# FIRE WEATHER INDEX AND FOREST FIRE DANGER MAPPING: INSIGHTS FROM A CASE STUDY IN ANTALYA - MANAVGAT FOREST, TURKIYE

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**KEY WORDS:** Fire Weather Index, dLST, dNBR, Fire Radiative Power, Fire Danger Map

**ABSTRACT:**

Forest fires in Türkiye, like in other regions, have detrimental effects on wildlife habitats, water quality, air pollution, climate change, and the economy. These fires become particularly concerning during the dry summer months. In 2021, forest fires affected over 150 thousand hectares of land across the country, with the Manavgat district in Antalya province alone witnessing the burning of approximately 60 thousand hectares of forest area. This study aims to assess the applicability and suitability of Fire Weather Index (FWI) data derived from meteorological station data in the Antalya region, as well as EFFIS FWI data generated using satellite-based meteorological information, for fire danger mapping during the Manavgat forest fire that occurred between 28 July and 6 August 2021. Additionally, correlation analyses were performed between the two FWI datasets and other relevant variables, including the difference in Normalized Burn Ratio (dNBR), the difference in Land Surface Temperature (dLST), and Fire Radiative Power (FRP) data detected from MODIS and VIIRS satellites. The results of the correlation analysis indicated that the FWI values obtained using in-situ meteorology station data showed much higher correlations than FWI values obtained from EFFIS, with the highest correlation (73%) observed with dLST data. Consequently, the fire danger map was created using the in-situ meteorological data, given its stronger correlation. The results prominently revealed a widespread high-risk level across the entire Antalya province, with the Manavgat district classified into the "Extreme" and "Very Extreme" FWI classes, emphasizing the critical importance of utilizing in-situ meteorological data for precise fire danger assessments and proactive fire management strategies.

## 1. INTRODUCTION

Türkiye is located in the Mediterranean basin, a significant fire-prone region that creates favorable conditions for forest fires caused by natural and anthropogenic factors. Over the last 20 years, Türkiye has experienced an annual average of 2-3 thousand forest fires, resulting in the burning of 7-8 thousand hectares of land (URL 1). On average, one or two of these fires each year can be classified as major megafires, impacting at least 5,000 hectares. Notably, in 2021, Türkiye witnessed more than 250 forest fires, primarily affecting the provinces of Antalya and Muğla, and were recorded as the largest forest fires in the country's history. These devastating fires impacted over 150 thousand hectares of forest area. The most extensive fires of 2021 occurred between July 28 and August 10 in the districts of Manavgat (approximately 60,000 ha) and Gündoğmuş (16,000 ha) in Antalya, as well as in Marmaris (12,000 ha), Köyceğiz (11,000 ha), and Milas (18,000 ha) in Muğla (URL 1).

To effectively combat forest fires, it is imperative to proactively identify high-risk areas and continuously monitor key climate factors, such as temperature, precipitation, relative humidity, and wind conditions in these regions. Additionally, fostering increased awareness and preparedness during fire seasons is crucial. Numerous indices have been developed to assess forest fire risk and generate risk maps for vulnerable areas. Among them, the Fire Weather Index (FWI), part of the Canadian Forest Fire Danger Rating System (CFFDRS), has been validated and recognized worldwide as one of the most trusted and important indicators for meteorological fire danger mapping (Varela et al., 2019). The FWI integrates various meteorological variables to provide a comprehensive assessment of fire danger potential, aiding in the prediction of fire behavior and facilitating effective fire management strategies. Other indices, such as the Fosberg Fire Weather Index (FFWI), McArthur Wildfire Hazard Index (MFFDI), Keetch-Byram Drought Index (KBDI), US National Fire Hazard Rating System (NFDRS), Angstrom Index, and Fire Potential Index, each offer unique contributions in evaluating fire danger based on specific factors relevant to their respective methodologies. By utilizing these indices collectively, authorities can make informed decisions, allocate resources effectively, and implement preventive measures in high-risk areas, thus minimizing the impact of forest fires and protecting valuable ecosystems.

Numerous studies in the literature have utilized the Fire Weather Index (FWI), indicating a strong correlation between forest fires and FWI, particularly in regions with Mediterranean climates. For instance, Dimitrakopoulos et al. (2011) evaluated FWI over two consecutive fire seasons in a Mediterranean environment in Crete, Greece. The study found that FWI values successfully predicted days of high fire risk, as demonstrated by the occurrence of actual fires. In another study, Chelli et al. (2015) calibrated the Fire Weather Index (FWI) for forest fuel moisture content in two Mediterranean regions in Greece. This calibration process involved comparing experimental field data with the values expected from the original application of FWI. The study's results suggested that further testing and expansion of FWI to other sample areas could enhance daily wildfire hazard estimation, providing better support for the forestland Conservation Agencies of Mediterranean countries. In climate change studies related to forest fires, FWI was used to investigate fires in the Antalya, Çanakkale, and Muğla Regional Directorates of Forestry in 2008 and 2009, as indicated by Calda et al., (2020).

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The results aligned with the actual fire data for those years, indicating successful fire risk estimation using FWI. Moreover, FWI is not only used for daily fire danger mapping but also for investigating changes in the frequency and intensity of future natural disasters (Fargeon et al., 2018; Camia et al., 2017).

The European Forest Fire Information System (EFFIS) provides the European Parliament with up-to-date information on fires in the EU and neighboring countries and works for the protection of forests against fires. For this reason, it generates fire danger forecasts with data from ECMWF (European Centre for Medium-Range Weather Forecasts) model (≈8 km) which provides forecasts for 1 to 9 days and MeteoFrance (French national meteorological service) model (≈10 km) which provides weather forecasts for up to 3. In addition to FWI, EFFIS provides data on fire danger indices such as McArthur Forest Fire Danger Index, the Keetch-Byram Drought Index (KBDI) and US National Fire Danger Rating System (NFDRS) estimated from the ECMWF deterministic model (URL 2).

Fire weather indexes examine the climatic conditions that cause fire occurrence. Seasonal conditions affect fire occurrence and fire behavior. In addition, fire intensity and fire severity provide information about fire size, fire speed, direction of spread, biomass consumption and fire interaction with the ecosystem. The energy released from organic matter during the combustion process and the intensity of the fire during the active period is expressed as fire intensity. Fire intensity is more related to the energy released, while fire severity or burn severity is related to the loss of organic matter and the response of the ecosystem to fire (Keeley, 2009). There are various metrics for measuring fire intensity and burn severity. Studies have shown that there is a relationship between burn severity and temperature increase during the fire (Çolak and Sunar, 2023).

In this study, FWI data for the region affected by the Manavgat fire were produced using two different datasets: i) in-situ meteorological station data and ii) satellite-based meteorological data from EFFIS. Correlation analyses were performed between these two sets of FWI values and other datasets, including the burned/unburned forest area samples (burned samples obtained from FRP (Fire Radiative Power) calculated from MODIS and VIIRS satellite data, dLST (the pre-fire and post-fire difference of Land Surface Temperatures generated from Landsat images), dNBR (Normalized Burn Ratio difference generated from Landsat images before and after the fire). Afterwards, the higher correlation performance between the two datasets was taken into account for fire danger mapping in the study area.

## 2. STUDY AREA

Antalya province, is situated in southwestern Turkiye and falls within the Mediterranean climate zone, characterized by hot and dry summers and mild and rainy winters. During the summer months, temperatures often rise above 40 $^{0}$C at noon. The province covers an area of 20,874 km², with its highest point reaching 3,085 meters in the South Taurus Mountains (URL 3). Due to the Mediterranean geography and climate zone, the region's forests are consistently at risk of fire, mainly attributed to the climate's characteristics and the presence of fire-sensitive tree species, particularly pine trees, that constitute the forest.

The study area, Manavgat is the largest district of Antalya Province with an area of 2283 km². It was founded on the fertile plain of the same name on both sides of the Manavgat River. The district center is approximately 3.5 km from the Mediterranean coast and 75 km east of Antalya (Figure 1). The region extending from the coastline to the Taurus Mountains is an agriculturally productive area with diverse plant life, including various fruits and trees. The Taurus Mountains are covered with shrubs and maquis vegetation, while red pine dominates the lower elevations in the south. As one moves to higher altitudes, larch, spruce, cedar, and juniper trees become more prevalent. River valleys are adorned with willow and plane trees. The climate is generally hot, with summer temperatures frequently exceeding 45 degrees Celsius (URL 4).

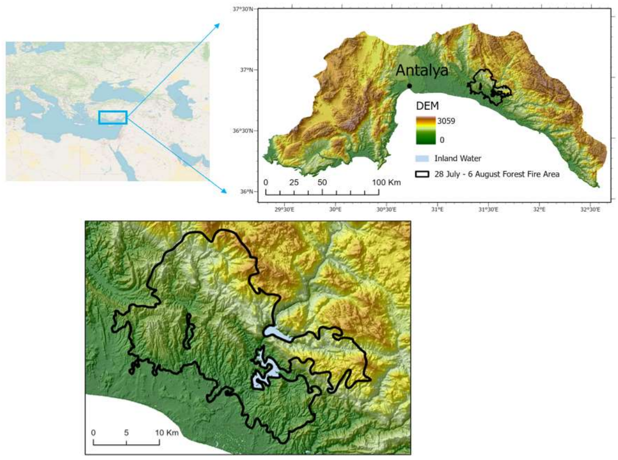


**Figure 1.** Location of the Manavgat 2021 forest fire in Antalya.

## 3. DATASET AND METHODOLOGY

### 3.1 Datasets

Antalya meteorological stations data, burned area information (from EFFIS and Ministry of Forestry), EFFIS FWI data and satellite data (Landsat 8, MODIS and VIIRS) were used in this study. The characteristics of the Landsat 8 satellite data used are given in Table 1.

| Satellite | Spectral resolution (µm) | Spatial resolution (m) | Temporal resolution (day) | Radiometric resolution (bit) |
|---|---|---|---|---|
| Landsat 8 OLI/TIRS | 9 optical bands 0.43–2.30 | 30<br>15 | 16 | 16 |
| | 2 thermal bands 10.60-12.51 | 100 | | |

**Table 1.** Characteristics of Landsat 8 OLI/TIRS.

Two products were employed for monitoring fire and thermal anomalies: MODIS (MCD14DL) and VIIRS (Suomi NPP, NOAA20). MODIS provides data with a spatial resolution of 1 kilometer (km) at nadir, while VIIRS, operating on two satellites, offers daily images with a higher spatial resolution of 375 meters (m) at nadir compared to MODIS (URL 5).

In the EFFIS system, fire danger classes are divided into 6 classes (Table 2). In this study, EFFIS classes are taken as a basis for comparison with ground truth data. In June 2021, the "Very Extreme" class with FWI values above 70 was added to the EFFIS fire danger classes to indicate the danger level of fires emerged in Mediterranean countries such as Türkiye, Greece and Italy during the summer of 2021 (URL 2).

| Fire Danger Classes | FWI |
|---|---|
| Low | 5.2 - 11.2 |
| Moderate | 11.2 - 21.3 |
| High | 21.3 - 38.0 |
| Very High | 38.0 - 50 |
| Extreme | 50 - 70 |
| Very Extreme | >= 70 |

**Table 2.** FWI fire danger classes (URL 2).

Figure 2 shows the FWI map (for 28 July 2021) generated by the Copernicus Emergency Management Service for EFFIS.

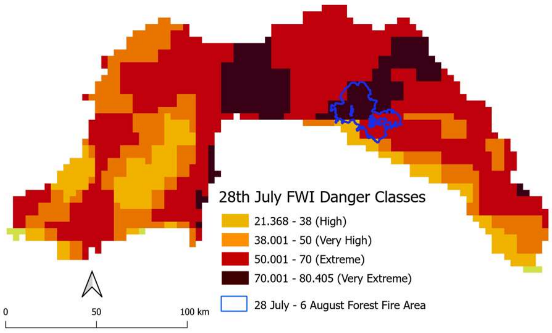


**Figure 2.** EFFIS FWI map (for 28 July 2021).

### 3.2 Methodology

In this study, various image-processing steps like FWI calculation, LST estimation, spectral burn indexes, and GIS data integration were applied to evaluate forest fire danger mapping for the Manavgat region. All the processing steps in the study are shown in Figure 3.

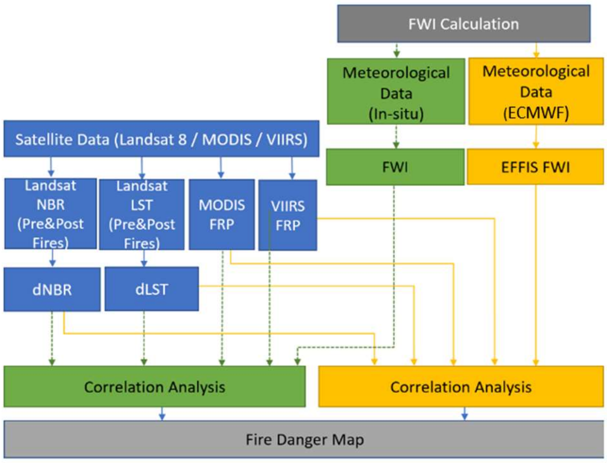


**Figure 3.** Flowchart of the study.

As a first step, the FWI calculation involves a series of mathematical operations (Wagner and Pickett, 1985) which are illustrated in the flowchart presented in Figure 4. As shown, the FWI system is comprised of six components: three fuel moisture codes (first-level intermediate outputs of the system: Fine Fuel Moisture Code, Duff Moisture Code, Drought Code), two fire behavior indices (second-level intermediate outputs: Initial Spread Index, Built Up Index) and the final output, the Fire Weather Index.

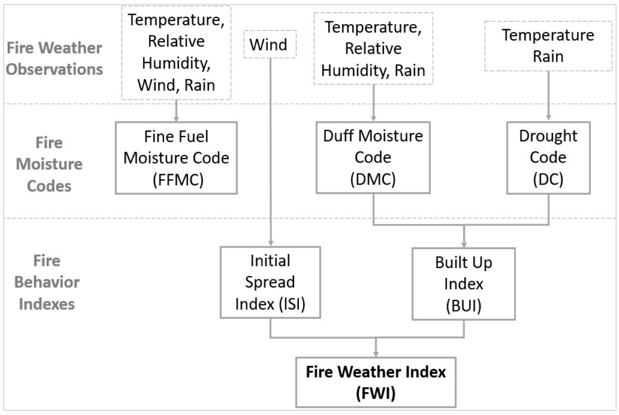


**Figure 4.** Flowchart of the Canadian Forest Fire Weather Index (FWI) system used in the study (Van Wagner, 1987).

The FWI values were obtained by analyzing daily maximum temperature, relative humidity, mean wind speed, and precipitation data collected from 16 meteorological stations in the Antalya region. Using Python codes, the FWI values were calculated by following the steps illustrated in Figure 4, which involve computing fire moisture codes and fire behavior indexes. This calculation enabled the determination of FWI values for each station, providing crucial insights into the prevailing fire weather conditions in the region.

Landsat LST maps were generated using the Google Earth Engine (GEE), a cloud computing platform that enables diverse geospatial analyses on Google's cloud infrastructure. GEE leverages a vast catalog of satellite imagery and geographic datasets, coupled with planetary-scale analysis capabilities (Gorelick et al., 2017), to facilitate the creation of these maps.

In this study, Land surface temperatures (LST) before and after the fire were obtained from Landsat 8 images, using the Planck function (Wang et al., 2019). Subsequently, their differences were computed to derive dLST values (Eq. 1).

$$dLST = LST_{post-fire} - LST_{pre-fire} \quad (1)$$

The Normalized Burn Ratio (NBR) is a widely used spectral index in remote sensing for assessing and monitoring burn severity following a fire event. It is founded on the principle that healthy vegetation exhibits high reflectance in the Near-Infrared (NIR) region and low reflectance in the Short-Wave Infrared (SWIR) region of the electromagnetic spectrum (Eq.2) (Key and Benson, 2005). The Delta Normalized Burn Ratio (dNBR or ΔNBR) was then derived by calculating the difference between NBR values before and after the fire. Subsequently, dNBR is employed to classify and establish burn severity levels (Eq.3) (Keeley, 2009; Çolak and Sunar, 2020; URL 6).

$$NBR = \frac{NIR-SWIR}{NIR+SWIR} \quad (2)$$

$$dNBR = NBR_{pre-fire} - NBR_{post-fire} \quad (3)$$

The fire radiative power (FRP) has been extensively employed to classify fire types and investigate fire intensity. FRP represents the radiative energy emitted per unit of time from all fires within a pixel, measured in megawatts. For this study, MODIS and VIIRS FRP estimates were obtained from the NASA website. The VIIRS instrument, with its superior resolution compared to

MODIS, is particularly effective in detecting hot spots of small fires and providing detailed fire mapping capabilities (URL 5).

In order to investigate the relationships between Landsat dNBR, Landsat dLST, MODIS FRP, VIIRS FRP, and the FWI data derived from both in-situ meteorological and satellite meteorological data, correlation analyses were carried out. Correlation analysis is a statistical method that quantitatively determines the extent and direction of relationships between two or more variables. The correlation coefficient ranges mathematically between -1 and +1, with the Pearson Correlation method being employed for this study to ascertain linear relationships, as frequently utilized (Obilor and Amadi, 2018).

## 4. RESULTS

FWI values were computed for each station utilizing meteorological data from 16 meteorological stations (dated 28 July 2021) and following the processing steps outlined in Figure 3. To generate the FWI map for the Antalya province, ordinary kriging with an exponential semivariogram model (Figure 5) was applied.

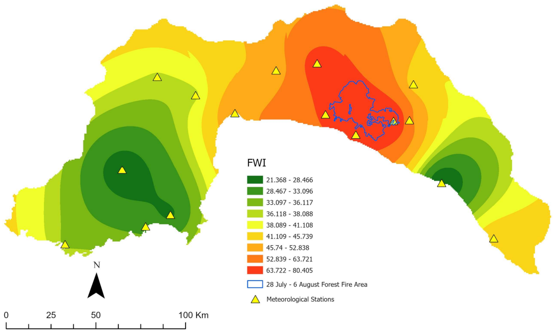


**Figure 5.** FWI map obtained with meteorological station data (28 July 2021).

Precipitation, air temperature, humidity, and wind speed are climatic conditions that pose a danger to fire outbreaks. Therefore, a graphical analysis was conducted using meteorological data from the four closest stations to the Manavgat fire area for the year 2021, in order to explore the relationship between FWI values and precipitation, as well as air temperature. The annual FWI values and air temperature data are presented in Figure 6.

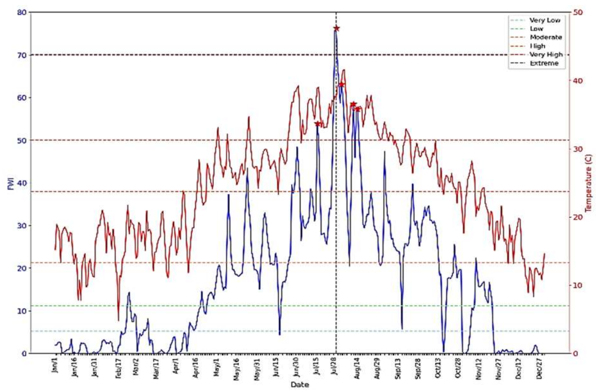


**Figure 6.** FWI and air temperature values for the Manavgat area (year 2021).

It can be observed that these two parameters follow a similar trend, indicating that an increase in air temperature leads to an increase in FWI. On 28 July, the day the fire started, the FWI value reached an average of 75.5 at the four stations closest to the initial fire area, marking the highest value recorded during the year 2021 (Figure 6).

Conversely, as depicted in Figure 7, there exists an inverse relationship between annual FWI and precipitation data, indicating that FWI increases during the dry season between mid-April and October.

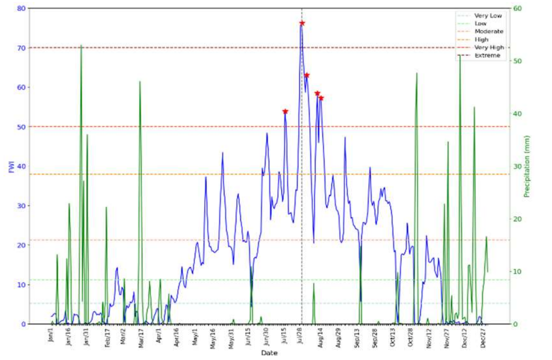


**Figure 7.** Annual FWI and precipitation values for the Manavgat area.

dNBR was calculated as the difference between the NBR values before and after the fire, and the resulting the dNBR map was generated by considering the burn severity levels proposed by USGS as presented in Table 3 (Figure 8).

| Severity level | dNBR range |
|---|---|
| Enhanced Regrowth, high (post-fire) | -0.500 to -0.251 |
| Enhanced Regrowth, low (post-fire) | -0.250 to -0.101 |
| Unburned | -0.100 to +0.99 |
| Low Severity | +0.100 to +0.269 |
| Moderate-low Severity | +0.270 to +0.439 |
| Moderate-high Severity | +0.440 to +0.659 |
| High Severity | +0.660 to +1.300 |

**Table 3.** Burn severity levels (URL 6).

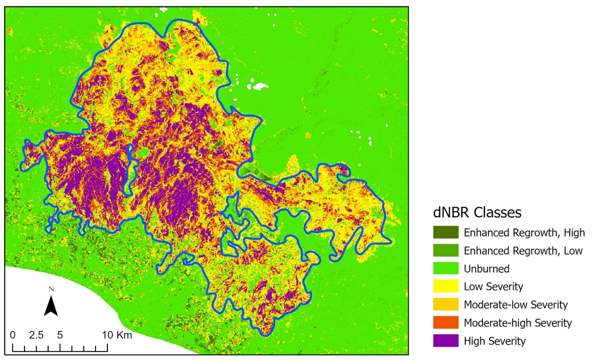


**Figure 8.** The dNBR map produced.

The dLST map, derived from pre-fire and post-fire LST image differences (Figure 9), shows a significant correlation with the dNBR map. This correlation indicates that regions experiencing significant increases in land surface temperature also coincide with higher burn severity levels, as depicted on the dNBR map. Within the dLST map, areas with significant temperature differences within the fire zone indicate severe burn impacts. The highest observed temperature difference is approximately 20°C, emphasizing the relevance of land surface temperature changes as a valuable indicator for fire damage assessment and management.

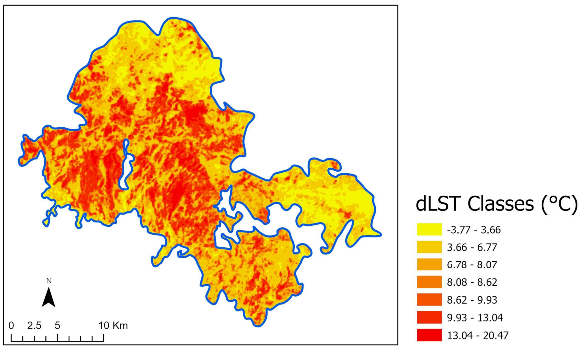


**Figure 9.** The dLST map produced.

Figure 10 displays the FRPs in megawatts alongside the active fire hotspot points detected by MODIS and VIIRS on the first day of the fire, i.e., 28 July. Based on these hotspots, it can be inferred that the fire originated in two distinct locations. In addition, it can be seen that VIIRS captures more points, as it has a higher resolution than MODIS.

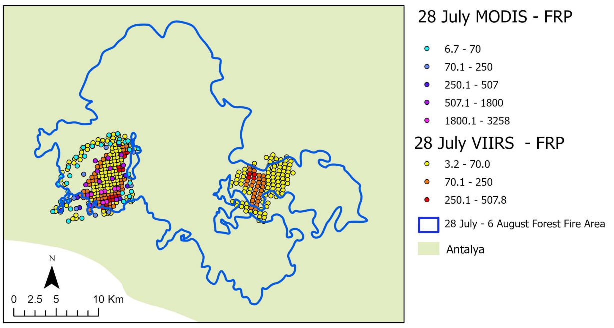


**Figure 10.** Active fire hotspot points detected by MODIS and VIIRS on 28 July 2021.

Given the magnitude and rapid spread of the Manavgat fire in 2021, active fire hotspots were acquired throughout its duration. Figure 11 presents a day-by-day visualization of the fire's progression, impacting an area of approximately 55,000 $m^2$.

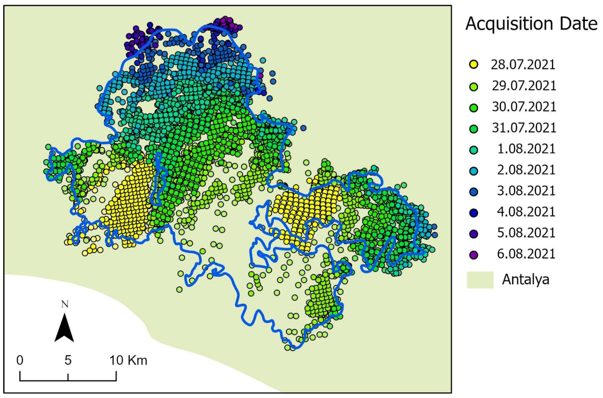


**Figure 11.** The spread of the Manavgat fire from 28 July to 6 August 2021.

Figure 12 illustrates the relationship between FRP and FWI over its duration, divided into six distinct classes. The data points displaying a strong correlation between both values are represented in dark blue, while weak correlations are shown in light pink. Notably, areas where the fire originated and spread exhibit remarkably high FWI and FRP values.

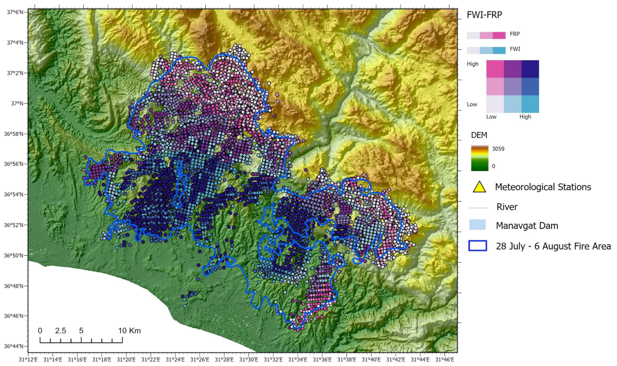


**Figure 12.** The relation between FWI and FRP.

One hundred random points in the fire zone and one hundred random points in the non-fire zone were selected, and correlation analyzes were made between Landsat dNBR, Landsat dLST, MODIS FRP and VIIRS FRP with both FWI data created with meteorological station data and EFFIS. Correlation matrix is given in Table 4.

| | dLST | dNBR | MODIS FRP | VIIS FRP |
|---|---|---|---|---|
| **FWI** | 0.73 | 0.63 | 0.26 | 0.57 |
| **EFFIS FWI** | 0.43 | 0.38 | 0.12 | 0.37 |

**Tablo 4.** Correlation analysis.

When the correlations were examined, it can be seen that correlations with the FWI values obtained using in-situ meteorology station data were much higher than FWI values obtained from EFFIS. Highest one was obtained with dLST data with %73. In addition, while correlation between dNBR and dLST was obtained 84%, their correlations with VIIRS FRP values were relatively low, at approximately 50%.

The correlation analysis revealed statistically significant positive correlation between the various derived variables and the FWI data, which was generated using meteorological data. This noteworthy correlation led to the production of the fire danger map (Figure 13), with FWI classes and colours depicted in Figure 2.

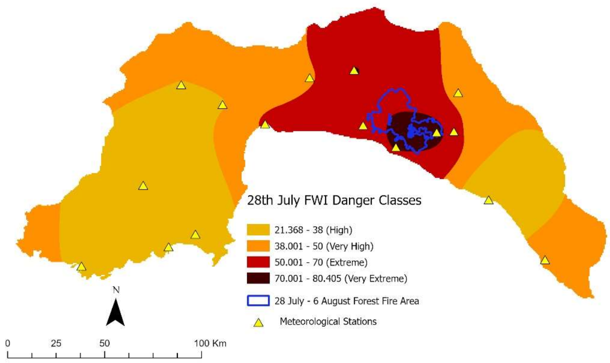


**Figure 13.** FWI Fire danger map produced (28 July 2021).


https://doi.org/10.5194/isprs-archives-XLVIII-4-W9-2024-53-2024 

Based on the danger classes presented in Figure 13, the entire Antalya province exhibits a prevalent high-risk level. Specifically, the Manavgat district, which experienced the catastrophic fire incident on 28 July, falls within the "Extreme" and "Very Extreme" danger classes.

## 5. CONCLUSION

The year 2021 witnessed a significant increase in forest fire incidents, surpassing 250 occurrences, with Antalya and Muğla provinces experiencing the most extensive and devastating fires ever recorded in Türkiye. Among them, the most significant fire outbreak transpired within the timeframe of July 28 to August 6 in Antalya's Manavgat district, resulting in an extensive burn area of approximately 60,000 hectares. Given the magnitude of these colossal fires, the imperative for conducting fire danger mapping and comprehensive risk analysis becomes apparent. Such proactive measures hold the potential to mitigate the catastrophic impact of future fire outbreaks and safeguard our invaluable natural resources.

In this study, fire danger mapping was performed using FWI data. Two distinct FWI datasets were generated—one utilizing in-situ meteorological station data and the other derived from EFFIS satellite-based meteorological data. Correlation analyses were conducted between these FWI datasets and other derived variables, including dLST, dNBR, and FRP. Correlation analysis revealed statistically higher positive correlations between FWI data generated using meteorological data and two specific parameters: dLST (73%) and dNBR (63%). Consequently, the fire danger map was developed based on the in-situ meteorological data due to its higher correlation. The findings clearly indicated a widespread high-risk level throughout the entire Antalya province. Notably, the Manavgat district was classified within the "Extreme" and "Very Extreme" FWI classes, underscoring the critical importance of employing in-situ meteorological data for accurate fire danger assessments and proactive fire management strategies.

For future research, a broader-scale study conducted over an extended time period would be advantageous in providing more conclusive evidence regarding the adaptability of the FWI to Mediterranean-type environments. This would enable a more comprehensive understanding of fire risk dynamics, further enhancing fire management and mitigation efforts in these regions.

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