite imagery and GIS," International Journal of Applied Earth Observation and Geoinformation 4(7), 1-10 (2002).
[32] Flannigan, M.D. and Harrington, J.B., "A Study of the Relation of Meteorological Variables to Monthly Provincial Area Burned by Wildfire in Canada (1953- 80)," Journal of Applied Meteorology 27, 441-452 (1988).
[33] Bessie, W.C. and Johnson, E.A. The Relative Importance of Fuels and Weather on Fire Behavior in Sub-alpine Forests. Ecology 76, 747-762 (1995).
[34] Finney, M.A., "Design of Regular Landscape Fuel Treatment Patterns for Modifying Fire Growth and Behavior," Forest Science 47, 219-229 (2001).
[35] Malamud, B.D., Millington, J.D.A., and Perry, G.L.W., "Characterizing wildfire regimes in the United States". Proc. National Academy of Sciences in the United States of America 102, 4694-4699 (2005).
[36] Rollins, M.G., Swetnam, T.W. and Morgan, P., "Evaluating a century of fire patterns in two Rocky Mountain Wilderness areas using digital fire atlases," Canadian Journal of Forest Research 31, 2107-2123 (2001).
[37] Yang J., He, H.S., Shifley, S.R. and Gustafson, E.J., "Spatial patterns of modern period human-caused fire occurrence in the Missouri Ozark Highlands," Forest Science 53, 1-15 (2007).
[38] Cooke, W.H., Mostovoy, G.V., Anantharaj, V.G. and Jolly, W.M., "Wildfire potential mapping over the state of Mississippi: a land surface modeling approach," GISci. Rem. Sens. 49(4), 492–509 (2012).
[39] T.M. Sofronova, M.A. Sofronov, P.M. Matveev and A.V. Volokitina., "Comparative analysis of meteorological factors in Russian and foreign fire-danger rating systems'1 http://www.fao.org/3/XII/0738-B3.htm
[40] Chuvieco, E. and Sales, J., "Mapping the spatial distribution of forest fire danger using GIS," International Journal Geogaphical Information Systems,10, 333– 345 (1996).