PREDICTION OF FOREST FIRE USING WIRELESS SENSOR NETWORK

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GAO DM, YIN XF & LIU YF. 2015. Prediction of forest fire using wireless sensor network. High incidence and destructiveness of forest fire determine the importance of forest fire prevention. Based upon local weather observations, one of the most recognised and widely applied fire-danger rating systems, the Canadian Forest Fire Weather Index (CFFWI) System, was found highly correlated with forest fire occurrence. This fire-danger system was evaluated and calibrated for Nanjing, the capital of Jiangsu Province, China. This wireless sensor network was utilised for collecting 24-hour weather data continuously. The components of CFFWI System, based upon the weather data for this region, provided insight of possibility of forest fires. The system showed that spring and autumn were seasons when the occurrences of forest fires were more dangerous. The components of the system indicated the possible dangers of the ignition of forest before the fire started. The components of CFFWI System are good indicators of fire danger in the Nanjing region of China and can be expended to build a working fire-danger rating system for the region.

Keywords: Fire management support systems, Canadian Forest Fire Weather Index System, fire regime, fire weather

INTRODUCTION

Forest fire is uncontrolled fire in forest area or wildland which can cause significant damage to nature and humans. It is one of the most dangerous disasters to ecological environment. Forest fire burns forests, destroy animal habitat, damage property and may cause high human death. Common causes of forest fire include lightning (Zumbrunnen et al. 2011), human activities (Donnegan et al. 2001) and extreme weather conditions such as heat and aridity (Feikema et al. 2013). In China, a total of 766,500 forest fires occurred from 1952 till 2008 (average 13,000 year^{-1}) (Niu & Zhai 2012). The fires destroyed about 778,200 ha of forest which amounted to USD20 mil in financial losses. On 6 May 1987, Daxing'anling forest fires shocked the whole country and the world when the fires swept over 1.14 mil ha of land, eradicating two cities and nine forestry centres. A total of 211 residents lost their lives and 50,000 were left homeless.

The ignition of forest closely depends on meteorological conditions of forest environment such as temperature, humidity, daily rain, wind velocity and wind direction (Wotton 2009). In higher temperature and lower humidity weather conditions, vegetation loses moisture faster and easily. However this signals higher possibility of forest ignition. Forest fire usually starts and spread in fine fuels (Mohamed & Majid 2009). If the temperature reaches 21 °C and relative humidity 45%, litter and fine fuels will lose two-thirds of its moisture content in about 16 hours (Mohamed & Majid 2009). Hence, there is significant need for obtaining data on meteorological variability at any time to predict forest fire before ignition of forest fuels. However, due to continually changing of meteorological conditions, this was not possible until the development of wireless sensor networks.

Wireless sensor networks comprise large number of low cost, low power, small size and multi-functional sensor nodes with finite battery life that can sense and process data and communicate with each other over a short distance. In recent years, researchers have paid much attention to wireless sensor networks due to their wide range of applications such as military,

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environmental, health and home applications. The technology of wireless sensor networks makes it possible for early detection and prediction of forest fire based on weather parameters. This significantly promotes the development of forest fire controlling techniques, evolving from human-based approach to satellite-based remote-sensing approach and wireless sensor network. We can obtain real-time information on forest environments using wireless sensor networks technology and analyse its relationship with forest fire. The possibility or risk of forest fire is reduced if one or more values of meteorological parameters reach the threshold, which is calculated by forest fire model or historical forest fire statistics. Hence, it is extremely possible to predict forest fire before it destroys the forest.

The Canadian Forest Fire Weather Index (CFFWI) System is a subsystem of the Canadian Forest Fire Danger Rating System, which is one of the most recognised and widely applied fire-danger rating system in the world (de Groot et al. 2007). The occurrence of forest fire increases steadily with the rise in Fire Weather Index (Hirsch & Fuglem 2006). Therefore, CFFWI System which shows the potential of fire ignition is utilised wildely for wildfire forecast and early detection. CFFWI System relies on mathematical analysis based on meteorological data (meteorological factors, fuel moisture calculations, small field ignition test) which are usually from meteorological observation stations and wireless sensor networks.

Wireless sensor networks are increasingly utilised for predicting and detecting forest fire (Doolin & Sitar 2005, Obregon et al. 2009, Tan & Panda 2011). A wildfire prevention system based on time-driven wireless sensor was introduced by Vicente-Charlesworth and Galmés (2011). The CFFWI System was evaluated for the Daxing'anling region of northern China for fire seasons which occurred from 1987 till 2006 (Tian et al. 2012). Results showed that the components (comprising fuel moisture codes and fire behaviour indices) of the CFFWI System were good indicators of fire danger in the Daxing'anling region of China. CFFWI System was evaluated in two consecutive fire seasons in Crete, Greece (Dimitrakopoulos et al. 2011). The system demonstrated the possibility for the system to be used as meteorological fire-danger rating index in the Mediterranean region.

We introduced the design and evaluated the CFFWI System for forest fire prediction in Nanjing. Our design was based on the fire-danger system using wireless sensor network. We collected real data and analysed the behaviour of the fire indices for various weather conditions such as temperature, humidity, wind speed and rain. The CFFWI System was calibrated to suit the Chinese conditions. This study would be of interest to computer science and engineering researchers working in areas having wireless sensor networks and their applications. We also determined the classes of fire dangers using this system. The main aim was to maintain attainability of the network for as long as possible and collect accurate data as much as possible to support research on forest fire prevention and detection.

Canadian Forest Fire Weather Index System

Apart from the Mediterranean regions, the CFFWI system has been used in several other countries to assess fire dangers such as Indonesia (Field et al. 2004) and New Zealand (Pearce & Alexander 1994). In these countries, the CFFWI System was evaluated and calibrated to suit local vegetation, climate and fire regime conditions. In these countries, the CFFWI System was operated nationally and utilised by fire and rescue agencies for fire prevention and early detection of fire. From experiences in these countries, the system was adapted for use elsewhere.

The CFFWI System was used to generate a set of indicators showing potential of forest fire depending solely on weather observations, namely, temperature, relative humidity, 10-m open wind speed and 24-hour accumulated precipitation, recorded at noon local standard time (Lawson & Armitage 2008). Meteorological parameter values were recorded hourly during the day using wireless sensor network. From the CFFWI system used in Canada, statistical data showed that the daily peak in fire danger was usually around 4 p.m.

The CFFWI System estimated moisture contents of three different codes of fuel classes, namely, Fine Fuel Moisture Code (FFMC), Duff (Humus) Moisture Code (DMC) and Drought Code (DC) (Van Wagner 1987). FFMC represents moisture content of litter and fine fuel, which is about 1.2 cm deep with dry weight about

0.25 kg m^{-2} in a forest stand. FFMC indicates relative ease of ignition or ignition probability. DMC represents moisture content of loosely compacted, decomposing organic matter of 7 cm depth and weighing about 5 kg m^{-2}, which determines the probability of fire ignition due to lightning. DC is the numerical rating of average moisture content and indication of the effects of seasonal drought on deep, compact, organic layers about 18 cm with fuel loading of about 25 kg m^{-2}. DC indicates the resistance of fire to extinguishing.

The three codes of CFFWI System are utilised to generate three fire behaviour indices: Initial Spread Index, Build-Up Index and Fire Weather Index which are used to describe the spread and intensity of wildfire (Van Wagner 1987). Initial Spread Index is calculated using values of wind speed and FFMC, which indicates the rate of fire speed after ignition. Build-Up Index combines the DMC and DC, which represents the total fuel available to fire and indicates the scale of difficulty to extinguish the fire. The Fire Weather Index is a weighted combination of the Initial Spread and Build-Up Indices, indicating the intensity of spreading fire. Even though the Fire Weather Index is not directly calculated from weather data, it depends on them and is used to indicate the overall fire danger.

It is customary to define fire danger classes for general public to distinguish the possibility of ignition. The CFFWI System is generally assigned different Fire Weather Index scales to fit the regional patterns of fire weather. For instance, in China, five fire danger classes are used in Huma and other weather stations, including at Daxing'anling (Tian et al. 2012). In Canada, six fire danger classes (with respective index) are used, namely, very low (0–1), low (2–4), moderate (5–8), high (9–16), very high (17–29) and extreme (30+). Each year, the average percentages of days throughout the fire seasons are 43, 16, 17, 13, 8 and 3% for each class respectively (Van Wagner 1987).

Weather data for CFFWI System are generally collected by weather stations, which are usually equipped with complex meteorological equipment and at least one fire brigade. It is impossible to set up several weather stations in a forest area due to high costs. Wireless sensor network technology provides enormous advantages in overcoming these shortcomings

and it is possible to replace expensive weather stations for collecting weather data. Due to their low costs, a considerable number of wireless sensors can be deployed in monitoring forest fire. Therefore, more data can be collected compared with traditional limited weather stations. Results are also more accurate. If the sensor can harness energy from ambient such as solar and wind, it can be set up to monitor forests which are usually untraversed and without infrastructure (Figure 1).

Every country has different environment conditions and weather characteristics. Even though the CFFWI System originated from Canada and was designed for Canadian fuel and weather conditions, fuel wetting and drying processes, which cause forest fire, are the same all over the world. Therefore, the CFFWI System, can be used for different countries. The overall objective of this paper is to evaluate the possibility of using the CFFWI System in Jiangsu Province, China which has high population density and frequent forest fires. The main aim was to maintain attainability of the network for as long as possible and collect accurate data as much as possible to support research on forest fire prevention and detection.

MATERIALS AND METHODS

Study area

The CFFWI System was applied in Nanjing, the capital of Jiangsu Province, China in the southern region of China. The main forest type of the province is deciduous needle leaved mixed forest
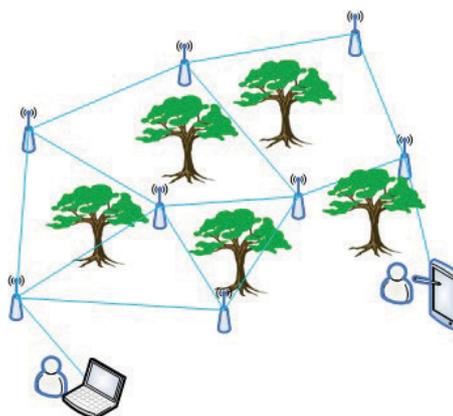

Figure 1 Wireless sensors are deployed in forest

in natural forest and plantation. The common tree species are coniferous, broadleaved, mixed wood and bamboo forests. Even though the study area has low forest coverage rate, the region has dense population and good economic conditions. Particularly, the area of plantations increased gradually during the past few years. Forest fires in this region are on the rise.

In 2011, Jiangsu Province had 2,174,500 ha of forest and 1,815,300 ha of woodland, which covered 21.2% of the land area. There were 51 cases of forest fires in 2011 where a total area of 141.3 ha were burned and 52.4 ha of forest disappeared. Nanjing is located in the middle and lower reaches of Yangtze River and has humid subtropical climate with four distinct seasons and abundant rainfall in summer. The region has 117 days of annual rainfall (average 1106.5 mm), relative humidity of 76% and frost-free period of 237 days.

Experimental set-up and implementation

In the simulation, up to 100 nodes were randomly deployed in a 500 m × 500 m forest field. Maximum communication range of each node was set at 100 m. All energy devices for nodes were rechargeable and transmission power was adjustable. Every two nodes could communicate with each other directly within their transmission range. The system consisted of a solar panel optimised for outdoor use, two target boards and one AAA battery pack which was rechargeable. The target board comprised a microcontroller, radio transceiver and an on-board antenna. The radio transceiver operated in 2.4 GHz band with data rate of 250 kbps and was designed for low power wireless applications. Harvested energy was stored in a thin-film rechargeable energy storage device with low self-discharge.

Sensor nodes in this experiment used energy from the environment (Figure 2). We deployed hundreds of sensor nodes and multiple sinks in the ZiJin Mountain and Nanjing Forestry University in Nanjing. These sensors were used to collect weather observations data (temperature, humidity, length of day) for Jiangsu Province.

In this study, the CFFWI System produced values of six components (FFMC, DMC, DC, Build-Up Index, Initial Spread Index and Fire Weather Index) in Nanjing from 1 January 2011

Figure 2　Sensor nodes set up in the experimental site

till 31 December 2012. The six components indicated the possibility of forest fire. Fire records during this period were obtained from the Forest Fire Prevention of Nanjing Forestry Bureau. The forest fires indicated by the CFFWI System were verified by the staff of the forestry department based on records of forest fires. Weather data were obtained from wireless sensors. Fire Weather Index was calculated indirectly using the values of temperature, humidity, wind speed and precipitation, all of which affected the index.

To further illustrate the relationship between weather data and fire danger, the Chandler Burning Index was used to indicate the possibility of forest fire. Even though, Chandler Burning Index is not a component of the CFFWI System, it has been utilised widely for fire weather study in the United States (McCutchan & Main 1989) and elsewhere (Roads et al. 2008). The Chandler Burning Index measures susceptibility based on temperature and relative humidity (Chandler et al. 1983).

The Chandler Burning Index was then equated to severity of fire danger whether extreme, very high, high, moderate or low. Chandler Burning Index is based solely on weather conditions. Intensity and spread components of the index are linearly related to temperature (an increase in temperature results in a proportionately higher index) but exponentially related to humidity (a small decrease in humidity results in a large increase

in the index). Chandler Burning Index was computed as

$$\frac{1}{60}\left[\begin{array}{l}((110-1.373\times RH)-0.54\times\\(10.20-T))\times124\times10^{-0.0142\times RH}\end{array}\right]$$

where RH and T = relative humidity and temperature respectively. Both variables were obtained every afternoon at 4 p.m. from the forest fire prediction system of Nanjing Forestry University.

RESULTS AND DISCUSSION

Figure 3 shows the relationship between the four weather data (temperature, humidity, wind speed and precipitation) and Fire Weather Index for two years. It was clear that temperature in Nanjing rose from January till July and dropped from July till January (Figure 3a). The temperature was maximum (40 °C) at the end of July or early August and minimum (-5 °C) at the end of December or early January. Even though the temperature in summer was higher than other seasons, Fire Weather Index was not the highest at this time. The main reasons for this result were more rainfall and higher relative humidity in

summer (Figures 3b and c). Relative humidity in Nanjing was high in summer due to the rainy season. During rainy season, rainfall lasted for at least 10 days and even reaching 20 days from 25 June till 18 July in 2012. The potential of forest fire was very low during rainy days. Highest wind speed was in spring and autumn and the fire weather indices were relatively higher in both seasons (Figure 3d).

We selected different periods for completing our seasonal fire severity analysis after considering the weather. The values for the six components of CFFWI system for Nanjing are illustrated in Figure 4, which shows the relationship between final Fire Weather Index and FFMC, DMC, DC, Initial Spread Index and Build-Up Index. Of these, FFMC, DMC and DC were calculated depending on four weather parameters directly. Therefore, they were strongly correlated with the weather data. When temperature rose and relative humidity dropped, these values increased gradually. Rainfall and high wind speed caused the values of FFMC, DMC and DC to increase rapidly, which indicated that forest fires occurred in these weather conditions.

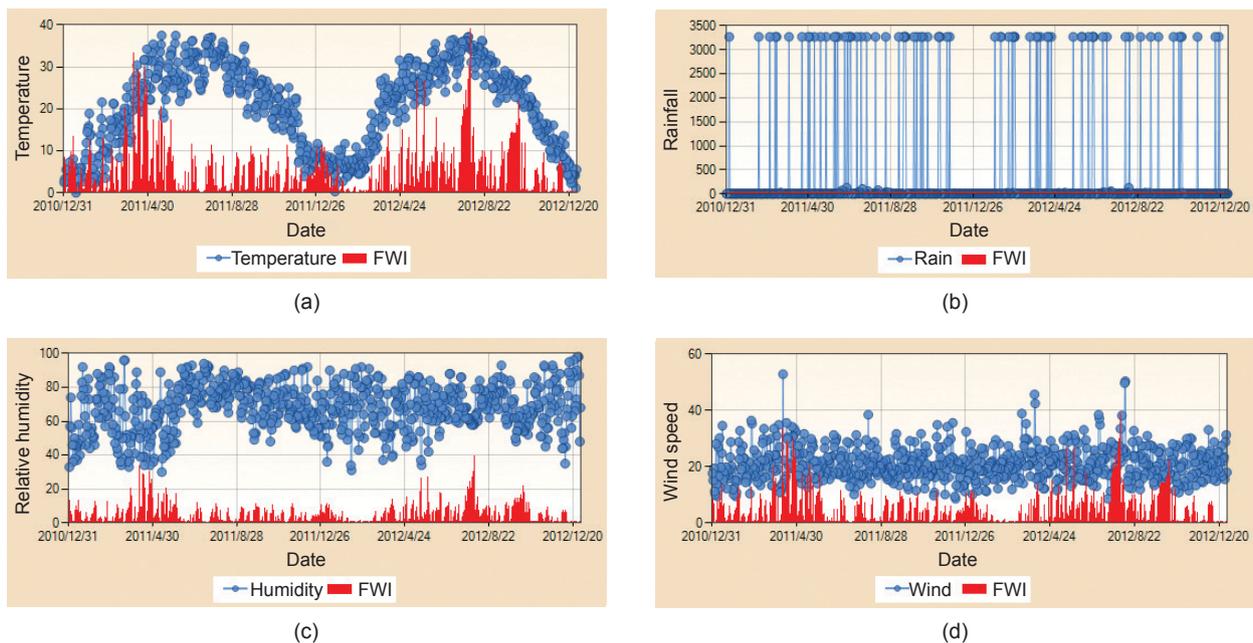The peaks of three components (FFMC, DMC, DC) were high in spring and autumn

Figure 3   Relationship between weather data and Fire Weather Index (FWI) from 1 January 2011 till 31 December 2012; dates are recorded as year–month–date
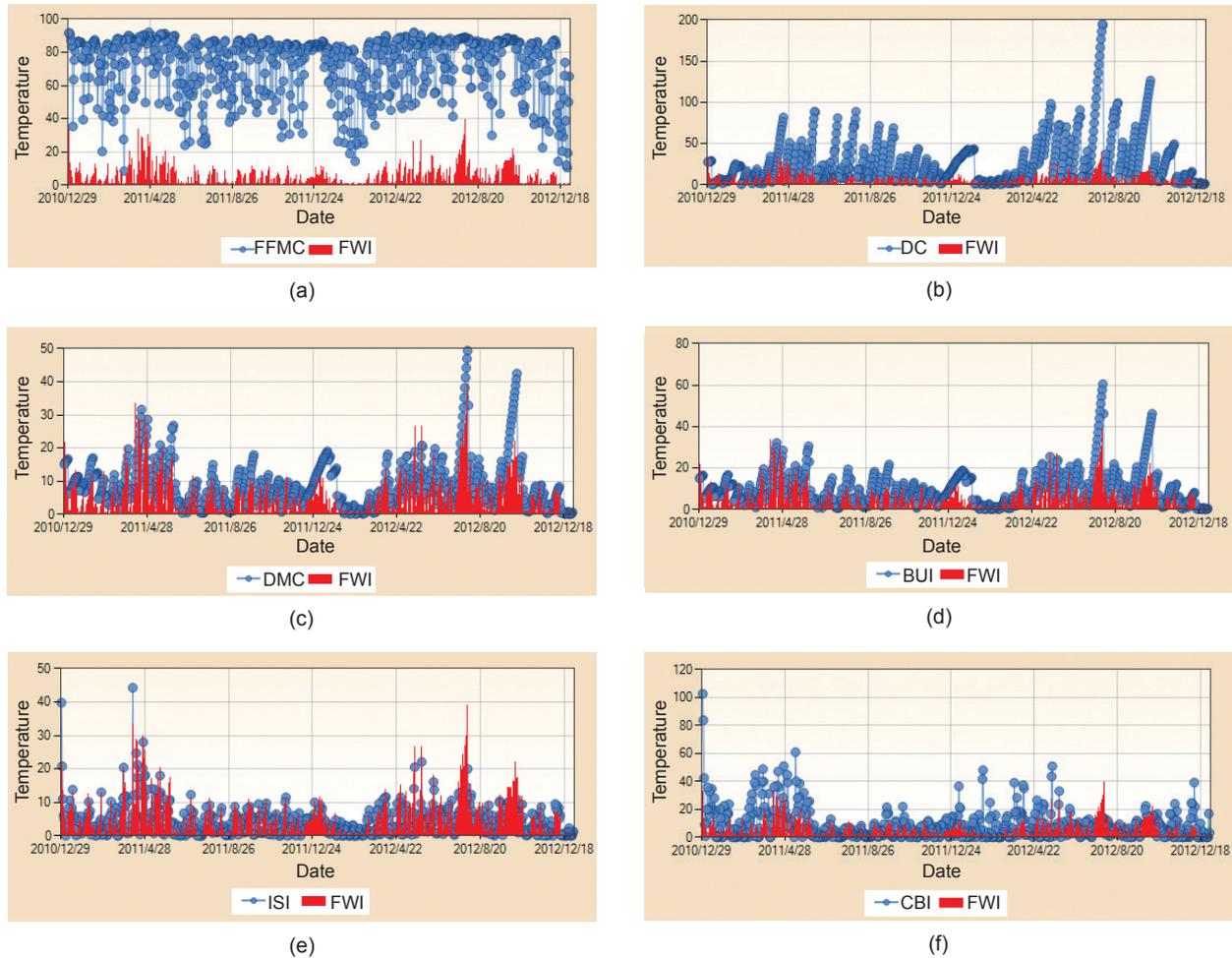
Figure 4 Relationship between (a) Fine Fuel Moisture Code (FFMC), (b) Drought Code (DC), (c) Duff Moisture Code (DMC), (d) build-up index (BUI), (e) Initial Spread Index (ISI) and (f) Chandler Burning Index (CBI) and Fire Weather Index (FWI); data were taken from 1 January 2011 till 31 December 2012; dates are recorded as year–month–date

with slight bimodal distribution (Figures 4a–c). FFMC, DMC and DC were used to calculate Initial Spread and Build-Up Indices, which showed that when the weather was dry, both indices were higher than the rest of the components and tallied with the actual situation. Our analysis showed that May and October had the highest forest fire activity with an average of half of the total times over the study period. The main causes of high incidence of fire in these months were increase in temperature, decrease in relative humidity and gradual drying of sediment leaves.

For most of the year, Nanjing experienced low or moderate level of forest fire danger and fewer days of extreme danger of forest fires.

Throughout the study, the city had different number of days for various fire danger levels for FFMC, DMC, DC, Initial Spread Index, Build-Up Index, Chandler Burning Index and Fire Weather Index (Figure 4f). There were few fires at the beginning of winter when Initial Spread Index was low due to insufficient drying of duff. This condition was unable to support fire growth until later in May. During summer, the region received significant proportion of its yearly precipitation. The total number of forest fire in summer accounted for less than 20% of the annual figure. Forest fires in summer normally burn surface grasses and spread slowly owing to high moisture content.
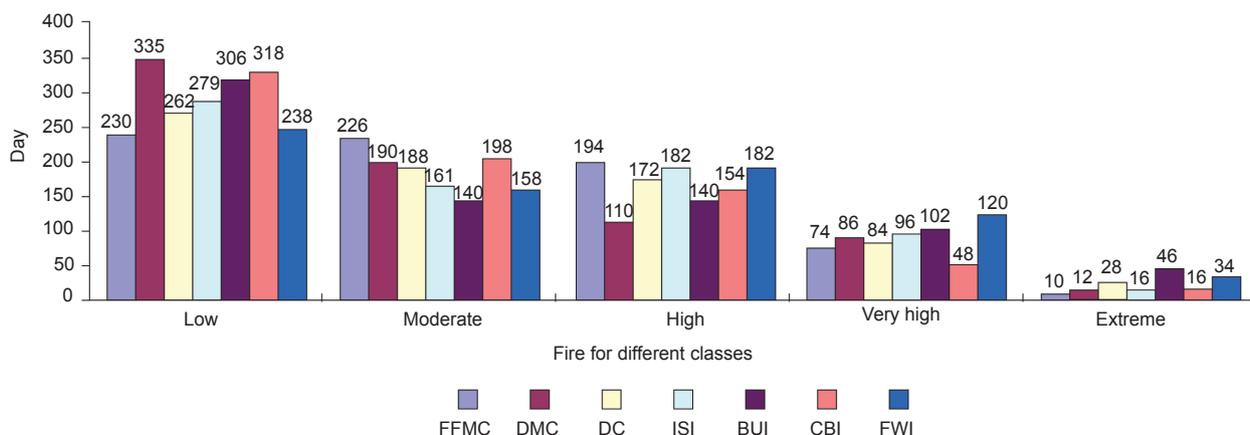
Figure 5   Duration of different fire danger levels according to fire components from 1 January 2011 till 31 December 2012 in Nanjing, China; FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Build-Up Index, CBI = Chandler Burning Index and FWI = Fire Weather Index

Table 1   Classification of fire danger levels for Nanjing

Class	FFMC	DMC	DC	ISI	BUI	CBI	FWI
Low	0–79	0–13	0–130	0–3.4	0–18	0–6	0–4
Moderate	79–86	13–23	130–330	3.5–5.8	19–29	6–13	5–9
High	86–88.5	23–41	330–390	5.9–9.5	30–46	13–22	10–17
Very High	88.5–90.5	41–66	390–450	9.6–16	17–80	22–36	18–30
Extreme	90.5+	66+	450+	16+	80+	36+	30+

FFMC = Fine Fuel Moisture, DMC = DMC, DC = Drought Code, ISI = Initial Spread Index, BUI = Build-Up Index, CBI = Chandler Burning Index and FWI = Fire Weather Index

Table 2   The percentages of fire days for different classes in Nanjing from 2011 till 2012

Class	FFMC	DMC	DC	ISI	BUI	CBI	FWI
Low	31.42	45.90	35.79	38.11	41.80	43.44	32.51
Moderate	30.87	25.96	25.68	21.99	19.13	27.05	21.58
High	26.50	15.03	23.50	24.86	19.13	21.04	24.86
Very High	10.11	11.75	11.48	13.11	13.93	6.56	16.39
Extreme	1.37	1.64	3.83	2.19	6.28	2.19	4.64

FFMC = Fine Fuel Moisture, DMC = DMC, DC = Drought Code, ISI = Initial Spread Index, BUI = Build-Up Index, CBI = Chandler Burning Index and FWI = Fire Weather Index

Based on the premise that extreme days should be less than 3% of the total study period (Van Wagner 1987), we classified the ranges for the CFFWI System danger classes to suit the local conditions (Table 1). This may be used as guide by local fire managers to understand potential fire behaviour in the region. Table 2 lists the percentages of the CFFWI components and Chandler Burning Index in each danger class. More than 50% days were in low and moderate fire danger classes while less than 10%, in extreme level. Most forest fires occurred in the extreme, very high and high fire-danger classes. Thus, special attention should be paid

to these days with extreme fire dangers and preparation be made for forest fire prevention and firefighting.

CONCLUSIONS

The CFFWI System was utilised for analysing forest fire danger in Nanjing. The components of the CFFWI System reflected accurately the status of forest fires for this region. Spring and autumn were seasons with high possibilities of forest fire dangers, which tallied with history records about the forest fire occurrences in this region.

Wireless sensor network allows 24-hour monitoring of meteorological factors. Due to their low cost and small size, a considerable number of sensors can be deployed in each monitoring area for collecting weather data. The data could used to calculate the components of CFFWI System and achieve better forest fire prevention. Since it is difficult to predict forest fire accurately, the wireless sensor network has proven to be reliable for real-time forest fire detection.

ACKNOWLEDGMENTS

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