Forest fire risk monitoring using fuzzy logic and IoT technology

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Article Info

Article history:

Received Nov 17, 2023
Revised Mar 11, 2024
Accepted Apr 2, 2024

Keywords:

Internet of things (IoT)
Fuzzy Logic
Monitoring
Temperature
Relative Humidity
Wind speed
Forest fire weather index (FWI)

ABSTRACT

Forest fire is one of the leading causes of ecological damage and environmental problems. This work aims to develop a forest fire risk monitoring system in which an artificial intelligence technique, fuzzy logic, has been used to determine the forest method risk (temperature, relative humidity, and wind speed). Fuzzy set theory implements categories or groupings of data whose boundaries are not clearly defined (i.e. fuzzy), consisting of rule bases, membership functions, and inference methods. We also use wireless sensor networks (WSN) and Internet of Things (IoT) technologies. In order to collect environmental information through WSN based environmental sensors, the collected information is transmitted to a database on a server through an Internet connection. Users can monitor the saved data using an internet browser in each whey. This provides the ability to analyze detailed data and then take the necessary precautions to protect threatened forests.

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1. INTRODUCTION

Forests cover about 30% of the earth's surface [1]. They play a crucial role in promoting equitable economic and social progress, not only providing trees but also producing valuable ecosystem products such as oxygen emissions, carbon sequestration, soil conservation, landscape protection, improving soil fertility, protecting and cleaning surfaces , as well as regulating water and climate conditions. However, forests face a significant threat in the form of wildfires, which can cause extensive damage and have severe ecological, social, and economic consequences. The heightened danger of fires is compounded by the effects of climate change, resulting in a rise in the frequency of wildfires on a global scale. Just in Algeria alone, at least 90 people died in 35 cities in the year 2022, with 89,000 hectares of land burned and billions of dollars spent annually on wildfire prevention and suppression efforts[2]. Many countries have enacted a range of strategies to address this challenge of forest fires prevention and control. The response time of emergency services has a significant impact on reverberation and the damage it causes. Furthermore, preventive measures remain limited in their impact or effectiveness in reducing the number of fires. Given the complexity and diversity of forest ecosystems [3], measures to address the telltale symptoms of extreme wildfires and traditional monitoring methods commonly used to prevent and extinguish fires are time-consuming and ineffective. Therefore, improving forest fire prevention and detection systems can be regarded as the primary goal of environmental protection. Work in this field has demonstrated the effectiveness and integration of multi-criteria decision-making (MCDN) in developing fire risk assessment maps for forest areas based on remote sensing and GIS (Geographic Information Systems) through thematic analysis of satellite images [2-5]. Therefore, fire risk mapping is an crucial factor in the process of recognizing forest regions that are most susceptible to fire. However, traditionally created fire risk maps no longer meet today's requirements. Therefore, fire prevention remains a community and national priority.

Furthermore, there is an urgent need to introduce smart measures, prevention and early detection methods, and even predictions based on new modern communication technologies, especially the Internet of Things (IoT) which is a new and ongoing revolution. It is based on Wireless Sensor Networks (WSN). Fuzzy control systems are a recent method that have been widely used in many fields such as forest fires. Fuzzy systems can predict meteorological forest fire risk well. It can be supported local forestry and disaster management services and conduct real-time environmental monitoring of the above wildfire risk factors. Wildfire research is based on a thorough understanding of the factors that contribute to the phenomenon, using multiple criteria alone or in combination to understand risks and problems. Additionally, it can be used with IoT for forest fire forecasting [6].

As such, it is highly appropriate for managing the risk of wildfires. The IoT-based solution proposed in[2] involves the use of IoT device architecture, it is highly appropriate for managing the risk of wildfires, and plans for firefighters, ultimately saving lives and property. In [7] the authors have developed a remote health system based on IoT technology that can transmit and store health data collected by biomedical sensors in the cloud. The system allows doctors or patients to monitor a patient's health in real-time from anywhere, reducing the need for direct interaction between them. In [8] the authors focused on the need for accurate early warning systems that use IoT and IA (Intiligente Atificiel) technologies to detect and predict wildfires. It highlights the importance of forests to environmental protection and the devastating impact of wildfires on forests and human health. This paper examines existing literature proposals for utilizing the IoTs to detect wildfires and their spread and provides a comprehensive evaluation and comparison of these works. This paper provides a comprehensive review and comparison of works utilizing IoT and IA for forest fire detection. In [3] the authors have presented the integration of IoT in forests and highlighted the importance of digitizing forests using reliable and robust communication protocols. The use of IoT technology and communication protocols for real-time data collection, monitoring, and forest inventory is discussed. It explores IoT concepts including real-time monitoring of environmental parameters and forest fire detection. The proposition sets forth a unified framework for monitoring forests and detecting fires, which encompasses a variety of technologies. It helps understand how to effectively use IoT to digitize forests to enable real-time monitoring and data analysis and improve the sustainability of forest ecosystems. In [9] the authors have used a server on a cloud platform to store and process data collected by an air quality monitoring system. The system monitors carbon dioxide, carbon monoxide, nitrogen dioxide, temperature, and humidity levels and stores the data in a database. An Android application is being developed to visualize real-time data. The real-time data captured wirelessly is transmitted to the network in the required form via the Internet connection. In [4] the authors proposed a smart greenhouse model that uses IoT technology to optimize plant growth and create a comfortable microclimate. The system uses WSN technology and fuzzy logic control to monitor and control the greenhouse environment. Data acquisition and processing are performed through an Arduino UNO board, and input variables are processed through fuzzy logic control software. Data can be monitored and analyzed remotely via a web browser via a Wi-Fi internet connection. The results demonstrate the effectiveness of fuzzy logic controllers in promoting a comfortable microclimate in greenhouses, as well as the efficiency of the proposed remote monitoring solution using IoT technology. In [6] the authors described the implementation of a wildfire risk controller based on fuzzy logic and IoT technology and WSN for real-time monitoring and detection of wildfire risks. The focus is on collecting and analyzing information such as meteorological conditions, pollutant concentrations, and oxygen levels in forest areas to prevent forest fires improve detection efficiency, and implement environmental risk alerts and security mechanisms such as Lamport signatures and block encryption algorithms.

So, considering related works cited, it can be established that daily weather conditions have a strong influence on the occurrence of fires and burned areas, especially the moisture content of vegetation. The biggest fires often occur during periods of severe drought and strong winds, causing fires to spread quickly and become difficult to control.

Daily fire risk forecasts are based on an index (Forest Fire Weather Index or FWI) inspired by Canadian empirical methods. Calculations are used to predict risk levels [10]. This enables combat units to be deployed in advance to high-risk areas. FWI calculates in real time based on simple meteorological data: temperature, relative humidity and wind speed. These components provide fuzzy logic models. The model is based on daily measurements in the field. WSN [7] are used to measure climate factors (temperature, relative humidity and wind speed) on a daily basis, especially during high-risk seasons [11-12].

In this paper, we propose a forest IoT system to determine FWI. The system is installed in the Beni Oudjana forest, one of the most important natural forests west of the Khenchela region (eastern Algeria). There is an increasing risk of bushfires in the region. This phenomenon can be attributed to widespread human activities in the region, particularly practices related to land use, as well as the effects of climate change. These factors have led to an increase in the frequency and severity of fires in the region.

The proposed system collects climate parameters through WSN and then calculates the FWI. To efficiently manage and store data, data is transferred directly to the cloud. Utilizing the developed website, the system allows users to access real-time data anytime and anywhere.

2. PROPOSED ARCHITECTURE

Fuzzy logic is not based on a precise mathematical model of the controlled system and does not require an accurate description of the controlled object. It is also rugged, adaptable, and easy for operators to learn. It's closer to natural thinking than clear logic, so it's easy to implement. In this paper, we describe the proposed method for accurately predicting meteorological wildfire risk using concepts and tools of fuzzy logic [4, 13-14]. The latter allows us to determine meteorological risk factors in real time. The river system proposed in this study was simulated using MATLAB to convert all fire factors into linguistic variables and analyzed them using fuzzy logic inference rules. This risk is reflected in climate data: temperature, wind speed and relative humidity.

FWI is an important tool used by meteorologists, firefighters, and forest managers to assess the potential risk of wildfires based on weather conditions. By combining several weather parameters such as temperature, humidity, wind speed, etc[15]. It is important to note that the FWI is not a direct predictor of wildfire occurrence, but rather an indicator of weather conditions that help fires spread quickly. High FWI values indicate increased fire danger, calling for increased vigilance and preparedness measures among firefighting interests users, or pioneers of forests. Regular monitoring and interpretation of FWI values allow proactive fire management strategies

According to our interpretation, we have three input variables, which results in a number being checked in the fuzzy set rule creation (27, which is 3^3)

2.1. The fuzzification step

Each input variable for each fuzzy set is examined and the number of groups is derived from the data distribution for each variable. By working with the forestry department and relevant experts, we can create a fuzzy inference system that can accurately predict FWI based on weather data in the study area. This approach can incorporate expert knowledge and deal with inaccurate or uncertain information, thereby improving the effectiveness of fire weather risk assessment and management efforts.

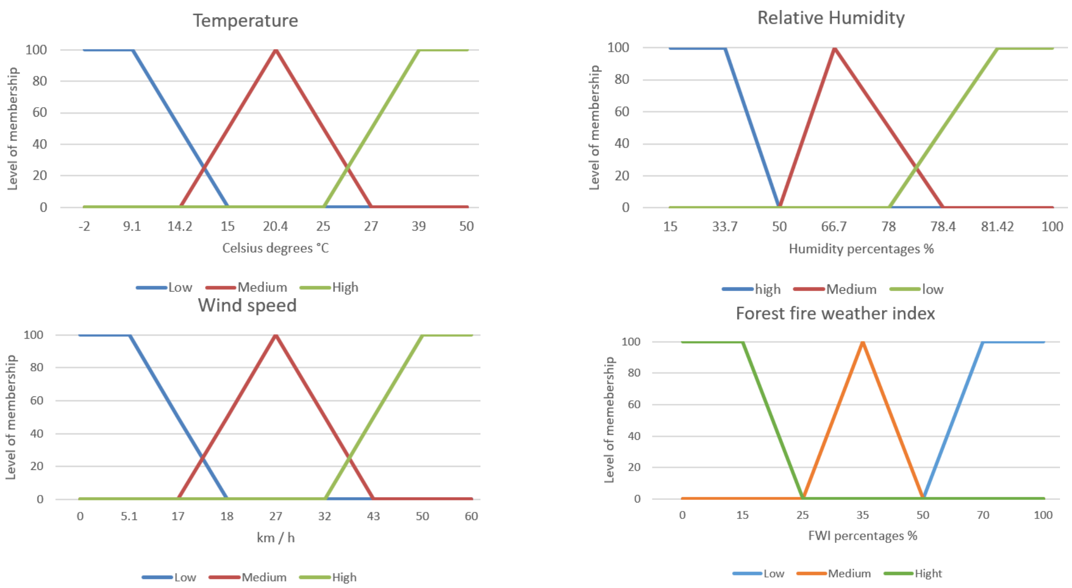

Figure1. The membership function of each input and output

Each input variable has three language values: low, medium, and high. The fuzzier input: temperature, wind speed, relative humidity, and output FWI as shown in Figure 1.

- Temperature: The distribution interval varies between [-2 50] (C°) such as: [-2 9.1 15] Low, [14.3 20.4 27.0] Medium, and [25 39 50] High.
- Wind speed: the data distribution interval varies between [0 60] (m/s) from where: [0 5.1 18] Low, [17 27 34] Medium, and [32 50 60] High.
- Relative Humidity: [15 100] from which it is divided into three fuzzy groups: [15 33.7 50] High, [50 66.7 78.4) Medium and [78 81.42 100] is Low:
- FWI output: is varied between [0 100] hence: [0 15 25] Low, [25 35 50] Medium, and [50 70 100] High.

These rules are expressed in the form of "if-then" statements, known as fuzzy inference rules. Difference Rules of FWI are summarized in the following table:

Table 1. Array (If-Then) of FWI

N°	Temperature	Wind speed	Relative Humidity	FWI
1	Low	Low	High	Low
2	Low	Medium	Low	Medium
3	Low	Medium	High	Low
4	Low	High	Low	High
5	Low	High	High	Low
6	Medium	Low	Low	Medium
7	Medium	Low	High	Low
8	Medium	Medium	Low	Medium
9	Medium	Medium	Medium	Medium
10	Medium	Medium	High	Low
11	Medium	High	Low	High
12	Medium	High	High	Medium
13	High	Low	Medium	High
14	High	Low	High	Low
15	High	Medium	Low	High
16	High	Medium	Medium	High
17	High	Medium	High	Medium
18	High	High	Low	High

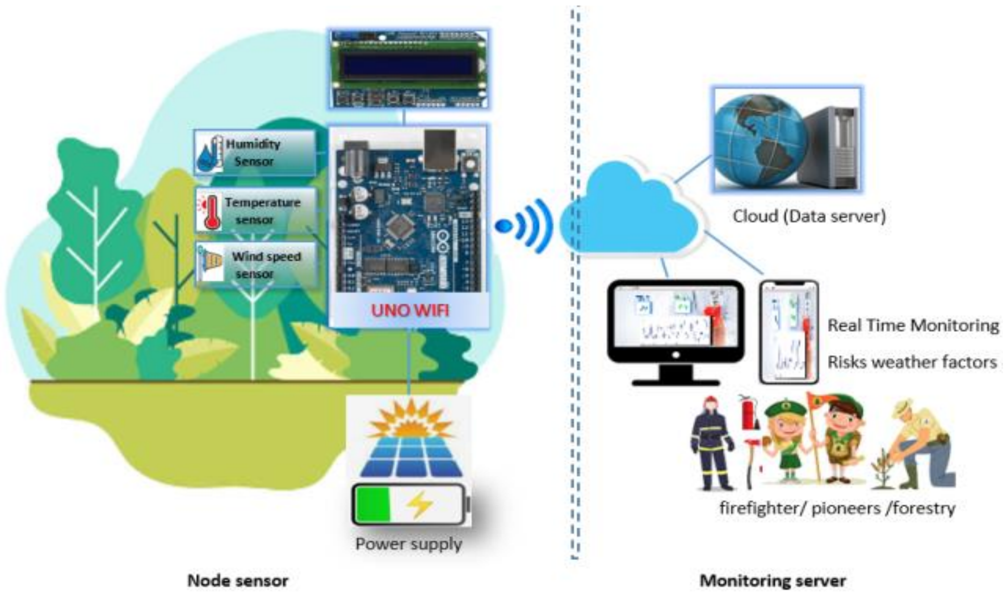

Figure 2. Overall architecture of the system

The proposed real-time wildfire risk prediction and monitoring system based on WSN has many characteristics of a continuous monitoring approach using small and low-cost solar-powered sensor nodes. The collected data is forwarded to UNO-WIFI. The data and FWI are then sent to a secure server via a WiFi internet connection, and the fuzzy logic is used to precisely determine FWI.

The server collects all information and stores the data in a database for further analysis [9, 16-18]. In turn, the web server allows users to view all information in real-time. This allows them to conduct real-time environmental monitoring of the aforementioned FWI factors.

The forest fire risk monitoring system is mainly composed of two parts: sensor nodes and monitoring servers. The overall block diagram of the system is shown in the Figure 2

2.2 ARDUINO UNO-WIFI

In this paper, we use Arduino due to its cost-effectiveness and ease of production. This seems practical in the context of creating prototypes. Since the number of rules is limited, implementing fuzzy logic in Arduino will be limited and easy. The calculator (controller) is the main element of the node that controls the entire application, and considering its sufficient features, we decided to use Arduino RobotDyn UNO + WIFI R3 board based on the ATmega328P microcontroller. Among them are the number of digital input/output pins, UART, and the different types of memories needed: Flash memory, SRAM, and EEPROM [5-7, 19]. The essential element added to this card is the ESP8266 WiFi chip, which is one of the essential parts of our design. This makes it a practical solution for developing projects that require Uno and WiFi. The ATmega328 and ESP8266 sketches and firmware can be updated via USB. Figure 3 illustrates this card [20].

2.3 DHT11

The main heat source is the sun. Fuel exposed to sunlight heats faster than fuel under forest cover. Higher temperatures make it very easy for fuels to catch fire, especially due to drought.

The spread, expressed as a percentage, between the amount of water vapor actually contained in the air and the absorptive capacity of the air at a given temperature. It does not directly affect the fire resistance phenomenon but affects the moisture content of the fuel. There are many sensors used to measure temperature and relative humidity [4], as shown in Figure 4. We chose the DHT11 sensor, a simple digital sensor that collects both temperature and relative humidity. Its characteristic is low cost.

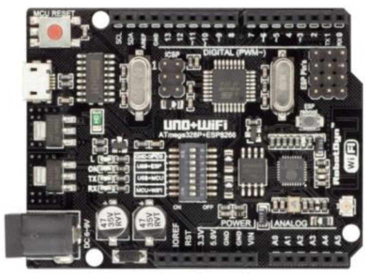

Figure 3. Arduino Uno wifi board

Figure 4. DHT11 Temperature and Humidity Sensor

2.4 Anemometer

Wind speed increases combustion and spread: [21]: - increases oxygen uptake, - dries out the fuel, - promotes heating of the fuel before ignition, - affects the direction in which the fire spreads, - carries sparks or other burning material over long distances. Anemometers measure wind speed and are an important part of a weather station. The sensor used here is an Adafruit anemometer. This latter can measure wind speeds up to 70 m/s or 156 mph, which should be enough for where we are. We can connect the Adafruit anemometer sensor to an Arduino and an OLED display. The sensor measures wind speed in meters/second and displays the value on the OLED screen. You can convert wind speed from m/s to miles per hour or kilometers per hour as shown in Figure 5.

2.5 LCD

Local users can also view information on a display connected directly to the Arduino. For this purpose, we have used 1602 LCD SHIELD (ARDUINO COMPATIBLE) as shown in Figure 6.

Figure 5. anemometer

Figure 6. 1602 LCD SHIELD

2.6 Powering the Arduino board and sensors

Solar modules power the nodes. Since all the nodes are in the forest, laying power supply lines is difficult. This is the best alternative to provide supply. The solar panel will charge the battery through the day under sunlight. It converts solar energy into electricity. The solar power elements used in the forest fire risk monitoring system as shown in Figures 7,8 and 9.

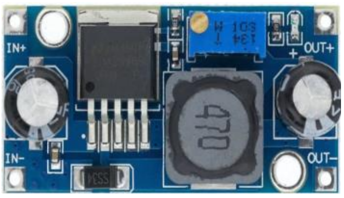

Figure 7. Adjustable voltage regulator

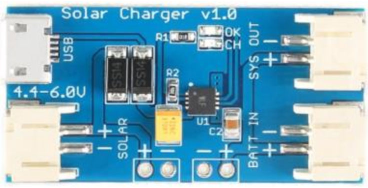

Figure 8. Solar Lipo Charger

Figure 9. Solar panel 20 W 6V

2.7 Monitoring server

Data stored in the cloud can be accessed by all visitors and users from anywhere with internet access using any device. Its purpose is to combine heterogeneous sensing, smart objects, semantic, big data, and cloud computing technologies in a platform enabling the IoT [22-24]. Process consisting of continuous iterations on data ingestion, data storage, analytics, knowledge generation, and knowledge sharing phases, as the foundation for cross-border information service provision [19,25-26].

For this, we have created a database and website. The server performs the reception of data from the various remote nodes permanently and in real-time [27]. Subsequently recording this data on a database hosted on the same server. The server allows the remote visualization of data, in numerical or graphic form, online or offline. For the server, we use the XAMPP package, this latter is an open-source localhost server providing a number of functionalities through the package of software it contains., which includes Apache Server, delivered with MySQL (database), PHP (server-side scripting language), FileZilla FTP Server and Mercury Mail Transport System.

3. RESULTS AND DISCUSSION

Important control parameters include temperature, which is often considered the most important factor to monitor. Humidity also plays an important role. It is recommended to avoid low humidity, which may cause plants to dry out. The influence of wind speed is evident in its ability to promote combustion and dispersion. . Additionally, proposed method prioritizes the monitoring of temperature, humidity, and wind speed, although its applicability extends to various other properties such as precipitation. Often, only certain variables are managed based on local prevailing climatic conditions.

Conduct real-time testing of the entire wildfire risk monitoring system. Integrate all modules/components to check if the system works as expected as shown in Figure 10.

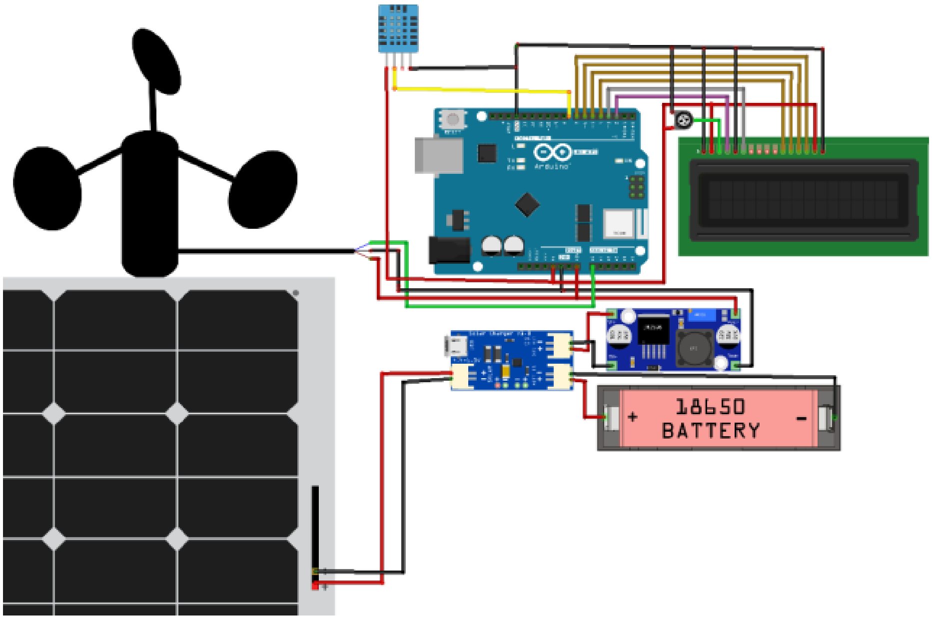

Figure.10 Modules/components of the circuit

As seen in Figure 11, the database is composed of a table of six columns: Id (data number), temperature, relative humidity, wind speed, FWI (risk), date, and time. When users want to view the data, they just need to enter the website address in the web browser through any device (laptop, smartphone, personal computer, etc.). In addition, from anywhere in the world, all you need is an internet connection. This allows them to connect to the server and web pages will be delivered to them through the browser. Figure 12 shows the first page (home page).

Browse | Structure | SQL | Search | Insert | Export | Import

←T→	ID	temperature	wind	humidity	risk	date	time
Edit Copy Delete	14	13.7	87.0	64.3	MOY	2022-10-02	08:15:45
Edit Copy Delete	15	13.8	81.8	64.1	MOY	2022-10-02	08:30:13
Edit Copy Delete	16	14.1	81.5	63.8	MOY	2022-10-02	08:45:28

Figure 11. Database

To facilitate understanding, we have created web pages that present the data in a visual format. This visualization consists of various components, including a visual element, a scale, a coordinate system, and a context. As depicted in Figure 1, this graphical representation allows for a quick grasp of the overall trend. It provides a straightforward approach and unveils the intricate data structure that would otherwise be difficult to comprehend. Moreover, it enables the discovery of unexpected outcomes and encourages questioning anticipated conclusions.

The risk of fire is greatly influenced by climate conditions. When the temperature is high, the wind speed is elevated, and the relative humidity is low, the likelihood of fire spreading increases. For instance, when the following values are observed: temperature = 30.9 wind speed = 38.7 and relative humidity = 85.2, the FWI reaches 74.1. Conversely, if we consider the values of temperature = 38.4, wind speed = 30, and relative humidity = 86.2, the FWI is calculated as 73.8.

We conclude that the strong effects of climate change lead to an increase in the number of days at risk in a year [28-29], and even outside of summer, higher temperatures are associated with greater extension of drought. The bigger it is, the bigger the risk.

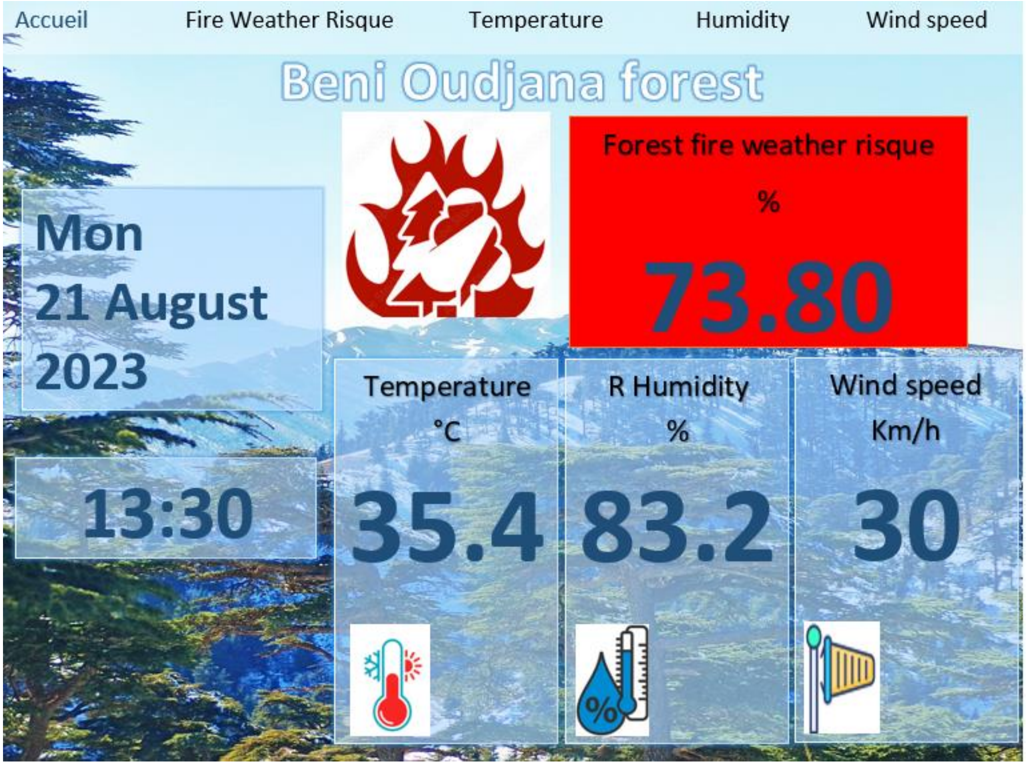

Figure 12 First page (home page).

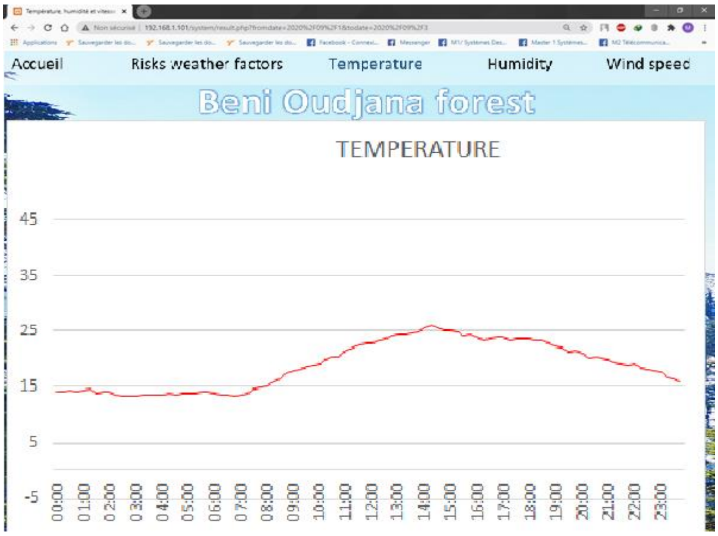

Figure 13. Example of temperature result visualization

However, effective forest fire prevention and control also depends on factors other than weather conditions, such as Fuel availability, human activity and infrastructure development in fire-prone areas. Overall, FWI is a valuable tool in mitigating the impacts of wildfires by providing early warning and informing decision-making processes to protect life, property, and ecosystems. This includes providing timely warnings to communities at risk.

In addition, fire monitoring and management practices require reliable metrics and assessment tools at a wide range of spatial and temporal scales from local to the national level and from the near-real time to the annual/seasonal outlook. As climate change would increase fire risks inevitably in the fire-prone regions at present, some historically low-fire-prone regions might also become high-risk areas in the future as also indicated by authors in Refs. 15 and 21.

Therefore, there is a critical need to assess the forest fire risk predictability at a range of spatiotemporal scales over the entire countries, especially in Algeria.

4. CONCLUSIONS AND FUTURE WORK

Forest fires represent a natural phenomenon and pose a significant threat to forests worldwide, particularly in Mediterranean regions. The most effective way to manage this event and mitigate its severe impact is through the use of IoT technology and fuzzy logic principles to predict fire danger, particularly related to weather conditions, as we applied in our investigation. Given that fire is inherently mysterious and ambiguous, this approach was deemed appropriate for addressing unpredictable phenomena.

In this paper, we propose a real-time wildfire risk monitoring system using WSN and IoT technologies. Our system is useful for foresters, firefighters, and forest pioneers. The advantage of this approach is the ability to track the system in real time via a web page (either a numerical display or a graphical display). This approach therefore helps improve outcomes by promoting optimal monitoring of wildfire risk.

Our system is designed to help protect forests from fire. However, based on our experience, the implemented system needs improvement and we can make some suggestions for improvements, summarized : A system for automatic creation of fire risk maps in real time will be established. Develop artificial intelligence technology to better analyze and utilize data. By combining other risk factors (fuels, terrain and human activities...) with data that may influence the occurrence of wildfires to obtain more precise and complete results, we can avoid these disasters and notify users via SMS, etc.

ACKNOWLEDGMENTS

"This work was supported by the Directorate General for Scientific Research and Technological Development (DG-RSDT) of Algeria".

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